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RURAL ELECTRIFICATION WITH THE SHIELD WIRE SCHEME IN LOW-INCOME COUNTRIES

Design, Construction, and Operation

ESMAP MISSION

The Energy Sector Management Assistance Program (ESMAP) is a global knowledge and technical assistance program administered by the World Bank. It provides analytical and advisory services to low- and middle-income countries to increase their know-how and institutional capacity to achieve environmentally sustainable energy solutions for poverty reduction and economic growth. ESMAP is funded by Australia, Austria, Denmark, the European Commission, Finland, France, Germany, Iceland, Japan, Lithuania, the Netherlands, Norway, Sweden, Switzerland, and the United Kingdom, as well as the World Bank.

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ACRONYMS AND ABBREVIATIONS

Ω	ohm
ΔC	increase in capacitance
µf	microfarad
µs	microsecond
ϕ-to-ϕ	phase-to-phase
ϕ-to-Gr	phase-to-ground
3-ϕ	three-phase
1-ϕ-to-Gr	single-phase-to-ground
°C	degrees Celsius
A	ampere
AAC	all aluminum conductor
AAAC	all aluminum alloy conductor
AACSR	aluminum alloy conductors steel-reinforced
AC	alternating current
ACSR	aluminum conductor steel-reinforced
Al	aluminum
ANSI	American National Standards Institute
Arms	root mean square amperes
ATP	Alternative Transient Program
BIL	basic insulation level
C	capacitance
CB	circuit breaker
CEB	Communauté Electrique du Benin
CEET	Electricity Distribution Company of Togo
cm	centimeter
CT	current transformer
Cu	copper
D/C	double-circuit
daN	deca Newton
dB(A)	decibel
DC	direct current
DIN	Deutsches Institute for Normung
DRCC	distribution regional control center
DS	disconnecting switch
Dyn	delta-star with neutral
e.m.f.	electromotive force
EHV	extra-high voltage
EMTP	Electromagnetic Transient Program
f	frequency
g	gram
GIS	Geographic Information System
Gr	ground
HP	horsepower
HSR	high-speed re-closure
HV	high-voltage
HVDC	high-voltage direct current
Hz	hertz
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IP	Protection degree
ISWS	Iliceto Shield Wire Scheme
IT	interposing transformer
k	kilo (1,000 times)
kA	kilo ampere
kArms	root mean square kilo ampere
kg	kilogram
kJ	kilojoule
km	kilometer
kN	kilonewtons
kV	kilovolt
kVA	kilovolt-ampere
kVAR	kilovolt-ampere reactive
kVrms	root mean square kilovolt
kW	kilowatt
kWs	kilowatt × second
L	inductance
LBI	load break interrupter
LV	low-voltage
m	meter
m/s	meters/second
MCOV	maximum continuous operating voltage
MHz	megahertz
LIWV	lightning impulse withstand voltage
LIPL	lightning impulse protection level
mm	millimeter
ms	millisecond
mV	millivolt
MV	medium voltage
MVA	megavolt ampere
MW	megawatt
N	Newton
nF	nanofarad
N.A.	not applicable
OHL	overhead line
ONAN	oil-natural air-natural
OPGW	optical ground wire
P	active power
p.f.	power factor
p.u.	per unit
PLC	power line carrier

PCB	polychlorinated biphenyl
PT	potential transformer
R	resistance
R.I.V.	radio interference voltage
R_g	grounding resistance
R-L	resistance-inductance
rms	root mean square
ROW	right-of-way
s	second
S/C	single-circuit
SA	surge arrester
SF6	sulfur hexafluoride
SIL	surge impedance loading
SIPL	switching impulse protection level
sqm	square meter
sqmm	square millimeter
SW	shield wire
SWER	single-wire earth-return
SWL	shield wire line
SWS	shield wire scheme
SW-to-Gr	shield wire-to-ground
TL	transmission line
TS	technical specification
U_R	rated voltage
UTS	ultimate tensile strength
V	volt
VA	volt-ampere
V-I	voltage-current
V_n	nominal voltage
V_{re}	potential to remote earth
V_1	positive sequence voltage
V_2	negative sequence voltage
VRA	Volta River Authority
W	watt
W/sqm	watts per square meter
X	reactance
ω	$2\Pi f$

"three-phase" ISWS	three-phase MV distribution system that uses two insulated shield wires of an HV line and the earth as the third phase conductor
"single-phase earth-return" ISWS	single-phase MV distribution system that uses one insulated shield wire of an HV line and the earth as the conductor for current return
"single-phase metallic-return" ISWS	single-phase MV distribution system that uses two insulated shield wires of an HV line
"V" ISWS	three-phase MV distribution system that uses two insulated shield wires of an HV line and the earth for the return of current, with "V" connection of the MV/LV transformers
"three-phase three-SWs" SWS	three-phase MV distribution system that uses three insulated shield wires of an HV line (the earth is not used as a conductor)

At the request of the heirs of Professor Francesco Iliceto, and with the agreement of the University of Rome La Sapienza, the Shield Wire Scheme (SWS) technology for the single and two shield wires was renamed as the Iliceto One and Two Wire Shield Wire Scheme, hereafter referred to in the Manual as the Iliceto Shield Wire Scheme (ISWS), in memory of Professor Francesco Iliceto, the inventor of the technology, who wrote this Manual from 2015 until his passing away in April, 2016'.

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The late Professor Francesco Iliceto, Emeritus Professor at the University of Rome 'La Sapienza' and the inventor of the Shield Wire Scheme technology, acted as the consultant and author for this manual. Prof. Iliceto has engineered the realization of the technology in several concrete applications at full industrial scale, for the benefit of rural populations in unelectrified areas.

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EXECUTIVE SUMMARY

PURPOSE OF THE MANUAL

The manual begins with a description of the concept and aims of the Iliceto shield wire scheme (ISWS). The scheme is applicable for minimum cost power supply from the grid to villages, small towns, farms, factories, and water pumping stations located near or at some distance from the route of the high-voltage (HV), 110 to 330 kV, transmission lines (TLs). The ISWS is a solution for rural electrification that is not economically justifiable with conventional solutions, which are long medium-voltage (MV) lines routed along the HV TLs or dedicated HV/MV transformer stations.

ISWS consist of the following:

- Insulating the shield wires (SWs) from the towers of the HV TL for MV operation (20 to 34.5 kV).
- Energizing the SWs at MV from the HV/MV transformer station at one end of the HV TL.
- Using the earth return of current as an MV distribution conductor.
- Supplying the loads by means of medium-voltage/low-voltage (MV/LV) distribution transformers connected between the SWs and the ground.

FEASIBLE ISWSs

Feasible ISWS and differences in comparison with conventional MV distribution lines are described in Chapter 2 and illustrated in Fig. 2.1.

If the HV TL is protected against lightning by one SW, only the "single-phase earth-return" ISWS can be applied for single-phase distribution.

If the HV TL is shielded by two SWs, by using the earth as the conductor of the third phase, a three-phase MV line can be constructed. This setup has been the most commonly applied ISWS in tropical low-income countries, where the TLs have been shielded by two SWs for the most effective protection against lightning. This scheme is referred to in the manual and Annexes as "three-phase" ISWS.

Two insulated SWs may also be used as a single-phase MV line without use of the earth-return of current. This scheme is referred to in the manual and Annexes as "single-phase metallic-return" ISWS.

The feasibility and additional cost of the optional SWS for three-phase electrification without use of the earth as a conductor, which requires the installation of three SWs in the HV TL, is examined in Chapter 14. The manual refers to this scheme as "three-phase three-SWs" SWS. The three SWs SWS has not yet been implemented in any part of the world but it is the view of the writer that this would not be difficult given the extensive calculations and experience accumulated so far with ISWSs.

Several Chapters go into detail on the fundamentals, planning, design, safety, and specification of the ISWSs.

USE OF THE EARTH AS A CONDUCTOR IN ISWSs

Chapters 3 through 9 describe all the technical aspects of MV shield wire lines (SWLs) that use the earth as a conductor. The manual focuses on the physical phenomena that affect the grounding systems used for continuous current flow in the earth, the calculation of the resistance and reactance, and the calculation and engineering of the grounding systems for the earth return of current. Rules are provided for reliable electrical and thermal operation of the grounding systems, with full safety for people and animals. The manual shows that use of the earth as a conductor has the following features:

- Earth is a technically and economically good conductor for rural electrification in regions with low load density.
- Earth has a very small cost: the cost of the grounding rods and conductors to be installed by local labor and used in common with the other conventional functions.
- Losses are very small (resistance per kilometer, at 50 Hz is equivalent to the resistance of an aluminum conductor of 570 sqmm).
- Unlike conventional insulated conductors, earth is not exposed to insulation failures or interruption (short circuits and broken wires cannot occur).
- Maintenance is negligible. Only periodic measurements are required (e.g., every 5 years) of the grounding system's resistance and the step and touch voltages, which can be simply performed with an electronic multimeter. The measurement method is described in Annex E.

Symmetrization of SWLs

Chapter 4 discusses the symmetrization of the SWLs. The inherent geometrical and electrical asymmetry of three-phase SWLs, which are formed by two SWs and the earth conductor, is compensated by the use of un-symmetrical power factor (p.f.) correction capacitors. The asymmetry of the three phases is calculated for cancelling out the asymmetry of the transversal capacitances of the SWL. The compensation of the differences of series impedance of the earth conductor, when necessary, is performed by a resistance-inductance (R-L) circuit inserted in the earth path of the current. The p.f. correction capacitors and R-L circuit are designed to limit the voltage imbalance in any location along the three-phase SWLs within very low values (≤ 1%).

Overvoltages and Their Effects on the Design of Insulation

Chapter 5 discusses overvoltages, which may stress the ISWSs, and their effects on the design of the insulation. It is at first reported that the Alternative Transient Program–Electromagnetic Transient Program computer analyses and many years of ISWSs in operation have shown that the insulation for MV of the SWs does not erode their shielding effectiveness against lightning and for prevention of back flashover. The Chapter also examines switching and temporary (internal) overvoltages, which may stress the insulation, and specifies the design criteria for failure-free operation of ISWSs.

The main message is that the phase-to-ground (ϕ-to-Gr) (that is, SW-to-Gr) operating voltage of the "three-phase" SWLs is equal to the ϕ-to-ϕ (that is, SW-to-SW) voltage, as opposed to the conventional three-phase MV distribution networks where the ϕ-to-ϕ (rated voltage) is √3 times the ϕ-to-Gr voltage. This difference must be taken into consideration in the specification of the rated voltage of the equipment, to avoid the types of errors that have been made in some countries in material procurement and/or construction works, sometimes resulting in equipment failures during commissioning. The Chapter also shows that, in spite of the increase in the ϕ-to-Gr operating voltage by √3, it is sufficient to increase the ϕ-to-Gr insulation levels by only 15 to 20%. The required dielectric tests of the apparatuses and characteristics of the surge arresters (SAs) are specified for the 30 and 34.5 kV "three-phase" ISWSs.

It is recommended to use rigid suspension and tension insulator strings for the SW insulation. The effects of the close electromagnetic coupling between the SWs and the conductors of the HV circuit are also examined and taken into account in the insulation design.

Procurement of Equipment for the ISWSs

Some difficulties had been reported for the procurement of switching equipment with the insulation levels specified for the "3-Phase" ISWSs. The Manual describes in Chapter 5.2.3 and in Chapter 14 two alternative solutions for eliminating the reported procurement difficulties.

Load Capacity and Distance Reach of SWLs

Chapter 6 addresses the load capacity and distance reach of the SWLs. The recommended simplified three-phase symmetrical modeling includes calculation of the voltage drops, voltage rises and power losses, choice of type and cross-section of the SWs, preliminary choice of the kVAR rating and location of the p.f. correction capacitors, and choice of the no-load ratios and regulation tappings of the MV/LV distribution transformers. The Chapter recommends the use of aluminum conductor steel-reinforced (ACSR) with total cross-section in the range of 75 to 125 sqmm and a large percentage of galvanized steel (for example, 37% in ACSR conductors with 7 steel and 12 aluminum wires), which is necessary for ensuring mechanical characteristics adequate for the long spans of the HV TLs.

The Chapter presents curve charts from a parametric study of the loading versus distance capabilities of 34.5 kV three-phase SWLs. Calculations have been performed to ensure a voltage variation that does not exceed ±5% at the LV terminals of all the MV/LV transformers and a voltage imbalance generally ≤ 1%.

In general, the loading capacity of "three-phase" SWLs is about the same as for conventional MV lines with the same rated voltage, length, and loading, with conductors of the same ohmic resistance of the SWs. A 34.5 kV SWL of length 100 km, loads with p.f. of 0.9 uniformly distributed, and SWs of 125 sqmm has a loading capacity of 5 MW.

Single-Line Diagrams of SWL Supply Bays at HV/MV Stations and MV/LV Transformer Stations

Chapter 7 presents the typical single-line diagrams of the supply bays of the SWLs from the HV/MV transformer stations. Two alternatives are described: supply from a dedicated tertiary winding of a main HV/MV power transformer, and supply through an MV/MV interposing transformer (IT). The single-line diagram of a minimum cost, technically acceptable MV/LV pole-mounted distribution transformer station is also recommended. Details are provided on the types and number of MV apparatuses to be used, power and energy measurements, etc.

Calculation of Short Circuit Currents

Chapter 8 presents the calculation of short-circuit currents. The Chapter points out that in “three-phase” SWLs, the only possible short circuits are ϕ-to-ϕ and 3-ϕ. It is recommended to make the calculation with the same simplified symmetrical electrical model as the one described in Chapter 6 for the steady-state analysis. Chapter 8 shows that short-circuit currents that may affect the “three-phase” SWLs are small. For the design of a selective protection system, it is therefore necessary to calculate the minimum short-circuit currents.

Fault Protection and Switching of SWLs and Distribution Transformer Stations

Chapter 9 describes the minimum cost selective protection scheme against the short circuits and overloads of the ISWSs. The protection scheme covers the supply bays of the SWLs, the SWLs, the spur MV lines to the villages, the MV/LV transformers, and the LV feeders. With the exception of a circuit breaker (CB) to be installed at the sending end of each SWL, the other components are protected with fuses. Switching of spur MV lines, MV/LV transformers, and LV feeders is generally done by MV fused cut-outs and LV draw-out fuses. A load break interrupter (LBI) is used only for switching the long MV spur lines.

Chapter 9 recommends criteria for the design of selective protection and coordination, which aims to remove from service the minimum part of the radial ISWS consistent with the requirement of fast-clearing of the faults. LBIs are not recommended for sectioning the SWLs, because experience has confirmed that SWLs undergo only transient faults, which are followed shortly thereafter by successful re-closure.

Environmental and Social Impacts

Chapter 10 addresses environmental and social impacts of SWLs that are implemented in the right-of-way (ROW) of the HV TL. SWLs avoid the acquisition of an independent ROW that is necessary for construction of an independent MV line. Even if the MV line is routed along the HV TL, a widening of the ROW is required. The clearing of the ROW of an independent MV line may have an impact on agriculture and forestry, as well as on the aesthetic of the landscape. In operation, the SWL does not need dedicated periodic bush clearing and patrolling, because these activities are required for the HV TL.

The only additional task is a visual check of the SWL insulators, which is done jointly with the patrolling of the HV TL.

On the social side, the project-affected persons impacted by the acquisition of the ROW of an HV TL equipped with the SWL will have access to electricity without any additional impact. Therefore, the project-affected persons are likely to accept the project.

The LV reticulation in the villages is discussed in Chapter 11. It is the same as in conventional LV rural electrification.

SWLs on HV TLs Shielded by Optical Ground Wires

Chapter 12 specifies the technical requirements for the use of optical ground wires (OPGWs) in SWLs. The Chapter points out that, to preserve the integrity of fiber optic telecommunications capacity, it is necessary to apply OPGWs of low ohmic resistance to limit heating by the load current. The largest parts of the OPGW cross-section are aluminum or aluminum alloy. The usual OPGWs grounded at each tower have the same requirement, because they can be crossed by the high short-circuit currents of the HV TL during the ϕ-to-Gr faults. The OPGWs available in the market are therefore suitable for use in the SWLs. The manual also specifies the accessories to be used for reliable insulation of the OPGWs. One of the SWs of the "three-phase" 34.5 kV SWLs in operation in two countries in Western Africa is an OPGW.

Feasibility of "Three-Phase" ISWS without Use of the Earth as a Conductor

Chapter 14 examines the technical and economic feasibility of SWSs for the three-phase power distribution without use of the earth as a conductor. This solution requires the installation of three SWs in the HV TL that have not been applied so far because the third SW does not appreciably increase the lightning protection efficacy of the TL. The manual discusses in detail the advantages and disadvantages of "three-phase" SWSs with three SWs in comparison with the three-phase two-SW ISWSs discussed in previous Chapters.

Chapter 14 provides three alternative outline drawings, at scale, of the upper part of the towers for installation of the third SW. Details of tower engineering, steel weight increase, and SW stringing are also provided. The Chapter shows that the cost of making electricity available in three-phase distribution at MV to the villages along the route of the HV TL is a small percentage of the cost of a conventional independent MV line. However, the cost of a three-SW three-phase distribution is much higher than the very low cost that can be achieved with a two-SW three-phase SWL. Cost estimates are provided in Section 14.3.

Recommendations

Chapters 15 and 16 provide recommendations for planning the ISWSs: data collection, choice of type, and rated voltage of the ISWS. Chapters 17, 18, and 19 provide recommendations for construction works, commissioning, and operation, paying special attention to differences in comparison with conventional MV lines.

Cost Estimates and Advantages of ISWSs

Chapter 13 reports the cost estimates for implementation of the ISWSs using the earth as a conductor. The cost in Western Africa for insulating the SW(s) necessary for protection against lightning, including the use of ACSR SW(s) instead of galvanized steel or alumoweld SW(s), additional brackets on tower SW(s) peak(s), transport, and installation is estimated at about $1,400/km of TL for two SWs and about $900/km for one SW. Taking into account the supply bay of the SWL in the HV/MV station and the ancillary equipment, the total cost for making electricity available at MV in three-phase distribution in any location along the route of an HV TL with the "three-phase" ISWSs is estimated at approximately $2,650/km for an SWL that is 100 km long. This cost is only about 13% of the cost of a conventional equivalent MV line providing electricity along the route of the HV TL.

The SWLs are part of the HV TL and their maintenance cost is negligible in comparison with conventional overhead MV lines. The SWLs do not need dedicated periodic bush clearing and patrolling, because this work has to be done for the TL.

The cost for the addition of the third SW in an HV TL in Western Africa for application of the "three-phase three-SW" SWS, (without use of the earth as a conductor) is estimated to be between $3,900/km and $4,700/km.

The overall cost of the MV and LV distribution systems in the villages is about the same as for conventional distribution systems.

The main advantages in comparison with the equivalent conventional rural electrification systems can be summarized as follows:

- The cost of SWLs is very low. The ISWS allows rural electrification along the route of HV TLs that are not economically justifiable with the conventional solutions.
- The maintenance costs of SWLs are negligible in comparison with the conventional equivalent MV lines.
- Power losses of SWLs using the earth as a conductor are somewhat lower in comparison with conventional equivalent MV lines.
- SWLs have been affected only by transient faults (generally caused by lightning), causing very short interruptions of service.
- The quality of service at consumer premises is not lower than what is achievable with conventional equivalent MV lines.
- SWLs have no environmental impact and do not require the acquisition of a right-of-way. SWLs have been proven to deter theft of TL components and vandalism.

One of the major causes of reluctance by the customers and utility engineers to application of the technology options of lower cost for rural electrification, such as the Single-Wire Earth-Return (SWER), has been how to serve the 3-phase loads. This constraint is eliminated by the "3-Phase" ISWS that is easily applicable in the TLs which are shielded by two SWs for the effective protection against lightning. Two SWs are recommended in the tropical countries with high keraunic level (≥ 50 stormy days per year).

Examples of Applications of ISWSs and Operational Experience Over Time

Single-line diagrams and photos of the ISWSs in Sub-Saharan Africa, South America (Brazil), and East Asia (Lao People's Democratic Republic) are provided in Annex D. Most of these ISWSs are 30 to 34.5 kV "three-phase" ISWSs using the earth as a conductor. The "single-phase metallic-return" ISWSs has been applied only in three HV TL projects. In Ghana, ISWSs have been in operation for over 25 years.

Operational experiences are reported in Chapter 20 and can be summarized as follows:

- The fault rate of SWLs has not been higher than the fault rate recorded for conventional equivalent MV lines (for the same length, rated voltage, loads, and ambient conditions).
- The effectiveness in protecting against lightning and fault rates of the HV TLs are not affected by the insulation of the SWs for MV.
- The quality of voltage service to consumers has been good: voltage at the LV terminals of the MV/LV distribution transformers is stable, with variations in the range of ±5% above and below the rated voltage.
- ISWSs engineered and built in accordance with the approved technical specifications generally have not undergone any equipment failure. A few failures that have been reported during commissioning were caused by errors in equipment procurement or by work that was not done in conformity with the specifications.
- Use of the earth as a conductor has been trouble-free.

A typical example of the planning and design of two ISWSs is reported in Chapter 21.

Retrofitting ISWSs in Existing TLs and Upgrading ISWSs When Load Increases

The insulation of the SW(s) for MV in existing TLs is generally feasible at low cost, with relatively short interruptions of service of the TLs. However, if the TL is shielded by one SW, only the "single-phase earth-return" ISWS is applicable. If the existing SWs are of galvanized steel, the loading capacity of the SWL will be limited, unless the steel SWs are replaced by ACSR SW(s).

Three examples of retrofitting of ISWSs in TLs existing or that were under construction are described in Section 16.4. Two have been constructed without replacing the existing SWs.

After several years of operation of long SWLs between two HV/MV stations, the construction of a new HV/MV transformer station at an intermediate point of the HV TL may be justified. The new station would serve the load of a town supplied by the SWL that has highly increased. Then the initial two long SWLs can each be split into two shorter SWLs. Two of the thus realized four SWLs will be supplied by the new HV/MV station. Loading capacity of each SWL will be higher and fault rate will be lower. In the town to be served directly by the new HV/MV station, the MV/LV transformers and LV networks will continue to be operated with only minor changes in the MV supply apparatuses (the MV/LV transformers will not be replaced).

Annexes

Annexes A and B provide the complete technical specifications and data sheets for the equipment for the three-phase two-SW ISWSs with rated voltages of 30 and of 34.5 kV.

Annex C provides an extensive set of construction drawings, at scale, for the 30 to 34.5 kV ISWSs using the earth as a conductor.

Annex D is a collection of single-line diagrams and photos of ISWSs in operation.

Annex E provides instructions for the measurement of resistance and the step and touch voltages of the grounding systems during operation, to be performed with a multimeter and a clamp-on ammeter. The method takes advantage of the current-voltage field in the ground created by the injection in the earth of the load current.

OVERVIEW

1.1 INTRODUCTION

In the early 1980s, the author of this manual was planning the long radial transmission line for the electrification of the major towns of northern Ghana with the extension of the high-voltage (HV) network of the Volta River Authority (VRA) in southern Ghana. The VRA's chief executive asked if it would be possible to find and recommend an economically acceptable solution for electricity supply to the many minor towns and villages located along the route of the planned 161 kV line, which was 650 km long. The funding available for the project did not allow rural electrification with the conventional schemes.

The new, unconventional Iliceto shield wire scheme (ISWS) which was conceived to meet the VRA's request, was first successfully field tested in 1985 in a pilot scheme on an existing 161 kV line in southern Ghana. Thereafter, the ISWS was applied extensively for commercial power distribution along the new 161 kV line in northern Ghana. The five ISWSs that were commissioned in 1989, over 25 years ago (see Fig. D.1 in Annex D) are still in operation, except one that has been recently replaced by conventional MV lines. VRA carried out part of the ISWS construction works with its own staff.

On the grounds of the satisfactory operational performance of the ISWSs in Ghana, several other countries have implemented ISWSs, including Brazil, Burkina Faso, Ethiopia, Lao People's Democratic Republic, Sierra Leone, and Togo.

1.2 PURPOSE AND SCOPE

1.2.1 Challenge of Electrification of Remote, Small Communities

In many low-income countries, the new HV transmission lines (TLs) which are built for power supply to major towns, or for connecting remote power plants to the grid, are routed adjacent or not far from highways, along which there are several small towns, villages, and farms without electricity supply. These communities may be located more than 100 km from the closest high-voltage/medium-voltage (HV/MV) transformer station. In many cases, it is not economically feasible to connect these communities to the electricity grid through conventional three-phase MV lines or the addition of HV/MV transformer stations, because of the communities' small power demand and the long distances involved.

In the past, some unconventional schemes have been proposed for rural electrification along the HV TLs. Although there was no significant commercial follow-up, the schemes are worth mentioning here.

1.2.2 Solutions Proposed in the Past for the Electrification of Remote, Small Communities

One scheme consisted of the single-phase supply of small communities by means of induced voltage on a stretch of an insulated shield wire of an HV TL by the capacitive coupling with the HV conductors. A medium-voltage/low-voltage (MV/LV), single-phase distribution transformer was connected between the shield wire (SW) at floating induced voltage and the ground for power supply from the LV winding. This scheme was not followed up because of two major inconveniences. The first was small single-phase power capacity (0.5 kW per km of insulated SW of a 161 kV line) without the possibility of supply of three-phase induction motors. The second inconvenience was that unconventional (electronic power) devices were needed, which were unsuitable for remotely located low-income communities, for keeping in an acceptable range the variation of supply voltage to consumers caused by the normal variation of load.

Another scheme that was proposed was to install three capacitor banks connected between each phase of an HV TL and the ground, to be used as a capacitive divider for the supply of three-phase MV/LV distribution transformers. The capacitor bank kVAR rating had to be of an order of magnitude larger than the kVA of load to be supplied. The scheme had voltage regulation problems versus variable consumer loads, similar to the above-mentioned capacitive induction scheme, to be solved with thyristor-controlled reactors. A budgetary price quotation for a HV/MV capacitor station made by a European manufacturer showed that cost was comparable to the cost of a conventional T-tapping HV/MV step-down transformer station.

A small load could be supplied by inductive-type HV potential transformers (PTs) operating at their thermal capacity, connected between the HV line conductors and the ground, without switching-protection apparatuses on the HV side for limiting the cost. The load that can be supplied with standard commercial PTs is very small (5 to 6 kW per single-phase commercial PT) and the cost per kW is therefore very high. Failure of an unprotected PT causes service interruption of the HV line, usually until the repair staff reaches the site.

Recently, the use of SF6 (sulfur hexafluoride) insulated, special single-phase high-voltage (HV) and extra-high voltage (EHV) transformers has been proposed (see Box 1.1).

The subject of this manual is the ISWS, which has been in commercial use since the late 1980s. The ISWS is conceived as follows (see Fig. 2.1):

- Insulate the SWs of the HV TLs (rated voltage of 110 to 330 kV) for operating at MV (usually at 30 or 34.5 kV). The HV lines are protected against lightning by one or two SWs.
- Use the earth as the conductor of one phase, thus with the insulated SWs creating an MV line, which is a three-phase line if the HV TL is protected against lightning by two SWs, or a single-phase MV line with earth return of current if the HV TL is protected by one SW.
- Energize the shield wire line (SWL), formed as described in the previous bullet, at MV from the HV/MV transformer station at one end of the HV TL.
- Supply the loads by means of MV/LV distribution transformers, with one terminal of primary winding connected to local ground electrodes and the other two terminals ("three-phase" ISWS) or one terminal ("single-phase" ISWS) connected to the SWs.
- Where the loads (villages, water pumping stations, saw mills, factories, farms, etc.) are located at some distance from the route of the HV TL shielded by the insulated SWs, the MV/LV distribution transformers are supplied through spur MV lines with two or one insulated conductors for three-phase or single-phase service, respectively.

BOX 1.1

Single-Phase HV and EHV Special Transformers of Small Rated Power

For several years, a new single-phase high-voltage (HV) and extra-high-voltage (EHV) special transformer of very small rated power has been available in the market, with manufacturer trademark TIP "SF6" Station Service Voltage Transformer. It is a single-phase HV/LV (or HV/MV/LV) SF6 insulated transformer that is reported to possess, in addition to the usual function of potential transformer for supply of the station protection–measuring–control circuits, a power transformer capacity ranging from 25 to 333 kVA, that is, 75 to 1,000 kVA for a set of three pieces according to the specified rating. It was conceived primarily for the supply of the auxiliary services of the HV and EHV stations where medium-voltage (MV) supply from local step-down HV/MV transformers is not available. The manufacturer also supplies a single-phase SF6 insulated HV (or EHV) circuit breaker combined with two disconnecting switches and two earthing switches, for the safe protection and switching of the transformer.

These special single-phase transformers and associated switching-protection apparatuses are also proposed by the manufacturer for installation in a small HV/LV or HV/MV station, for the supply of an isolated village or small town from a nearby HV TL. The investment for a set of three single-phase transformers, of the associated three single-phase switching-protection apparatuses and controls was provided by the manufacturer. The cost is increased by 30% for transport of equipment, civil engineering works, equipment erection, and purchase of HV surge arresters, and estimated as follows in U.S. dollars (with conversion of equipment purchase prices at 1€ = US$1.2):

Rated HV	Rated Power	Cost (US$)
150–170 kV	$3 \times 100 = 300$ kVA	$800,000
150–170 kV	$3 \times 333 \cong 1{,}000$ kVA	$1,200,000
380–420 kV	$3 \times 333 \cong 1{,}000$ kVA	$1,920,000

The HV SF6 equipment requires periodic checks and occasional maintenance. Electrification of several villages and small towns, located along a long HV TL and distant from each other, would need several of the simplified HV/LV or HV/MV transformer stations with expenses several times higher than for application of the ISWSs.

The new SF6 insulated transformers have reportedly been applied as the technically and economically best solution for the supply of the auxiliary services of HV-EHV stations that do not have a local internal MV supply. They can also be economically acceptable for the supply of a single load near the route of an HV TL and located far from any HV/MV transformer station. If the load is small and the single-phase supply is accepted, only one single-phase transformer is required and the investment is attractive. The transformer primary current returns in the earth but is very small (~3 A for a single-phase load of 300 kVA supplied by a 161 kV TL).

The ISWS as outlined above has been commercially applied in low-income countries for rural electrification. In some countries, the initial implementation of the ISWS faced challenges in material procurement and/or construction, sometimes resulting in equipment failures during commissioning. The failures were caused by lack of capacity of the utility's technical staff, consultants, or contractors, who were unfamiliar with the ISWS technology. This manual is aimed at removing the technical barriers to the application of the ISWS, which is a very low-cost electrification technology.

For the sake of completeness, some physical explanations of the phenomena specific to the ISWS are included in the manual. The most important paragraphs for planning, engineering, specification, commissioning, and operation of the ISWSs are in italics.

1.2.3 Iliceto Shield Wire Scheme Solution

In 1989, when most of the "3-Phase" ISWSs were commissioned in Ghana (ref. Fig. D1 in Annex D), the rate of rural electrification in the Northern-Upper regions of the country was almost nonexistent. A survey made in year 2000 showed that the ISWSs supplied a rural population estimated at 180,000, as well as water pumping stations, an oil pumping station, several saw-mills, a rock crushing plant, one harbor in the Volta Lake and a station of the Ghana Broadcasting Corporation.

In Sierra Leone, at the time of writing, a "3-Phase" ISWS supplies at the receiving end the town of Makeni, with a population estimated at ~ 80,000 (ref. Fig. D4 in Annex D) and the town of Magburaka with a spur MV line from Makeni.

In 1996, when four "Single-Phase Earth-Return" ISWSs were commissioned in the Lao People's Democratic Republic, the rate of rural electrification in the Northern regions of the country was almost nil. In 2002–03, when an additional five "3-Phase" ISWSs were commissioned (ref. Fig. D3 in Annex D) the ISWSs supplied ~ 180 villages, including two towns. As of 2015, the "Three-Phase" ISWSs are reported to be all in operation. No information are available to the author on the present status of the Single-Phase Earth-Return ISWSs.

DESCRIPTION OF ILICETO SHIELD WIRE SCHEMES

2.1 TYPES OF ILICETO SHIELD WIRE SCHEMES

Feasible Iliceto shield wire schemes (ISWSs) in high-voltage (HV) transmission lines (TLs) protected by one or two SWs are shown in Fig. 2.1. The rated voltage of 34.5 kV referred to in the circuit diagrams in Fig. 2.1 and in other figures in this manual is the maximum standard medium voltage (MV) in use for public distribution and is suitable for long shield wire lines (SWLs). The ISWSs can of course be implemented for any of the other MVs in use.

Scheme A is applicable in HV TLs protected by one shield wire (SW) for single-phase MV distribution with earth return of current. It is referred to in this manual as *"single-phase earth-return" ISWS.*

Scheme B is applicable for single-phase MV distribution with metallic return of current in HV TLs protected by two SWs. It is referred to in this manual as *"single-phase metallic-return" ISWS.*

Schemes C1 and C2, which differ only in the supply method of the SWL in the HV/MV station, are applicable in HV TLs protected by two SWs. They perform three-phase MV distribution equivalent to a conventional three-phase, three-wire MV line. Schemes C1 and C2 are referred to in this manual as *"three-phase" ISWS,* which is also suitable for supply of loads that consist entirely of three-phase induction motors (water pumping stations, saw mills, etc.).

Scheme D, referred to as *"V" ISWS,* is applicable in HV TLs protected by two SWs. It is conceived as an asymmetrical, three-phase MV distribution ISWS. This SWL is supplied by two phases of the MV winding of a HV/MV transformer, with the neutral of the MV winding solidly grounded, as shown in Fig. 2.1, Panel D. "V" ISWS allows supply of only a small percentage of three-phase loads (induction motors) from couples of "V" connected single-phase MV/LV transformers, as shown in Fig. 2.1, Panel D (the so called "open wye–open delta connection"). Most of the load must be single-phase. Because of this restriction, "V" ISWS was applied in only two commercial ISWSs in the early days, because it is not equivalent to a conventional three-phase MV line. "V" ISWS will therefore not be further dealt with in any detail in this manual.

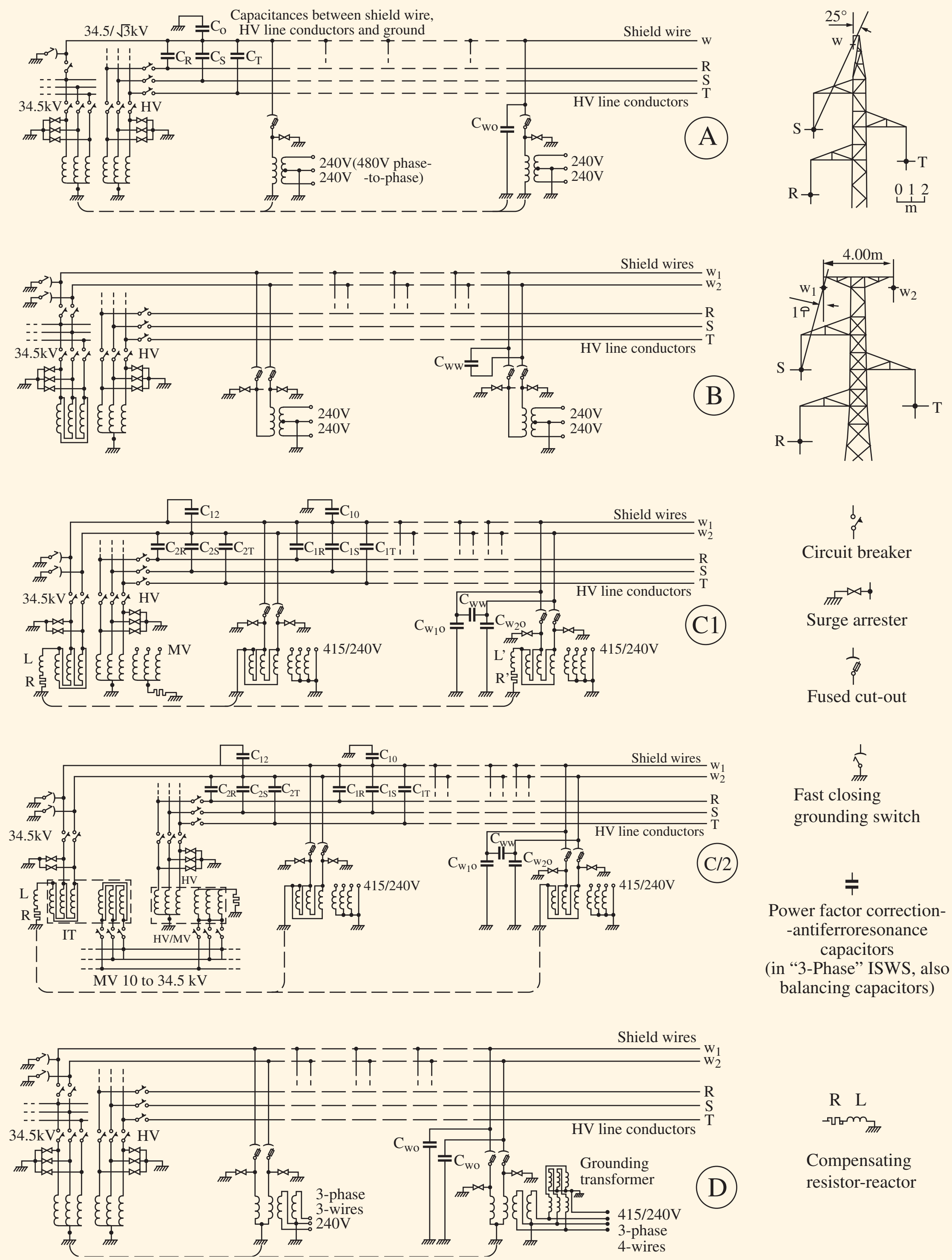
2.2 INSULATION OF SHIELD WIRES: ILICETO SHIELD WIRE SCHEMES WITH THE EARTH AS A CONDUCTOR

SWs insulated for low-voltage (LV) have been used in long, very highly loaded extra-high-voltage (EHV) TLs, for reducing the joule losses caused by the currents induced by the TL conductors in the galvanized steel or alumoweld SWs. Prior to the use of optical ground wires (OPGWs), SWs were also slightly insulated in only a few TLs for telecommunications with the power line carrier technology.

ISWSs require insulation of the SWs for MV (usually 30 to 34.5 kV) instead of insulation for LV as in the above-mentioned applications. However, it has been proven by computer analysis and confirmed by

FIGURE 2.1

ISWSs Applicable to a HV (Vn* 110 kV) Single-Circuit Line



Panel A: "Single-Phase Earth-Return" ISWS; Panel B: "Single-Phase Metallic-Return" ISWS; Panels C/1, C/2: "Three-Phase" ISWS; Panel D: "V" ISWS. Typical line towers are shown for ISWS A on top right and for ISWSs B, C, and D on middle right.

operational experience that MV insulation does not appreciably erode the degree of protection of the SWs against lightning (see Section 5.1).

ISWS schemes A, C, and D have been developed for minimum cost rural electrification along the route of HV TLs, taking advantage of the large experience on the earth return of current gained with the single-wire earth-return (SWER) rural electrification system. The SWER system consists of the construction of MV lines equipped with only one conductor supported by dedicated poles, which are generally supplied as a spur line from a main conventional three-phase MV line for single-phase distribution.

SWER rural electrification has been applied for many decades in New Zealand, Australia, Canada, and, more recently, in Brazil, Tunisia and South Africa.

The ohmic resistance of the earth return path is much lower than that of a typical metallic SW. The resistance is independent of the resistivity of soil and is proportional to the frequency. The reason for this behavior of the earth path is given in Section 3.1, which describes in detail the use of the earth as a conductor. The inductance of the earth path has a value close to the inductance of an SW (see Section 3.1). Use of the earth as a conductor requires care in the design and construction of the grounding systems crossed by the current at the sending end of the SWL, in the locations of the MV/LV distribution transformers, and of the power factor correction capacitors.

The earth return of current used in ISWSs A, C, and D (Fig. 2.1) is the most economic technology, because the cost is only the cost of the grounding electrodes, which is small for the current flows of interest. In the "single-phase earth-return" ISWS (A in Fig. 2.1), the earth return of current is 1 A for every ~20 kVA of load supplied at 34.5/√3 kV. In the "three-phase" ISWS (C1 and C2 in Fig. 2.1), the current in the earth path (third phase conductor) is 1 A for every ~60 kVA of load supplied by a 34.5 kV SWL.

2.3 MV SUPPLY OF ILICETO SHIELD WIRE SCHEMES A, B, AND D

In ISWSs A, B, and D (Fig. 2.1), the supply of the SWL can be made in some cases directly from the same secondary MV winding of the HV/MV transformer that supplies the conventional distribution lines. However, exceptions are the applications requiring an MV higher than that used for the local conventional distribution, for limiting the voltage drop and the losses in long SWLs (length may reach or exceed 100 km). Furthermore, for ISWSs A and D, using earth return of current, the direct supply of the SWL from the MV secondary winding of the HV/MV step-down transformer is practicable only if the MV winding has the neutral solidly grounded, or grounded through a grounding transformer or a neutral reactor of very low homopolar impedance. A low neutral grounding impedance limits the impedance increase of the earth-return path and makes the voltage to ground of the neutral of the MV supply network very small. Evidence of this requirement is provided in Fig. 2.1, Panels A and D. If the MV neutral is high impedance grounded or when the MV is too low for the long SWLs, the supply of schemes A and D is made through an MV/MV interposing transformer (IT), with the secondary winding of rated MV voltage tailored to the load and length of the SWL, to be operated with one terminal grounded (as shown for the "three-phase" ISWS in Fig. 2.1, Panel C2).

2.4 MV SUPPLY OF ILICETO SHIELD WIRE SCHEMES C1 AND C2

In the "three-phase" SWLs (Fig. 2.1, Panels C1 and C2), the conductor of one phase is the earth path, obviously at ground potential. The SWL must therefore be supplied with one of the following alternative schemes providing the necessary galvanic insulation:

- It may be supplied from a dedicated tertiary winding of the HV/MV step-down transformer, with one terminal permanently grounded, as in Fig. 2.1, Panel C1. The SWL is switched and protected by a two-pole circuit breaker (CB).
- It may be supplied through a dedicated MV/MV IT supplied by the MV busbars of the HV/MV step-down transformer station, with one terminal of the winding that supplies the SWL permanently grounded, as in Fig. 2.1, Panel C2. A standard MV CB is installed on the supply side of the IT, for switching and protecting the IT and the SWL as one block (no CB is needed on the SWL side; see Chapter 7, Fig. 7.1, Panel B).

2.5 SUPPLY OF LOW-VOLTAGE LOAD IN ILICETO SHIELD WIRE SCHEMES A, C, AND D

In ISWSs A, C, and D, the loads along the HV line route are supplied by MV/LV conventional three-phase or single-phase distribution transformers. However, one of the MV winding terminals is permanently grounded to local grounding electrodes; the other two MV terminals (Fig. 2.1, Panels C and D) or one MV terminal (Fig. 2.1, Panel A) are connected to the insulated SW(s).

In most cases, the MV/LV pole-mounted transformers are installed at some distance from the HV line, ranging from approximately 100m to several km. Supply is made through spur MV lines with two (in ISWSs B, C, and D) or one (in ISWS A) insulated conductor(s) for the three-phase or single-phase distribution. A perspective of the implementation in a "three-phase" ISWS (schemes C1 and C2) is shown in Fig. 3.2.

2.6 COMMERCIAL USE OF ILICETO SHIELD WIRE SCHEMES C1 AND C2

In most commercial ISWSs built in the past, preference has been given by the utilities to the "three-phase" ISWSs (C1 and C2 in Fig. 2.1). These ISWSs enable the supply of large, three-phase induction motors (rated at 200 kW in one ISWS in Brazil), which are used in water pumping stations, saw mills, corn mills, soy bean dryers, rock crushing plants, etc.

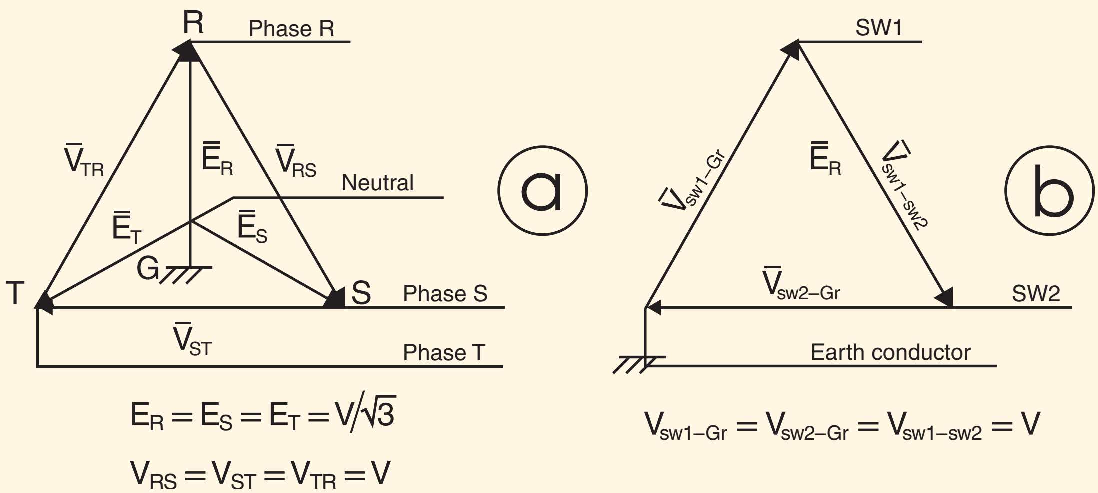
"Three-phase" ISWSs C1 and C2 warrant simplicity of operation and quality of service equivalent to the conventional three-phase MV lines of the same rated voltage and length.

2.7 EQUIPMENT VOLTAGE SPECIFICATIONS OF ILICETO SHIELD WIRE SCHEMES

The voltage vector diagrams of a conventional three-phase MV line and a "three-phase" SWL are shown in Fig. 2.2, Panels A and B. In the conventional line (Panel A), the phase-to-ground (ϕ-to-Gr) voltages in normal operation are $E = V/\sqrt{3}$, where V is the phase-to-phase (ϕ-to-ϕ) voltage (rated voltage). In the

FIGURE 2.2

Voltage Vector Diagrams



Panel A is a diagram of conventional medium-voltage distribution; Panel B is a diagram of "three-phase" ISWS.

three-phase SWL (Panel B), the shield wire-to-ground (SW-to-Gr) voltages are equal to the SW-to-SW voltages (rated voltage V), that is, they are √3 times higher than in the conventional lines.

During the 1-ϕ-to-Gr and ϕ-to-ϕ-to-Gr short circuits, the healthy phase(s) of the conventional MV lines generally undergo a power frequency overvoltage. The amplitude of the overvoltage depends on the neutral status of the MV network: it may be close to the ϕ-to-ϕ voltage if neutral is high-impedance grounded. Overvoltage does not occur in the SWL that uses the earth as a phase conductor.

The insulation of the SWs eliminates the joule losses caused by the current flowing in the SWs when they are grounded in all the towers. These currents are caused by the electromotive forces (e.m.f.) induced by the currents of the HV conductors. The losses are significant only when the currents of the HV circuit are high.

The design, equipment procurement, and construction of the ISWSs consequently require attention to the following phenomena, which are not present in conventional distribution:

1. The operating voltage between the SWs and the ground in the "three-phase" ISWS is equal to the phase-to-phase voltage. For example, in a 34.5 kV, "three-phase" ISWS, the ϕ-to-Gr voltage is 34.5 kV; in conventional distribution, the ϕ-to-Gr voltage is 34.5/√3 = ~20 kV. The choice of the ϕ-to-Gr insulation and rated voltage of surge arresters (SAs) must therefore be somewhat increased, as specified in Section 5.2.

2. There is an electrostatic and electromagnetic coupling between the SWs and the HV conductors. This coupling is present in all the SWLs in Fig. 2.1 and in the prospective ISWSs with three metallic SWs, which are discussed in Chapter 14. The induced transient voltages and currents have been analyzed and taken into account in the design and operation rules specified in this manual.

3. One phase conductor is the earth path. Consequently, the SWL is a somewhat unbalanced three-phase MV line, because of the low resistance of the earth path, and the asymmetrical leakage capacitive currents and electromagnetically induced voltages from the HV conductors to the two SWs and the ground path. Simple balancing means are applied.

Low-cost and dependable solutions for these requirements are described in detail in the respective Chapters of this manual.

A comparative summarizing table of the main characteristics and differences of the various types of ISWSs is provided in Chapter 22.

USE OF THE EARTH AS A CONDUCTOR OF SHIELD WIRE LINES

3.1 ANALYSIS OF RESISTANCE AND REACTANCE

Long, favorable experience with the earth return of current has been acquired over more than half a century of operation of single-wire earth-return (SWER) rural electrification, which has also been applied in countries with high resistivity of soil. And there have been many decades of experience with sea return and earth return of current of high intensity, which is available from the operation of monopolar (single overhead conductor) high-voltage direct current (HVDC) long distance transmission lines (TLs).

Mathematical analysis shows that at 50 and 60 Hz, the path of current in the earth adheres to the route of the overhead conductor. Practically the whole of the current flows in the soil in filaments underneath the line route, through a cross-section of several square km, at depth and width depending on soil resistivity and frequency. If the overhead high voltage (HV) line with insulated shield wires (SWs) has a zig-zag route, the same occurs for the earth return path, which for electromagnetic phenomena must be close to (underneath) the SWs. The situation is entirely different for the sea and earth return of direct current (DC) in HVDC transmission, where current flows at large depth in enormous volumes of the earth, down to the magma (theoretically in the whole Earth) if the HVDC transmission distance is very long.

Analysis shows that, at power frequency, the barycenter of the current filaments under the alternating current (AC) overhead line axis is located at depth D, calculated with the following formula:

$$D = 658\sqrt{\frac{\rho}{f}}\,[m], \qquad (3.1)$$

where ρ *is resistivity of soil (*Ω*m) and f is frequency (Hz). If* ρ *= 100 or 1,000* Ω*m, aand f = 50 Hz, formula 3.1 yields* D_{100} *= 930 m and* D_{1000} *= 2,943 m, respectively. At a distance of 3 to 4 times D from the overhead conductor, the current density in soil becomes practically nil.*

The analysis also shows, and measurements have confirmed, that the ohmic resistance of the earth path is independent of soil resistivity, proportional to frequency (see Box 3.1), and calculated with formula 3.2:

$$r = 10^{-4}\,\Pi^2 f\,[\Omega/km]. \qquad (3.2)$$

At 50 Hz, formula 3.2 yields r = 0.05 Ω/km. This resistance is equivalent to that of an aluminum conductor of 570 sqmm; that is, it is an order of magnitude lower than the ohmic resistance of conductors typically used in rural medium-voltage (MV) lines (0.54 Ω/km at 20°C for an aluminum alloy conductor with a 50 sqmm cross-section). The power losses and resistive voltage drop per km of the earth conductor are therefore very small.

BOX 3.1

Effect of Frequency and Soil Resistivity on the Earth Path Resistance

The higher the resistivity of soil, ρ, the higher the depth, D (see formula 3.1). The earth cross-section in subsoil, S, crossed by the current increases proportionally to the square of D: $S = KD^2 = K \cdot 658^2 \rho/f$, where K is a constant. Then the resistance per unit length of the earth path is:

$$r_e = \frac{\rho}{S} = \frac{\rho}{K 658^2 \frac{\rho}{f}} = K'f$$

That is, resistance is proportional to frequency and independent of soil resistivity.

In a monopolar high-voltage direct current (HVDC) transmission line with sea or earth return of current, the resistance of the earth path is practically nil. Formula 3.2 (in the text) yields $r_e = 0$ for $f = 0$. Only the resistance of the sea or earth electrodes at the two ends of the HVDC line have to be taken into account.

In the earth conductor of a shield wire line (SWL), the resistance of the grounding electrodes of the transformers at the sending and receiving ends must be added to the resistance of the earth path calculated from formula 3.2, to obtain the effective resistance.

Calculation of the reactance of the earth path used as a conductor must take into account the large area crossed by the current in the earth. A precise calculation is performed with Carson's method. Although the barycenter of the current filaments flowing in the earth is at a large distance from the shield wires (formula 3.1), the reactance has a value close to the reactance calculated for each wire in conventional three-wire and two-wire MV overhead lines.[1] The reactance value is not increased by the large distance between the shield wires and the barycenter of the currents in the earth because of the very large cross-section of the earth conductor (several square km) and the consequential importance of the so-called internal flux in the conductor. The influence of soil resistivity ρ on the reactance is negligible, because as ρ increases, the depth D of the current barycenter increases (formula 3.1); the cross-section of current flow also increases (it is proportional to D^2).

In summary, calculations performed with the Carson method yield a reactance of ~0.37 and ~0.44 Ω/km at 50 and 60 Hz, respectively, for the earth path used as a phase conductor in three-phase SWLs. The reactance of each shield wire of a three-phase SWL is calculated with formula 3.3 of the note at the end of Chapter 3, by entering as D the distance between the two shield wires. Typical values are ~0.42 and ~0.50 Ω/km at 50 and 60 Hz, respectively.

In the single-phase earth-return SWLs, Carson's theory yields the following approximate simplified formula for calculation of the total series reactance of the SW and earth return (from Westinghouse, *Transmission and Distribution Reference Book Westinghouse Electric Corporation, East Pittsburgh, 1965, Chapter 3):*

$$x = 0.0029\, log_{10} \frac{658\sqrt{\rho/f}}{kr} (\Omega/km), \qquad (3.3)$$

where kr is the mean geometric radius of the SW.[1]

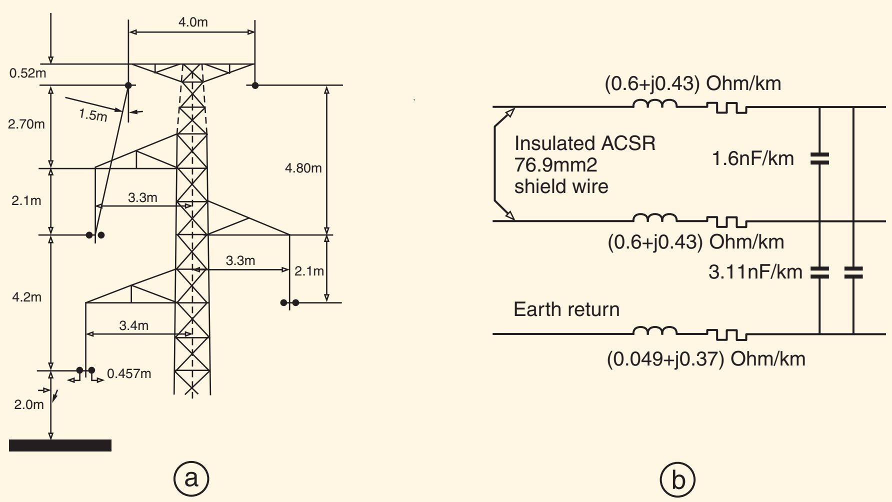
Formula 3.3 yields values of ~0.8 and ~0.95 Ω/km at 50 and 60 Hz, respectively, in soil with resistivity of 300 Ω m and an SW with diameter 12 mm. At 50 Hz, ~0.37 Ω/km can be attributed to the earth return and ~0.43 Ω/km to the insulated SW. The influence of soil resistivity ρ on reactance is quite small, because in formula 3.3 ρ enters as the log_{10} of the square route of ρ. If ρ = 100 Ωm, formula 3.3 yields ~0.77 Ω/km at 50Hz and ~0.34 Ω/km can be attributed to the earth return.

The capacitances between the two SWs, and between the SWs and the HV conductors and the earth, are calculated with conventional methods by computer programs.

Fig. 3.1, Panel A, shows the outline of the upper part of the tangent suspension towers of the single-circuit 161 kV lines with two insulated SWs used in Ghana. Fig. 3.1, Panel B, shows the resistances,

FIGURE 3.1

Diagrams of a Conductor Arrangement and Equivalent Circuit, Kumasi-Techiman-Tamale Line in Ghana



Panel A shows the conductor arrangement in the 161 kV twin bundle conductor line; Panel B shows a simplified equivalent circuit, per unit length of line, of the SWL.

reactances, and capacitances per km of the “three-phase” SWLs, equipped with aluminum conductor steel-reinforced (ACSR) SWs with a cross-section of 76.9 sqmm.

3.2 DESIGN AND CONSTRUCTION RULES FOR THE GROUNDING SYSTEMS

3.2.1 Design Criteria

The SWLs are supplied by a high-voltage/medium-voltage (HV/MV) step-down transformer station (see Fig. 2.1), where the current of the earth phase conductor flows to the ground via the grounding system of the substation, which is usually ≤ 1 Ω or close to this value. In the medium-voltage/low-voltage (MV/LV) distribution stations supplied by the SWLs, one terminal of the transformer MV winding is grounded via grounding electrodes of modest extension, the ohmic resistance of which must be tailored to the primary rated current of the load, to limit the step and touch voltages and ensure thermal stability of the electrodes.

The grounding electrodes for the continuous current flow through the ground must be checked for soil heating, step and touch voltages, and interference with metallic telecommunications lines. The solution for these problems is facilitated by the low values of current flowing in each MV/LV distribution station, and by the large dimensions of the grounding system of the feeding HV/MV stations where much greater currents flow.

It is necessary to prevent the soil from drying out near the grounding electrodes. Drying can be caused by high losses in the soil and consequent temperature rise, because an uncontrolled increase in resistance and power losses in the soil would occur (thermal instability). Soil temperature increase to 100°C or higher would cause the evaporation of soil humidity, progressive increase in electrode ohmic resistance (R_g) and soil heating ($R_g I^2$), arcing in soil near the electrodes, and eventually explosion of soil. To check that this phenomenon will not occur, Ollendorff’s formula should be applied:

$$V_{re} \leq \sqrt{2\lambda\rho\vartheta_e}\ \text{V}, \tag{3.4}$$

where V_{re} = potential of grounding electrode with respect to remote earth (V), ϑ_e = temperature rise of electrode and contiguous soil above ambient temperature (°C), ρ = resistivity of soil (Ωm), and λ = heat conductivity of soil (W/m °C). Formula 3.4 is applicable to grounding electrodes of any shape in soil of uniform electrical and thermal resistivity.

Assuming an ambient temperature of soil of 40°C, ϑ_e should not exceed 60° to prevent fast evaporation of moisture. Then, by assuming for λ the typical value of 1 W/m°C, formula 3.4 yields the following maximum acceptable values of V_{re}:

$$V_{re} = 50 \text{ V for } \rho = 20\ \Omega\text{ m}$$

$$V_{re} = 110 \text{ V for } \rho = 100\ \Omega\text{ m}$$

$$V_{re} = 345 \text{ V for } \rho = 1{,}000\ \Omega\text{ m}$$

If the ground current is 5 or 50 A (~300 or 3,000 kVA, respectively, in a "three-phase" 34.5 kV Iliceto shield wire scheme (ISWS)), and the lower electrode potential limit V_{re} = 50 V calculated for ρ = 20 Ωm (extremely low soil value) is considered, the grounding resistance limit is 50 V/5 A = 10 Ω or 50 V/50 A = 1 Ω, respectively. The corresponding step and touch voltages are low (usually a small fraction of 50 V).

These design criteria are in keeping with those that have been applied in Canada in the SWER rural electrification. The Electrical Utility Regulation in Alberta had stipulated the following limits for the SWER distribution systems: current infeed in individual grounding systems of MV/LV distribution transformer < 10 A, and continuous potential rise of electrodes to remote earth $V_{re} \leq 50$ V. For reasons of safety, multiple grounding electrodes, well separated and loop interconnected, have been applied. The V_{re} limit of 50V is currently considered a safe value.

A typical design of the grounding system of a pole-mounted MV/LV distribution transformer, in non-corrosive soil of low (e.g., 100 Ωm) or medium resistivity, consists of three galvanized steel rods (diameter of 19 mm), about 3 m long, placed at the corners of a triangle with sides of length 4 to 5 m and interconnected by galvanized steel conductors buried at a depth of ~0.5 m (see, for example, Figs. C.5, Panels A, B, and C, in Annex C). In high-resistivity soil (sandy, gravely, rocky, etc.), the grounding system is extended to include the grounding rod of one or a few poles of the supply MV line, paralleled via an overhead ground conductor strung under the energized conductor(s), as shown in Fig. 3.2.

The use of earth as a conductor for rural electrification does not cause technical and safety problems, if care is taken in the design, construction, and commissioning checks of the grounding systems used for the continuous operating current flow to the earth. In particular, attention should be paid to the grounding systems located along the SWL, MV/LV transformer stations, shunt capacitors, and MV/MV transformers in large communities already electrified with MV networks supplied by local (for example, diesel) generators.

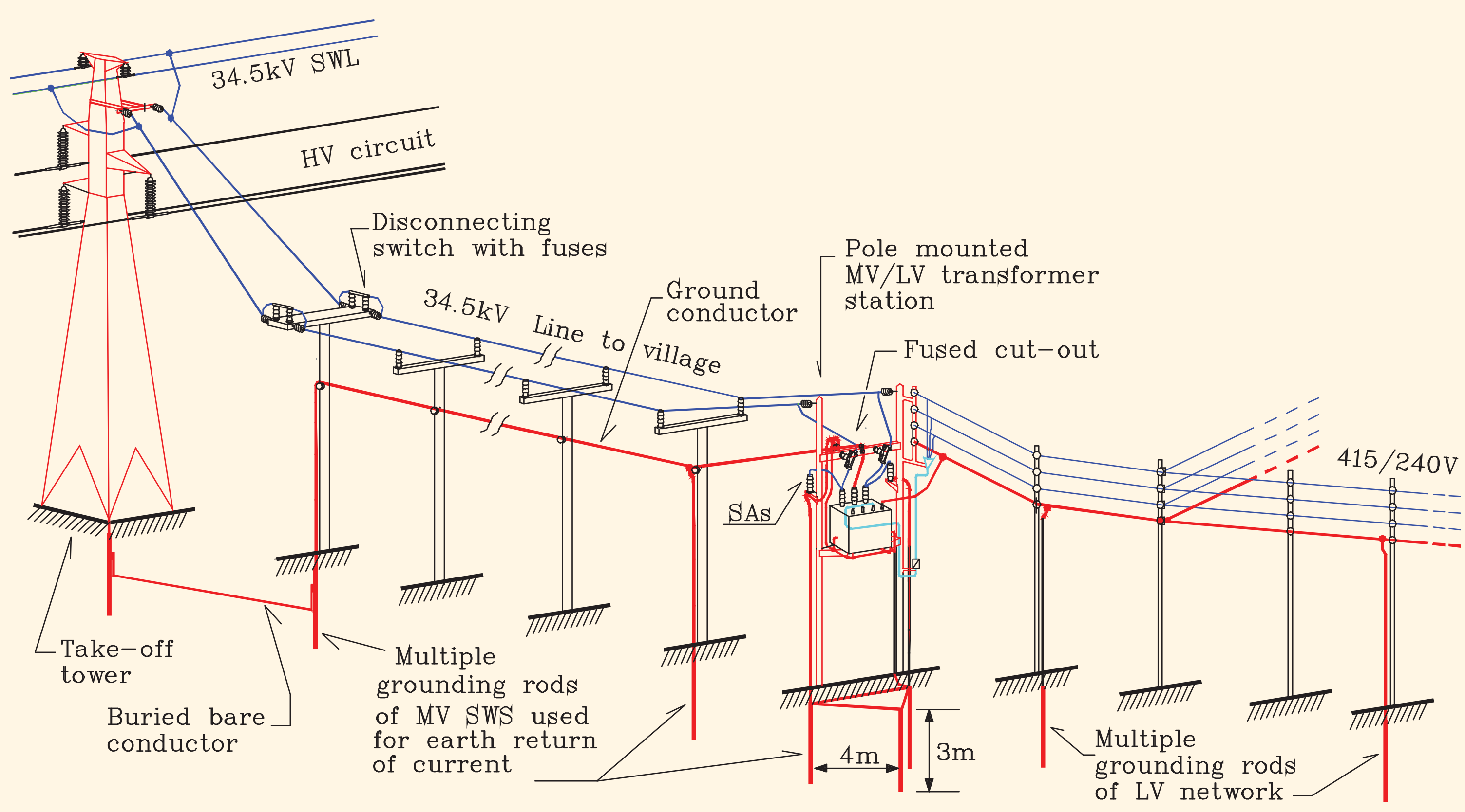
In the HV/MV step-down transformer stations that supply the SWLs, the meshed grounding system usually has resistance on the order of 1Ω. The system is designed to limit the step and touch temporary (short duration) voltages inside and at the borders (fencing) of the switchyard within the limits stipulated by the safety standards (International Electrotechnical Commission (IEC), American National Standards Institute (ANSI), or other) during the short circuit in the HV and MV networks.

The step and touch voltages caused by the use of earth as a phase conductor of the SWLs are continuously present. Therefore, these voltages must be limited within values lower by two orders of magnitude than the values accepted during the short circuits in the HV grids.

In an HV/MV station with grounding resistance of 1Ω, a current flow to the earth of 50 A (corresponding to a load of 3,000 kVA for a three-phase, 34.5 kV SWL) causes a potential to remote earth V_{re} = 50 V. The associated step and touch voltages are usually a few volts and are generally not sensed by people or animals. A value of V_{re} = 100 V may also generally be accepted (load of 6,000 kVA for a three-phase 34.5 kV SWL) consistently with safe values of the step and touch voltages, if the resistivity of the soil is ≥ 100 Ωm, such that thermal stability of the grounding system is warranted (as found by application of formula 3.4).

FIGURE 3.2

Circuit Schematic of Three-Phase Iliceto Shield Wire Scheme Distribution for Villages, Showing Independent Earthing of Medium- and Low-Voltage Networks



3.2.2 Additional Design Considerations and Construction Rules

The meshed grounding systems of the HV/MV transformer stations that supply the SWL are, for other requirements, generally adequate for the earth-return of currents up to at least 50 A, as demonstrated in the previous subsection. It has never been found necessary to lower the station grounding resistance for the supply of the ISWSs that have been constructed so far.

The following paragraphs address the calculation and construction rules of the grounding systems of the MV/LV distribution transformers, MV capacitor banks, and MV/MV interposing transformers that may have to be installed for supply from the SWLs of the towns already provided with an MV network supplied by local generators.

Although a potential to remote earth, V_{re}, of 50 V is accepted by the IEC standards for long-term exposure, a precautionary design rule is to have $V_e \leq 30$ V where this is practically feasible.

The calculations and measurements made for small grounding systems, such as the ones practically feasible for the MV/LV transformer stations, show that the step and touch voltages are generally $\leq \frac{1}{3} V_{re}$, that is, $\leq \frac{1}{3} \times 30$ V = 10 V. This voltage is fully harmless, because it causes a current flow on the human body ≤ 3 mA by assuming the lowest possible resistance of the body in series with low contact resistances with the hands and feet.

Table 3.1 provides the maximum acceptable grounding resistance, R_g, for 34.5 kV three-phase and single-phase distribution transformers and capacitor banks of typical rated power, calculated by assuming V_{re} = 30 V:

$$R_g = V_{re}/I, \tag{3.5}$$

TABLE 3.1
Maximum Acceptable Grounding Resistance Values

RATED POWER OF TRANSFORMER (kVA)[a]	ACCEPTABLE GROUNDING RESISTANCE R_G FOR 34.5 kV DISTRIBUTION TRANSFORMERS	
	THREE-PHASE TYPE (Ω)	SINGLE-PHASE TYPE (Ω)
800	2.25	N.A.
630	2.85	N.A.
315	5.70	N.A.
200	9.00	5.20
100	18.00	10.35
50	18.00	20.70
25	—	20.70

[a] *The table is also applicable for shunt capacitors with the same three-phase and single-phase kVAR.*

where I is the transformer or capacitor rated current. If a small area is fenced around a distribution transformer or capacitor bank because of very high soil resistivity and/or high current flow to the earth, step and touch voltages up to 25 V are accepted inside the area with no access to the public. In this case, the acceptable resistances in the table are multiplied by 2.5, but the step and touch voltages outside the fence must be checked during commissioning to be ≤ 10 to 12 V.

If initially the transformers are loaded much less than their rated power, higher values of R_g are acceptable, in compliance with the V_{re} limit of 30 V. In the future, if V_{re} will exceed 30 V because of load increase, additional grounding electrodes with spacing ≥ 5m will have to be installed for reducing R_g as required.

The total earth conductor resistance is calculated by adding the resistances R_g of the sending and receiving grounding systems to the earth path resistance calculated with formula 3.2. As an example, consider a 100 km long SWL, with $R_g = 1\Omega$ at the sending end and $R_g = 10\ \Omega$ at the receiving end. The total resistance at 50 Hz is:

$$R = 1\Omega + 100 \times 0.05\ \Omega + 10\ \Omega = 16\ \Omega$$

The resistance of the grounding systems may be predominant on the total earth conductor resistance.

The reactance of the grounding systems is small and can be neglected.

In the design of the grounding systems, it should be kept in mind that the value of R_g for an assigned configuration of the grounding system is proportional to the soil resistivity, ρ, that is amply variable from site to site. For example, if $\rho = 3{,}000\ \Omega$m, R_g is 30 times greater than in soil with $\rho = 100\ \Omega$m.

In the selected optimal location of a distribution transformer, ρ may be high. However, there may be a site nearby where the value of ρ is low, because of the use of fertilizers on cultivated land, or because of the permanent presence of water (creeks, fountains), or marshy land, etc. In this case, instead of installing many additional grounding rods in the high ρ location, it may be convenient to parallel, via the ground conductor of the spur MV line or via a buried bare galvanized steel conductor, a few grounding rods installed at the site with low ρ.

3.2.3 Typical Circuit Schematic of a "Three-Phase" Iliceto Shield Wire Scheme

Fig. 3.2 shows in perspective the typical circuit schematic of a "three-phase" ISWS in a village. The figure shows that, to lower the resistance of the grounding system of the MV/LV pole-mounted transformer station, the three interconnected grounding rods can be paralleled to the grounding rods of a few poles of the MV spur line supplying the village from the SWL, by means of an overhead ground conductor strung under the insulated conductors. If soil resistivity is high and the spur MV line is short (a few hundred meters), the above described multiple-rod grounding is conveniently connected to the grounding system of the HV take-off tower of the SWL, which must have as far as possible a low resistance for efficacious protection of the HV TL against lightning: Rt ≤ 10 Ω or ≤ 15 Ω in TLs of 150 and 220 kV, respectively. Fig. 3.2 shows that in the short slack span between the take-off tower and the first pole of the spur MV line, the ground connection is made through a buried conductor.

Fig. 3.2 also shows that the neutral of the LV network is not grounded in the MV/LV transformer station. Multiple neutral grounding is made out in some poles of the LV lines, to have independence of the LV neutral grounding from the MV grounding system. This is necessary for:

1. Avoiding the exposure of the LV neutral that is wired inside the houses, to temporary overvoltages during the short circuits in the MV supply line and in the MV/LV transformer station

2. Avoiding the continuous operation of the LV neutral at the potential of the MV grounding system, which is caused by the current flow to the earth on the MV side, although this potential is small and harmless.

The LV neutral grounding system is considered independent from the local MV grounding system if the potential to remote earth, V_{re}, induced in the LV neutral grounding from the current flowing to earth on the MV grounding system is ≤ 5% of the potential to remote earth of the MV grounding system. In practice, independence is attained, as shown in Fig. 3.2, in general by making the first grounding of the LV neutral in the first or second pole of the LV line(s) some 40 m apart from the MV/LV transformer.

To ensure the safety of people in vicinity of the pole-mounted MV/LV transformers and capacitor banks, it is mandatory to install at least two independent connections to the earthing system of the grounded MV terminal of the transformer and capacitor banks branched between the SW(s) and the ground. It must not be overlooked that, in the presence of only one connection to the earth, the accidental interruption at or below man height (or intentional interruption for theft) would expose people to very dangerous contact with the MV.

In Fig. 3.2, a connection to earth is shown in each of the two poles supporting the transformer. However, additional connections to ground of one transformer terminal are provided by the grounding rods of the ground conductor that is strung in the last few spans of the MV spur line that supplies the transformer (see Fig. 3.2). Security of people is therefore ensured.

3.2.4 Construction Precautions

Additional construction precautions for safety are the following:

- Protect the connection wire to the grounding system of the transformer station inside a sturdy plastic pipe fastened to the pole, with height of 2.5m from the soil.
- Install a bolted clamp (optional) above the plastic pipe for isolation, allowing the measurement of the ground resistance of the individual electrode.
- As a deterrent to theft, do not use copper conductors for the connection to the earth.

As is justified in Chapter 4, a capacitor bank is installed at an intermediate point of each SWL, as shown in the circuit schematics of Fig. 2.1. The capacitor bank has three functions: power factor correction; prevention of ferroresonance; and, in the “three-phase” ISWSs, symmetrization of the SWL. The capacitors that are connected phase-to-ground drain relatively important currents to the earth. Multiple grounding is necessary for safe operation.

No accidents to people or animals have occurred in all the ISWSs that have been in service for many years. The above-described simple and inexpensive design and construction safety rules have been applied, with one exception.[2]

3.3 SAFETY CONSIDERATIONS

The specification, design, and tests of the ISWSs and the relevant components are in conformity with IEC standards. From the point of view of the safety of the operation and maintenance staff and the public, almost all the components of the ISWSs are conventional for installation, operation, maintenance, and ultimate disposal.

The application in the HV TLs of insulated SWs energized at MV is also in conformity with international standards and practice, which allow operation of multiple-circuit HV lines also with circuits of different rated voltage, including HV and MV circuits supported by the same towers. The precautions required for maintenance of the HV TLs with SWLs are the same as for multiple-circuit combined transmission and subtransmission lines.

Use of the earth as a conductor is a peculiarity of the ISWSs, which may be a point of safety worry for engineers and technicians who are not familiar with this technology. More than 60 years of safe operational experience with SWER rural electrification (in Australia, Canada, and New Zealand) is reassuring, as well as 25 years of operation of some ISWSs.

Earth and sea return have also been used for over half a century in HVDC transmission for continuous return of high-intensity direct current (1,000 A and over).

To avoid any technical or safety problem from the use of the earth as a conductor, some simple rules must be applied in the design, construction, and commissioning checks of the grounding systems used for earth current flow, as recommended in this manual and in the Annexes. Care is necessary for the grounding systems located along the SWLs: MV/LV transformer station; shunt capacitors; and interposing MV/MV transformers in large communities previously electrified with MV networks supplied by local (for example, diesel) generators, to be picked up without modification by the ISWSs.

3.4 SUMMARY ON THE USE OF THE EARTH AS A CONDUCTOR IN ILICETO SHIELD WIRE SCHEMES

The design and construction of the grounding electrodes continuously crossed by the current of the distribution transformers and MV capacitor bank installed along the SWL requires some care, although these currents are of low intensity. However, the rules to be applied are elementary and can be easily complied with by the local engineers, technicians, and workers.

The grounding system of the HV/MV transformer stations that supply the SWLs are, for other requirements, generally adequate for the earth return of currents up to at least 50 A (that is, 3,000 kVA in a 34.5 kV "three-phase" ISWS), without any modification.

Interference with the telecommunications lines has not created problems in any of the ISWSs that have been in operation for many years, because use of overhead telephone lines with metallic wires over long distances parallel to the HV lines has generally been eliminated. Box 3.2 shows that SWLs do not adversely affect or interfere with the wired communication lines of railways.

Commissioning and periodic measurements of the potential to remote earth and step and touch voltages are performed with a multimeter. A very simple method is used, as described in Annex E, based on the fact that the operating current is continuously injected in the grounding system for the earth return of current.

BOX 3.2

Comments on the Effects of the SWLs on the Railways Communication Lines

It has been reported that, in the early 2000s, application of an Iliceto shield wire scheme (ISWS) in a high-voltage (HV) transmission line (TL) in Africa was not accepted because of fear of interference with the telecommunications of a railway. This topic has not been dealt with in the literature on shield wire lines (SWLs). Some details are provided here.

In modern railways electrified with alternating current, telecommunications systems are made with fiber optics or at high frequency with electromagnetic waves. There is therefore no risk of interference.

In some railways electrified with direct current, a power-frequency low voltage is applied between the rails in each short railway section to detect the presence of any train on the railway. A train causes a short circuit between the rails. The very small differential electromagnetic force (e.m.f.) between the two rails induced by the load currents of an adjacent SWL with earth return of current cannot interfere with this safety detection system. However, the 3-phase symmetrical load currents of an adjacent HV TL (150 to 230 kV), loaded at surge impedance loading (SIL), induce between the two rails a small differential e.m.f. that is the same magnitude as the e.m.f. induced by the SWL. This induction cannot interfere with the signaling system.

Old railways may have metallic wired telecommunications lines installed along the rails. In this case, the main worry is the e.m.f.s induced by the short circuit currents in the nearby adjacent HV TL and SWL. Analyses have been performed for three-phase 34.5 kV SWLs of 150 to 230 kV TLs, by taking into account the impedance of the usual transformers that supply the SWLs (high-voltage/medium-voltage; medium-voltage/medium-voltage interposing transformer; see Fig. 7.1 in Chapter 7). The analyses show that the one-phase-to-ground (1-ϕ-to-Gr) short circuit currents in the HV circuit are generally higher than the ϕ-to-Gr and 3-ϕ short circuit currents in the SWLs. This difference occurs when the HV network has the neutral efficaciously grounded, as usual, and has short circuit power $\geq$ 300 MVA at the 150 to 230 kV supply busbar of the HV TL, as generally occurs. The e.m.f.s induced by the short circuits of the HV circuits are therefore generally higher than the e.m.f.s induced by the short circuit of the SWL. If the route of the HV TL and adjacent wired telecommunications line is long, protective measures against overvoltages are applied in the telecommunications line, regardless of whether the HV TL is equipped with an SWL.

The continuous flow of the load currents of the HV TLs and SWLs using the earth as a conductor induce e.m.f.s in an adjacent nearby telecommunications line. By assuming the load current of the SWL is 30 A (~1,800 kVA in a 34.5 "three-phase" SWL) and distance from the telecommunications line to the closest SW is 20 m, the induced

BOX 3.2 (CONTINUED)

longitudinal e.m.f. is ~9 V/km in communications wires. Analysis shows that about the same e.m.f. per km of parallel communications wire is induced by the load currents of an HV TL (150 to 230 kV) that is symmetrically loaded at SIL and with the closest conductor at a distance of 20 m, because of the different distances of the three HV conductors. The vectorial sum of the longitudinal e.m.f.s induced by the load currents of the HV circuit, and the e.m.f.s induced by the SWL, is somewhat higher or lower for each component; however, it is in the same range of magnitude.

The protective measures applied in railway telecommunications lines to control overvoltages induced by short circuit currents also compensate the voltage induced by the load currents of the HV circuit and SWL by a large margin.

In conclusion, it is important to note the following features:

- Earth is a technically reliable conductor, appropriate for rural electrification in areas with low load density.
- Use of the earth as a conductor has a small cost: the cost of grounding rods and conductors installed entirely by local labor of low cost in the low income countries. It is used in common for other purposes.
- Losses are very small (at 50 Hz, the earth circuit is equivalent to an aluminum conductor of 570 sqmm).
- Unlike conventional insulated conductors, earth is not exposed to insulation failure or interruption ("short circuits" and "broken wires" cannot occur).
- Maintenance is negligible. Usually, only periodic checks of the grounding systems are performed, approximately every 5 years. Measurement of grounding resistance and touch-and-step voltages is very simple, because they are proportional to the operating current flow to the earth. A description of the method is provided in Annex E.

ENDNOTES

[1] The reactance of three-wire lines with conductors at the corners of a triangle with side D, as well as the reactance of a two-wire line with distance D, is calculated with the following formula:

$$x = 2\pi f \times 0.46 \log_{10} D/kr\,(\Omega/\text{km}), \qquad (3.3)$$

where f is the frequency, r is the radius of the conductors, k is a factor accounting for the magnetic flux internal to the conductor and depending on the conductor material and stranding (type (aluminum conductor steel-reinforced; all aluminum conductor; all aluminum alloy conductor), number of wires, and layers). kr is referred to as the mean geometric radius. Typical values of k are in the range 0.7 and 0.85.

[2] In Ethiopia, only a single-rod grounding was erroneously installed in a single-phase pole-mounted capacitor bank rated at 300 kVAR, injecting 12 A continuously into the earth. The soil surrounding the electrode exploded, caused by thermal runaway, evaporation of soil humidity, progressive increase of ohmic resistance and heating, and arcing in the soil. A simple correction was made as per the technical specification, by paralleling the local grounding rod to the grounding rods of the spur MV line, as shown in Fig. 3.2, such as to comply with Equation (3.4).

4

SYMMERTIZATION OF ILICETO SHIELD WIRE SCHEMES

4.1 VOLTAGE IMBALANCES IN "THREE-PHASE" ILICETO SHIELD WIRE SCHEMES

As reported in Sections 3.1 and 3.2, the resistance of the earth path on long shield wire lines (SWLs) is much less than the resistance of any practical metallic shield wire (SW); the reactance of the earth path is slightly less than the reactance of the SWs. However, the capacitive leakage currents in the air space terminating in the SWs and the earth (third phase of the SWL) are unsymmetrical, because of the diversity of the geometry of the conductor system of the SWL and high-voltage (HV) circuit and the diversity of the voltages between them, which control the capacitive leakage currents in the air. The voltages longitudinally induced in the SWs and earth conductor by the currents flowing in the conductors of the HV circuit are also somewhat unsymmetrical.

These asymmetries cause a small difference of the voltage drops or rises in the SWs and earth path, with the buildup of a small voltage imbalance (negative sequence component, V_2) at the supply premises of the three-phase loads. It is known that the voltage imbalance may cause overheating of the stator and rotor windings of the three-phase induction motors and consequential de-rating of their rated mechanical power.[3]

The IEC standard 50160 therefore specifies that the negative sequence component in the power networks must not exceed 2% of the positive sequence component, V_1 ("in 95% of the 10 minute mean rms [root mean square] values every week"). In some areas with large single-phase or two-phase loads, an imbalance up to 3% is accepted by the IEC standard.

Voltage imbalances (negative sequence component, V_2, in percent of positive sequence, V_1) of ~2% or even larger are continuously present in some conventional distribution systems. In the three-phase system, as a precautionary measure, the Iliceto shield wire schemes (ISWSs) are designed to have a voltage imbalance, when supplied with symmetrical voltages, not exceeding in general 1% in any location along the SWLs.

The three-phase circuit formed by the two SWs and the earth conductor is made electrically symmetrical, with good approximation, by means of the simple, reliable compensating components described in the following subsections. The components introduce complementary asymmetries, entirely devoid of electronic power devices, tailored to cancel out or drastically reduce the inherent asymmetries of the SWL.

4.2 SOLUTIONS FOR VOLTAGE IMBALANCES IN "THREE-PHASE" ILICETO SHIELD WIRE SCHEMES

4.2.1 Compensating Resistor-Reactor

In most "three-phase" ISWSs, the terminal of the transformer winding that supplies the earth conductor of the SWL in the high-voltage/medium-voltage (HV/MV) station is connected to the grounding system of the substation via a compensating resistor–reactor (resistance-inductance (R-L)) (see Fig. 2.1, Panels C1 and C2). The R-L circuit is in fact connected in series with the earth path so that it raises the total voltage drop in the earth path conductor to about the same value as the voltage drops on the SWs.

The "longitudinal" symmetrization by the R-L circuit is very precise if the load of the SWL is concentrated at the receiving end. However, the symmetrization is sufficiently approximated in the most common SWLs with load distributed along their route.

Installation of the R-L circuit is not necessary in SWLs of moderate length, or in SWLs that are long but lightly loaded. In these cases, the longitudinal asymmetries (of voltage drops or rises in the SWs and earth path) are small, within the accepted tolerance.

In special cases, where a long SWL takes over the supply of an existing medium-voltage (MV) network of a town previously supplied by local generators (for example, diesel), an MV/MV interposing transformer (IT) is installed in the town with one terminal grounded on the SWL side. The terminal grounded on the SWL side may be connected to the earth mesh via a second R-L circuit (R′–L′ in Fig. 2.1, Panel C1), sharing the compensation function with the R-L circuit installed at the sending end of the SWL. This was the case of the supply from the Nam Leuk–Muang Cha SWL of the 20 kV pre-existing three-phase network in the town of Muang Cha in the Lao People's Democratic Republic (with a final forecast load of 3,950 kW) via a 34.5/20 kV IT (see Fig. D.3, Panel B, in Annex D).

The practical values of resistance R vary from a few ohms to ~20 Ω for short and very long SWLs, respectively. The resistor is metallic, naturally air-cooled. Practical values of reactance $X = \omega L$ are small (usually $\leq 5\Omega$). In some SWLs, X is not needed and only the resistor R is installed.

It should be noted that the resistor R, where applied, is crossed by the load current of the earth path conductor and therefore partly reinstates the joule losses, which are saved in the inherently low resistance of the earth path.

The R-L circuit is used in "three-phase" ISWSs instead of the neutral grounding resistor or grounding transformer applied in conventional MV distribution; however, their functions are entirely different.

4.2.2 Power Factor Correction Capacitor Bank

The power factor (p.f.) correction capacitor bank, which is installed in the optimal location for voltage regulation along the SWL (see Fig. 2.1, Panels C1 and C2), is delta connected. The capacitor bank is formed by a capacitor branched between the two shield wires (C_{ww} in Fig. 2.1, Panels C1 and C2), which is purposely larger than the capacitors branched between each shield wire and the ground (C_{w10} and C_{w20} in Fig. 2.1, Panels C1 and C2). The asymmetry of the capacitors is calculated to yield currents terminating in the SWs and the earth path that have an asymmetry approximately complementary to the asymmetry of the distributed capacitive currents flowing in the air to the SWs and the earth, which are caused by the voltages between the conductor system of the HV and SWL circuits. The target is to obtain the total capacitive currents flowing to the SWs and the earth (vector sum of the leakage currents in the air and the p.f. correction capacitor currents), which are of equal amplitude and phase shifted by 120° and 240°, respectively.

Chapter 5 explains that the p.f. correction capacitors also have a third function: the elimination of the risk of temporary overvoltages on the SWs, which may be caused by the ferroresonance phenomenon. Therefore, in addition to the symmetrization function, the p.f. correction capacitors of the “three-phase” SWLs always have to be in service. The consequential possibly somewhat leading p.f. compensation during operation at low load of the SWL is accepted without violation of the specified voltage regulation range in any load location.

In general, a capacitor bank calculated for p.f. correction of the load of an SWL from 0.9 to 1 is adequate for the balancing and anti-ferroresonance functions.

4.2.3 Summary of the Symmetrization of “Three-Phase” Iliceto Shield Wire Schemes

In summary, the symmetrization of three-phase SWLs is performed (see Fig. 2.1, Panels C1 and C2) by:

- An R-L circuit in the HV/MV station inserted in the connection to the station grounding mesh of one terminal of the MV winding that supplies the SWL.
- A delta connected p.f. correction capacitor bank with the capacitor branched between the two SWs larger than the capacitors connected from the SWs and the ground.

Details on these components are provided in Annexes A, B, and C.

The load at the sending end of a three-phase SWL is balanced, if the single-phase consumers of the LV networks are statistically equally distributed in the three phases, as is usual in conventional distribution. “Three-phase” ISWSs therefore do not create any imbalance in the supply MV busbars of the HV/MV substations.

4.3 SINGLE-PHASE ILICETO SHIELD WIRE SCHEMES

“Single-phase earth-return” and “single-phase metallic-return” ISWSs (Fig. 2.1, Panels A and B) are equivalent to single-phase loads supplied by HV/MV step-down transformer stations. Checks and, in rare cases, corrective measures may be required for limiting the voltage and current imbalances in the three-phase supply networks. A precautionary rule is that the negative sequence voltage component, V_2, caused in the MV busbars by the single-phase SWL load shall generally be ≤ 1% of the positive sequence component, V_1, as recommended in Section 4.1 for “three-phase” SWLs serving three-phase induction motors.

The load imbalance is the ratio, in percent, of the negative sequence and positive sequence total currents absorbed by the loads.

The balancing requirement is the same as for single-wire earth-return (SWER) rural electrification and similar measures are applicable.

There may be more than one single-phase SWL supplied from an HV/MV substation or by electrically close substations in the same region. In this case, a simple solution is to ensure uniform distribution in the three phases of the MV supply busbars of the single-phase SWLs, as far as possible, to create a three-phase load of minimized imbalance.

In the case of one, two, or three single-phase SWLs supplied by the same MV busbar, the analysis shows that the negative sequence voltage $V_{2,\%} = 100\ V_2/V_1$ is readily calculated with the following approximate formula:

$$V_{2,\%} = 100\frac{\sqrt{P_r^2 + P_s^2 + P_t^2 - P_rP_s - P_rP_t - P_sP_t}}{P_{sc}} \qquad (4.1)$$

where

P_r, P_s, P_t = single-phase loads (kVA) of the SWLs supplied by phases r, s, and t in the node of interest

P_{sc} = three-phase short circuit power at the same node.

When the SWLs originate from different HV/MV substations in the same region, ad hoc computer programs may be used for a precise calculation of $V_{2,\%}$.

If there is only one single-phase SWL with load P (kVA), equation (4.1) yields $V_{2,\%} = 100\ P/P_{sc}$: if $P \leq 0.01\ P_{sc}$, $V_{2,\%} \leq 1\%$. In exceptional cases of a heavily loaded single-phase SWL supplied by a busbar with low P_{sc}, $V_{2,\%}$ might be measured higher than the IEC limit of 2%. Then the installation of a compensating circuit formed by two MV capacitors and one MV reactor, delta connected, can be applied for lowering $V_{2,\%}$ at the supply three-phase busbars to less than 1%. Details are provided in ref. [3] by Iliceto, Gatta, and Cinieri (1994). This compensating circuit has never been needed in the single-phase ISWSs that have been implemented so far.

ENDNOTE

[3] The impedance of a three-phase induction motor for the negative sequence voltage components at rated speed is about equal to the impedance with stalled rotor (start-up impedance). For example, assume that a motor has a start-up current six times the rated current (that is, start-up impedance is 1/6 = 0.167 p.u.). If the supply voltage has a negative sequence component $V_2 = 1\%$ or $V_2 = 2\%$, it causes a negative sequence current flow in the windings of $1\% \times 6 = 6\%$, or $2\% \times 6 = 12\%$, respectively, superimposed to the load current, with a possible de-rating of the motor rated mechanical power. The percent de-rating is however reduced, or entirely eliminated, if the motor is operated at an ambient temperature lower than the maximum specified temperature (usually it is specified +45°C in Sub-Saharan Africa).

OVERVOLTAGES AND INSULATION COORDINATION OF ILICETO SHIELD WIRE SCHEMES

5.1 LIGHTNING OVERVOLTAGES

5.1.1 Lightning Performance of High-Voltage Circuits and SWLs

In the late 1980s, at the conception stage of the Iliceto shield wire scheme (ISWS), computer simulations and experimental investigations were performed, to evaluate the effects of installation of the shield wires (SWs) on the lightning performance of the high-voltage (HV) circuits and associated shield wire lines (SWLs). Attention was focused on the impact of the fault rate and the extinction of the secondary arcs on the SWLs caused by lightning, which can strike the insulated SWs, the HV conductors in case of shielding failure, and the ground in a swath on the two sides of the HV transmission line (TL).

Computer analysis and records of faults and high-speed automatic re-closure of the SWLs in operation confirm the following lightning performance:

- The outage rate of the HV circuit is practically not affected by the insulation for medium-voltage (MV) of the SWs.
- The fault rate of the SWLs is not higher than the fault rate of conventional MV lines of the same rated voltage and length in the same region.
- All the faults of the SWLs that have been in operation since the late 1980s have been transient in nature, as opposed to a certain percentage of permanent faults affecting the conventional MV lines, which require repair work (~7% of permanent faults have been recorded in the 34.5 kV lines in northern Ghana). Details on physical phenomena associated with lightning, the computer analyses, the experimental investigations, and statistical records of the operations are reported in references [2] (1989), [5] (1999), [6] (2000), [9] (2002) and [10] (2004).

Highlights of the physical phenomena are provided in the following sub-sections. Some details on the operational performance records of ISWSs are provided in Chapter 20.

- Because of the usually long spans of HV TLs and the high mechanical reliability required for the components of TLs, the SWs have been insulated with suspension insulators, with only one exception for an HV TL that was under construction, where fiberglass-silicon rubber post–type composite insulators have been installed on top of the SW tower peaks for implementing a single-phase earth-return ISWS (porcelain post-type insulators were not available in the market for the necessary cantilever strength).
- Fig. 5.1 shows the rigid, toughened glass insulator strings, which have been applied in 34.5 kV SWLs built in tropical countries. The cap of one disc and the pin of the adjacent disc are made of one piece.

5.1.2 Use of Rigid Insulator Strings

Reasons for giving preference to rigid insulator strings are the following:

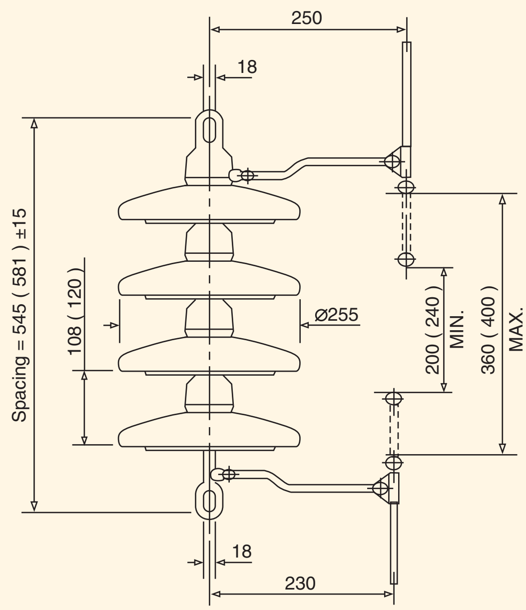
- The gap spacing between the arcing rod-gap is kept constant at the specified pre-adjusted value, regardless of external actions (wind, etc.).
- Total string length, including fittings, is less than the length of a conventional equivalent insulator string.
- Cost is moderate, not higher than the cost of a conventional cap-and-pin insulator string and fittings.

The arcing rod-gap (Fig. 5.1) must be sturdy and the relevant bolts must be securely tightened, because they can be crossed by high-intensity lightning currents.

On the basis of the many years of very good operation experience, preference is to be given to the above described toughened glass rigid insulator strings which warrant a very long industrial life and allow the visual assessment of their operational status during the usual TL patrolling, because a faulty glass disc, if any, is completely shattered. There are toughened glass insulator strings which have been in operation in Europe for over 50 years and are still in good status.

FIGURE 5.1

Rigid Toughened Glass Insulator String for 30 to 34.5 kV "Three-Phase" and "Single-Phase Earth-Return" Shield Wire Lines



- Dimensions are in millimeters
- Dimensions and withstand voltages in brackets apply for disc spacing of 120 mm
- Wet 50 Hz-60 s withstand voltage________130 (143) kVrms +)
- Dry 1.2 / 50 us impulse withstand voltage __ 270 (295) kVpeak +)
- Creepage distance ____________________ 1200 mm
- Electromechanical falling load __________ Ø50 kN

+) without arcing horns

Fibre glass-silicon rubber insulators do not have an operation experience of equivalent durability and may require climbing on tower top for location of faulty units. Porcelain rigid cap and pin insulator strings can also be successfully applied, if porcelain is of high quality, suitable for manufacturing of HV insulators.

The operating voltage of the insulated SW(s) is very small (negligible) compared with the very high potential of the lightning leader approaching the ground. The shielding efficiency (capacity to intercept lightning) is therefore unchanged.

5.1.3 Behavior of Shield Wire Lines during a Lightning Strike

When lightning strikes an insulated SW or a tower, the closest protective gaps of the SW insulators will spark over and ground the SW through the arc, thereby raising the level of current of the lightning which is liable to cause back-flashover in the HV circuit to the same level as occurs in HV TLs protected by conventional grounded SWs. The gap spark-over will initiate a short circuit to the ground on the SWL, which will be tripped by the protection relays in the supply HV/MV station, unless the power arc self-extinguishes quickly, as may occur if the fault current is small. This behavior is typical of all conventional MV lines.

After trip-off of the circuit breaker (CB) of the SWL, a secondary arc current may flow in the ionized air path at the fault location because of the capacitive and electromagnetic voltage induction from the HV circuit. These secondary arc currents may reach 4 to 5 A in a 100 km long SWL, during a one-phase-to-Gr fault or one-open-phase condition in a 161 kV HV circuit. Laboratory tests and extensive operational experience of SWLs have shown that the secondary arc currents self-extinguish in all cases.

The back-flashover phenomenon of typical HV TLs with insulated SWs or conventional grounded SWs has been analyzed and compared with the Alternative Transient Program/Electromagnetic Transient Program (ATP/EMTP) program (reference [9] (2002)). The analysis shows that, if an SW is insulated and energized at 34.5 kV, the lightning current causing the back-flashover in the HV circuit is reduced only very slightly (by ~5% and ~4% in 161 kV and 230 kV TL, respectively). The effect on the back-flashover rate is negligible. However, if desired, it could be cancelled out simply by reducing the average tower grounding resistance by the same amount (e.g., to 9.5 Ω in 161 kV TL towers that have 10 Ω grounding resistance).

The SWs are on top of the TL towers. Their average height above ground is therefore greater (about twice as high) than the average height of the conductors of a conventional MV line. This geometric status widens the swath on the two sides of the HV TL where lightning may strike the SWs or the nearby ground, causing electromagnetically induced overvoltages on the SWs which can exceed the withstand voltage of the SW's insulation.

However, statistical records of SWLs in operation have shown that the increased lightning fault rate of SWLs caused by the widened collection swath of lightning by the SWs is compensated by the following features of the SWLs:

- The lightning impulse withstand voltage of the insulators of SWs with typical characteristics (as in Fig. 5.1) is higher in comparison with the insulators of conventional MV lines.
- SWLs do not have arcing or faults to vegetation.

- Because of the large distance between the SWs (generally at least 3 m), there is negligible risk of SW-to-SW short circuits that may be caused by wind gusts or big birds.
- There is low risk of HV TL tower collapse or flashovers on SW insulation caused by bush fires.
- The "three-phase" SWL and "single-phase earth-return" SWL have one insulated conductor less than a conventional MV line (the earth path conductor is not subject to insulation failure (short circuits) or interruption (breakage)).

In summary, if the coordination and setting of the protections (relays and fuses) are correct, the overall fault rate of SWLs is not higher than the fault rate of conventional MV lines of the same rated voltage, length, and route of installation. The SWLs are not exposed to the permanent faults that sometimes occur in conventional MV lines.

5.2 INSULATION LEVELS AND COORDINATION

5.2.1 Basic Requirements

The designers and contractors in charge of the engineering, material procurement, and construction of ISWSs should keep in mind the following simple, inherent features of ISWSs and act in accordance:

1. One of the phase conductors of "three-phase" and "single-phase earth-return" ISWSs is the earth path, that is obviously permanently grounded (see Fig. 2.1, Panels A, C1, and C2). By contrast, in conventional three-phase ML lines, it is the neutral that is usually grounded, solidly or through an impedance.
2. Consequently, in three-phase SWLs, the shield wire-to-ground (SW-to-Gr) operating voltages are in reality phase-to-phase (ϕ-to-ϕ) voltages, with a root mean square (rms) value equal to the SW-to-SW voltage (Fig. 2.2, Panel B). By contrast, in a conventional three-phase MV line, the ϕ-to-Gr voltages are the ϕ-to-ϕ voltage divided by $\sqrt{3}$. For example, in a conventional three-phase, 34.5 kV line, the ϕ-to-Gr voltages are $34.5/\sqrt{3}$ kV ≅ 20 kV; in a "three-phase" 34.5 kV SWL, the SW-to-Gr voltages are 34.5 kV.

The above basic difference between ISWS and conventional MV lines must be considered in the specification of the following:

- The rated voltage and maximum continuous operating voltage (MCOV) of the surge arresters (SAs) connected between the SW(s) and the ground
- The rated primary winding voltage of the MV/LV single-phase distribution transformers (which is the ϕ-to-ϕ voltage, not the ϕ-to-Gr voltage)
- The ϕ-to-Gr factory acceptance test voltages and creepage length of the insulators of the apparatuses and the SWLs.

5.2.2 Important Equipment Specification

Misinterpretation of the above features by utility staff and contractors who were not familiar with the ISWS has caused erroneous specification of some equipment, which failed during commissioning of the ISWSs. Some information is provided here to prevent repetition of the same errors in any future ISWS.

In two 34.5 kV "three-phase" ISWSs, single-phase distribution transformers with rated primary voltage of 20 kV were connected SW-to-Gr. When energized at 34.5 kV, they were over fluxed by a factor √3 and failed after a short time.

In the "three-phase" ISWS, the primary voltage of the single-phase distribution transformers (if applied) and the potential transformers installed in the supply bay of the SWL in the HV/MV station, as well as the rated voltage of the single-phase power factor (p.f.) correction capacitors, must be specified to have the same rated voltage of the three-phase equipment, that is, the rated voltage of the ISWS.

In some 34.5 kV "three-phase" ISWSs, SAs connected SW-to-Gr with MCOV = 27 kV, and rated voltage U_r = 33 kV were installed, which are suitable for a conventional 33 to 34.5 kV network with grounded neutral where SAs are normally energized at 19 to 20 kV. Energization at 34.5 kV of SAs with MCOV = 27 kV caused the failure. The SAs for the 34.5 kV ISWSs (maximum operating voltage 36 kV) were specified to have MCOV of 38 kV and rated voltage U_r = 47 kV.

Extensive computer analyses of the switching and temporary overvoltages have been performed for the "three-phase" ISWSs. Details of the simulations and results are reported in references [2] (1989), [3] (1994), [5] (1999) and [6] (2000).

Analyses have shown that the increase of the ϕ-to-Gr operation voltage in the "three-phase" ISWSs by the factor √3 (i.e., by 73% over the ϕ-to-Gr voltages of conventional MV networks of same voltage level) requires the increase of the ϕ-to-Gr lightning impulse and 1′ power frequency withstand voltages of the equipment by only 15–20% above the test voltages specified by the International Electrotechnical Commission (IEC) Standards 60694 for the conventional MV networks of same rated voltage.

This favorable pattern stems from the fact that in the ISWSs A, C1 and C2 of Fig. 2.1 one phase is permanently grounded. Therefore, the SW(s) (energized conductor(s)) are not exposed to the power frequency temporary overvoltages that affect conventional three-phase MV networks: in particular, the overvoltages in the healthy phases during the 1-ϕ-to-Gr short circuits in conventional networks, operated with neutral not solidly grounded. This feature allows transformers of ISWSs to be effectively protected by SAs.

For example, the equipment to be applied in the "three-phase" and "single-phase earth-return" ISWSs with rated voltage U_r = 34.5 kV (maximum operating voltage of 36 kV) shall be specified to be tested ϕ-to-Gr at 200 kV peak lightning impulse and at ~82.5 kV rms wet power-frequency for 1′, instead of 170 kV peak and 70 kV rms, respectively, which are usual in conventional 34.5 kV three-phase networks.

It is important to note that the test voltages across the open contacts of switching apparatuses and between the phases of all the equipment used in the ISWSs do not need to be increased, because the overvoltages between the open contacts and between the phases are practically the same in ISWSs and conventional MV networks of the same rated voltage.

The increase of the ϕ-to-Gr test voltages of the MV/LV transformers, MV/MV interposing transformers (if any), and capacitor banks does not cause procurement problems, because these components are designed and manufactured for the test voltages specified by the purchaser. Incidentally, the MV winding of the 34.5 kV/LV distribution transformers can be manufactured with basic insulation level

(BIL) = 200 kV peak with enameled wire, that is, with the simple conventional insulation technology in use for BILs ≤ 170 kV peak.

SAs have a modular design. Manufacturers' catalogues of SAs include rated voltages, U_r, and MCOV of the values (or very close to the values) of interest, including the SAs with $U_r \cong 47$ kV and MCOV ≅ 38 kV suitable for the "three-phase" and "single-phase earth-return" 34.5 kV ISWSs.

5.2.3 Procurement of Iliceto Shield Wire Scheme Equipment

There may be difficulties in the procurement in the European market of load break disconnectors, fused cut-outs, potential and current transformers, circuit breakers (if needed), and earthing switches with ϕ-to-Gr BIL = 200 kV peak and power frequency test voltage of 82.5 kV rms. In this case, the project can use apparatuses with rated voltage of 38 kV, as per IEC standard 60694, Table 1b, Rated Insulation Levels of Series II, North American Practice, which specifies a ϕ-to-Gr BIL = 200 kV and 1′ power frequency test voltage of 95 kV rms dry and 80 kV rms wet. These withstand voltages are adequate for the 34.5 kV ISWSs.

However, there is an alternative solution for any difficulty in the procurement of switching distribution apparatuses with the required ϕ-to-Gr insulation levels. The solution stems from the fact that the switching and temporary overvoltages have amplitudes proportional to the operating voltage. If the operating voltage is decreased by ~15%, for example, from 34.5 kV to 30 kV, the ϕ-to-Gr factory test voltages of the apparatuses can be reduced in the same proportion. That is, BIL at $200 \times 0.85 = 170$ kV peak and 1′ power frequency test at $82.5 \times 0.85 = 70$ kVrms. These are the ϕ-to-Gr test voltages specified by IEC standard 60694, Series I, European Practice for Apparatuses, with rated voltage of 36 kV, for which there is easy commercial procurement, and which can be applied in "three-phase" ISWSs with rated operating voltage of 30 kV.

In many cases, SWL rated voltage of 30 kV (maximum operating voltage 31.5 kV) can be chosen instead of 34.5 kV, when 30 kV has a distance reach and loading capacity sufficient for the areas to be electrified.[4]

The creepage distance of the insulators of "three-phase" and "single-phase earth-return" ISWSs should be, for each kV of rated voltage, 25 to 28 mm in clean agricultural areas and 35 to 40 mm in areas with moderate contamination.

5.3 INTERNAL OVERVOLTAGES THAT CAN AFFECT ILICETO SHIELD WIRE SCHEMES

5.3.1 Ferroresonance: Explanation of the Phenomenon and Preventive Measures

The phenomenon of ferroresonance has been analyzed with the EMTP at the University of Rome. The results are provided in reference [2] (1989). Only a physical description is presented here, as well as a simple rule for dependably preventing the buildup of the phenomenon.

With reference to Fig. 2.1, Panel A, consider opening the CB that supplies the SWL. The isolated SW has distributed electrostatic couplings with the HV conductors and to the earth, approximated by the lumped capacitances C_R, C_S, C_T, and C_O. The medium-voltage/low-voltage (MV/LV) transformers branched between the SW and the ground, if operated at no-load, are equivalent to a saturable magnetizing inductance, L_{TR}, which is nonlinear and largely variable with the energization voltage; it becomes low when the magnetic cores saturate (magnetic induction B > ~2 Tesla).

The circuit diagram in Fig. 2.1, Panel A, shows that the transformers' inductance, L_{TR}, is in parallel with C_O. If $\omega L_{TR} < 1/(\omega C_O)$ ($\omega = 2\pi f$), the $L_{TR} - C_O$ circuit is equivalent to an inductance, L'_{TR}, that is also variable with the energization voltage. If the CB supplying the SW is open, the SW is at floating potential: the SW behaves like a "connection busbar" between the capacitances C_R, C_S, and C_T and the series connected inductance L'_{TR}. Because of the variability of L'_{TR}, the circuit may go in resonance and put the SW at high distorted overvoltage to ground. It is a classic ferroresonance phenomenon, which might also affect the ISWSs in Fig. 2.1, Panels C and D.

The ferroresonance might be ignited by some switching maneuvers or faults of the SW(s) and the HV circuit.

It is important to note that the phenomenon might occur only if the MV/LV transformers are at no-load or extremely lightly loaded. If a small load is supplied (very low percent is sufficient), the equivalent resistance of loads in parallel with L'_{TR} eliminates the risk of ferroresonance overvoltages.

The phenomenon of ferroresonance is eliminated in any operating condition by installing a capacitor, C_{wo}, between each SW and ground (see Fig. 2.1, Panels A, C, and D), calculated such as to make capacitive the reactance formed by C_o, C_{wo}, and L_{TR} in parallel. The resonant circuit is in this manner transformed into a capacitive divider with the SW in the middle and renders very small (not dangerous) in any possible event the induced power frequency overvoltages on the SWL when it is switched off at the sending end. Analyses have shown that the anti-ferroresonance capacitors C_{wo}, should have a rated kVAR at the rated voltage of the SWL ≥ 20% of the aggregate power of the MV/LV transformers connected to the SWL.

The capacitors C_{wo} also perform the p.f. correction. In the "three-phase" ISWS (Fig. 2.1, Panels C1 and C2), jointly with the capacitor $C_{w,w}$ connected between the two SWs, they form a three-phase capacitor bank, which also performs the symmetrization function described in Chapter 4, and limits switching overvoltages. Because of their use as a p.f. correction, the necessary capacitors C_{wo} generally do not cause an increase in cost.

A safety rule is to forbid the operation of the SWLs open at floating potential, exposed to switching overvoltages (see next paragraph) and to low but long duration induced overvoltages. The rule is to operate the SWLs either energized from the HV/MV station, or grounded automatically in the same supply station by a fast-closing (spring operated) grounding switch. Closure is initiated by the manual or automatic opening of the SWL.

In summary, the following operation rule is to be applied:

The SWLs shall be either in operation energized from the HV/MV stations, or solidly grounded. The SWLs will be open and un-grounded at the sending end (that is, with the grounding switch momentarily open) only during the short time interval before the manual energization and, if it is applied, during the dead time before the automatic high-speed re-closure.

To remove any worry, it is worth noting that the application of the p.f. correction–anti-ferroresonance capacitors backed for redundancy by the fast-closing grounding switch has prevented the buildup of ferroresonance in all ISWSs, some of which have been in operation for 25 years.

5.3.2 Switching Overvoltages

Switching overvoltages are caused by the: closing and opening maneuvers of switching apparatuses (CBs, load break interrupters (LBIs), and fused cut-outs); ignition and clearing of faults; and high-speed re-closure of the lines. The duration of these overvoltages is very few cycles (in many cases, only one or two cycles).

Extensive analyses of switching and temporary overvoltages have been performed with ATP/EMTP, with the methodology and rigor in use for extra-high-voltage (EHV) transmission systems. The simulated events, applied system models, and results of the analyses are reported in references [2] (1989), [3] (1999), [5] (1994) and [6] (2000).

Analyses have shown that the switching overvoltages that may affect the single-phase earth-return and "three-phase" ISWSs are generally low (≤ 2.1 p.u., 1 p.u. being the peak value of the rated voltage sine wave). However, an exception is the case of an HV circuit that is shunt compensated by shunt reactors and is switched on as one block with pre-connected shunt reactors to limit power frequency overvoltages. Analyses have shown that, if the HV shunt compensated circuit is switched on when the SWL is energized, an overvoltage much larger than 2.1 p.u. might build up in the SWL. Analyses have also shown that the shunt compensated HV circuit, in open and un-grounded status, may undergo important induced overvoltages from the SWL if it is in energized status.

The following operation rules should therefore be applied when the HV line is shunt compensated:

- If the HV shunt compensated line is switched off for any reason, the SWL shall also be automatically switched off at the same time.
- An SWL can be continuously in service only if the shunt compensated HV circuit is also in service or if the HV circuit is de-energized and grounded. The SWL shall not be operated with the shunt compensated HV circuit open at floating potential.
- Prior to switching on a shunt compensated HV circuit, the SWL will be switched off and re-energized after closing the HV circuit.
- The rule in the second bullet should also be applied for normal, non-shunt compensated HV TLs.

Operational experience has shown that the faults of the SWLs have been transient in nature, almost entirely caused by lightning. In most of the ISWSs, the SWLs are successfully re-closed manually by the operators after a few minutes. In some cases, automatic delayed re-closure has been applied.

Analyses have shown that automatic high-speed re-closure (HSR) is also applicable to SWLs (references [3] (1994) and [5] (1999)).

The switching overvoltages in the SWLs caused by HSR depend on the HV circuit and SWL configuration, the type of fault in the SWL (SW-to-Gr or three-phase) with or without simultaneous fault in the HV circuit, etc. Maximum amplitude of the HSR switching overvoltages is limited by the SAs within 2.1 p.u.: overvoltages are lower by a large margin than the insulation levels recommended in Section 5.2.

The small secondary arc current that flows at the fault location from the SW to the ground after the tripping of the SWL CB in the HV/MV supply station (Section 5.1) is generally self-extinguished if the dead time before the HSR of the SWL is appropriately set (time to be adjusted on the basis of the recorded success of re-closure in operation). The SWL remains un-grounded (grounding switch open) during the dead time before re-closure.

The HSR of the SWLs is expected to be successful in most cases, as is usual for HV and EHV TLs. In case of unsuccessful re-closure, the SWL will be automatically switched off, for a follow-up manual re-closure by the operators a few minutes thereafter, which is generally successful.

Many years of operation experience have confirmed that the insulation of the SW(s) of the HV (115 to 230 kV) TLs does not create limitations of the usual operation rules of the HV circuits. The ATP-EMTP analyses have shown, and operation experience has confirmed, that the high-speed single-pole reclosure (HSSPR) of the HV circuits is applicable without restrictions and with the same probability of success if the TL is provided with a SWL.

As to the SWLs, ferroresonance overvoltages are prevented to occur by the antiferroresonance capacitors (see Section 5.3.1). The temporary overvoltages induced by the 1-ϕ-to-Gr faults in the HV circuit and by the operation with one open phase before the HSSPR, are limited within 1.5 p.u. if equation (5.1) is complied with and are of short duration, harmless for the insulation of the SWLs. In summary, the various switching manoeuvres and short circuits of the HV circuits do not cause damages to the SWLs, which are to be operated with the rules dealt with in this Chapter and in Chapter 19.

5.3.3 Temporary Overvoltages

Temporary overvoltages have a long duration, ranging from a fraction of 1 second to a few minutes. In most cases, temporary overvoltages have a sine wave shape at power frequency; in some cases, the voltage pattern versus time is distorted because of the non-linearity of some system components. The ferroresonance phenomenon dealt with in Section 5.2 is a very distorted temporary overvoltage caused by transformer core saturation. Ferroresonance is fully and dependably prevented in a simple manner, as described in Section 5.2, and is not a concern.

Insulation coordination of the ISWSs requires attention to be given to the temporary overvoltages induced in the SWL during the 1-ϕ-to-Gr faults in the HV circuit, which are approximately proportional to the inducing short circuit current, $I_{1\phi,sc}$ (kArms symm) and to the SWL length, L (km); the most critical 1-ϕ-to-Gr fault location is the receiving end of the SWL.

Analyses have shown that if:

$$I_{1\phi,sc} \times L \leq 250\,\text{kA} \times \text{km}, \qquad (5.1)$$

the induced overvoltages SW-to-GR do not exceed 1.5 p.u.

This overvoltage is withstood by the "single-phase earth-return", "single-phase metallic-return", and "V" ISWSs that are supplied directly from the MV busbars of an HV/MV station, as in Fig. 2.1, Panels A, B, and D. These ISWSs are implemented with components having the same insulation levels and the same SA ratings that are applied in conventional MV networks of the same ϕ-to-Gr rated voltage. That is, in 34.5 kV networks the values are 1.2/50 μs lightning impulse of 170 kV peak, and 1′ power frequency of 70 kVrms. Concerning the "three-phase" ISWS (Fig. 2.1, Panels C1 and C2), the insulation levels are specified in Section 5.2 for ISWSs with rated voltage of 34.5 and 30 kV.

The ISWSs are applied in low-income regions where the networks have low or moderate 1-ϕ-to-Gr short circuit current, generally complying with equation (5.1). The induced voltage in the SWLs by the 3-ϕ short circuits in the HV circuit, are low because of the small electromagnetic coupling with the SWs, and can be neglected. The ϕ-to-ϕ-to-Gr short circuit currents induce voltages that are not higher than the 1-ϕ-to-Gr short circuit currents, and can therefore also be neglected if the setup complies with equation (5.1).

Contact between an insulated SW and an underlying conductor of the HV circuit would cause the highest temporary overvoltage which may affect an SWL. This type of incident has never occurred in SWLs, several of which have been in operation for 25 years.

Breakages of SW of TLs have been reported by utilities because of very heavy ice formation and corrosion of steel SWs. Ice formation is not a problem for countries in Sub-Saharan Africa, which may be interested in applying the ISWS. As is justified in Section 6.2, SWLs are generally made with aluminum conductors steel-reinforced (ACSR), or aluminum alloy conductors steel-reinforced (AACSR), with greased steel core, or rarely with alumoweld conductor, to obtain a sufficiently low ohmic resistance and current carrying capacity. The cross-section of SWs of the SWLs is in the range of 75 to 125 sqmm. For these conductors, corrosion and consequential breakage is not a concern, as is usual for the ACSR and AACSR conductors of the HV TLs.

Lightning strikes hitting SWs may break a few wires of the external aluminum or aluminum alloy layer. However, experience shows that the presence of the steel core with a relatively large cross-section prevents lightning from causing total breakage of the SWs.

In case of contact between an SW of an SWL and an underlying HV conductor, the CBs of the HV circuit and the CB at the sending end of the SWL are tripped by the protection relays and usually de-energized in less than 150 ms. The overvoltage on the SWL before fault clearing may however widely exceed 2 p.u. and, because of the relatively long duration, can damage the SA(s) connected to the broken SW. This risk is acceptable because, as explained in the previous paragraph, in the SWLs the probability of a broken SW or contact between an SW and an HV conductor is extremely low.

The ignition and clearing of short circuits in SWLs (generally SW-to-Gr) cause only small switching and temporary overvoltages.

5.3.4 Specification of Surge Arresters

Selection of the insulation for the ISWS equipment is performed with the normal criteria applied in conventional MV distribution systems. However, the engineers in charge of design, material procurement, and construction must not overlook the fact that, in the “three-phase” ISWS, the SW-to-Gr operating voltage is equal to the ϕ-to-ϕ operating voltage (Fig. 2.2, Panel B). This is different from conventional MV networks, in which the ϕ-to-Gr normal operating voltage is (ϕ-to-ϕ)/√3 (Fig. 2.2, Panel A). Another difference is that there is only one insulated phase in the “single-phase earth-return” ISWS and there are only two in the “three-phase” and “V” ISWSs.

In ISWSs where the SW-to-Gr operating voltage is equal to the ϕ-to-Gr voltage of the three-phase MV supply network, equipment with the same insulation levels and insulator creepage length as in use in the conventional MV networks is applicable. This is the case of the ISWSs in Fig. 2.1, Panels A, B, and D, where the assumed SW-to-Gr voltage is 34.5/√3 ≅ 20 kV. The standard 30 to 34.5 kV equipment with the ϕ-to-Gr lightning impulse test voltage (BIL) of 170 kV peak and 1′ power frequency wet test voltage of 70 kVrms are applicable.

Many examples in this manual refer to the rated MV of 34.5 kV, which is the maximum MV in use in public distribution networks. This choice is justified by the fact that 34.5 kV is attractive for SWLs, which are usually very long (examples are reported in Annex D). The planner of the “three-phase” ISWS has the freedom to choose the rated voltage, because “three-phase” ISWSs are supplied from a dedicated tertiary winding of an HV/MV step-down transformer, or via an interposing transformer (Fig. 2.1, Panels C1 and C2). There is the same freedom for the “single-phase earth-return” ISWS, if it is supplied via an interposing transformer.

Conventional three-phase MV public distribution systems that are neutral grounded via a high impedance (Petersen coil) or an impedance that is not low (grounding transformers or resistors), during the 1-ϕ-to-Gr short circuit, are affected by large, temporary overvoltages in the healthy phases. ISWSs that use the earth as a phase conductor are practically exempt from this overvoltage, because the SW-to-Gr short circuits are ϕ-to-ϕ short circuits. This allows the effective protection of the transformers with SAs and a limitation of the p.u. amplitude of the switching and temporary overvoltages.

Analyses of switching and temporary overvoltages that affect ISWSs are briefly summarized in Sections 5.3.1–3 (details are available in the reference papers [2], [3], [5], [6]). The analyses have shown that, as anticipated in Chapter 4, for “three-phase” ISWSs, it is sufficient to increase the ϕ-to-Gr insulation levels by only 15% to 20% over the values generally in use in conventional distribution networks of the same rated voltages, in spite of the fact that the SW-to-Gr operating voltage is higher by √3. This insulation design rule does not cause any increase in the risk of insulation failure, as confirmed by many years of operation.

The first step in insulation coordination is the choice of the characteristics of the SAs. Examples are provided in Table 5.1 for “three-phase” ISWSs with rated voltages of 30 and 34.5 kV and MCOV of 31.5 and 36 kV, respectively.

TABLE 5.1
Characteristics of Surge Arresters

CHARACTERISTIC	RATED VOLTAGE OF “THREE-PHASE” ISWSs	
	30 kV	34.5 kV
MCOV	≥ 33 kVrms	~38 kVrms
U_r	~ 42 kVrms	~47 kVrms
10 kA lightning impulse protection level	≤ 115 kV peak	≤ 130 kV peak
0.5 kA switching impulse protection level	≤ 90 kV peak	≤ 100 kV peak
Discharge class of SAs for:		
Transformers in HV/MV supply station	Class 2	Class 2
MV/LV transformers (protected by SAs if rated power ≥ 200 kVA)	Distribution class	Distribution class
Other characteristics	See data sheets (Annex B)	See data sheets (Annex B)

Note | *HV = high voltage; LV = low voltage; MCOV = maximum continuous operating voltage; MV = medium voltage; SA = surge arrester; ISWS = Iliceto shield wire scheme; UR = rated voltage.*

Again, SAs with MCOV of about 27 kV (suitable for conventional 33 to 34.5 kV networks with neutral solidly grounded) have been installed (because of a contractor mistake) in some 34.5 kV ISWSs, and have failed at first energization.

5.3.5 Test Voltages and Insulation Levels of the Iliceto Shield Wire Schemes

Table 5.2 provides the withstand test voltages of the apparatuses (disconnecting switches, CBs, LBIs, fused cut-outs, post-type insulators, etc.) specified by IEC standard 60694, which are coordinated with the overvoltages that may affect the “three-phase” ISWS of 30 and 34.5 kV rated voltage and are protected with the SAs in Table 5.1.

The MV/LV distribution transformers are specially designed as per purchaser specification. As recommended in Section 5.2, the following test voltages and creepage lengths of the bushings are specified for the “three-phase” ISWSs and “single-phase earth-return” ISWSs with rated voltage of 30 and 34.5 kV:

- 1.2/50 μs lightning impulse test of HV windings 200 kV peak
- 1′ power frequency test of HV windings 82.5 kVrms
- Induced voltage test in HV windings 82.5 kVrms
- Creepage length of HV bushings ~1,050 mm

These test voltages are somewhat higher than the test voltages of the transformers applied in conventional 33 to 34.5 kV networks, but do not cause manufacturing difficulties, and cost increase is negligible or only a few percent. However, if the rated voltage of the ISWS is 30 kV, the test voltages of

TABLE 5.2

Withstand Test Voltages of Switching and Protection Apparatuses

SPECIFIED CHARACTERISTIC	RATED VOLTAGE OF "THREE-PHASE" ISWSs	
	30 kV[a]	34.5 kV[b]
Rated voltage	36 Kv	38 Kv
1.2/50 μs lightning impulse withstand voltage:		
ϕ-to-Gr and ϕ-to-ϕ	170 Kv	200 Kv (Min. 180 Kv)
Across the isolating distance	195 Kv	200 Kv (Min. 195 Kv)
Power frequency 1′ withstand voltages:		
- ϕ-to-Gr and ϕ-to-ϕ, wet test	70 Kv	80 Kv
- ϕ-to-Gr and ϕ-to-ϕ, dry test	80 Kv	95 Kv
- Across the isolating distance, wet test	80 Kv	85 Kv
- Across the isolating distance, dry test	—	95 Kv
Creepage length of insulators in clean air or low-pollution areas	900 Mm	1,050 Mm
Distance of arcing rod-gap in SWL insulator strings (Figure 5.1):		
- For altitude ≤ 1,000 m	30 Cm	33 Cm
- For altitude > 1,000 m	33 Cm	36 Cm

[a] IEC 60694, rated voltage 36 kV, Table 1a (Series I, European Practice).

[b] The specified test voltages are not lower than the voltages specified by IEC standard 60694, for rated voltage 38 kV, Table 1b (Series II, North American Practice). See also American National Standards Institute standards, rated voltage 38.5 kV.

the MV/LV transformers, as per IEC standard 60076-3 for class 36 kV, may be accepted (BIL of 170 kV peak, 1′ power frequency, and induced overvoltage of 70 kVrms).

The supply bay in the HV/MV substation of a "three-phase" SWL requires a few apparatuses: two current and two potential transformers, disconnectors, support insulators, and a circuit breaker only if the SWL is supplied by the tertiary winding of the HV/MV transformer. For these apparatuses, the insulation levels in Table 5.2 could be applied. However, they are very few in number and are more important for operation than the equipment of the many MV/LV pole-mounted transformer stations. A precautionary approach is therefore to specify for these apparatuses insulation levels somewhat higher, as recommended in the data sheets in Annex B.

Redundant insulation is also justified for the capacitor banks (one for each SWL), which, as a rule, are designed and manufactured specifically as per purchaser specifications (see Annexes A and B).

Detailed characteristics and data sheets for all the equipment applied in the "three-phase" ISWSs with rated voltage of 30 and 34.5 kV are provided in Annex B.

TABLE 5.3

Minimum Distances in Air

OPERATING CONDITION	MINIMUM CLEARANCE IN AIR ϕ-TO-GR AND ϕ-TO-ϕ	
	UR = 34.5 kV	UR = 30 kV
Normal (no wind)	45 cm	40 cm
With maximum wind[a]	25 cm	22 cm

Note | ϕ = phase; Gr = ground; U_r = rated voltage.

a. Suspension insulator strings of shield wire lines are rotated 60° from vertical.

Table 5.3 specifies the minimum clearances in air, ϕ-to Gr and ϕ-to-ϕ, to be applied in the design of SWLs and the supply bays in the HV/MV stations for the "three-phase" ISWSs with rated voltages of 34.5 and 30 kV.

In general, the creepage distance of insulators for the "three-phase" ISWSs and single-phase earth-return ISWSs should be 25 to 28 mm/kV of rated voltage in clean air areas and 35 to 40 mm/kV of rated voltage in polluted areas.

ENDNOTE

[4] In general, the loading capacity of a long MV line is controlled by the voltage drop, which is inversely proportional to the square of the operating voltage. With this constraint, an assigned 34.5 kV line, if de-rated at 30 kV, has a loading capacity of $(30/34.5)^2$ 100 = 75%.

POWER AND DISTANCE CAPABILITIES OF SWSS AND TYPES OF CONDUCTORS FOR SHIELD WIRE LINES

6.1 GENERAL REQUIREMENTS

Shield wire lines (SWLs) are operated as the conventional medium-voltage (MV) distribution feeders. Analyses (see Section 6.3) show that three-phase SWLs have about the same power distribution capabilities as conventional three-phase MV feeders of the same rated voltage and length, equipped with conductors of the same ohmic resistance as the shield wires (SWs).

As is usual for conventional MV feeders, the following requirements should be fulfilled for SWLs:

1. Limitation of voltage variations at consumer premises within specified limits (as far as possible ±5% above and below the rated voltage).
2. The SW current carrying capacity at the thermal limit must not be exceeded.
3. MV power factor (p.f.) correction capacitors are applied. Optimal rated power and location must be determined.
4. Economic optimization is determined (present worth of joule losses and investment).
5. Quality of supply voltage stability and reasonably low rates of faults and interruptions must be ensured for very long SWLs.

An additional technical requirements for the "three-phase" SWLs is:

6. The voltage imbalance (negative sequence voltage component, $V_{2,\%}$) caused by SWL residual dissymmetry must be limited, generally within 1% at the low-voltage (LV) terminals of all the MV/LV distribution transformers; however, not exceeding 2% to account for a possible small imbalance that may be contributed by the supply network of the SWL, as accepted by International Electrotechnical Commission (IEC) standards and in keeping with the regulations for conventional distribution systems.

The insulated SWs of high-voltage (HV) transmission lines (TLs) should have the following characteristics:

- Sufficiently low ohmic resistance for limiting the ohmic voltage drops to the values in use for the conventional MV lines
- Current carrying capacity and SW sagging values, calculated at maximum allowed SW operating temperature, tailored to the final load forecast (e.g., 20 to 25 years ahead)
- Mechanical ultimate tensile strength (UTS) suitable for use in the long spans of the HV TLs, providing a sag lower than the sag of the HV conductors (e.g., ≤ 90%), for warranting redundant clearance to the HV conductors at mid-span in all operating conditions

- Compliance with the previous bullet with a design every day stress (conductor tension in still air, at average yearly ambient temperature, in percent of UTS) not exceeding the value that warrants operation without aeolian vibrations of the SWs.

The requirements of the last two bullets are normal for HV TLs and are well known by the designers of HV TLs.

6.2 CHARACTERISTICS OF SHIELD WIRES FOR SHIELD WIRE LINES

Compliance with all the requirements in Section 6.1 is easy, by using aluminum conductor steel-reinforced (ACSR) or aluminum alloy conductor steel-reinforced (AACSR) SWs that have a large percentage of steel in the cross-section, much greater than in the ACSR conductors used in HV TLs, for ensuring the necessary mechanical strength and sags lower than the conductor sags.

Suitable ACSR SWs, which have been used without any inconvenience in several SWLs, have a total cross-section from 75 to 125 sqmm and a stranding of 19 wires of the same diameter: a core of 7 galvanized steel wires and an external layer of 12 aluminum wires (cross-section of aluminum is 63%). This formation provides sufficiently low ohmic resistance for SWLs with length up to 100 to 120 km; it also ensures adequate ultimate mechanical tensile strength.

The characteristics of three ACSR SWs with a core of 7 wires of steel and 12 wires of aluminum in the external layer, for total cross-sections of 76.9, 100, and 125.1 sqmm, are reported in Table 6.1. All these

TABLE 6.1
Characteristics of Typical ACSR SWs

Cross-Section (sqmm)	76.9	100	125
Stranding (N° × mm)	7 × 2.27 steel 12 × 2.27 aluminum	7 × 2.58 steel 12 × 2.58 aluminum	7 × 2.89 steel 12 × 2.89 aluminum
Diameter (mm)	11.35	12.94	14.45
Ohmic Resistance at 20°C (Ω/km)	0.60	0.45	0.37
Current at Thermal Limit[a] (A)	185	218	250
Weight (kg/km)	360	470	585
Ultimate Tensile Strength (kg)	4,230	5,500	6,875
Modulus of Elasticity, Final (Kg/sqmm)	10,750	10,750	10,750
Coefficient of Linear Expansion (per °C)	$15{,}7 \times 10^{-6}$	$15{,}7 \times 10^{-6}$	$15{,}7 \times 10^{-6}$

Note | *ACSR = aluminum conductor steel-reinforced; SW = shield wire.*

[a]Calculated with ambient temperature = +40°C; shield wire temperature = 80°C; air motion = 0.25 m/s; solar radiation = 1,000 W/sqm.

conductors are redundant from the corona point of view for the 34.5 kV ISWSs that use the earth as a conductor (maximum operating voltage of 36 kVrms ϕ-to-Gr). The cross-section is chosen depending on SWL length and load forecast, as for conventional long MV lines, unless a larger cross-section is retained for other requirements (to hold against lightning, for use of optical ground wires (OPGWs), or for TL mechanical design).

If an ISWS is implemented in an existing HV TL that is usually protected by galvanized steel or alumoweld SW(s), it is possible to insulate the SW(s) with suspension insulator (as per Fig. 5.1) fitted with a small additional steel bracket (see tower head outline in Fig. 2.1, top right). This transformation was made with suspension insulators in the pilot "V" ISWS in Ghana in 1985 (see photo D.1 in Annex D) and in the first three commercial "single-phase earth-return" ISWSs implemented in the Lao People's Democratic Republic. Alternatively, post-type composite fiberglass-silicon rubber insulators bolted on top of the SW tower peak can be used. The transformation with post-type insulators has been made in three "single-phase earth-return" ISWSs in Ethiopia. Some details on these projects are provided in Section 16.4.

Galvanized steel and alumoweld SWs have an ohmic resistance that is much higher than the ACSR and AACSR SWs and therefore their loading capacity is much lower. A 60 sqmm galvanized steel SW has a resistance at 20°C of 2.66 Ω/km and a current carrying capacity at thermal limit of 85 A with the same ambient conditions assumed in Table 6.1. The power distribution capacity of steel SWs is controlled by the voltage drop, and also by the power losses; in some cases, it is controlled by the reduction of the short circuit currents, caused by the high impedance of steel SWs. The latter might, in exceptional cases, limit the load current consistent with the fault detection capacity of the protective apparatuses. In practice, the carrying capacity at the thermal limit of steel SWs can be used only partly, say half, because of voltage drop and power loss.

OPGWs can be insulated for MV and perform, in addition to the lightning shielding and telecommunications functions, rural electrification with the ISWSs. This application of OPGWs is discussed in Chapter 12.

The types of SWs in Table 6.1 that have been used for ISWSs, have also been used in some HV TLs in the past as conventional SWs grounded at every tower.

6.3 STEADY-STATE OPERATION ANALYSIS OF ILICETO SHIELD WIRE SCHEMES

A parametric study of the power and distance reach capability has been performed for the "three-phase" ISWS, which is the scheme generally preferred by the power utilities for distribution of large power (some MWs), without restrictions for the supply of three-phase motor loads.

Two types of ACSR SWs have been considered: one is the 76.9 sqmm ACSR conductor in Table 6.1, which has been applied in various SWLs. The other one is the ACSR conductor Code Penguin, with cross-section of 125 sqmm and resistance at 20°C of 0.265 Ω/km, which was a standard SW used in HV TLs in Brazil, and was applied in Mato Grosso in the 34.5 kV three-phase SWLs of 60Hz–230 kV TLs with the HV conductors in a horizontal plane.

The following assumptions have been made in the parametric study:

1. Length of SWL: up to 150 km.

2. The load supplied by the SWL is assumed to be three-phase, uniformly distributed or concentrated at the remote end.

3. Loads are simulated at the LV terminals of the 34.5 kV/LV distribution transformers, with two values of the p.f. (on the LV side): 0.90 and 0.97. The rated power of the distribution transformers is assumed to be 1.5 times the active power load, and the impedance voltage is assumed to be 4.5%.

4. The p.f. correction/anti-ferroresonance/balancing non-symmetrical capacitors are connected between the two SWs and SW-to-Gr, at 60% of line length from the sending end. The three-phase kVAR total rating of capacitors is 25% of active power load.

5. An optimized R + jX grounding circuit has been simulated at the sending end, this being sufficient to limit V2 anywhere within 1% for SWL length up to 100 km.

For uniformly distributed loads, the R + jX circuit that minimizes the weighted mean value of V2 along the SWL is rated at about 1/3 of the difference of the series impedances of a shield wire and of the earth-return path. The effects of electromagnetic induction of the HV circuit on the SWL (on voltage drop and V2) are computed by simulating the HV circuit as normally transposed with a power flow from no-load to surge impedance loading in either direction. The SWs are not transposed.

6. The supply MV of SWLs is assumed to be regulated by means of the on-load tap-changers of transformers from 1 p.u. at no-load up to 1.05 p.u. at full load.

7. Other details of the simulation are based on reference [2] (1989).

In a tropical environment, as a precaution, the current carrying capacities at the thermal limit of the two types of SWs considered have been assumed to be 230 and 145 A, that is, 13.8 and 8.7 MVA for a three-phase 34.5 kV line, for the large SW (S = 125.1 sqmm) and the smaller one (S = 76.9 sqmm), respectively.

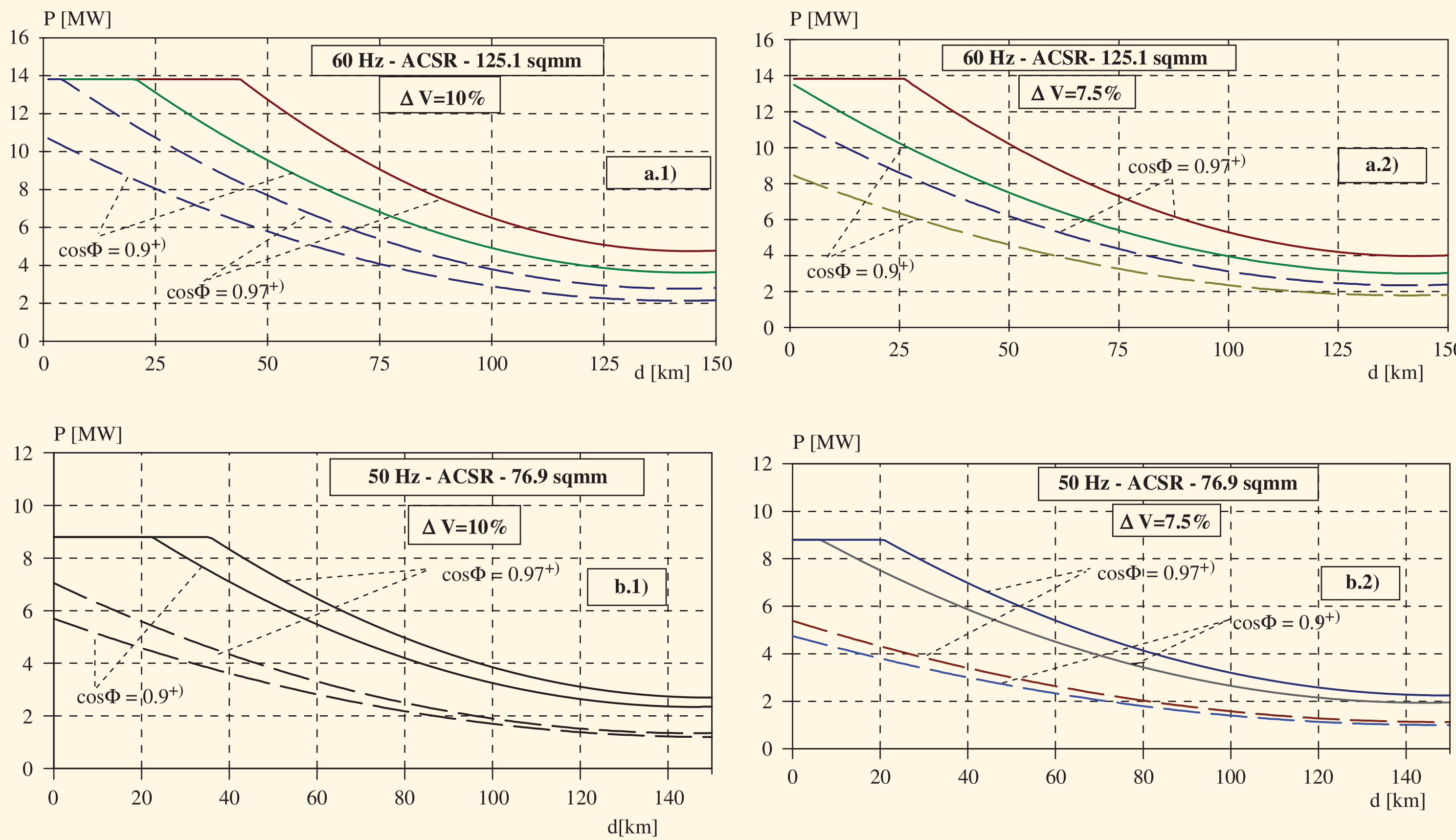
In the parametric analysis, the following additional assumptions were made:

- Voltage drop on the 34.5 kV SWL (excluding the drops in the transformers) shall not exceed 7.5% or, alternatively, 10% (from no-load to full-load).
- The residual negative-sequence voltage component, V2, at any point along the 34.5 kV SWL and the LV side of MV/LV transformers shall not exceed 1% in any operating condition, for SWL length up to 100 km; the upper limit of V2 is 1.5% for SWL length of 150 km.
- Voltage rise on SWLs at no-load shall not exceed 3%.

The curve charts in Fig. 6.1 show the loading capabilities of the analyzed SWLs, with length up to 150 km. Distributed and concentrated loads are considered. The curve charts in Fig. 6.1, Panels a1 and a2, were computed for 60 Hz SWLs with cross-section 125.1 sqmm. The curve charts in Fig. 6.1, Panels b1 and b2, were computed for 50 Hz SWLs equipped with ACSR SWs of smaller cross-section (76.9 sqmm).

FIGURE 6.1

Loading Capability Versus Length of "Three-Phase" Shield Wire Lines Operated at 34.5 kV



In Panels a1 and a2, ACSR, S = 125.1 sqmm shield wires on a 230 kV 60 Hz line (Brazil); in Panels b1 and b2, ACSR, S = 76.9 sqmm shield wires on a 161 kV 50 Hz line (Ghana).

+) load p.f. on LV side of MV/LV transformers ——— Distributed load; – – – Concentrated load

For the assumed operating conditions, the voltage variation range at the LV terminals of all the MV/LV transformers along the SWL does not exceed ±5% above and below the rated voltage, by considering a voltage drop up to 10% in the SWL.

In conclusion, the parametric study of the "three-phase" ISWSs shows that the installation in appropriate locations along the SWLs of p.f. correction shunt capacitors, performing also the anti-ferroresonance and balancing functions, and installation of a resistance-inductance (R-L) grounding circuit at the sending end of the SWL allow loading of the "three-phase" SWLs generally at the same loading of an equivalent conventional MV overhead lines with the same rated (ϕ-to-ϕ) voltage and conductors.

The reported parametric study was performed with a special computer program allowing the simulation of multi-wire asymmetrical circuits and capacitive and inductive couplings between the HV conductors, SWs, and earth. The program also allows the optimal choice of location and ratings of the compensating capacitors and the grounding R-L circuit of the "three-phase" ISWSs.

Table 21.3 in Chapter 21 reports the voltages and voltage imbalances calculated for a 34.5 kV three-phase SWL in Lao PDR, which is 129 km long.

The power carrying capability of "single-phase ground-return" SWLs, with the same ϕ-to-Gr voltage as "three-phase" SWLs, the same ACSR SW type, and equivalent system and loading conditions (network frequency, load p.f., allowed voltage drop, soil resistivity, etc.) is found to be ~50% of the corresponding load capability of "three-phase" SWLs.

6.4 SIMPLIFIED METHOD FOR CALCULATIONS AT THE PLANNING STAGE OF THE ILICETO SHIELD WIRE SCHEME

At the planning stage of an ISWS, an approximate calculation is simply performed with a load flow program used for planning conventional MV and LV distribution networks. This allows for analysis of the voltage drops/rises on SWLs and power losses, the choice of the ratios and tappings of the MV/LV transformers (and MV/MV interposing transformers, if any), the choice of type and cross-section of the SWs, and the preliminary choice of the location and kVAR rating of a three-phase p.f. correction capacitor bank. The voltage drops/rises are mostly controlled by the series resistance and reactance of the metallic SWs.

A simplified model of a "three-phase" SWL to be applied at the planning stage is the model used for three-phase MV symmetrical lines, as follows:

- It is formed by three metallic conductors equal to the SWs. Distance between wires has little influence on reactance and capacitance, because it is entered as the logarithm function in the calculation formulas. It can be assumed to be 4 to 5 m.
- The spur MV lines that supply the villages are simulated as symmetrical three-phase MV lines with three conductors equal to the two metallic wires placed at the corner of a triangle with sides equal to the distance between the two overhead wires.

- The HV circuit and earth, and the relevant electromagnetic coupling, are neglected.
- The series reactance x (Ω/km) of the conductors is calculated with formula 3.3 with k = 0.8. Typical values of x are 0.42–0.43 Ω/km at 50 Hz. Resistance r (Ω/km) of SWs at +20°C is taken from the manufacturers' catalogues. Resistance shall be increased by 0.4% per each °C of conductor operating temperature above 20°C. In tropical countries, an operating temperature of 40°C to 50°C can be assumed.
- The location and kVAR rating of the p.f. correction capacitors are chosen with the same criteria applied for conventional MV lines, in relation to the size, p.f., location of the loads, and length of the SWL. With load distributed along the SWL, an intermediate point is found suitable for capacitor location. If load is concentrated at the end of the SWL, the preferable location of the capacitors is at the site of load location.

In any case, the three-phase capacitor bank should have a kVAR rating of at least 20% of the sum of the kVA ratings of the MV/LV transformers connected along the SWL, and shall be assumed always in service, to prevent any risk of the ferroresonance phenomenon if all the MV/LV transformers happen to be in service at no-load. This is a precautionary measure, because a load of the MV/LV transformers of a very few percent is sufficient for averting the risk of ferroresonance.

- The p.f. correction capacitors, which are also kept in service at very low load, may cause operation of the SWL with a somewhat leading p.f. and a small voltage rise. Operational experience confirms that this is not a problem.
- The SW-to-SW and SW-to-Gr capacitances can be neglected if the SWL is short. If the SWL is long, the service capacitance of the simplified symmetrical three-phase line can be simulated as distributed capacitances, or simply as lumped three-phase symmetrical capacitances at mid-length of the SWL. The service capacitance (that is, the capacitance ϕ-to-Gr with three-phase positive (or negative) sequence voltages) is about 8.10^{-3} μF/km and can be used for the lumped simulation at mid-length of the SWL.

Application of the simplified calculation to very long SWLs yields voltage drops somewhat higher than the precise simulation. The results are therefore in favor of planning security. An explanation is provided in Box 6.1.

At the technical specification stage of the "three-phase" ISWSs, an additional analysis should be made with a computer program suitable for mathematical modeling of the multi-circuit asymmetrical line, including the earth conductor and the electromagnetically induced voltages on the SWL by the HV circuit, which is assumed to be operated at maximum load, if foreseen in either direction, and also at no-load. The findings of the study will be: a precise calculation of the voltage drops/rises in the SWLs; the increase, ΔC, to be assigned to the p.f. correction capacitor, $C_{w,w}$, connected SW-to-SW (see Figs. 2.1, C1, and C2) ($\Delta C = C_{w,w} - C_{w,o}$); and the ohmic ratings of the R-L circuit, for limitation of voltage imbalance in any location within 1%.

In general, if the loads are distributed along the SWL, the R-L circuit is found to have a resistance R in the range of one-third of the series resistance of an SW.

BOX 6.1

Simplified Calculations for Very Long SWLs

For very long shield wire lines (SWLs), application of the simplified method for calculations at the planning stage of the Iliceto shield wire scheme yields voltage drops somewhat higher than those in the precise simulation. The main reason for this behavior is that, in the SWLs, proximity to the conductors of the HV circuit at high potential creates transversal capacitive currents (in the air) toward the SWL conductors, which support the voltage, acting as an additional shunt capacitor bank. The phenomenon is equivalent to an increase in the transversal capacitance of the SWL. A smaller difference in the results provided by the simplified model occurs because of the longitudinally induced electromotive forces (e.m.f.s) from the currents of the HV conductors. This depends on loads and direction of power flow on the HV circuit, and on the geometry of the HV conductors and SWs. The induced e.m.f.s add vectorially to the SW operating voltage, and the resultant voltage drops or rises depend on the phase shift between the HV conductors and the SW-to-Gr voltages. Usually the two supply phases of the SWs are selected in the HV/MV station such as to minimize the effect of the induced e.m.f.s.

The steady-state operation analysis of the "single-phase earth-return" ISWS and "single-phase metallic-return" ISWSs can be performed with the load flow program used for planning conventional MV/LV distribution networks.

The series reactance of a single-phase earth-return SWL is calculated with the formula 3.3 (Section 3.1). The resistance of the earth-return conductor is calculated as addressed in Section 3.1.

Location and rating of the p.f. correction capacitor of "single-phase" SWLs is made as for conventional MV distribution lines. However, the kVAR rating of the capacitor should be ≥ 20% of the sum of the rated power of all the MV/LV transformers connected to the SWL, to eliminate any risk of ferroresonance.

A check of voltage imbalance is required only at the three-phase MV busbar that supplies the single-phase SWLs. Calculation is simply made with formula 4.1 (Section 4.3).

SINGLE-LINE DIAGRAMS OF SWL SUPPLY BAYS AND MB/LV TRANSFORMER STATIONS

7.1 "THREE-PHASE" SHIELD WIRE LINE

The Typical single-line diagrams of the supply bays of the "three-phase" shield wire lines (SWLs) are shown in Fig. 7.1, Panels a and b. The diagram in Fig. 7.1, Panel B, is applied when the bay is supplied via a medium-voltage/medium-voltage (MV/MV) interposing transformer (IT), which provides the galvanic insulation and appropriate operating voltage of the SWL.

The diagram in Fig. 7.1, Panel A, is applied when the "three-phase" SWL bay is supplied by a dedicated tertiary winding of the main high-voltage/medium-voltage (HV/MV) power transformer, which performs the same functions as the IT. Both schemes have been used in the SWLs that are in operation.

As far as the station equipment is concerned, the "three-phase" SWL bays have only two phases at MV potential; the third phase is the earth conductor. Single-phase apparatuses, such as surge arresters (SAs), current transformers (CTs), and potential transformers (PTs), are connected phase-to-ground (ϕ-to-Gr) in two pieces. MV switching apparatuses, such as the circuit breaker (CB) and disconnecting switch, if not commercially available as two-pole apparatuses, are installed as commercial three-pole apparatuses and one phase remains un-used as a spare pole.

In the single-line diagrams in Fig. 7.1, Panels A and B, the numbers in brackets close to the symbols for each component are the required numbers of poles or single-phase apparatuses.

One low-voltage (LV) CT is inserted in the connection to the station grounding mesh of one terminal of the supply transformer through the resistance-inductance (R-L) compensating circuit: this is the CT of the third phase, for measurement and protection. The two MV PTs connected ϕ-to-Gr are sufficient for measurement and protection, because the two secondary windings of the PTs, in "V" connection (open delta), provide all the ϕ-to-ϕ voltages (as shown in Fig. 2.1, Panel D, for three-phase power supply by two single-phase MV/LV distribution transformers in the villages).

The three-phase power and energy counters are connected with the "Aron" scheme, which is applicable to three-wire, three-phase systems. Aron's scheme is formed by two single-phase power measuring instruments which are each supplied from one of the two MV CTs and the ϕ-to-Gr PT connected to the same phase.

The rated voltage of the SWLs and associated equipment can be, instead of 34.5 kV, another of the rated voltages specified in the International Electrotechnical Commission (IEC) and American National Standards Institute (ANSI) standards.

When an IT is applied (Fig. 7.1, Panel B), the installation of a CB on the SWL supply side of the IT is omitted. Actually, the IT and the supplied SWL are switched on and off and protected as one block by the three-pole CB on the MV primary side of the IT. Omission of the CB on the SWL side of the IT is feasible if the IT is designed as specified in Section A.13.4.3 in Annex A and Table B.21 in Annex B.

Conversely, when the SWL is supplied by a dedicated tertiary winding of the HV/MV main transformer (Fig. 7.1, Panel A), a two-pole CB is needed downstream of the tertiary winding for switching and protection of the SWL. The rated power of the IT or the tertiary winding is specified for the future load forecast, approximately 15 to 20 years ahead. Typical values are from 4 to 8 MVA for each SWL.

SAs are installed for protection of the IT or tertiary winding. In the anchor gantry of the HV TL, the shield wires (SWs) are anchored with tension insulators to the gantry SW peaks. The SWLs are protected by the arcing rod-gap, with the gap distance to be set for the 30 and 34.5 kV three-phase SWLs, as specified in Table 5.2. A bird anti-perching spike should be fitted in the tension insulator strings of the SWs. The galvanized steel spike is fastened to the cap in the middle of the rigid glass insulator string in Fig. 5.1 (Section 5.1).

The grounding switch is a fast-closing type, spring operated. This feature ensures that the SWL cannot remain at floating potential for any significant time during the switching transients, which could cause important induced overvoltages. Two-pole, ad-hoc designed fast-closing grounding switches, manually and motor operated, are available in the market.

Descriptions of the supply bay equipment and technical data sheets are provided in Annexes A and B. An example of the layout of an SWL supply bay with IT (Fig. 7.1, Panel B) is provided in Annex C.

7.2 "SINGLE-PHASE EARTH-RETURN" SHIELD WIRE LINES

The supply bay of "single-phase earth-return" SWLs is similar to the ones in Fig. 7.1, Panels A and B; however, the R-L circuit is not needed. Use is made only of single-phase apparatuses. If the ϕ-to-Gr voltage of the three-phase MV available in the HV/MV transformer station is sufficiently high for the supply of the SWL and has the neutral solidly grounded (or grounded via a very low impedance), the "single-phase earth-return" SWL can be supplied directly from one phase of the station MV busbars, as shown in Fig. 2.1, Panel A (Chapter 2).

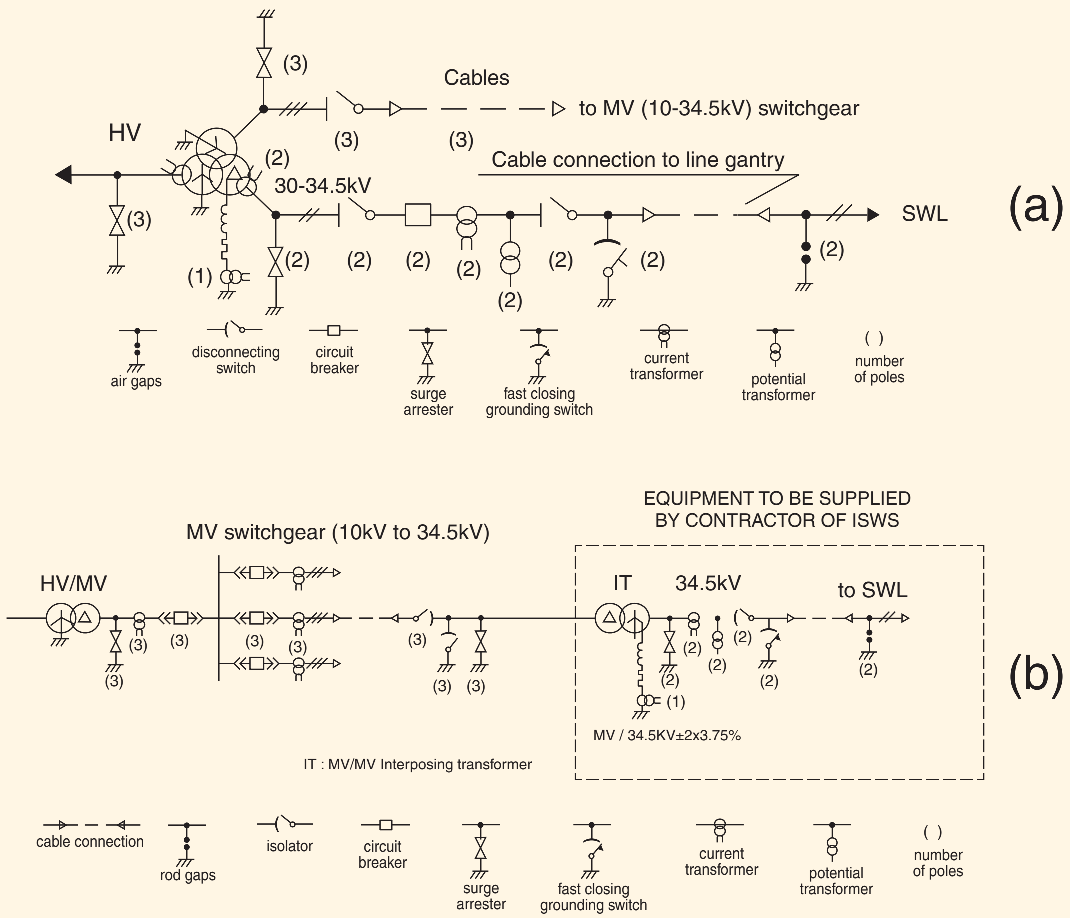
7.3 SINGLE-LINE DIAGRAM OF THE THREE-PHASE MV/LV DISTRIBUTION TRANSFORMER STATIONS

Fig. 7.2 shows a typical single-line diagram of the MV/LV distribution transformer stations, which are usually pole-mounted in rural areas. The transformer is switched on and off and protected against faults by two single-pole fused cut-outs, manually operated from the ground with a long insulating stick, which also allows taking down and putting back the fuse holder for replacing the fuse link. Fuse melting is shown by the downward rotation of about 180° of the fuse holder.

MV/LV transformers with rated power ≤ 200 kVA can be protected against lightning and switching overvoltages by the arcing rod-gap fitted in the MV bushings, with gap distance set for the ϕ-to-ϕ rated voltage of the SWL (at altitude ≤ 1,000 m, 145 mm for the 34.5 kV SWLs and 125 mm for the 30 kV SWLs). Protection with two SAs can be economically justified for transformers with rated power > 200 kVA.

FIGURE 7.1

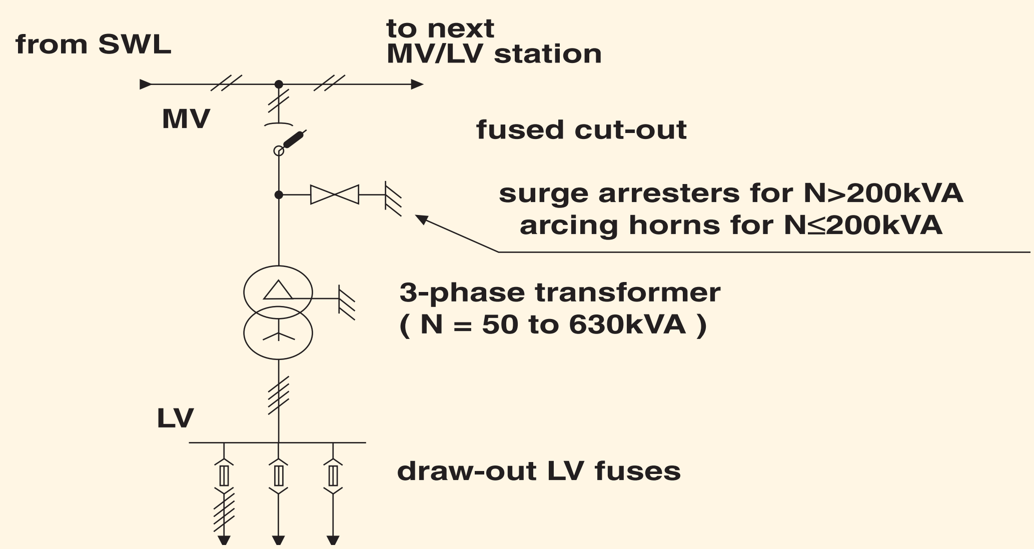
Typical Single-Line Diagram of the 30 to 34.5 kV Supply Bay of "Three-Phase" Shield Wire Lines



The MV/LV transformers are practically equal to the transformers applied in conventional distribution (with three MV bushings and four LV bushings). The only difference is the dielectric test voltages of the MV windings, which are specified 15% to 20% higher than for conventional distribution transformers of the same rated voltage, as justified in Section 5.3. However, if the "three-phase" and "single-phase earth-return" ISWSs are operated at the rated voltage of 30 kV, the same insulation levels as the transformers in use in conventional 33 to 35 kV distribution systems are acceptable (basic insulation level (BIL) of 170 kV and 1′ power frequency test and induced overvoltage test of 70 kVrms, as per the rated

FIGURE 7.2

Typical Single-Line Diagram of a Three-Phase Medium-Voltage/Low-Voltage Transformer Station



voltage of 36 kV of IEC standard 60076-3). Other details on insulation are dealt with in Section 5.3.5. The characteristics of SAs for the 34.5 and 30 kV ISWSs are specified in Table 5.1.

The MV windings of the MV/LV transformers are delta connected. The LV windings are star connected with four bushings, which supply the four-wire LV lines, as in conventional distribution. The neutral of LV lines is multiple-grounded along the LV lines, as specified in Section 3.2.

The requirements of the grounding systems of the MV/LV distribution transformers are specified in Section 3.2. Typical layout drawings of MV/LV transformer stations of various types, including the grounding systems, are provided in Annex C.

7.4 MEDIUM-VOLTAGE SPUR LINES, CAPACITOR BANKS, AND LOW-VOLTAGE LINES

The LV three-phase and single-phase distribution networks are equal to the LV network of conventional distribution for rural electrification.

The LV lines are switched and protected in the cheapest and simplest manner by draw-out fuses with fuse holders for rainproof outdoor installation. In the pole-mounted transformer stations, the LV fuses can be fixed on the poles at a convenient height. Periodic measurements of the voltages and currents on LV feeders can be made with a multimeter and a clamp-on ammeter.

The spur MV lines that supply the villages from the SWLs are protected and, in case of maintenance or works, are switched on and off at their first pole close to the take-off HV tower, as follows:

1. If the length of the spur line is short (≤ 2 km), a fused cut-out is applied. In this case, a standing instruction to be given to the operators is that all the MV/LV transformers supplied by the spur line must be switched off before opening and closing the fused cut-out of the spur line.

2. If the MV spur line is long, a two-pole (or three-pole if two-pole is not available) load break interrupter (LBI) is installed at the take-off from the SWL, with built-in fuses, or separate fuses installed downstream of the LBI. The separate fuses are conveniently two single-pole commercial fused cut-outs, which have low cost and allow replacement of any melted fuse link by means of an isolating stick, with the SWL remaining in operation. Fuse links have a negligible cost in comparison with the fuses that are part of the LBIs, and require full replacement in case of melting. The LBI allows the switching on and off of the spur line under load (with all the MV/LV transformers connected and loaded).

Typical layout drawings of the connection slack span from the SWL to the spur MV lines and the switching-protection equipment of the spur MV line are provided in Annex C.

As justified in previous Chapters, a power factor (p.f.) correction/anti-ferroresonance capacitor bank is to be installed in an intermediate location along each SWL. The bank is three-phase and also performs the symmetrization function in the "three-phase" ISWSs. The three-phase capacitor bank is formed by three single-phase capacitors, delta connected as shown in Fig. 2.1, Panels C1 and C2. The capacitor connected SW-to-SW, $C_{w,w}$, has a larger capacitance than the two equal capacitors, $C_{w,o}$, connected SW-to-Gr.

The capacitor bank must always be in service to ensure the anti-ferroresonance function, and therefore it is directly (solidly) connected to the SWL and installed adjacent to an HV take-off tower of a spur line to one of the villages, in a location appropriate for p.f. correction. The technical specification and data sheets for the capacitor banks are provided in Annexes A and B. Typical layout drawings for procurement and installation are provided in Annex C. In almost all the SWLs, the capacitors have been pole-mounted.

Section 5.3.1 specifies that the anti-ferroresonance function is ensured by a relatively small capacitor bank, generally smaller than the capacitor bank that will be required for p.f. correction when the SWL load becomes large. The supplementary p.f. correction is performed by installing a second three-phase, symmetrical and switchable capacitor bank, generally located close to the take-off HV tower to another village.

8

CALCULATION OF SHORT-CIRCUIT CURRENTS

The short circuits in the "three-phase" Iliceto shield wire schemes (ISWS) can only be ϕ-to-ϕ and 3-ϕ. An SW-to-Gr short circuit is, as a matter of fact, a ϕ-to-ϕ short circuit.

Because of the geometrical location of the shield wires (SWs) on top of high-voltage (HV) transmission line (TL) towers, with large spacing between the two SWs (and to the HV conductors), an SW-to-SW short circuit is extremely improbable, unless it occurs via the tower metallic members; in this case, it becomes a three-phase (3ϕ) short circuit. The latter is the case of lightning hitting the top of an HV tower and causing a flashover across the arcing rod-gap of the insulator string of both SWs. However, in the medium-voltage (MV) spur lines that supply the villages from the shield wire line (SWL), the two energized wires may come in contact (caused by wind gusts, large birds, overgrown branches of trees, etc.) and cause a ϕ-to-ϕ short circuit.

In summary, only the ϕ-to-ϕ and 3ϕ short circuits must be considered for the "three-phase" SWLs.

The maximum short circuit currents in the "three-phase" SWLs are low even if the short circuit occurs close to the supply HV/MV station, because the current is drastically limited by the impedance voltage of the interposing transformer (IT) (Fig. 7.1, Panel B) or by the equivalent impedance voltage between the HV winding and tertiary winding of the main HV/MV transformer (Fig. 7.1, Panel A). For example, a 3-ϕ short circuit current at the secondary terminals of an IT rated at 6 MVA with impedance voltage of 7% is < 1.4 kArms, that is, much lower than the breaking capacity of commercial circuit breakers (CBs), and of the thermal and electrodynamic short circuit duties of commercial MV apparatuses.

The short circuit current decreases progressively for the short circuits located out along the SWL and spur MV lines. At the ends of long SWLs, the short circuit current may be 0.4 to 0.5 kA.

The grounding systems designed as described in Section 3.2 for continuous load current flow in the earth ensure that the step and touch voltages remain within the limits specified by the International Electrotechnical Commission (IEC) standard during the short circuits anywhere along the SWL and in the MV spur lines.

Calculation of the short circuit currents is necessary for the choice of the protection equipment against the faults and the correct coordination of their settings for selective, fast clearing of the faults. Therefore, the minimum short circuit currents must be calculated to ensure the clearing of faults occurring where the fault current is lowest.

The lowest fault currents occur for faults at the remote receiving end of the SWL, in particular in the last MV/LV distribution station of the spur MV line, which may be branched off at the remote end of the SWL.

A good approximation for protection of "three-phase" ISWSs is achieved by calculating the ϕ-to-ϕ and 3-ϕ short circuit currents with the simplified symmetrical SWL and spur MV line model described in Section 6.4 for the steady-state analyses. This simplified method yields short circuit currents a little *lower (in the range of 10%) than the calculation performed by simulating the earth as the third phase conductor and the electromagnetic coupling with the HV circuit. It is therefore a good approximation, somewhat in favor of safety, for the study of protection.*

When the three-phase short circuit currents, $I_{3\text{-}\phi}$, have been calculated, the ϕ-to-ϕ short circuit currents, $I_{\phi\text{-}\phi}$, are simply calculated as:

$$I_{\phi\text{-}\phi} = \left(\sqrt{3}/2\right) \times I_{3\text{-}\phi}$$

In the "single-phase earth-return" ISWSs, the faults can be only phase-to-ground (ϕ-to-Gr). Calculation can be performed by modelling the SWL with the series reactance and resistance formulas provided in Section 3.1, and by neglecting the induction from the HV circuits (which can be significant only in the case of a simultaneous ϕ-to-Gr short circuit in the HV circuit).

The "single-phase metallic-return" SWL (Fig. 2.1, Panel B) can be affected by ϕ-to-ϕ, ϕ-to-Gr, and ϕ-to-ϕ-to-Gr short circuits. Calculations can be performed as for the conventional MV network that supplies the ISWS.

FAULT PROTECTION OF SHIELD WIRE LINES, MV SPUR LINES, AND MV/LV TRANSFORMERS SUPPLIED BY SHIELD WIRE LINES

9.1 GENERAL REQUIREMENTS

The protection system of the Iliceto shield wire scheme (ISWS) is designed with the concepts applied for radial conventional public medium-voltage (MV) and low-voltage (LV) distribution systems. However, it must be kept in mind to limit, as far as possible, the initial investment and maintenance costs, and adhere to the requirement of simplicity of operation with minimized risk of failure of equipment. At the same time, the usually long length and radial design of the shield wire lines (SWLs) inevitably cause an increase in the yearly average number of interruptions and interruption time of consumers' supply in comparison with the MV and LV lines of many industrialized countries, which are conceived with the possibility of supply from either end, are generally shorter than SWLs, and in many locations are underground cable lines.

Currently in European countries, the regulations in force stipulate that a penalty is to be paid by the power distribution utilities to consumers that have experienced a total yearly interruption time ≥ 60′ in rural areas (≥ ~ 30′ in large cities), by accounting for all the interruptions ≥ 3′ caused by disturbances and faults in the MV and LV distribution networks and high-voltage/medium-voltage (HV/MV) step-down transformers. To achieve this target, expensive solutions and complex technologies must be applied, including telecommunications and remote control of switching apparatuses.

In urban areas and in general in the industrialized countries the economic value and the impact on human activities and on safety of power interruptions is high and justify large investments for granting a high continuity of service. In rural networks of low income countries such stringent requirements do not need to be adhered to, enabling simpler network design at low cost.

9.1.1 Application to Shield Wire Lines

SWLs are generally not exposed to permanent faults. Therefore the re-energization (automatic or thereafter manual) is generally successful. Moreover, the outage time of the SWLs for maintenance is short (even shorter than maintenance time for the HV circuit). For these reasons, even if the SWLs are long and supply many villages in different locations, there is no justification for installing LBIs in the shield wires (SWs), neither upstream nor downstream of the take-off of the MV spur lines to the villages, nor at the separation point of the two SWLs supplied from the HV/MV stations at the two ends of an HV transmission line (TL) (the two SWLs are separated by removing the SW jumpers in a tension tower). Incidentally, the installation of the LBIs in the SWs would be physically difficult and expensive because of the location of the SWs on top of the HV line towers.

The fault evolution is different in the MV spur lines, which supply the villages from the closest tower of the HV TL. The length of the MV spur lines may be very short (from some tens up to several hundreds of meters) or long (many km). The spur lines are similar to the conventional MV lines, and subject to permanent faults requiring repair work. The MV/LV transformers and associated apparatus may also undergo permanent faults, as in the conventional MV/LV distribution stations.

In almost all the ISWSs that are in place so far, the SWLs are very long, with many spur lines and MV/LV transformers for satisfying the required electrification of all the villages along the route of the HV TLs.

Single-line diagrams of SWLs in operation are provided in Annex D. One of the three-phase 34.5 kV SWLs in the Lao People's Democratic Republic has a length of 104 km, extended to 129 km by a spur line of ~25 km connected at the remote end; it supplies more than 30 villages. In Ghana, a three-phase 30 kV SWL, that was initially 104 km, was extended to 176 km for supply during several years of a repeater station of the Ghana Broadcasting Corporation in Kintampo.

It is obvious that the very long SWLs that supply many spur MV lines require selective protection that automatically isolates any permanently faulty spur line and MV/LV transformer station. In the absence of a selective protection scheme, a faulty spur MV line or MV/LV station that happens not to be isolated will put the entire SWL out of service for the time required to locate the fault by the maintenance staff. The location may be difficult to find and time consuming. The same problem, or even worse, would affect an equivalent conventional MV line (of the same length, configuration, rated voltage, and loading conditions).

It is therefore necessary to install a protection system that automatically, rapidly disconnects any faulty spur line or MV/LV transformer station that has undergone a permanent fault, for achieving acceptable continuity of service of the SWL and easy location of the fault for repairs.

9.2 SIMPLEST SCHEME FOR SELECTIVE PROTECTION

9.2.1 Switching and Protection Apparatuses

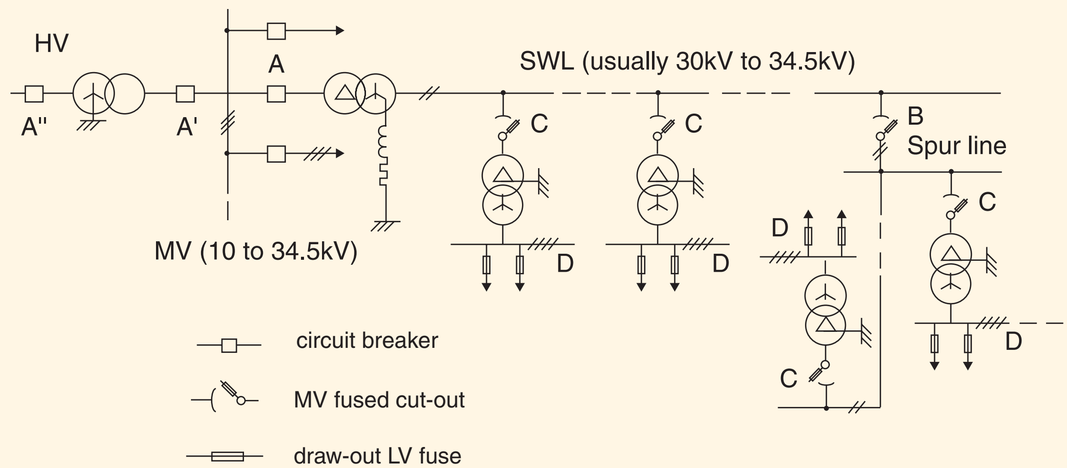
A schematic of the protection system that is usually applied is shown in Fig. 9.1. The SWL, which is supplied without a CB by the interposing transformer (IT), is switched and protected as one block by a CB, labeled A in Fig. 9.1, installed on the primary side of the IT. If the SWL is supplied by the tertiary winding of the main HV/MV transformer, CB A is located downstream of the tertiary winding, as shown in Fig. 7.1, Panel A.

The spur lines are protected by fuses, labeled B in Fig. 9.1, at the take-off from the SWL. The MV/LV transformers are protected on the MV side by fuses, labeled C in the figure. The LV lines are also simply protected by fuses, labeled D in the figure. In some ISWSs, LV CBs have been applied instead of fuses at the request of the distribution utility, for switching and protecting the LV lines.

Selective protection must comply with the following elementary requirements, with reference to Fig. 9.1:

- Faults on LV lines must be cleared by fuses D, without melting any fuses upstream.
- A fault in an MV/LV transformer should be cleared by fuse C, without melting upstream fuse B and without tripping CB A.
- A fault in an MV spur line must be cleared by fuse B, without tripping CB A.

FIGURE 9.1
Single-Line Diagram Showing the Simplest Switching-Protection Apparatuses of "Three-Phase" Iliceto Shield Wire Scheme



Note: Only protection-switching apparatuses and power transformers are shown

- A fault in an SWL must be cleared by CB A, without tripping any other CB in the HV/MV substation.
- A fault in the IT must be cleared by CB A. A fault in the HV/MV transformer with the tertiary winding that supplies the SWL (Fig. 7.1, Panel A) is cleared by the CBs on the HV and MV sides of the transformer, and is isolated from the SWL by CB A.

9.2.2 Selectivity of Protection of Shield Wire Lines

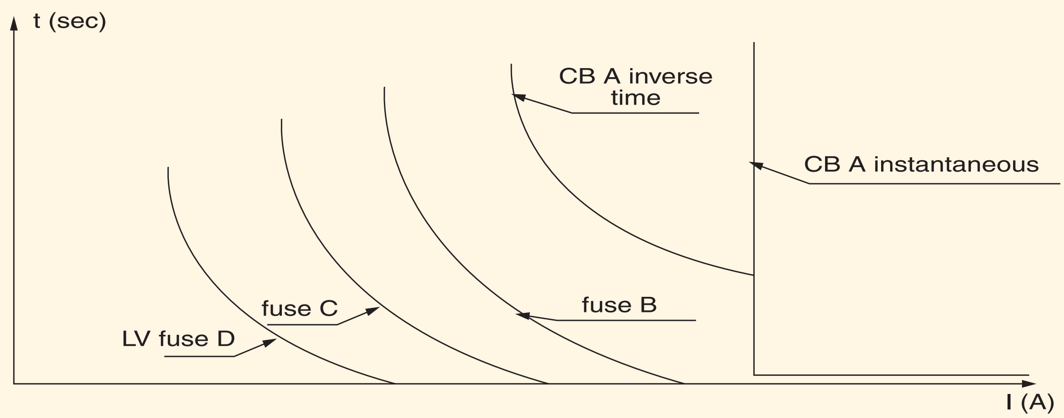
The curve chart in Fig. 9.2 shows how the selectivity of protection of the series connected distribution sections (Fig. 9.1) should be implemented. The time-current intervention characteristic of the protection of any one section should be entirely below the time-current intervention characteristic of the protection of the upstream adjacent section, with a sufficient margin and for all the possible short circuit currents.

The selectivity margin between the characteristics must take into account the pick-up tolerances. In particular, for the fuses, a pick-up band between the lowest and highest melting times curve should be considered instead of a single curve.

The LV fuses D, which protect the LV lines, are fast melting, of type and rated currents as used in the LV feeders of conventional public distribution.

FIGURE 9.2

Selective Coordination of Time versus Current Intervention Characteristics of Protection



The fuse curves labeled in the figure refer to the fuses in Figure 9.1.

The C fuses are applied for protecting the transformer against internal short circuits and also provide back-up protection for faults on the LV feeders not cleared for any reason by the LV fuses.

The rated current and melting characteristics of the C fuses should be such as not to melt because of transformer core saturation by lightning surges hitting the MV lines, or by the inrush of current at transformer energization. The rated current of the C fuses is usually two to three times the rated current of the transformer. A fast-melting fuse, such as type K, can be applied; however, the current surge riding-through capability should be checked with the manufacturer.

There are two C fuses for each three-phase MV/LV transformer and the C fuses are part of two single-pole fused cut-outs (Fig. 7.2). Single-phase transformers supplied from one SW and the ground (Gr) are protected by one fuse.

There are two B fuses for each MV spur line. Selectivity between the C and B fuses (Figs. 9.1 and 9.2) can be achieved, because the rated current of the B fuses is selected to be much higher than for the C fuses, and in any case not lower than two times the sum of the rated current of all the transformers supplied by the same spur MV line. The time-current characteristic of the B fuses must remain below the time versus short circuit current characteristic of the overcurrent relay of CB A.

CB A is tripped by an overcurrent relay with fast intervention for short circuit currents of high intensity and delayed (usually, inverse time) intervention for overload and fault current of low intensity. A very small intentional delay may however have to be assigned to the high intensity short circuit current relay, for preventing tripping of SWL CB A in case of a short circuit in a nearby spur MV line, to be selectively cleared by the B fuses. Tripping of CB A is also initiated by differential protection of the IT (Fig. 7.1, Panel B) or of the main HV/MV transformer if the SWL is supplied by tertiary winding (Fig. 7.1, Panel A).

9.2.3 Detection of Shield Wire-to-Ground High-Resistance Faults

SW-to-Gr faults are generally low-resistance faults, because usually the current flows to the ground via the steel tower and the grounding resistance of the HV tower. Although high-resistance SW-to-Gr faults are very unlikely to occur, for safety it is justified to ensure their detection for alarm and tripping of CB A. This cannot be done by overcurrent earth fault relays with low homopolar current setting, as applied in three-phase conventional MV lines, because in SWLs any overcurrent relay setting must be higher than the load current.

It is worthwhile to point out that "three-phase" SWLs are special three-phase lines where in any operating condition (including the SW-to-SW and SW-to-Gr short circuits) the vectorial sum of the currents flowing in the two SWs and the earth is always nil: the homopolar current $I_o = (I_{SW1} + I_{SW2} + I_{GR})/3 = 0$. It is therefore obvious that the protection detecting the homopolar ("earth fault") current cannot be applied. The applicable protections can be activated only by phase currents.

In "three-phase" ISWSs, SW-to-Gr high-resistance faults are detected by the buildup of an imbalance between the current intensities in the two SWs, which in absence of SW-to-Gr faults are almost equal load currents. The current imbalance during an SW-to-Gr fault causes the buildup of a negative-sequence current component that is detected by a function normally available in modern numerical overcurrent relays. By assuming that the load currents are reasonably balanced, the setting for tripping 34.5 kV SWLs can be made for a current imbalance between the two SWs of 20 or 25 A, for detecting SW-to-Gr faults of very high resistance (up to ~1,600 Ω or ~1,300 Ω, respectively).

9.2.4 Protection Selectivity Testing During Commissioning

During the commissioning of the ISWSs, it is recommended to make selectivity of intervention field tests of the protections, to check that the contractor has succeeded in properly coordinating the settings as specified. The following tests should be made:

1. Between CB A and the B fuses of the spur line branched off at the receiving end of the SWL, as well as the spur line that is closer to the sending end of the SWL.
2. Between the B and C fuses in the spur line close to the sending and receiving ends of the SWLs.

If an LBI is installed in the take-off of the spur line from the SWL, the LBI is at first switched off and an artificial SW-to-SW-to-Gr short circuit (with a copper wire) is made downstream of the B fuses. Then the LBI is manually switched on. If, in addition to melting the B fuses, CB A is tripped, a short time delay will be set in the overcurrent relay of CB A and the test will be repeated. If the spur line is switched and protected only by a fused cut-out, the SWL will at first be de-energized by opening CB A. Then the SW-to-SW-to-Gr artificial short circuit will be made, the line will be switched on again by closing CB A, and the selectivity between the B fuses and CB A will be assessed. The test will be performed for the two fault locations specified in item i.

The test in item ii should be made by making an artificial short circuit on the MV bushings of the MV/LV transformer installed closer to the spur line take-off from the SWL. The test will then be made by closing the nearby LBI or, if not available, CB A. Checks are made that only the C fuses on the MV/LV transformer are melted.

10 ENVIRONMENTAL IMPACT OF ILICETO SHIELD WIRE SCHEMES: DETERRENCE OF VANDALISM AND THEFT OF HIGH-VOLTAGE TRANSMISSION LINES

The shield wire lines (SWLs) and the relevant supply equipment in the high-voltage/medium-voltage (HV/MV) stations do not change the environmental impact of the HV transmission lines (TLs) and the station where they are implemented. The supply bay of the SWL is an MV bay with a low profile and is built in a small area of the HV/MV main station. The SWL requires only the addition of the insulators of the shield wires (SWs), with no adverse visual impact, as shown in the photographs in Annex D.

The minimal impact on the environment is particularly important if the SWLs are retrofitted on existing HV TLs.

Conversely, an independent MV line routed along an HV TL requires the acquisition of a right-of-way (ROW) or the widening of the ROW of the HV TL, and may have an impact on agriculture and forestry, as well as on the aesthetic of the landscape.

In operation, the SWL does not need dedicated periodic bush clearing and patrolling, because these activities have to be done for the HV TL. The only additional task is the visual check of the SWL insulators, which is made during patrolling of the HV TL.

In the villages, the environmental impact of the MV and LV lines and of MV/LV transformer stations is similar to the impact of conventional distribution systems. The grounding systems for the earth return of current are entirely underground, in the ROW of the spur MV lines and in a small area around the MV/LV transformers, which is not usable for residential purposes. The precautionary limitation of the step and touch voltages and the criteria used in multiple grounding, as specified in Section 3.2, warrant against any risk of impact on the safety of people and animals.

Operational experience has shown that shield wire lines (SWLs) are an efficacious deterrent of vandalism and theft of components of the HV TL, because the inhabitants along the HV TL receive electricity from the ISWS and therefore they have to preserve the integrity of the HV TL. Communities crossed by HV TLs that are built only for providing electricity to large cities or connecting power plants may understandably oppose the expropriations for the ROW, which disturbs agriculture and forestry, and the visual impact imposed only for the benefit of others.

MEDIUM- AND LOW-VOLTAGE NETWORKS SUPPLIED BY ILICETO SHIELD WIRE SCHEMES

11.1 COMPONENTS OF MEDIUM- AND LOW-VOLTAGE LINES

Medium-voltage (MV) spur lines to villages, medium-voltage/low-voltage (MV/LV) distribution transformer stations, and their protection and grounding principles are discussed in Chapters 3, 7, 8 and 9. Detailed technical specifications and typical construction drawings are provided in Annexes A, B, and C.

Although each distribution utility has its own technical standards for LV reticulation, this Chapter provides some general recommendations on minimum-cost solutions in rural areas.

LV reticulation in villages and connection schemes of private and public consumers, pumping stations, farms, etc. supplied by the Iliceto shield wire schemes (ISWSs) are the same as those applied for conventional LV distribution networks.

If wooden poles are available locally, they are generally the lowest-cost option for LV lines. Poles are erected directly in an excavation, which is preferably partly back-filled with compacted big stones for structural strengthening and rain water drainage from the pole foundation. Angle poles and branch-off poles of spur LV lines are usually reinforced with a steel guy.

Aluminum conductors are generally used in LV lines, bare or insulated with light plastic to prevent short circuits by wind, birds, contact with trees, etc. Pre-twisted, four-core insulated cables are sometimes used to minimize the risk of faults. However, the cost of the pre-twisted cables is higher and special fittings are necessary.

Conventional LV conductors are supported by poles with reel-type insulators. The length of a typical span is ~40 m. The poles also support street lamps, which are individually switched by a daylight-sensitive relay.

All aluminum alloy conductors (AAAC) are suitable for the MV spur lines. A 50 sqmm AAAC has been used in the spur lines of several ISWSs. The span length should be correctly tailored to the number of conductors (1 or 2 or 3), to the climate, to the structural loading assumptions, to the available poles and to the conditions of terrain of the country.

In some cases, an MV line that supplies other MV/LV stations in a village, is supported by the LV poles and strung over the LV conductors, by using higher and stronger poles. The MV span length may be double that of the LV spans by supporting the MV circuit on one of every two adjacent LV poles.

The MV spur lines supplied by “three-phase” SWLs and connecting MV/LV stations in villages are equipped with two phase conductors. However, in a few spans near each MV/LV station, they are often equipped with a ground conductor for performing low resistance multiple grounding for earth return of current (see Fig. 3.2). Drawings of typical conductor configurations and insulation of MV spur lines are provided in Annex C.

11.2 CONNECTION OF CONSUMERS

The three-phase LV lines supplied by "three-phase" ISWSs have four wires. Connection to single-phase consumers is made as usual, with two wires between one phase and the neutral.

Single-phase LV lines supplied by "single-phase earth-return" or "single-phase metallic-return" ISWSs preferably have three wires, supplied by a split in two secondary windings of the MV/LV transformers, as shown in Fig. 2.1, Panels A and B. One wire is the neutral, with multiple grounding along the LV lines. The voltages, E, between each of the other two wires and the neutral (e.g., E = 240 V) are in phase opposition, thus providing a voltage of 2 E between them (e.g., 2 × 240 = 480 V). Small consumers are connected, along each LV line, between one of the phase conductors and the neutral. If connection of loads is equally distributed on the two phase wires, as common practice, the current in neutral wire is almost nil and the LV line is seen from the MV/LV transformer almost as a single-phase load supplied at voltage 2 E (e.g., 480 V). This three-wire, single-phase distribution scheme drastically reduces the voltage drop, which is inversely proportional to the square of the voltage. The distance reach of the LV lines, which is usually controlled by the voltage drop, is much increased. Large single-phase motors can be supplied directly at voltage 2 E (e.g., 480 V).

The charge for connections of consumers, protection, and energy meters in rural areas should be low. In many sub-Saharan African countries, charges for service connection in rural areas are reported to be disproportionately high and often constitute the main barrier for increasing the connection rate in villages served by electricity from the grid. Reasons thereof, statistical information and recommendations for minimizing the charge for consumer connections are provided in reference [12] (2015).

SHIELD WIRE SCHEMES ON HIGH-VOLTAGE TRANSMISSION LINES SHIELDED BY OPTICAL GROUND WIRES

12.1 USE OF COMMERCIAL OPTICAL GROUND WIRES FOR SHIELD WIRE LINES

Optical ground wires (OPGWs) are normally grounded at all the towers of high-voltage (HV) transmission lines (TLs). However, OPGWs have been insulated since 1996 in some extra high–voltage (EHV) TLs carrying a heavy load, to eliminate the joule losses in the shield wires (SWs), caused by the circulating currents induced by the HV conductors. As usual in EHV TLs shielded by conventional galvanized steel or alumoweld SWs insulated for elimination of the joule losses, the OPGWs are divided in sections of 3 to 5 km and are grounded in one tower only of each section.

Insulated OPGWs have also been used as a conductor in some medium-voltage (MV) lines that are not shielded by an SW, for providing telecommunications in addition to power distribution. In this case, the insulated OPGWs are referred to as optical phase conductors, and have a design similar to OPGWs. Energization of OPGWs has no effect on their telecommunications performance.

A leading requirement for OPGWs is limitation of temperature rise in the fiber optics, which is caused by the current circulation, because of excessive temperature of the fibers, which causes a rapid increase of light signal attenuation and might spoil the telecommunications capacity.

In HV-EHV TLs, OPGWs, grounded as usual in each tower, are exposed to circulation of the homopolar (earth return) current during the 1-ϕ-to-Gr and ϕ-to-ϕ-to-Gr short circuits in the HV-EHV circuit. The homopolar currents circulate in two parallel paths: the earth, through the grounding system of the towers, and the SWs. Generally, conventional grounded SWs and grounded OPGWs carry the largest part of the earth current in a number of spans close to the fault location. In highly electrified countries, exposure of grounded OPGWs to dangerous overtemperature is highest in the case of line 1-ϕ-to-Gr short circuits of high intensity, which occur in proximity of the substations.

Concerning the insulated OPGWs used in shield wire lines (SWLs) (and as a phase conductor in MV lines), attention must be focused on limitation of heating by the continuous circulation of the load current, and prevention of long-duration short circuits in the SWL (or MV lines), which might not be cleared quickly because of the miss-operation of the protection relays if no back-up protections are installed or in case of a circuit breaker (CB) that is stuck closed.

To limit the temperature rise of grounded OPGWs during faults to ground of HV-EHV TLs, OPGWs are manufactured by a long-established practice with the largest part of the cross-section of aluminum or aluminum alloy, to ensure low ohmic resistance and a drastic reduction in joule losses. The cross-section and percentages of aluminum or aluminum alloy, and of steel in commercial OPGWs, are similar to the ones for aluminum conductor steel reinforced (ACSR) conductors used in SWLs (typical characteristics are provided in Table 6.1).

In conclusion, the stranding and cross-section of commercial OPGWs that are commonly applied as an SW in HV-EHV TLs are also suitable for use as insulated SWs in SWLs.

It is worthwhile to point out the following:

- The load current of the SWL causes an operating temperature of the OPGWs that is lower than 80°C in the most unfavorable ambient conditions (ambient temperature of 40°C to 45°C; almost still air (0.25 m/second); and maximum solar radiation (1,000 W/sqm)).
- The overcurrent circulating during short circuits in SW(s), in "three-phase" SWLs and single-phase SWLs supplied by an interposing transformer (IT), is low (see Chapter 8) and fully harmless with the usual normal fault-clearing time.
- During the 1-ϕ-to-Gr and ϕ-to-ϕ-to-Gr short circuits in the HV TL with a simultaneous flashover in the arcing rod-gap of the OPGW insulators in the same location, the short circuit current in the OPGW of the SWLs is only slightly increased because of induction from the HV conductors and not harmful for the OPGW.

12.2 SPECIFICATIONS OF THE OPTICAL GROUND WIRES FOR USE IN SHIELD WIRE LINES

For the sake of security, the following precautionary measures are applied in the specifications for use of OPGW in SWLs and protection relays:

- Preferably (but not mandatorily), the OPGW fibers should be inside a steel tube with same diameter as one of the steel wires in the core, because there is no plastic material in contact with the fibers that could melt or degrade because of over temperature and cause an increase of signal attenuation. Steel tube OPGWs are fabricated by various manufacturers, at prices that are competitive with prices for other types of fiber protection.
- In addition to the overcurrent relay, which protects the SWL in the supply HV/MV station, back-up protection should be installed to eliminate the risk of long-duration faults. The back-up relay can be a relay sensitive to the imbalance of the currents circulating in the two SWs of the three-phase SWL, as described in Chapter 8, to ensure dependable protection. Alternatively and preferably, a dedicated relay (independent from the overcurrent relay) may be installed, which could also be assigned a second overcurrent protection function.
- The usual CB failure protection of the HV/MV station supplying the SWL(s) should also cover the CBs of the SWL(s), to ensure fast tripping of the CB(s) upstream, if the CB of the SWL fails to open for any reason.

Fig. C.10a in Annex C shows a typical cross-section of a commercial OPGW that is suitable for SWLs. The main technical characteristics are provided in Fig. C.10b in Annex C.

Accessories for the insulated OPGWs are all available in the market. The accessories include: insulated suspension splicing to be installed on the towers out along the HV line, insulated post-type terminations at the ends of the line, by-pass (jumpers) at tension towers, and special suspension clamps and armor rods that are used in suspension towers. Typical drawings of these accessories are provided in Figs. 10b-c of Annex C.

COST ESTIMATES FOR ILICETO SHIELD WIRE SCHEMES WITH THE EARTH AS A CONDUCTOR AND COMPARISON WITH CONVENTIONAL MV LINES

13

13.1 COST ELEMENTS OF ILICETO SHIELD WIRE SCHEMES

The cost of medium-voltage (MV) spur lines, medium-voltage/low-voltage (MV/LV) transformer stations, and LV networks in villages supplied by the "three-phase" Iliceto shield wire scheme (ISWS) (Fig. 2.1, Panels C1 and C2) are about the same as for the equivalent equipment for conventional MV/LV distribution networks with the same rated voltages.

Shield wire lines (SWLs) require an investment that is by far lower than that for a conventional network to make electric power available all along the route of a high-voltage (HV) transmission line (TL). The cost comparison must include the supply bay of the SWLs in the HV/MV station, for which ISWSs usually require some additional investment for the special apparatuses. Therefore, the cost evaluation here focuses on these two parts of the projects, in particular the following design modifications:

1. Instead of one or two usually galvanized steel or alumoweld shield wires (SWs), application of aluminum conductor steel-reinforced (ACSR) SW(s) of cross-section equal or somewhat higher for implementing a "single-phase earth-return" or "three-phase" ISWS, respectively. Replacement is not needed if the planned SWs are ACSR type of low ohmic resistance similar to the SWs in Table 6.1.

2. Insulation of the SW(s).

3. Minor adjustment of the SW tower peak for warranting the required electrical clearances of the insulated SWs.

4. In addition to the costs of the above three items, the following costs are to be evaluated:

5. The cost of the interposing transformer (IT) or the tertiary winding of the main HV/MV step-down transformer, if this is specifically required for supply of the SWL.

6. The cost of the resistance-inductance (R-L) symmetrization circuit of the "three-phase" SWL, if the computer analysis has shown that installation is necessary.

7. The cost of a power factor (p.f.) correction/anti-ferroresance/balancing capacitor bank.

8. The cost of the MV supply bay of the SWL.

13.2 COST ESTIMATE OF SHIELD WIRE LINES

The total investment required for making electricity available along the route of an HV TL is the sum of costs i, ii, iii, vi, vii, and, if applicable, iv and v. This investment can be compared with the investment required by an equivalent independent MV line on the same or a nearby right-of-way (ROW) summed up to the costs vi, vii, and iv if applicable, for evaluation of the savings achievable with the ISWS.

An estimate of the costs for items i through vii is made here for a "three-phase" ISWS in a single-circuit 161 kV TL with the tower top as in Fig. 3.1, Panel A, by assuming an average weight of the towers of 10,000 kg/km of TL. All estimated costs include material procurement, transport, and installation costs.

Market unit prices for year 2014 were generally available in euros. Prices were converted to U.S. dollars at the rate €1 = US$1.2.

i.	The purchase price of the ACSR SWs in Table 6.1 is about the same as the price of galvanized steel SWs with a 30% to 40% lower cross-section. Only a small extra cost for stringing the two SWs should be taken into account, say:	$360/km
ii.	Insulation of two SWs is made with insulators as per Fig. 5.1 (or equivalent composite insulators), at a price of ~$90 per string: N° 8 insulator strings:	$720/km
iii.	Increase of tower weight is 1% to 1.5% for a 161 kV single-circuit TL. By assuming 1.25%: 125 kg/km at $2.4/kg:	$300/km
	Total additional cost for i + ii + iii	**$1,380/km**
iv.a	Cost of MV/MV three-phase IT rated at 3 to 6 MVA:	$65,000 – $100,000
iv.b	Alternative cost of the tertiary winding of the HV/MV main transformer, with rated power of 4 to 8 MVA:	$40,000 – $50,000
v.	Cost of R-L circuit depending on ohmic and current ratings	$12,000 – $20,000
vi.	Cost of 30 to 34.5 kV capacitor bank:	$9,000 – $14,000
vii.	Cost of 30 to 34.5 kV supply bay of the SWL:	$48,000 – $60,000

The total additional project cost for implementation of a "three-phase" ISWS with ACSR SWs of 100 sqmm and length 100 km, to be supplied by the tertiary winding of the HV/MV main transformer, including the R-L circuit and capacitor bank, is estimated as follows:

$$100 \times 1{,}380 + 45{,}000 + 16{,}000 + 12{,}000 + 54{,}000 = \$265{,}000 \text{ (or \$2,650/km).}$$

The investment can be compared with the cost of a 30 to 34.5 kV three-phase independent line with ACSR or all aluminum alloy conductors of ~100 sqmm and average span of ~230 m, supported by galvanized steel lattice poles providing a mechanical-electrical security and durability comparable to the SWL. The turn-key cost in northern Ghana for this type of MV line was $20,000/km in 2014. For an MV line of 100 km, including the supply bay and a shunt capacitor bank, the cost is:

$$20{,}000 \times 100 + 36{,}000 + 10{,}000 = \$2{,}046{,}000$$

The cost is $20,460/km ($20,820/km if supply of the MV line requires a tertiary winding of the HV/MV main transformer).

The investment for making electricity available at MV with the SWL of 100km along the route of the HV TL, in percent of the cost of an equivalent conventional MV line, is therefore:

$$2{,}650/20{,}460 \cong 13\%$$

In 1995 a 161 kV 200 km line was contracted in Sierra Leone with two 60 sqmm galvanized steel shield wires grounded in each tower. A variation order was issued to the contractor for the installation of two 108 sqmm ACSR shield wires insulated for operation at 34.5 kV with the insulator strings in Fig. 5.1. The total turn-key price increase (supplies, transport, erection, commissioning, etc.) was $1,700 per km of line.

14 FEASIBILITY STUDY OF SHIELD WIRE SCHEMES WITHOUT EARTH RETURN OF CURRENT

14.1 TECHNICAL COMPARISON WITH ILICETO SHIELD WIRE SCHEMES THAT USE THE EARTH AS A PHASE CONDUCTOR

Use of the earth as a phase conductor has the practical and economical advantage that only minor modifications of the shield wire (SW) peaks of the towers are required, for addition of the insulators. The structural loading conditions of towers (transversal, vertical, and longitudinal) remain about the same. Redesign of towers is not required and application of the "three-phase" and "single-phase earth-return" Iliceto shield wire schemes (ISWSs) is also possible on existing transmission lines (TLs). Minor tower design adjustments are necessary. The "three-phase" ISWS with three metallic SWs requires a modification of tower design to accommodate the third SW and involves an increase in the cost of the TLs, which are dealt with in Sections 14.2 and 14.3.

However, some power distribution engineers may be hesitant to accept the use of the earth as a conductor, a technology with which they are not familiar.

ISWSs implemented with all metallic SWs have functional and operational similarities to the ISWSs that use the earth as a phase conductor, because of the close electromagnetic coupling with the high-voltage (HV) conductors. However, SWSs implemented with three SWs allow important simplifications of the electrical analyses and medium-voltage (MV) material specification and procurement. Construction becomes similar to the practice in use for conventional MV networks.

The comparison of the features of the two-SW and three-SW "three-phase" SWSs can be summarized as follows:

1. Because of the electromagnetic coupling between the SWs and the HV conductors, the exposure of the shield wire line (SWL) to switching and temporary overvoltages is similar for the two-SW and three-SW SWSs.

   The precautionary use of capacitors connected between each SW and the ground is recommended for limiting the induced voltages in the SWs when they are at floating potential with the HV circuit energized. However, in the three-metallic shield wire SWS, this function is performed by a conventional symmetrical three-phase power factor (p.f.) correction capacitor bank, star-connected, with neutral solidly grounded.

   A three-phase, fast automatic closing grounding switch should be installed in the supply bay of each SWL in the HV/MV station, for the reasons described for the one-SW and two-SW ISWSs.

   Lightning behavior is expected to be the same for the two-SW and three-SW SWLs.

2. The supply of the three-SW SWLs for the three-phase distribution and two-SW SWLs for single-phase distribution (Fig. 2.1, Panel B) is possible in some projects as it is for conventional MV lines, that is, directly from the MV busbars of an HV/MV substation. Direct supply of the SWL eliminates the need for an interposing transformer (IT) or a dedicated tertiary winding of the HV/MV main transformer, which is mandatory for the three-phase two-SW ISWSs.

However, in many applications, SWLs are very long and the forecast load is high for the required electrification of all the communities located along the HV TL between two HV/MV substations (see examples in Annex D). If the MV available for conventional distribution is in the range 10 to 20 kV, it may be insufficient for the direct supply of the SWLs. Boosting the voltage to 30 to 34.5 kV is to be done with an IT or from a dedicated tertiary winding of the HV/MV transformer. All the two-SW "three-phase" ISWSs in operation have a rated voltage of 30 or 34.5 kV.

3. In an SWL with three metallic SWs, the phase-to-ground (ϕ-to-Gr) voltages are the (ϕ-to-ϕ)/√3 voltage as in conventional distribution. There is therefore no need to increase the ϕ-to-Gr insulation levels of the MV apparatuses by 15% to 20% above the levels applied for conventional apparatuses of the same rated voltage. This makes it easier to implement material specifications and procurement, and obtain spare apparatuses.

4. The voltage imbalance that occurs along the two-SW "three-phase" SWLs, because of the unsymmetrical configuration of the SWs and the earth conductor in the presence of the HV circuit, is drastically reduced or almost eliminated in the three-SW SWLs. The resistance-inductance (R-L) grounding circuit at the sending end of the SWL is not installed. As pointed out in item 1, the three-phase p.f. correction capacitor bank to be installed is symmetrical. Only in rare cases could the analysis of a specific, very long three-SW SWL show a voltage imbalance ≥ 1%. Then a remedy will be the transposition of the SWs.

5. The MV spur lines from the three-SW SWL to the villages must be equipped with three conductors and are conventional MV lines.

The MV apparatuses of the supply bay of the "three-SW three-phase" SWL in the HV/MV substations, at the take-off of the spur line from the SWL and in the medium-voltage/low-voltage (MV/LV) transformer stations, are standard three-phase apparatuses (circuit breakers, disconnecting switches, and load break interrupters) and sets of three standard single-phase apparatuses (potential transformers, current transformers, surge arresters (SAs), and fused cut-outs).

In the "single-phase metallic-return" ISWSs (Fig. 2.1, Panel B), the MV apparatuses and spur MV lines are bi-polar instead of the monopolar required in the "single-phase earth-return" SWSs (Fig. 2.1, Panel A).

The overall installed cost of short MV spur lines and MV/LV transformer stations of the "three-phase three-SW" SWS will not change significantly because of the addition of the third insulated phase. However, if an MV spur line is long, the higher cost of a three-wire instead of a two-wire line should be taken into account.

The three-wire connection between the three SWs and the three-phase spur line to the villages at the take-off from the HV tower is physically more complex than the two-wire connection of the "three-phase" SWL that uses the earth as a phase conductor.

6. As noted in Chapter 11, the three-phase and single-phase LV networks in the villages are of conventional type, and are the same whether or not the earth is used as a phase conductor on the MV side.

7. The protection system of the three-SW SWLs is functionally as specified in Chapter 9. However, the high-resistance ground faults are detected by an earth fault (homopolar) overcurrent relay with low pick-up current setting, as in conventional MV distribution.

   The three-pole switching and protection apparatuses applied in the SWSs with three SWs have ϕ-to-Gr insulation level as in MV conventional networks, that is, somewhat lower than the two-pole apparatuses applied in the two-SW ISWSs. Overall, the cost of the switching and protection apparatuses is estimated to be about the same.

8. The setup should allow for efficacious protection by means of SAs of the MV equipment of the "three-phase three-SW" ISWSs, and for limiting switching and temporary overvoltages. For achieving this feature, it is desirable, although not mandatory, to supply the SWLs from an MV network operated with the neutral solidly grounded (this has been common practice in North America for the rural-suburban areas served by MV overhead lines).

   If the SWL with three SWs is supplied by an IT or by the tertiary winding of an HV/MV transformer, the desired solid grounding of neutral is provided by specifying the winding that supplies the SWL to be star-connected with grounded neutral.

9. Quality of service to consumers, in particular the number of interruptions per year, is expected to be about the same for the three-phase two-SW and three-SW schemes. Faults on three-SW SWLs are expected to be transient (without equipment damage), as in the SWL with earth return of the current.

   Losses of SWLs are somewhat increased because the third metallic SW has an ohmic resistance that is much higher than the earth conductor, in spite of the partial re-instatement of the resistance and losses of the earth conductor in the two-SW "three-phase" ISWS by the R-L grounding circuit when this is applied.

10. A sufficiently accurate calculation of voltage drops/rises, losses, choice of no-load ratios and regulation tappings of transformers, choice of type and cross-section of the SWs, choice of location and kVAR rating of the three-phase p.f. correction capacitor bank, and calculation of the short circuit currents can be made for the three-SW SWLs with the simplified model and method described in Section 6.4 for the preliminary planning of SWLs that use the earth as a conductor.

14.2 MODIFICATION OF HIGH-VOLTAGE TOWERS FOR ADDITION OF THE THIRD SHIELD WIRE

A long-established practice has been to shield the HV and extra-high-voltage (EHV) TLs against lightning with one or two SWs. Two SWs are applied in regions highly exposed to lightning or in important TLs (TLs with the phase conductors in horizontal configuration, heavily loaded EHV TLs, and long radial HV

TLs serving important loads or generating stations). The second SW considerably improves the shielding against lightning and also appreciably reduces the back-flashover rate caused by lightning.

Three SWs have not been applied so far in TLs, because the third SW does not increase the lightning protection efficacy. It is therefore worthwhile to advise how the third SW can be fitted on the TL towers.

Various alternative modifications of the top part of the towers have been studied within the scope of this manual for the addition of a third SW. Solutions should be electrically and structurally sound; simple for the line construction works as far as possible; and aesthetically acceptable.

Three alternative schemes are shown in Fig. 14.1 for a double-circuit (D/C) TL with HV conductors of each circuit in vertical configuration. The drawings are at scale for a 161 kV TL with a 34.5 kV SWL. The distance between two adjacent SWs is assumed to be 3 m, which is also sufficient for very long spans (up to 700 to 800 m). The resulting distance between the two external SWs is 5.2 m in the scheme in Fig. 14.1, Panel A; 6 m in the scheme in Fig. 14.1, Panel B; and close to 6 m in the scheme in Fig. 14.1, Panel C. The shielding angle is < 10°, ensuring very effective shielding. The small circles with centers in the SWs shown in the drawings mark the clearance limit required in normal operation (radius 400 mm) and in exceptional conditions with insulator string deviation > 60° caused by wind (radius 200 mm).

In scheme A (Fig. 14.1, Panel A), in the suspension tower, the middle SW is supported with sliding clamps by a post-type insulator bolted on top of the body of the tower. In tension towers, the middle SW is anchored on the two sides with tension strings, as for the external SWs. The SW jumper crosses over the tower crossarm and is supported by a light post-type insulator bolted on the center of the crossarm. This solution was applied once in the late 1990s for the insulation of the SW of a long 132 kV TL under construction, for implementing a "single-phase earth-return" SWL. Composite fiberglass silicon–rubber post-type insulators with a sliding clamp bolted on top were applied, to warrant the withstand to the broken SW. Some details of this retrofitting are provided in Section 16.4.

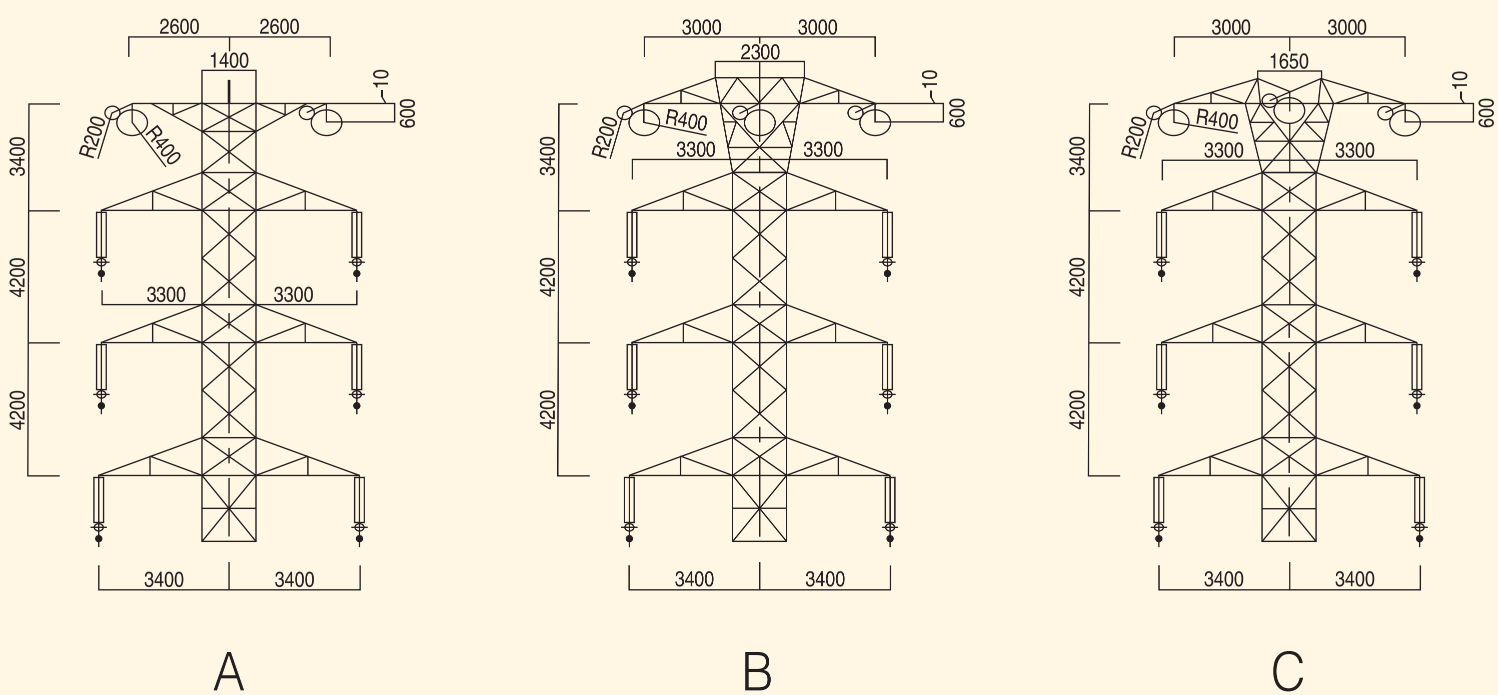
Solution A (Fig. 14.1, Panel A) is unconventional because of the non uniform insulation of the three SWs. For stringing the middle SW, it requires special self-supporting wire running blocks to be temporarily firmly secured over the crossarm, instead of the suspended-type running blocks used for the external SWs.

In solution B (Fig. 14.1, Panel B), the middle SW is placed inside a delta-shaped window and suspended (anchored on tension towers) at the same height as the two external SWs. Solution B requires manually passing the running rope across the delta window for stringing the middle SW; this is required also in the case of stringing with an helicopter. The consequent increase in cost for stringing the SWs is however modest if the cost of local labor is low. Solution B is the most conventional from the structural point of view.

In solution C (Fig. 14.1, Panel C), the middle SW is suspended with an insulator string to the vertex of two galvanized steel rods in a "V" assembly set, which is to be supplied by the manufacturer of the line accessories. In solution C, the middle SW stringing is made before installing the "V" suspension assembly, practically without additional cost, by suspending the wire running block on a temporarily laid "L" or "T" steel section member across the two SW crossarms.

FIGURE 14.1

Alternative Outlines of the Modified Shield Wire Crossarm on a Double-Circuit 161 kV Transmission Line for Addition of the Third Shield Wire



Panel A, with a post-type insulator on mid SW crossarm; Panel B: with a delta-window under the SW crossarm; Panel C: with a "V" assembly set on center-top of SW crossarm.

The three solutions can be considered electrically equivalent and mechanically sound.

In single-circuit (S/C) TLs with HV conductors in triangular configuration, the same three solutions are applicable.

If an S/C TL has the HV conductors in a horizontal configuration, only solutions similar to A and C can be applied.

The increase in the weight of the TL towers caused by the addition of a third SW is estimated as follows:

Solution A: + ~5% for S/C towers; + 3 ÷ 3.5% for D/C towers

Solution B: + 8 ÷ 10% for S/C towers; + 5% to 7% for D/C towers

Solution C: + 10 ÷ 13% for S/C towers; + 7% to 9% for D/C towers

14.3 ESTIMATE OF ADDITIONAL COST FOR "THREE-PHASE" SHIELD WIRE SCHEMES WITH THREE SHIELD WIRES

The insulation of one or two SWs for application of the ISWSs with earth-return of current requires only the additional cost for procurement, transport, and installation of the insulators and fittings of the SW(s). A small amount is also needed for the increase in tower weight, because the price of aluminum conductor steel-reinforced (ACSR) SWs is about the same as the price of the more usually applied galvanized steel or alumoweld SWs. Details on costs are provided in Chapter 13. Insulation of one or two SWs applied for lightning protection and in many cases for telecommunications, is easily added at the design stage; it may also be feasible in existing TLs without important modifications of the towers.

The following items should be considered for estimating the extra costs (material procurement, transport, and erection) of installation of the third SW, to be added to the cost estimated in Chapter 13, for the insulation of the two SWs of the "three-phase" ISWSs that use the earth as a phase conductor:

- Transmission line: third SW; insulators, fittings, stringing of the third SW; and increase of structural members and weight of towers.
- Supply bay of the SWL in the HV/MV station: there are savings in comparison with the "three-phase" ISWS with two SWs, if the available MV is sufficiently high for the supply of the SWL. In this case, the provision of a dedicated tertiary winding of the main transformer or of an IT is eliminated.
- The cost of the R-L grounding circuit, which in most cases is necessary in "three-phase" ISWSs with earth return of current, is eliminated.

Among the three alternative solutions presented in Fig. 14.1, an estimate of the additional cost for the third SW is made below for solution B, which is based on the most conventional TL design rules. As an example, a 161 kV TL is considered with twin bundle ACSR Toucan conductors, shielded by two SWs for lightning protection, and designed with the structural loading assumptions and regulations of Ghana.

The average weight of the towers is estimated at 10,000 kg/km for the S/C TL and 15,000 kg/km for the D/C TL. ACSR SWs with cross-section of 100 sqmm and aluminum/steel wire stranding as per Table 6.1 are considered.

Market unit prices from year 2014 were generally available in euros. Prices were converted to U.S. dollars at the rate €1 = US$1.20.

There is no application experience of the third SW on TLs. However the modification of towers and of TL erection works are simple conventional technologies suitable for all line contractors. It is therefore reasonable to assume, for the cost estimates, unit prices, inclusive of material procurement, transport, and erection that are approximately the average of prices in the markets in Western Europe and China, as follows:

- $2.4/kg for tower steel members
- $3.6/kg for ACSR SWs
- $480/km for the fittings
- $90 for the insulator strings as per Fig. 5.1.

The additional cost for 1 km of TL is estimated as follows:

• For the towers, additional weight for 1 km of TL (Fig. 16.1, Panel B):	
○ S/C TL: 0.09 × 10,000 = 900 kg/km at $2.4/kg	$2,160/km
○ D/C TL: 0.06 × 15,000 = 900 kg/km at $2.4/kg	$2,160/km
• 100 sqmm ACSR SW weighing 470 kg/km at $3.6/kg (inclusive of stringing):	$1,692/km
• Insulators with arcing rod-gap as per Fig. 5.1,	
N° 4 per km at $90 per piece	$360/km
• Fittings for SW	$480/km
Total additional cost for S/C or D/C TL	**$4,692/km**

This additional cost is reduced to ~$3,960/km if the third SW is supported by a post-type insulator on top of the body of the tower, as in tower scheme A in Fig. 14.1, Panel A.

The cost variations of the supply bay of the SWL in the HV/MV station and the spur MV lines depend on the specific requirements of each project. However, the overall cost variation per km of three-SW SWLs will be small for long SWLs, owing to the much higher cost per km of the third SW.

For a three-SW SWL supplied directly at the distribution MV available in the HV/MV step-down transformer station (that is, without MV/MV IT or tertiary winding of an HV/MV transformer), the cost reduction of the supply bay, compared with the cost of the supply bay of a "three-phase" two-SW SWL, can be estimated at ~$85,000 with the unit prices assumed in Chapter 13, that is, $850/km for a 100 km SWL. The savings are much smaller if the supply bay of the three-SW SWL is made by an IT or a dedicated tertiary winding.

With the above assumptions, the total cost for the construction of a three-SW SWL, instead of a TL shielded against lightning with two conventional SWs grounded at each tower, is estimated as follows:

- \$4,692/km + \$1,380/km = \$6,072/km for installation of the third SW as per scheme B in Fig. 14.1, Panel B.
- \$3,960/km + \$1,380/km = \$5,340/km for installation of the third SW as per scheme A in Fig. 14.1, Panel A.

The estimated costs for the addition of the third SW and for insulation of the two SWs applied for lightning protection are \$4,692/km or \$3,960/km and \$1,380/km, respectively (see Chapter 13). Lower turnkey prices might be achieved with international competitive bidding.

The total additional cost per km of a three-SW versus a two-SW SWS is a little less than the above-estimated cost of the third SW, because there are some savings in the supply bay of the three-SW SWL.

14.4 ESTIMATE OF THE ADDITIONAL COST OF THE "SINGLE-PHASE METALLIC-RETURN" ILICETO SHIELD WIRE SCHEME WITH TWO INSULATED SHIELD WIRES COMPARED WITH THE COST OF A "SINGLE-PHASE EARTH-RETURN" ILICETO SHIELD WIRE SCHEME

A comparison is made of the costs of the single-phase SWSs of Fig. 2.1, Panels A and B.

If the HV TL is provided with two SWs for lightning shielding, an additional cost for the "single-phase metallic-return" ISWS compared with the "single-phase earth-return" ISWS is the cost of insulation of two SWs instead of one SW. With the unit prices assumed in Chapter 13, the cost is estimated at ~\$750/km. However, the comparison must take into account the possible difference in the cost of the supply bay of the SWL and the effect of the supply voltage (ϕ-to-ϕ and ϕ-to-Gr) on voltage drop and losses.

If the HV TL is provided with one SW for lightning shielding and the "single-phase earth-return" ISWS is applied, the cost for the insulation of the SW, based on the unit prices assumed in Chapter 13, can be estimated at $1{,}380 \times 2/3 \cong \$900$/km.

The cost of the two-pole or one-pole supply bay of the SWL in the HV/MV station is about the same if use is made of one standard three-phase feeder of the MV switchgear. However, if an IT is installed in the single-phase ISWS with earth-return of current only because the neutral of the MV local network is grounded via a high impedance (see Chapter 2), the cost of the IT is to be deducted in the evaluation of the additional cost of the "single-phase metallic-return" two-SW ISWS, which can be supplied directly from two of the MV substation phases.

In the case of direct supply of the single-phase two-SW and one-SW SWL directly from the station MV busbars, as assumed in Fig. 2.1, Panels A and B, the two-SW SWL is supplied at a voltage $\sqrt{3}$ higher than the one-SW SWL. However, the reduction in voltage drop and losses on the two-SW SWL and associated MV spur lines caused by the increase in operating voltage is markedly eroded in comparison with the ISWS with earth return of current. The reason is the negligible ohmic resistance and somewhat lower series reactance of the earth-return conductor in comparison with a metallic SW.

If the two-SW and one-SW single-phase SWLs are supplied by an IT at the same voltage, voltage drop and losses in the two-SW SWL with metallic return of current are considerably higher than in the one-SW earth-return SWL, because of the low ohmic resistance and somewhat lower reactance of the earth-return conductor.

The cost of the MV/LV single-phase distribution stations is approximately the same for the two alternative schemes. The cost of the LV reticulation is the same.

The cost of a one-wire MV spur line is much lower than the cost of a two-wire spur line. The difference should be evaluated if the spur MV line is long. A one-wire MV spur line can be designed with spans of 275–300m, thus drastically reducing the number of poles and foundations. Commercial poles can be used, by choosing a conductor suitable to limit the sag on long spans.

15

DATA COLLECTION FOR PLANNING ILICETO SHIELD WIRE SCHEMES

15.1 HIGH-VOLTAGE TRANSMISSION LINES

- Country and region of implementation; location of terminal substations. If available, single-line diagram of the regional high-voltage (HV) network.
- Main climatic conditions.
- Rated voltage, length, and type of transmission line (TL) (single circuit (S/C) or double circuit (D/C)).
- Number of planned shield wires (SWs) for lightning shielding and, if any, telecommunications.
- If available, planned outline of TL towers with the geometry of the conductors: triangular or horizontal configuration for S/C TLs; number of tower crossarms for D/C TLs.
- If known, the type of HV conductors: aluminum conductor steel reinforced (ACSR), all aluminum conductor (AAC), all aluminum alloy conductor (AAAC), single or bundle conductors.
- A plan showing the preliminary route of the TL.
- Estimated power (MW) to be transmitted by the HV TL and the direction of power flow (mono-directional or bi-directional).

15.2 TERMINAL SUBSTATIONS OF TRANSMISSION LINES

- Type of substations: public high-voltage/medium-voltage (HV/MV) step-down transformer station, power plant step-up transformer station, or privately owned factory station.
- Rated MV in existence or planned: of local MV conventional distribution; of generators in case of power plants, or other.
- Single-line diagram and, if available, lay-out drawings of terminal substations; maximum and minimum three-phase short circuit current at the HV busbars of the stations that will supply the Iliceto shield wire schemes (ISWSs); and soil resistivity (Ωm) at the substation sites.

15.3 LOADS TO BE SUPPLIED BY THE ILICETO SHIELD WIRE SCHEME

- A map showing the location of the loads to be supplied: villages, communities, hospitals, pumping stations, large farms, factories, and other loads to be supplied.
- Distance along the TL route for each load from the HV/MV station that supplies the shield wire line (SWL) and the approximate distance of the loads from the route of the HV TL.

- For each community:
    - Number of inhabitants and estimated number of families, foreseen number of consumers to be supplied.
    - Load forecast: initial, after 10 years, and after 20 years. High and low load forecasts may also be provided.
    - Motors with rated power ≥ 5 kW to be supplied by the ISWSs.
    - For pumping stations and factories requiring large motors: total kW demand, approximate rated power and number of large motors (3-ϕ induction motors rated at 200 kW have been supplied by a “three-phase” 34.5 kV SWL in Brazil).
- If off-grid local generators are in existence in some locations, inform:
    - Location
    - Types (diesel, hydro, eolian, solar, biomass)
    - Installed rated kW of efficient generators: aggregate and individual units
    - Unsuppressed load peak demand of the village/town
    - If an MV network is in existence in a village/town: rated voltage, number of MV/LV transformer stations, and approximate total miles of the MV lines.
- If it is known, soil resistivity (Ωm) at the prospective locations of the MV/LV stations and capacitor bank.
- Type of distribution acceptable by the local power distribution utility: three-phase, single-phase, or mixed.

PLANNING ILICETO SHIELD WIRE SCHEMES

16.1 CHOICE OF TYPE OF ILICETO SHIELD WIRE SCHEMES

The applicable Iliceto shield wire schemes (ISWSs) are described in the previous Chapters. Implementation is possible in single-circuit and double-circuit high voltage (HV) transmission lines (TLs), with rated voltage in the range 90 to 345 kV. Feasibility for higher rated voltages is to be assessed, as no experience and analyses have been conducted to date.

If the candidate HV TL for electrification with the ISWS is shielded by one shield wire (SW), the "single-phase earth-return" is the only applicable ISWS. This scheme can supply residential and commercial consumers with the lowest investment, including the single-phase induction motors rated up to 5 to 6 kW, which are available in African markets. Special single-phase motors rated up to tens of kW with low start-up current and 3-phase standard motors supplied by a 1-ϕ to 3-ϕ electronic converter are however available in the international markets. The applicable solutions are described in reference [12] (2015).

If the HV TL is a new project and it planned to be shielded by two ISWs for effective lightning protection (advisable for long TLs in tropical countries), the applicable ISWSs are the "three-phase" ISWS with the use of the earth as the third phase conductor or, alternatively, the "single-phase metallic-return" ISWS. The former has been generally preferred, because the electrification is carried out in three-phase, and because it has a power distribution capacity about double that of the single-phase SWL at the same rated voltage and with SWs of the same ohmic resistance. A further alternative, analyzed for the first time in Chapter 14 of this manual, can be a TL equipped with three SWs, which allows the three-phase supply by a shield wire line (SWL) without the use of earth as a conductor.

A guideline for estimating the investment required for the insulation and addition of SWs is provided in Chapters 13 and 14.

If there are communities or pumping stations/factories to be picked up by the planned SWL, which are already supplied by local three-phase stand-alone generators, a "three-phase" ISWS should be planned. The existing generators (for example, hydroelectric, biomass, etc.) can be operated synchronously connected to the grid via the SWL.

If a town has a medium-voltage (MV) distribution network, it can be supplied from the SWL via an MV/MV interposing transformer (IT). Alternatively, if the extension of the existing MV network and number of medium-voltage/low-voltage (MV/LV) transformer stations are small, the local MV network can be modified with the technology and rated voltage of the ISWS, for direct supply from the SWL.

The ISWS that has been applied most often in the past is the "three-phase" with use of the earth as a phase conductor. The "single-phase earth-return" ISWS has been applied only in cases of HV TLs equipped with one SW, at an advanced stage of construction or already commissioned (see Section 16.4).

The second step after the choice of the type of ISWS is the definition of the sections of the TL route where the ISWS will be implemented. In many cases, the route of the HV TL is close to a highway along which many villages are located, and the agency in charge of electrification requires the provision of electricity to all the villages, initially or in two or three stages. In these cases, the SWs are insulated along the length of the TL.

If the TL is long, two ISWS are implemented, to be supplied from each of the terminal HV/MV stations of the TL. The length of each of the two sections is selected according to the location and size of the loads, not necessarily of equal length. For example, the criterion may be to have almost equal voltage drop, with attention also to losses and continuity of power supply in both sections. The separation between two adjacent sections is made in a tension tower of the HV TL, simply by not installing the jumpers usually bridging the anchor insulators of the insulated SWs. Separation may be relocated in another tension tower after some time in accordance with the evolution of the loads. Typical single-line diagrams of ISWSs in operation are shown in Annex D.

16.2 CHOICE OF THE RATED VOLTAGE OF THE SHIELD WIRE LINES

A further planning step is the choice of the rated voltage of the SWLs. The “three-phase” SWLs that use the earth as a phase conductor must be supplied by an IT or tertiary winding of the main HV/MV transformer, which provides the necessary galvanic separation. There is, therefore, freedom for the optimal choice of the rated voltage of the SWLs. If the SWLs are long and the future load forecast is important, as is usual in many projects, a rated voltage of 30 or 34.5 kV is chosen for reducing the voltage drop and losses. A high rated voltage of the ISWSs also reduces the current flow in the earth and facilitates the construction of the grounding systems.

For the other types of ISWSs (see Fig. 2.1), direct supply from the MV busbars of the HV/MV step-down transformer station is possible. However, if the available rated voltage is 10 to 20 kV and is too low for the supply of the planned long SWLs (excessive voltage drop and losses), the 30 or 34.5 kV rated voltage may be chosen and the SWLs will be supplied by an IT or tertiary winding of an HV/MV transformer.

16.3 CHOICE OF THE SUPPLY MEDIUM-VOLTAGE BAY OF THE SHIELD WIRE LINES

The choice of the supply MV bay is made as recommended in Chapter 7.

The single-line diagram of the supply bay of the “three-phase” ISWS that uses the earth as a conductor can be as per Fig. 7.1, Panel A, if supply is made from the tertiary winding of the HV/MV main transformer, or as per Fig. 7.1, Panel B, if supply is made by an IT.

The supply bay of the “single-phase earth-return” SWLs is similar to the bay in Fig. 7.1, Panel B, if an IT is used for boosting the voltage, or because the neutral of the local MV network is neither solidly grounded nor grounded with a very low impedance. However, one phase only is implemented and the resistance-inductance (R-L) circuit is not applied. The IT is single-phase and has one terminal on the SWL side solidly grounded.

“Three-SW three-phase” SWLs (Chapter 14) can be supplied from a standard feeder of the MV switchgear of the HV/MV substation if the available MV is sufficiently high. If the voltage is to be boosted by an IT, the IT is supplied by one feeder of the MV switchgear and the SWL is terminated in the HV/MV station with a three-phase bay similar to the two-phase bay in Fig. 7.1, Panel B, with the addition of the third phase. An alternative is the supply from a dedicated tertiary winding of a HV/MV main transformer. The R-L circuit is not required and the star winding of the IT or tertiary winding of the HV/MV transformer that supplies the SWL should preferably have the neutral solidly grounded. The single-line diagram is shown in Fig. 16.1, Panel A. It is possible to switch on and off and protect the IT and the three-SW SWL as one block with the MV circuit breaker (CB) on the primary side of the IT.

If a three-SW SWL is supplied by a dedicated tertiary winding of an HV/MV main transformer, the supply bay is as shown in Fig. 16.1, Panel B.

Three-phase three-SW ISWSs can have rated voltage of 34.5 kV with the use of apparatuses with the standard International Electrotechnical Commission (IEC) insulation levels for 36 kV Class (ϕ-to-Gr BIL of 170 kV peak and 50 Hz – 1′ test voltage of 70 kVrms).

If there are two ISWSs of the same type and the same rated voltage originating from an HV/MV station, it is possible to supply both SWLs from only one IT or tertiary winding of the main HV/MV transformer, with a dedicated CB for each SWL. However, if the two ISWSs are “three-phase” with the earth as a phase conductor, the R-L circuit, if needed, is necessarily used in common for the two SWLs. It should therefore be checked that the R-L circuit can be assigned an impedance acceptable for the symmetrization of both SWLs.

16.4 CHOICE OF THE SHIELD WIRE LINE SUPPLY BY A TERTIARY WINDING OR AN INTERPOSING TRANSFORMER

The investment, installation space and power losses are all lower with the supply from the dedicated tertiary winding of a main HV/MV step-down transformer in comparison with use of an IT. However, the choice is limited for each project by the following specific conditions.

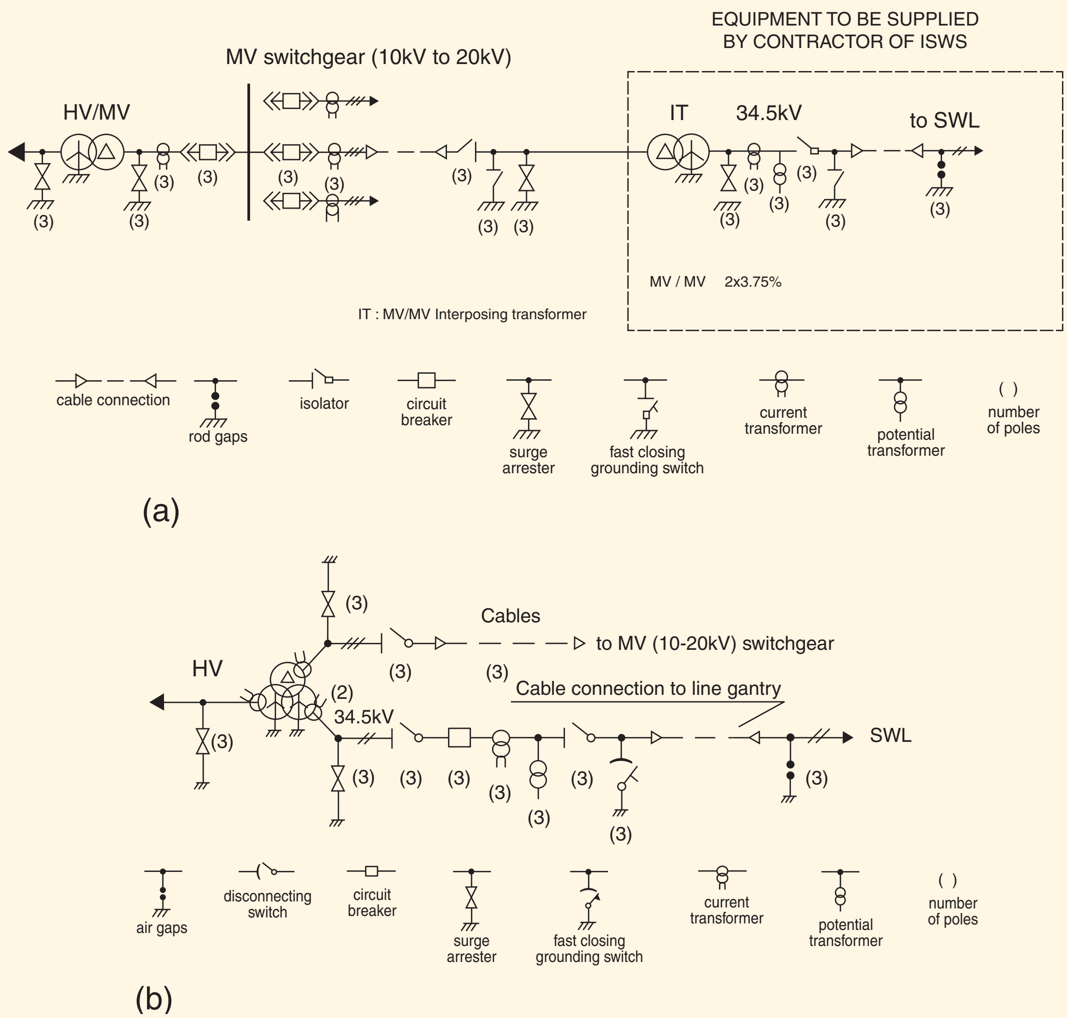
i. Use of an IT is necessary if, in the HV station which supplies the SWLs, the HV/MV step-down transformers are already in existence or under manufacturing. The IT is also a set choice if the SWLs are supplied by a power plant where HV/MV step-down transformers for distribution are not installed. Provision of the dedicated tertiary winding in a step-up transformer of a generator is not practicable for various operational reasons (continuity of supply, etc.).

ii. If the power utility has a standardized HV/MV step-down transformer type in use in the network, ordering only 1 or 2 transformers with the tertiary winding would require a new design and type tests. If a spare unit is required, provision of a dedicated spare transformer would be too expensive in comparison with a spare IT.

iii. If a rural electrification projects comprises several SWLs, to be supplied by different new HV/MV stations to be built, use of tertiary winding is the optimal solution. A multipurpose

FIGURE 16.1

Typical Single-Line Diagrams of the 34.5 kV Supply Bay of the "Three-Phase" Shield Wire Line with Three Shield Wires



Panel (a) shows the supply bay with an interposing transformer; Panel (b) shows the supply bay with a tertiary winding of the high-voltage/medium-voltage transformer.

spare 3-winding transformer may be purchased, unless in one or more stations two equal transformers are installed and one could in emergency be used as the spare without customer supply interruption.

iv. A requirement to be kept in mind is that the IT or the tertiary winding of a main HV/MV transformer must be designed and manufactured for withstanding the electrodynamic forces caused by repetitive short circuit currents during the faults in the SWLs. This capability is also necessary for the HV/MV transformers supplying the conventional public overhead distribution networks. The specific requirements for the design and type test of the IT and for the tertiary winding of main transformer are specified in the Appendices A and B.

v. The IT is the practicable solution when a Single-Phase Earth-Return ISWS is built and the ϕ-to-Gr rated voltage on the MV side of the available HV/MV 3-phase step-down transformer is too low for the direct supply of a long SWL. In this case a single-phase IT is the preferable solution, instead of a HV/MV transformer with a 3-phase dedicated tertiary winding to be used for supply of a single-phase load.

vi. The above criteria have addressed the choice of supply by ITs or tertiary windings of the ISWSs in operation, the single-line diagrams of which are reported in Annex D.

    In the Lao People's Democratic Republic (Fig. D3) five 3-Phase ISWSs have been supplied by the dedicated tertiary winding of the equal step-down transformers of five new substations. The first manufactured transformer has been tested in KEMA Laboratories to withstand the electrodynamic forces caused by the short circuit currents. The Single-Phase Earth-Return ISWSs (not reported in Annex D) have been supplied by ITs.

    In Sierra Leone the Bumbuna-Makeni ISWS (ref. Fig. D4) is supplied from the Bumbuna hydroelectric power plant via an IT.

    In Togo (ref. Fig. D6), one ISWS is supplied by the Atakpamé substation via an IT, because the main HV/MV transformer was in existence. In the Kara new substation, two equal HV/MV step-down transformers have been installed, provided of a dedicated tertiary winding for supply of the ISWSs. The choice has been similar for the supply of the ISWSs in Burking Faso (ref. D.7).

16.5 EXPERIENCE WITH RETROFITTING ILICETO SHIELD WIRE SCHEMES ON TRANSMISSION LINES UNDER CONSTRUCTION AND ALREADY COMMISSIONED

16.5.1 Ghana

SWLs have been implemented on TLs under construction and already commissioned, in three cases. The first application was an experimental scheme in Ghana, for checking the viability of the ISWSs. A pilot ISWS was implemented in 1985 on the TL between Cape Coast and Takoradi, a 161 kV double-circuit TL, in operation since 1965 with only one circuit strung. The line is shielded by two alumoweld SWs with a cross-section of 36 sqmm. Details on this pilot scheme are provided in reference [1] (1985).

SWs have been insulated on 31 km of line by means of rigid insulator strings similar to the ones in Fig. 5.1. A photograph of the modified tower head with the insulated SWs and of a pole-mounted 100 kVA transformer for supply of a village in single-phase is shown in photo D.1 in Annex D (see reference [2] (1989)).

The SWL was supplied by the 161/33/11 kV step-down transformer at the Cape Coast substation. A tertiary winding to be dedicated to the SWL was not available. An MV/MV IT was also not available in Ghana. The "V" ISWS was therefore applied (Fig. 2.1, Panel D), with the two SWs supplied ϕ-to-Gr at 33/√3 kV from two phases of the station's 33 kV busbars. An available grounding transformer with low homopolar impedance (10 Ω) was installed to allow current return through the earth.

The "V" SWL had supplied along the route of the TL three villages in single-phase and, at the end of the insulated SW section, had supplied in three phase the television broadcasting station of the southwest of Ghana (previously supplied by diesel generators) with two "V" connected single-phase standard North American 100 kVA distribution transformers (Fig. 2.1, Panel D). The load included three-phase induction motors rated up to 5 HP.

Insulation of the SWs was made by bolting at the two ends of the SW crossarm short brackets fabricated with a "U" galvanized steel section bar, for ensuring the necessary electrical clearances.

The arcing rod-gap of the insulator strings was set at 23 cm. The SWs were re-connected to the insulator strings through their existing suspension clamps. Of course, the materials ("U" steel section bars and insulator strings) were all properly manufactured so as to simplify the fieldwork.

The fieldwork on the TL was done by the maintenance staff of the Volta River Authority (VRA), with teams working simultaneously in different line stretches to minimize the out-of-service of the TL. The work was done with the 161 kV TL de-energized, when allowed by the system dispatching center without interrupting any load, and completed in less than 1 month.

All the measurements and tests of the operational features of interest for the new ISWSs, including the "three-phase" ISWS, were found in keeping with the design assumptions and satisfactory.

The pilot scheme was in commercial operation for many years, until the region was extensively electrified from the grid, and the SWL was replaced by a 33 kV conventional distribution line.

16.5.2 Lao People's Democratic Republic

In the Lao People's Democratic Republic, in 1991, the National Electricity Corporation decided to apply the ISWSs in 211 km of 115 kV TLs that were under construction between Thalat and Luang Prabang. Towers had been fabricated and line erection had been completed in 64 km between Thalat and Vang Vieng. The TL had been designed with one galvanized steel 60 sqmm SW, which had been strung in the Thalat–Vang Vieng TL. The "single-phase earth-return" scheme was therefore the only practically applicable ISWSs.

Galvanized steel small brackets were fabricated and bolted on existing holes on top of the SW peak of all the towers, for installation of rigid insulator strings, similar to the ones in Fig. 5.1, with the necessary electrical clearance. The outline of the suspension tower head is as in the top right of Fig. 2.1.

In the 147 km Vang Vieng–Luang Prabang TL, the SW had not been strung. An aluminum conductor steel reinforced (ACSR) SW with a cross-section of 76.9 sqmm was applied instead of the originally planned 60 sqmm galvanized steel SW (see data in the first column of Table 6.1 in Section 6.2).

The insulation works of the already strung galvanized steel SW in the Thalat–Vang Vieng TL were made as described for the pilot ISWS in Ghana.

Three “single-phase earth-return” SWLs were implemented in Lao PDR with rated voltage of 25 kV. Each SWL is supplied by a single-phase 22 kV/25 kV ±2 × 2.5% IT. Initially, in 1996, the three ISWSs supplied 47 villages with about 90 single-phase 25 kV/LV transformers. In the following years, other villages were electrified by these ISWSs and many MV/LV single-phase transformers were added. Fig. D.3 in Annex D shows only the single-line diagrams of the three-phase 34.5 kV ISWSs that were built later in Lao PDR.

As discussed in Section 6.2, galvanized steel and alumoweld SWs have high ohmic resistance, which limits the load capability. However, they were sufficient for the pilot ISWS in Ghana and for one of the “single-phase earth-return” ISWSs in Lao PDR.

16.5.3 Ethiopia

The application of the ISWS in Ethiopia was decided in 1998–99, for the Ghedo-Nekempte-Ghimbi 200 km 132 kV single-circuit line, which was under construction. The line had been designed with a triangular configuration of phase conductors and lightning shielding by one galvanized steel SW of 60 sqmm. When the decision to implement the ISWSs was made, the towers had already been manufactured and partly erected; wire stringing had not yet started. The only practicable solution was therefore the application of the “single-phase earth-return” ISWS, with the following minor changes in line design: use of an ACSR SW, with a cross-section of 76.9 sqmm (Table 6.1), instead of the galvanized steel SW; use in suspension towers of post-type fiberglass-silicone rubber composite insulators with arcing rod-gaps, bolted on the top plate of the towers’ SW peak by using the same four holes available for fitting the SW clamp; and in the tension towers, use of two tension insulator strings and a light post-type composite insulator on top of the SW peak for supporting the jumper overcrossing the SW peak. The connection from the insulated ACSR SW to the short lines supplying the villages was made with an all aluminum alloy conductor (AAAC) supported by light post-type insulators fastened in the centerline on one transversal face of the tower.

Each SWL was supplied via an MV/MV IT, at the rated voltage of 34.5 kV. Fig. D.5 in Annex D shows the single-line diagrams.

A check of the tower’s structural design showed that the above modifications were feasible without violating the specified safety factors of the tower’s mechanical design. Use of composite post-type insulators warrants the mechanical withstand in the case of broken SW (cantilever strength of the commercial post-type porcelain insulators was insufficient). In suspension towers, the shielding of ACSR SW was improved (shielding angle was slightly reduced because of the 65 cm increase in height).

The tower grounding resistance and the HV/MV substation grounding mesh resistance were specified not to exceed 10 Ω and 1 Ω, respectively. The three implemented “single-phase earth-return” ISWSs supplied 15 villages and small towns by means of MV/LV single-phase transformers.

Some component failures and a soil explosion around a grounding rod (see note[2] at the end of Chapter 3) have occurred in these ISWSs in Ethiopia, caused by the procurement of apparatuses and construction works not in conformity with the technical specifications. The SWLs have reportedly been replaced by three-phase MV conventional lines to satisfy the request for three-phase supply of motors by the consumers in the villages. The recovered apparatuses can be used in conventional single-phase distribution.

16.5.4 Concluding Remark

As a concluding remark, it is worthwhile to note that, in general, the insulation of the grounded SW(s) of an existing TL is feasible without changing the tower's structural design, and without violation of the specified safety factors. In general, the originally strung or specified galvanized steel SW(s) can be replaced by ACSR SW(s).

16.6 SUPPLEMENTARY RECOMMENDATIONS

ISWS planning should also include the following checks and provisions in view of future expansions:

i. Formula (5.1) in subsection 5.3.3 should be used to check that the temporary overvoltages induced in the SWL by the 1-ϕ-to-Gr short circuits in the HV TL do not exceed 1.5 p.u.

ii. If a single-phase ISWS is to be constructed, formula (4.1) in Section 4.3 should be used to check that the negative sequence voltage at the MV supply busbars of the SWL at full load is lower.

iii. During the construction of the HV TL, plans should be made for implementation of the take-off conductors at all the foreseen locations of loads to be supplied in the future, to avoid the interruption of service of the HV TL for the take-off. It is sufficient to install a short slack span from the SW(s) to the first pole of the MV spur line that will be built in the future. Typical layout drawings of these connections are provided in Annex C.

iv. In some cases, after several years of operation of SWLs between two HV/MV transformer stations, the construction of a new HV/MV transformer station at an intermediate point of the HV line may be justified, to serve the load of a town initially supplied by an SWL that has increased markedly. In this case, the two long initial SWLs can each be split into two shorter SWLs, with larger loading capability and lower rate of faults, being supplied also by the new HV/MV station. In the town served directly by the new HV/MV station, the MV/LV transformers and the LV networks will continue to be operated with only minor changes in the MV supply equipment (MV/LV transformers remain the same).

CONSTRUCTION OF ILICETO SHIELD WIRE SCHEMES

17.1 SITE WORKS FOR CONSTRUCTION OF ILICETO SHIELD WIRE SCHEMES

Construction of Iliceto shield wire schemes (ISWS) includes the following site works:

i. Installation of insulated aluminum conductor steel reinforced (ACSR) shield wires (SWs) in high-voltage (HV) transmission line (TL)

ii. Installation of shield wire line (SWL) supply bay(s) in high-voltage/medium-voltage (HV/MV) stations

iii. Construction of MV and LV networks for supply of the loads.

17.2 INSTALLATION OF INSULATED ACSR SHIELD WIRES IN THE HIGH-VOLTAGE TRANSMISSION LINE

The construction works will proceed smoothly and without errors, if materials have been procured in compliance with the technical specifications (TSs) in this manual and in Annexes A and B. The installation drawings should be prepared in keeping with the engineering drawings in Annex C.

Installation of ACSR insulated SWs differs from the installation of conventional grounded SWs because of the addition of the insulators. Stringing ACSR insulated SWs is done with the same methods and precautions in use for stringing the HV conductors of the TL.

The construction program of the SWL should be far-sighted, to avoid any additions or modifications in the future involving the outage of the HV circuit. The cross-section of the SW should be chosen for the final load, for example, 20 years ahead. The ACSR SWs in Table 6.1 of Section 6.2 are generally suitable for the final load.

As per recommendation iii in Section 16.5, the take-off from the HV TL towers for tapping from the SWL of the spur MV lines that supply the villages should all be built during the TL construction works, including the locations to be electrified in later stages. The take-off can be built with overhead slack spans, as per the drawings in Figs. C.3a, C.3b, C.3c, and C.3d in Annex C. Overhead slack spans are reliable and very low cost (insulated cables shall not be used, because their cost is much higher and exposure to faults (by lightning) is much higher).

The grounding systems of the HV TL towers, as designed for lightning protection (back flashover prevention) and for safety requirements for people and animals, are sufficient for the operation of the ISWSs.

Fig. C.9b, in Annex C, shows how the rigid, toughened glass insulator strings of Fig. C.9a must be suspended to prevent the impact of the upper glass disc with the steel crossarm when the string is rotated up to 60° by transversal wind on the SW, and also because of the line angle, if any. Suspension through a "U" bolt of some centimeters warrants against the impact and possible breakage of the upper insulator disc.

The distance in the arcing rod-gap shall be set to the value specified in Table 5.2 in subsection 5.3.5 for the 30 and 34.5 kV SWLs. Gap setting will be precisely made, preferably in the supply factory of the insulator strings or at the site before installation in the towers, by using a wooden rod cut to the specified distance, and will be centered over the four glass discs, as shown in Fig. C.9a, in Annex C. Tension strings shall be provided with a bird anti-perching spike centered on the arcing rod-gap.

If an optical ground wire is part of the SWL, suitable accessories shall be used, in particular for the suspended insulated fiber optic splicing and the terminal coupling units. Typical fittings are shown in Figs. C.10b and C.10c, in Annex C.

The insulated SWs do not change the constructability issues, such as outage restrictions, power line crossing requirements, time to restore to service during an emergency, and induction from parallel power lines.

The onsite TL supervisor(s) should overview the implementation of all the above construction requirements and the conformity with the TSs and engineering drawings. Any departure shall be reported to the employer's designer(s) of the SWL.

17.3 INSTALLATION OF THE SHIELD WIRE LINES SUPPLY BAY(S) IN THE HV/MV STATIONS

This manual and Annexes A, B, and C provide details on the single-line diagrams of the supply bays of the SWLs, specification of the apparatuses, protection against short circuits, and a conceptual layout of the supply bay of a "three-phase" SWL. Construction techniques for the supply bays of SWLs using the earth as a phase conductor do not differ from the techniques in use for outdoor MV switchyards. However, the employer's engineers or the contractor's consultants and engineers in charge of design, construction, and operation of the ISWSs should be familiar with the specific features of ISWSs that use the earth as a conductor, and should not overlook the effects of the electromagnetic coupling between the HV circuit and the SWL, which are dealt with in this manual. Experience has shown that the lack of knowledge of elementary features of the ISWSs has caused trivial errors, some failures of equipment, delays, and unnecessary investments. In one project, the surge arresters (SAs) had an erroneous rated voltage and failed during commissioning.

17.4 CONSTRUCTION OF THE MEDIUM- AND LOW-VOLTAGE NETWORKS FOR SUPPLY OF THE LOADS

Design and construction requirements for the MV spur lines to the villages and the MV/LV transformer stations have been dealt with in Chapters 3, 7, 9 and 11 of this manual. TSs of equipment are provided in Annexes A and B. Construction drawings of take-off from the HV towers, the spur MV lines, the MV/LV transformer stations, the grounding electrodes, and multiple grounding and capacitor banks are provided in Annex C.

In the 34.5 kV ISWSs using the earth as a conductor, the phase-to-ground (ϕ-to-Gr) insulation levels of commercial 36 kV fused cut-outs can be increased with the addition of a post-type insulator of class ≥ 10 kV, as shown in Fig. C.4 in Annex C. The support insulator is not needed if the rated voltage of the ISWS is 30 kV.

If the rated voltage of the "three-phase" ISWS using the earth as a conductor is 30 kV, 36 kV commercial switching and fault clearing apparatuses (load break interrupters, disconnecting switches, fused cut-outs, etc. with basic insulation level = 170 kV and 50 Hz – 1′ test of 70 kVrms) are applied in the MV distribution networks of the villages.

Special attention should be given to the grounding systems of the MV/LV transformer stations and capacitor banks. The simple design requirements and technologies are dealt with in detail in Chapter 3. Typical engineering drawings of the grounding systems of MV/LV transformer stations are provided in Figs. C.5a, C.5b, and C.5c in Annex C.

An early measurement of the soil resistivity at the installation sites will allow the design of multiple grounding systems and approximate calculation of the ground resistance by using the formulas applicable for the multiple rods and the connecting buried bare conductors (or, if available, with a computer program). The requirement is to obtain for each site a ground resistance not exceeding the values specified in Section 3.2. The commissioning verification measurements of grounding resistance and step and touch voltages are specified in Annex E.

18 COMMISSIONING ILICETO SHIELD WIRE SCHEMES

18.1 SUMMARY OF REQUIREMENTS

Commissioning of Iliceto shield wire schemes (ISWS) should include the following activities:

- Visual inspections
- Measurement and, if necessary, improvement of grounding systems
- Energization of the shield wire line (SWL). Energization of the spur MV lines to the villages, of the medium-voltage/low-voltage (MV/LV) transformers, and load pick-up
- Measurement of voltages at the LV terminals of the MV/LV transformers and voltage imbalance
- Choice of the tapping position of the transformer tap-changers
- Measurement of currents at the sending end of the SWL and at the power factor (p.f.) correction/anti-ferroresance/balancing capacitors
- Setting of protections and checks of intervention selectivity

18.2 VISUAL INSPECTIONS

Visual inspections shall cover all the components of the ISWSs. Conformity of materials and installations with the technical specifications and approved engineering drawings will be checked. In addition to the usual checks of HV and MV installations, the correctness of the MV circuits and protection-control circuits of the supply bay of the SWL and of p.f. correction capacitor banks shall be checked. The correctness of the equipment characteristics will be verified in the nameplates, in particular of the surge arresters, resistance-inductance grounding circuit, capacitor banks, and MV/LV transformers.

In the SWLs, sample checks will be made of the clearances between live parts and towers, and the distance in the arcing rod-gap of the insulators.

If one of the shield wires (SWs) is an insulated optical ground wire, the special accessories (suspended insulated splicing and terminal coupling units) will be checked, and the transmission performance of the fiber optic signal will be measured.

Inspections in the villages will include the slack spans and relevant clearances in take-off from the SWL, the load break interrupters (LBIs) and fused cut-outs, the type and rated current of fuses, and the conformity of MV spur lines and the MV/LV transformer stations with the approved design drawings. Careful checks shall be made of the connections to the grounding system for earth-return of current and the location and number of grounding electrodes.

18.3 MEASUREMENT OF GROUNDING RESISTANCES AND STEP AND TOUCH VOLTAGES

The method is described in Annex E.

18.4 ENERGIZATION AND LOADING OF THE "THREE-PHASE" ILICETO SHIELD WIRE SCHEME VOLTAGE AND CURRENT MEASUREMENTS

The first energization of an ISWS will be made step by step. It is assumed that the functionality of all the apparatuses and circuits has been individually checked and found satisfactory.

All the circuit breakers (CBs), disconnecting switches (DSs), LBIs, and fused cut-outs at the sending end of the SWL and in the villages will at first be put in open position and the SWL grounding switch will be closed. It will be checked that the capacitor bank located out along the SWL is solidly and correctly connected to the SWs and properly grounded for earth-return of current (see Figs. 2.1, C.1 = C2, and Fig. C.3a in Annex C).

The energization of the SWL will be made at first, if possible, with the HV circuit out of service and grounded and, thereafter, in a second test with the HV circuit energized and loaded. If the HV circuit is needed to be in service, the first energization of ISWS will be made in this condition.

If the SWL is supplied via an interposing transformer (IT) (Fig. 7.1, Panel B), the IT will be switched on at no-load and after a few minutes will be de-energized. The correctness of the protections of the IT will be checked. Then the DS of the SWL will be closed, the grounding switch of the SWL will be opened, and the SWL will be energized by closing the MV CB on the primary side of the IT.

If the SWL is supplied from the tertiary winding of an HV/MV transformer (Fig. 7.1, Panel A), the SWL will be energized by closing the CB downstream of the tertiary winding.

If the SWL energization is successful, the charging capacitive currents of the SWL inclusive of the capacitor bank currents will be measured and recorded in the supply bay, from the two current transformers (CTs) on the SWs and the CT on the earthed phase. Thereafter, the SWL will be switched off and it will be checked that the fast-closing grounding switch has automatically grounded the SWL. The grounding switch, which is interlocked as usual with the CB, will then be opened manually and the SWL will be re-energized.

In the following step, the operation staff will travel to the take-off of the nearest spur MV line and close the LBI and/or fused cut-out therein. A further step is the energization one by one of the MV/LV local transformers with the fused cut-outs. The three ϕ-to-ϕ and ϕ-to-neutral voltages on the LV side will be measured with a multimeter and recorded. If the LV is too high or too low, the position of the transformer tap-changer will be changed, and the transformer will be re-energized and loaded by closing the LV fused cut-outs.

The imbalance of the voltages (negative sequence voltage as a percent of the positive sequence voltage) will be directly measured if a suitable three-phase digital instrument (power quality analyzer) is available, or will be calculated with a computer program from the voltage values measured in close succession with the multimeter. The imbalance limits specified in Chapter 4 should not be exceeded at no-load and maximum load.

The phases and neutral load currents of the transformer and LV feeders will be measured with a clamp-on ammeter and recorded. If the currents are imbalanced, the connections to the three phases of the LV single-phase consumers will be redistributed. If there are large motors, they should be started and transient voltage drop observed.

The energization of all the spur lines and MV/LV transformers will be made one by one and the same measurements will be performed.

At the capacitor site, the current injected to the grounding electrodes by each of the two capacitors connected SW-to-Gr will be measured with the clamp-on ammeter, checked to be equal, and recorded. Measurement shall be made just above the wire that connects in parallel the two wires connecting to ground the capacitors (located above the 2,5m plastic protection pipe; see Fig. C.1a in Annex C).

The loaded SWL will allow the measurements of the resistance and step and touch voltages of the grounding systems of the MV/LV transformer stations and capacitor bank with the simple method described in Annex E.

The above set of tests will be completed with the manual de-energization of the SWL and re-energization a few minutes thereafter, with all the loaded MV/LV transformers connected. It will be checked that the inrush current does not cause the intervention of the overcurrent protections.

18.5 SETTING OF PROTECTIONS AND CHECKS OF INTERVENTION SELECTIVITY

The procedures are specified in Section 9.2.

OPERATION OF SHIELD WIRE SCHEMES

The operation rules of the shield wire lines (SWLs) are mostly the same as those applied for conventional long medium-voltage (MV) overhead lines. The SWL can be switched on and off with all the medium-voltage/low-voltage (MV/LV) transformers connected and loaded, as a conventional radial MV distribution line. However, because of the electromagnetic coupling between the high-voltage (HV) circuit and the SWL, the setup must comply with some switching rules, with interlocking circuits and standing instructions to the operators.

For convenience, the switching rules that are explained and specified in subsections 5.3.1 and 5.3.2 are repeated below:

i. The SWLs shall be either in operation energized from the HV/MV stations, or solidly grounded. The SWLs will be open and un-grounded at the sending end (that is, with the grounding switch momentarily open) only during the short time interval before the manual energization and during the dead time before the automatic high-speed re-closure (HSR) of the SWL, if the HSR is applied.

ii. If the HV circuit is shunt compensated with shunt reactor(s) connected at one or both ends of the transmission lines (TLs), the following switching rules will be applied:

   a. If the HV shunt-compensated line is switched off for any reason, the SWL shall also be automatically switched off at the same time.

   b. An SWL can be continuously in service if the shunt-compensated HV circuit is also in service, or if the HV circuit is de-energized and grounded. The SWL shall not be operated with the shunt-compensated HV circuit open at floating potential.

   c. Prior to switching on a shunt-compensated HV circuit, the SWL will be switched off and re-energized after the HV circuit has been energized.

   d. The rule in the second bullet should also be applied for the normal, non-shunt-compensated HV TLs.

Additional operation rules are the following:

iii. Lightning in tropical countries may cause simultaneous tripping of the HV circuit and the SWL. If the fault on the HV circuit is not cleared by the HSR, a manual re-energization of the HV circuit will be at first attempted, with the SWL that has been automatically grounded by the fast-closing grounding switch and is still grounded. The SWL will be re-energized after energization of the HV circuit.

iv. Maintenance of the HV de-energized circuit can also be performed with the SWL in operation. In this case, the HV circuit shall be grounded by the earthing switches at both ends of the TL and, in addition, at any worksite so that the workers will not be exposed to the induced overvoltages.

v. If the SWL is tripped by the protection relays or manually, it can be re-energized with the HV circuit in operation a few minutes thereafter by the operators. Automatic fast re-closure is also feasible.

vi. The potential to remote earth, resistance, and step and touch voltages of the grounding systems for the earth return of current should be periodically measured in the MV/LV stations and capacitor banks, and compared with the previously measured values. Checks should be made approximately every 5 years. However, a large increase in the load of a transformer and/or high soil resistivity may justify specific checks. Measurements are simply made with the method described in Annex E.

vii. Routine inspections of the MV/LV transformer stations are made as in conventional distribution: status of equipment, loads of transformer and LV feeders, local value of the voltage, and imbalance of the currents in the LV feeders. In addition, if the load of the SWL has increased, the symmetry of the voltages should also be checked, in particular if large three-phase induction motors are present.

Power line carrier telecommunications on the HV conductors are not adversely affected by the presence of the SWL. This has been evaluated by analyses performed for the 161 kV lines in northern Ghana in the late 1980s, and confirmed by the operation of the HV lines with ISWSs.

The increase in the homopolar impedance of the HV circuit caused by the insulation of the SWs has very little effect on setting the line protection relays. However, it can easily be taken into account for the calculation of the short circuit to ground currents.

Many years of operational experience of SWLs have shown that they are affected only by self-cleared transient faults. There has been no need to put the HV circuit out of service for repairs of the SWL.

If an Iliceto shield wire scheme (ISWS) is to be decommissioned and it is not possible to put the HV circuit out of service for removing the insulators of the shield wires (SWs), a simple solution is to keep the SWs insulated and to ground the SWs in the tower at both ends of the SWL.

If a three-phase MV conventional supply is performed from a local new HV/MV station because the load has become very high in a town that is supplied by a "three-phase" ISWS, the MV/LV transformers shall not be changed. If transformers are protected by two surge arresters (SAs), these will be replaced by three SAs of lower rated voltage. If transformers are protected by arcing horns, the gap distance will be reduced. A third fused cut-out will be installed. The third phase conductor can be strung in the MV spur lines. The LV networks are not affected.

In some of the countries which have been operating the ISWSs (ref. the single-line diagrams in Annex D) the HV TLs are owned and operated by the transmission company; the distribution networks supplied by the SWLs are owned and operated by the distribution company. To the writer knowledge, this duality of the responsibility has not created problems. In fact the TLs provided with the SWL differ structurally from the conventional TLs only by the insulation of the SW(s), that is made by sturdy toughened glass cap and pin insulator strings of good quality, which have not been reported to have experienced failures in all the ISWSs in operation for many years.

The out of service time for maintenance of the HV TLs is much shorter than the time required for the maintenance and the extension works of the distribution systems in the villages. Some maintenance-repairs works on the TLs can be carried out with the associated SWL in operation. As recommended elsewhere in this Manual, all the take-off down leads for supply of the MV spur lines from the SWL, including the ones for the future foreseen spur lines to the villages, should very preferably be built at the time of construction of the TL, to avoid the out of service of the TL when it is in operation.

Experience has shown that disputes are avoided by the timely coordination of the construction, operation and maintenance between the stakeholders of the TLs and ISWSs. A coordination is required also in conventional distribution, because in many cases the HV/MV stations which supply the distribution networks are owned and operated by the transmission company.

20 EXPERIENCE WITH ILICETO SHIELD WIRE SCHEMES IN OPERATION

20.1 INTRODUCTION

Information on the experience of Iliceto shield wire schemes (ISWS) in operation is reported in the previous Chapters of this manual. A summary is provided below on the power quality indicators:

- Statistical records of fault rates of shield wire lines (SWLs)
- Fault rate of high-voltage (HV) transmission lines (TLs) shielded by insulated shield wires (SWs)
- Quality of voltage service at consumer premises
- Equipment failure
- Earth return of current

20.2 STATISTICAL RECORDS OF SHIELD WIRE LINE FAULT RATES

No permanent faults have been reported for the SWLs. One reason for this performance is that the SWLs are part of the HV TL and designed and operated with criteria of high reliability, generally not applied for medium-voltage (MV) lines.

Conventional MV lines, including MV spur lines to the villages supplied by SWLs, may undergo faults, which are sometimes permanent, caused by contacts with trees, bush fires, damaged poles, short circuits between wires caused by large birds or wind, broken conductors, or impacts with vehicles. Experience has shown that, because of the location of the SWs on top of high towers, the SWLs do not undergo arcing to vegetation. SW-to-SW short circuits do not occur because there is a large distance between the SWs (minimum 4 m) and between the SWs and HV conductors. One of the conductors of the SWLs is the earth path, which is inherently free of insulation faults and interruptions.

Operation records show that the cause of faults in SWLs is almost invariably lightning, in particular during the rainy season in tropical countries. In spite of their higher exposure to lightning strikes compared with conventional MV lines, because of the almost double height of the SWs, the recorded total rate of faults of SWLs in tropical countries is not higher than the fault rate of equivalent conventional MV lines.

During a three-year observation period in Ghana (reference [6] (2000) by Iliceto, Gatta, and Dokyi), the SWLs had 29 faults per 100 km per year, all transient. Restoration of service was done manually by the operators, generally ~5 minutes after the trip-out. Application of automatic fast re-closure of SWLs is expected to lower the outage rate by 70% to 80%, because flashovers are caused by lightning. MV conventional lines in the same region, during the same three-year period, had a higher fault rate than SWLs, with ~7% permanent faults.

Rural electrification planners should be aware and consider that very long SWLs (e.g., 100 km), which supply many villages in areas with high keraunic level, aimed at massive electrification with minimal investment cost, undergo a rate of transient faults and generally short supply interruptions to consumers that are unavoidably proportional to the length of the SWL. This situation also occurs for MV conventional lines of the same length of. An example is a 34.5 kV three-phase SWL in the Lao People's Democratic Republic, with length of 129 km, which supplies more than 30 villages (see Fig. D.3 in Annex D and Table 21.3 in Chapter 21). In Ghana, the 30 kV three-phase SWL Tamale-Buipe (initially 104 km; see Fig. D.1 in Annex D) was extended to 176 km to supply a repeater station of the TV Ghana Broadcasting Corporation at Kintampo.

20.3 FAULT RATE OF HIGH-VOLTAGE TRANSMISSION LINES SHIELDED BY INSULATED SWs

Operational experience has shown that the fault rate of HV TLs is not affected by the insulation for MV of the SWs. Comparative statistics are reported in reference [2] (2000) for the 161 kV TLs in Central-Northern Ghana. In a three-year period, a fault rate of only 2.1 per 100 km per year has been recorded in the 161 kV TLs with two insulated SWs. A similar behavior has been reported for the TLs with ISWSs in operation in Brazil and in the Lao People's Democratic Republic (reference [10] (2004)).

20.4 QUALITY OF VOLTAGE SERVICE AT CONSUMER PREMISES

Use of high MV in the ISWSs (30 to 34.5 kV) markedly limits voltage drop and facilitates voltage control, in spite of the long length of the SWLs.

Statistical records show that, if the tap-changer position of the transformers is properly set, the voltage at the low-voltage (LV) terminals of the MV/LV transformers is stable in the range of ±5% above and below the rated voltage.

Voltage imbalance at the supply points of three-phase consumers in "three-phase" ISWSs has generally been ≤ 1%.

20.5 EQUIPMENT FAILURE

The equipment failures that have occurred in the ISWSs were generally caused by banal errors of apparatus procurement or erection (departure from the technical specifications). These failures are mentioned in Sections 3.2 and 5.2. A priority aim of this manual is to avoid the repetition of the same errors in any new ISWS that may be implemented in the future.

20.6 EARTH RETURN OF CURRENT

Grounding systems that have been engineered and built with the rules specified in Chapter 3 have had good operational results: redundant thermal stability, low or acceptable grounding resistance and step and touch voltages, and stability for many years.

In a few locations with high soil resistivity, the grounding system has been improved during commissioning by extending the multiple grounding technique described in Chapter 3.

The only case of reported thermal instability with soil explosion occurred in Ethiopia, as mentioned in Section 3.2, caused by a banal construction error.

EXAMPLE OF PLANNING AND DESIGN OF ILICETO SHIELD WIRE SCHEMES

21.1 TOGO

As an example of planning and design, two of the Iliceto shield wire schemes (ISWSs) in Togo are considered here. The two ISWSs are in operation in Togo on the 161 kV single-circuit Atakpamé–Kara transmission line (TL), which is 244 km long.

The Atakpamé–Kara 161 kV TL is routed not far from the national highway, along which the villages to be electrified are located. In the mid-1990s, CEB (Communauté Electrique du Benin) and CEET, the Electricity Distribution Company of Togo, prepared a list of 24 villages to be electrified in two or three subsequent stages, and carried out the population census and load forecast for 20 years of operation with the usual methodology. Because of the size of the various villages and the use of induction motors, three-phase supply was requested for most of the villages. It was also requested that the shield wire lines (SWLs) had to be implemented along the whole length of the 244 km of the TL to provide electricity to all the villages, although this required the implementation of two very long SWLs.

Originally, the Atakpamé–Kara 161 kV TL was planned to be provided with two shield wires (SWs). Application of the "three-phase" ISWSs using the earth as a conductor was retained, with rated voltage of 34.5 kV, because of the forecast loads and the length of each of the two SWLs to be supplied from the Atakpamé and Kara high-voltage/medium-voltage (HV/MV) stations, respectively.

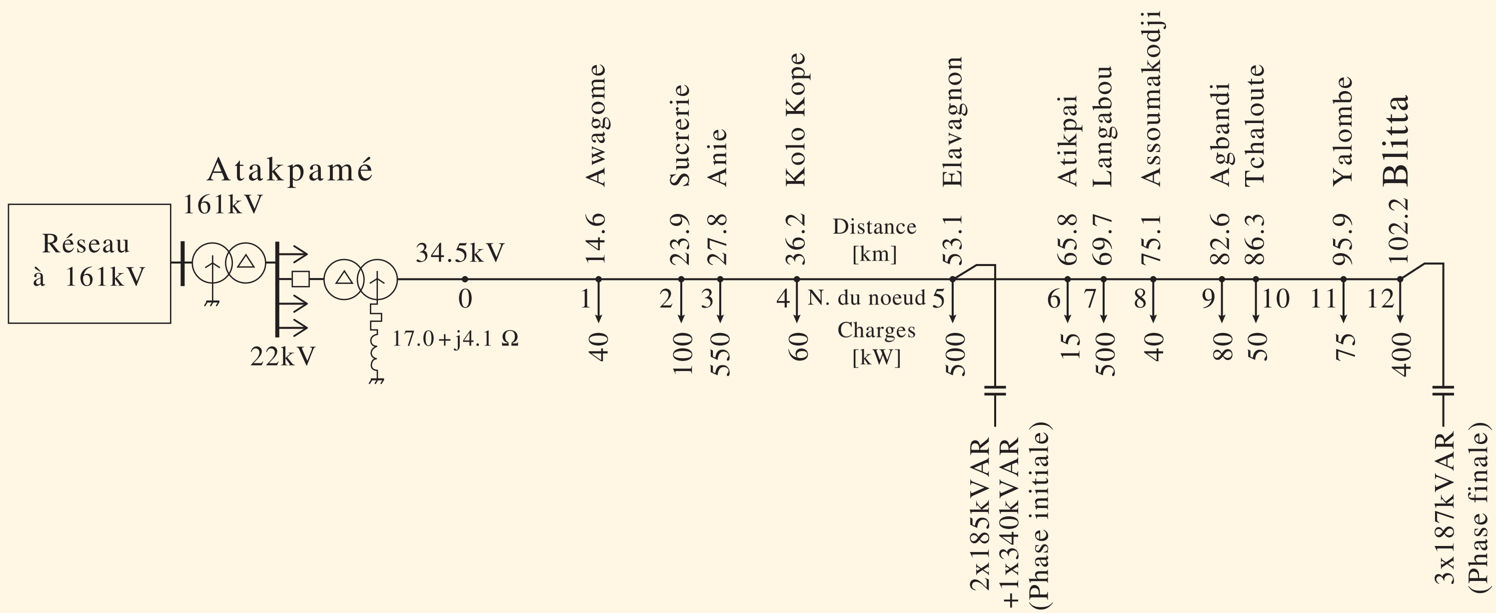
The topographical survey of the line route and the load forecast allowed preparation of the single-line diagrams of the two SWLs in Figs. 21.1 and 21.2. The diagrams show the names of the villages, the progressive distance from the Atakpamé and Kara HV/MV stations, and the peak load forecast 20 years after commissioning. A preliminary calculation of the voltage drops and losses showed that the optimal separation location between the two SWLs was in a tension tower between the villages of Blitta and Tchébébé. The resulting length of the two SWLs is ~135 km from Kara to Blitta and ~102 km from Atakpamé to Tchébébé.

The load flow analysis justified the choice of the aluminum conductor steel reinforced (ACSR) code Minorca for the SWs, with 12 aluminum wires and 7 steel wires of the same diameter (Table 6.1), with diameter 12.2 sqmm and total cross-section 88.9 sqmm. It was also decided that one SW had to be an insulated optical ground wire (OPGW), with an ohmic resistance not far from the one of the Minorca ACSR conductor. The OPGW and insulation thereof were chosen in compliance with the criteria reported in Chapter 12.

In the Atakpamé substation, a 20 MVA – 161/22 kV step-down transformer had already been installed. The SWL was therefore supplied by a 5 MVA – 22 kV/35 kV ±2 × 2.5% interposing transformer (IT). In Kara, a new 161 kV station was built. The SWL has been supplied by the tertiary winding of an HV/MV

FIGURE 21.1

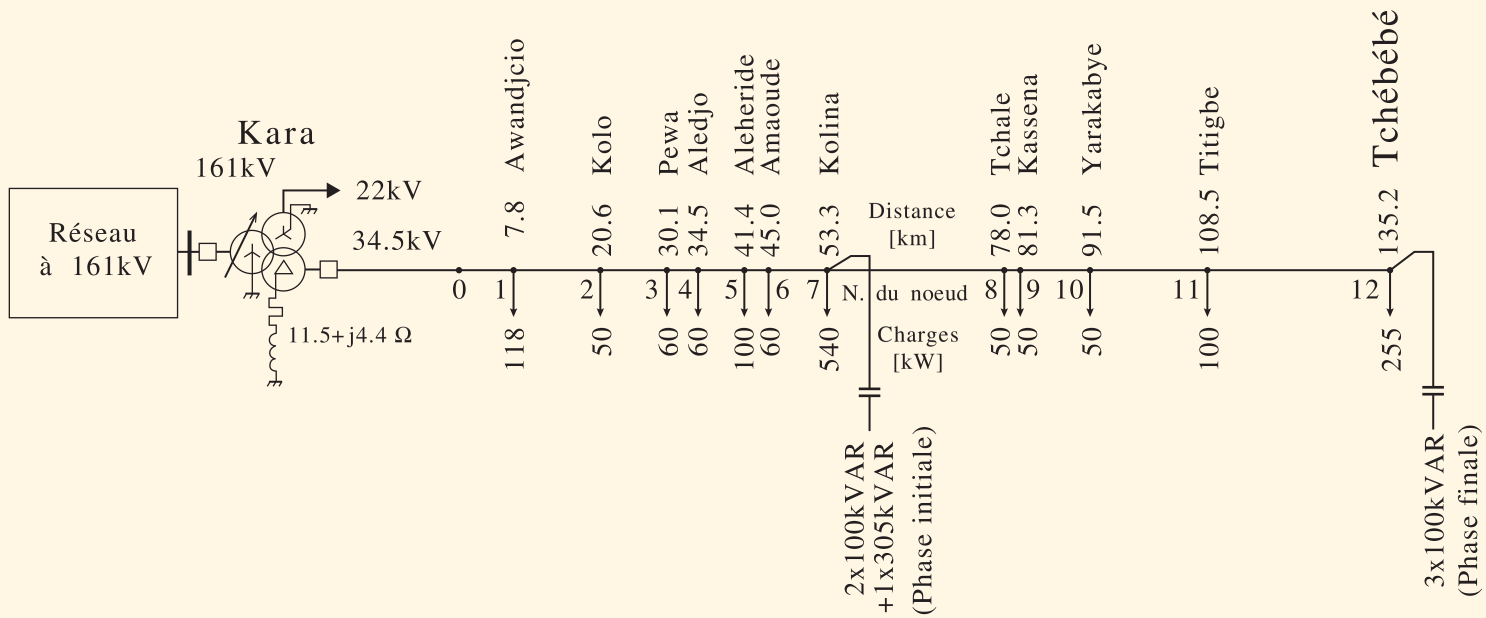
Single-Line Diagram of the "Three-Phase" 34.5V SWL Atakpamé—Blitta (Togo)



- Total load forecast after 20 years: 2410kW
- Maximum load considered in the analyses: 3615kW (150% of the total load forecast after 20 years)
- Total length of the SWL: 102.2 km

FIGURE 21.2

Single-Line Diagram of the “Three-Phase” 34.5kV SWL Kara—Tchébébé (Togo)



- Total load forecast after 20 years: 1493kW
- Maximum load considered in the analyses: 2230kW (150% of the total load forecast after 20 years)
- Total length of the SWL: 135.2 km

step-down transformer, with no-load ratio 161 kV ±8 × 1.25%/23 kV/35 kV ±2 × 3.75%, rated at 20 MVA/16 MVA/7 MVA and with winding connection: star with grounded neutral/star/delta. One terminal of the 7 MVA – 35 kV tertiary winding is grounded via the resistance-inductance (R-L) compensating circuit. The rated power of 7 MVA is higher than the rated power of the Atakpamé 5 MVA IT, because the same tertiary winding in Kara also supplies the SWL to Koumerida (at the border with Benin).

The SWs are insulated with rigid insulator strings, as per Fig. C.9a, and installed as shown in Fig. C.9b (in Annex C). The grounding resistance of the 161 kV towers was specified to be as far as practicable ≤ 10 Ω.

Field inspections have been made along the whole route of the HV TL and in the villages, for the preliminary choice of the locations and number of medium-voltage/low-voltage (MV/LV) transformers to be installed in the villages, for the choice of the take-off towers from the SWL of the MV spur lines to the villages, and for measurement of the length of the spur lines. Soil resistivity was measured in the locations of a few of the planned MV/LV transformers, which were considered representative of the various typical soils of the region.

The collected field information was used to run computer analyses of the two ISWSs at the University of Rome with a program suitable for accurate simulation of the unsymmetrical multiple-circuit lines, including the electromagnetic coupling between the HV circuit and SWL. The results of the analyses for the two SWLs are reported in Tables 21.1 and 21.2.

Analyses were performed for operation at no-load and at 50%, 100%, and 150% of the peak load forecast 20 years after the commissioning of the ISWSs; these loads are reported in the single-line diagrams in Figs. 21.1 and 21.2. The first line in the tables shows the simulated power flow and load power factor (p.f.) in the HV circuit from Atakpamé to Kara. Various typical load p.f.s were assumed for the SWLs. The voltage drops in the SWLs in the most remote village and the joule losses are reported in the last two lines in the tables for the various loads and load p.f.s.

The analyses also provided the resistance and reactance to be assigned to the R-L circuit and the location and kVAR ratings of the dissymmetrical p.f. correction/anti-ferroresonance/balancing capacitors. Ratings and locations are summarized in the bottom window of the tables.

The negative sequence components of the voltage have been calculated for all the load locations and for various load conditions by assuming symmetrical supply voltages of the SWL in the HV/MV stations. The tables show that imbalances caused by the residual dissymmetry of the SWLs are in general ≤ 1%.

The load flow analyses with the simulation inclusive of the MV/LV transformers show that the voltage at the secondary LV terminals of the transformers remains in the range of ±5% above and below the rated LV in all the villages and all loading conditions. This result is achieved with the appropriate choice of the position of the off-voltage tap-changers of the MV/LV transformers and of the IT or tertiary winding that supplies the SWLs. These voltage controls with the off-voltage tap-changers are supplemented by the automatic voltage regulation with the on-load tap-changer of the HV/MV transformer. The latter should increase the voltage on the station MV busbars in steps, up to ~5%, when the load varies from minimum to maximum.

TABLE 21.1

"Three-Phase" 34.5kV SWL Atakpamé—Blitta (Togo)

161kV HV Line Load (MW)		65	37	15	15	15	15	15	0
Load Power Factor		0.9	0.9	0.85	0.85	0.85	0.85	0.85	
Load of the SWL (% of Load Forecast after 20 Years)		150	150	100	100	100	50	50	0
Load Power Factor		0.95	0.95	0.95	0.90	0.85	0.90	0.80	
Busbar	Village/Town	Negative Sequence Voltage at the LV Terminals of MV/LV Transformers (V2,%)							
1	Awandjcio	0.89	0.91	0.60	0.60	0.62	0.29	0.19	0.18
2	Kolo	0.46	0.50	0.31	0.33	0.35	0.13	0.15	0.07
3	Pewa	0.16	0.22	0.11	0.14	0.16	0.03	0.07	0.09
4	Aledjo	0.07	0.12	0.03	0.05	0.08	0.04	0.05	0.12
5	Aleheride	0.20	0.15	0.11	0.07	0.04	0.10	0.08	0.19
6	Amaoude	0.28	0.23	0.18	0.14	0.11	0.15	0.12	0.23
7	Kolina	0.44	0.39	0.32	0.26	0.23	0.22	0.18	0.31
8	Tchalo	0.59	0.57	0.47	0.41	0.36	0.28	0.22	0.34
9	Kassena	0.62	0.60	0.49	0.43	0.38	0.29	0.23	0.35
10	Yarakabye	0.69	0.68	0.56	0.50	0.45	0.31	0.26	0.36
11	Titigbe	0.79	0.79	0.67	0.59	0.54	0.35	0.29	0.37
12	Tchébébé	0.89	0.92	0.78	0.70	0.64	0.37	0.32	0.38
Maximum Voltage Drop (%)		4.60	5.09	2.44	3.16	4.24	1.75	1.98	–1.51
Total Active Power Losses (%)		3.11	3.53	2.70	2.65	2.69	1.25	1.36	—
Compensating Resistor Reactor, at Busbar					Ohm		11.54 + j4.41		
	Capacitors, Initial Stage				Busbar		7		
	$C_{W\text{-}W}$ (SW-to-SW)				kVAR/nF		176/470		
	$C_{W\text{-}G}$ (SW-to-Gr)				kVAR/nF		100/268		
	Capacitors, Final Stage				Busbar		12		
	$C_{W\text{-}W}$ (SW-to-SW)				kVAR/nF		100/268		
	$C_{W\text{-}G}$ (SW-to-Gr)				kVAR/nF		100/268		

Length: 102.2 km ACSR shield wire with diameter of 12,2m

Total Load (100%): 2,410kW

TABLE 21.2

"Three-Phase" 34.5kV SWL Kara—Tchébébé (Togo)

161kV HV Line Load (MW)		65	37	15	15	15	15	15	0
Load Power Factor		0.9	0.9	0.85	0.85	0.85	0.85	0.85	
Load of the SWL (% of Load Forecast after 20 Years)		150	150	100	100	100	50	50	0
Load Power Factor		0.95	0.95	0.95	0.90	0.85	0.90	0.80	
Busbar	Village/Town	Negative Sequence Voltage at the LV Terminals of MV/LV Transformers (V_2,%)							
1	Awandjcio	0.89	0.91	0.60	0.60	0.62	0.29	0.19	0.18
2	Kolo	0.46	0.50	0.31	0.33	0.35	0.13	0.15	0.07
3	Pewa	0.16	0.22	0.11	0.14	0.16	0.03	0.07	0.09
4	Aledjo	0.07	0.12	0.03	0.05	0.08	0.04	0.05	0.12
5	Aleheride	0.20	0.15	0.11	0.07	0.04	0.10	0.08	0.19
6	Amaoude	0.28	0.23	0.18	0.14	0.11	0.15	0.12	0.23
7	Kolina	0.44	0.39	0.32	0.26	0.23	0.22	0.18	0.31
8	Tchalo	0.59	0.57	0.47	0.41	0.36	0.28	0.22	0.34
9	Kassena	0.62	0.60	0.49	0.43	0.38	0.29	0.23	0.35
10	Yarakabye	0.69	0.68	0.56	0.50	0.45	0.31	0.26	0.36
11	Titigbe	0.79	0.79	0.67	0.59	0.54	0.35	0.29	0.37
12	Tchébébé	0.89	0.92	0.78	0.70	0.64	0.37	0.32	0.38
Maximum Voltage Drop (%)		4.60	5.09	2.44	3.16	4.24	1.75	1.98	–1.51
Total Active Power Losses (%)		3.11	3.53	2.70	2.65	2.69	1.25	1.36	—
Compensating Resistor Reactor, at Busbar				Ohm		11.54 + j4.41			
	Capacitators, Initial Stage			Busbar		7			
	$C_{W\text{-}W}$ (SW-to-SW)			kVAR/nF		176/470			
	$C_{W\text{-}G}$ (SW-to-Gr)			kVAR/nF		100/268			
	Capacitators, Final Stage			Busbar		12			
	$C_{W\text{-}W}$ (SW-to-SW)			kVAR/nF		100/268			
	$C_{W\text{-}G}$ (SW-to-Gr)			kVAR/nF		100/268			

Length: 135.2 km ACSR shield wire with diameter of 12,2m

Total Load (100%): 1,493kW

The technical specifications of the components of the ISWSs, which were necessary for the call for bids, were prepared in conformity with the recommendations reported in the Annexes to this manual.

21.2 LAO PEOPLE'S DEMOCRATIC REPUBLIC

Table 21.3 shows the results of the analysis performed for the longest "three-phase" ISWSs in the Lao People's Democratic Republic, including the voltages at the LV winding terminals of the MV/LV transformers and the choice of the position of the transformer tap-changers for the optimal voltage regulation. If the tap-changer positions are well set during the ISWS operation and the LV distribution lines are designed for a moderate voltage drop (e.g., ≤ 5%), the voltage excursion at consumer premises will not exceed ±5% above and below the rated voltage. The single-line diagram of the ISWS referred to in Table 21.3 is shown in Fig. D.3 in Annex D.

TABLE 21.3

Results of the Analyses of the Iliceto Shield Wire Scheme Xieng Khuang—Muang Cha, Lao PDR

Active power flow on 115 kV circuit				0 MW		10 MW		37 MW (SIL)	
SWL load in % of year 2018 peak load of 3,100 kW				0%		50%		100%	
Load power factor on LV side of MV/LV transformers				—		0.9		0.9	
Node	Village/town	Year 2018 peak load (kW)	Distance from Xieng Khuang (km)	Phase-to-neutral positive sequence voltage, V_1, and voltage imbalance $K_i = 100\ V_2/V_1$ on LV side of MV/LV transformers					
				V_1 (V)	K_i (%)	V_1 (V)	K_i (%)	V_1 (V)	K_i (%)
1	B. Nano, B. Xa, B. Namtom	160	6.93	231.6	0.39	228.8	0.64	230.9	1.00
2	B. Dong Dane	80	10.04	231.9	0.32	228.8	0.54	230.3	0.88
3	B. Thakek	40	10.04	231.9	0.32	228.6	0.54	229.9	0.88
4	B. Phonxai, B. Hoy, B. Tham	80	12.67	232.2	0.28	228.8	0.47	229.9	0.78
5	B. Gnoun	40	15.27	232.4	0.24	228.6	0.41	229.1	0.69
6	B. Kosi	80	16.98	232.6	0.21	228.8	0.38	229.3	0.63
7	B. Nong Nam, B. Koua	119	19.39	232.9	0.16	228.8	0.31	228.8	0.49
8	B. Phang	80	20.51	232.9	0.16	228.8	0.31	228.8	0.49
9	B. Na Ou	40	21.69	233.1	0.14	228.6	0.28	228.2	0.44
10	B. Xang	80	24.29	233.4	0.12	228.9	0.26	228.3	0.36
11	B. Nasay	80	27.16	233.5	0.12	228.9	0.25	228.1	0.29

(*continued*)

TABLE 21.3 continued

Results of the Analyses of the Iliceto Shield Wire Scheme Xieng Khuang—Muang Cha, Lao PDR

12	B. Siphom	128	27.16	233.5	0.12	229.1	0.25	228.5	0.29
13	B. Phosi, B. Thum	80	28.12	233.6	0.12	228.9	0.25	227.9	0.27
14	B. Phaivat, B. Phon, B. Nasy	240	28.12	233.6	0.12	228.9	0.25	227.9	0.27
15	B. Hongsi	40	28.12	233.7	0.13	228.7	0.25	227.5	0.24
16	B. Naho	128	31.74	233.9	0.16	229.2	0.23	227.9	0.10
17	B. Keokhuang	80	37.91	228.2	0.19	229.0	0.26	227.0	0.04
18	B. Kafe	128	39.92	228.3	0.20	229.2	0.27	227.3	0.08
19	B. Xieng Khong	80	55.93	228.8	0.28	229.2	0.49	225.8	0.39
20	B. Vieng Thong	40	61.11	228.9	0.31	229.0	0.56	230.7	0.48
21	B. Nasay, B. Nasong	40	63.34	228.9	0.31	229.0	0.56	230.7	0.48
22	B. Dong, B. Nahong	256	66.41	229.1	0.33	229.5	0.62	231.3	0.55
23	B. Phonhom	80	68.39	229.1	0.34	229.3	0.63	230.7	0.58
24	B. Kohai	80	77.39	229.3	0.37	229.0	0.65	230.0	0.70
25	B. Namla	128	77.39	229.3	0.37	229.3	0.65	230.4	0.70
26	B. Nadi, B. Na Mouang, Muang Om	280	83.29	229.5	0.40	228.8	0.66	229.4	0.79
27	B. Thamlo	80	89.12	229.6	0.43	228.8	0.67	229.1	0.85
28	B. Pialuang	80	91.08	229.7	0.44	228.7	0.68	229.0	0.87
29	Muang Ao Kang	80	121.35	230.0	0.50	228.4	0.73	228.1	1.03
30	Muang Ao Nua	128	123.28	230.0	0.50	228.7	0.73	228.5	1.03
31	Muang Ao Tai	45	129.28	229.9	0.49	230.1	0.70	231.1	0.97
Total peak load (kW)		3100							
Transformers' tap position: 115 kV ± 8 × 1.25%/23 kV/34.5 kV ± 2 × 3.75% MV/LV 34.5 kV ± 2 × 2.5%/400 – 231 V				0 / – / –1 × 3.75% 0% / + 1 × 2.5%		0 / – / 0 0% / + 1 × 2.5%		0 / – / + 1 × 3.37% 0%/–1 × 2.5%/–2 × 2.5%	
Grounding impedance (all loading conditions) located at Xieng Khuang: $Z_c = 13.6 + J\,0\,\Omega$									

P.f. correction-anti-ferroresonance-balancing capacitors located at Phaivat, sufficient up to ~50% of the final load: $C_{W,Gr} = 2 \times 170$ kvar; $C_{W,W} = 1 \times 225$ kvar

Additional capacitors with 100% of final load, to be located in the future at Naho: $C_{W,Gr} = 2 \times 170$ kvar; $C_{W,W} = 1 \times 225$ kvar

22

COMPARATIVE SUMMARY OF THE MAIN CHARACTERISTICS OF THE FEASIBLE SHIELD WIRE SCHEMES

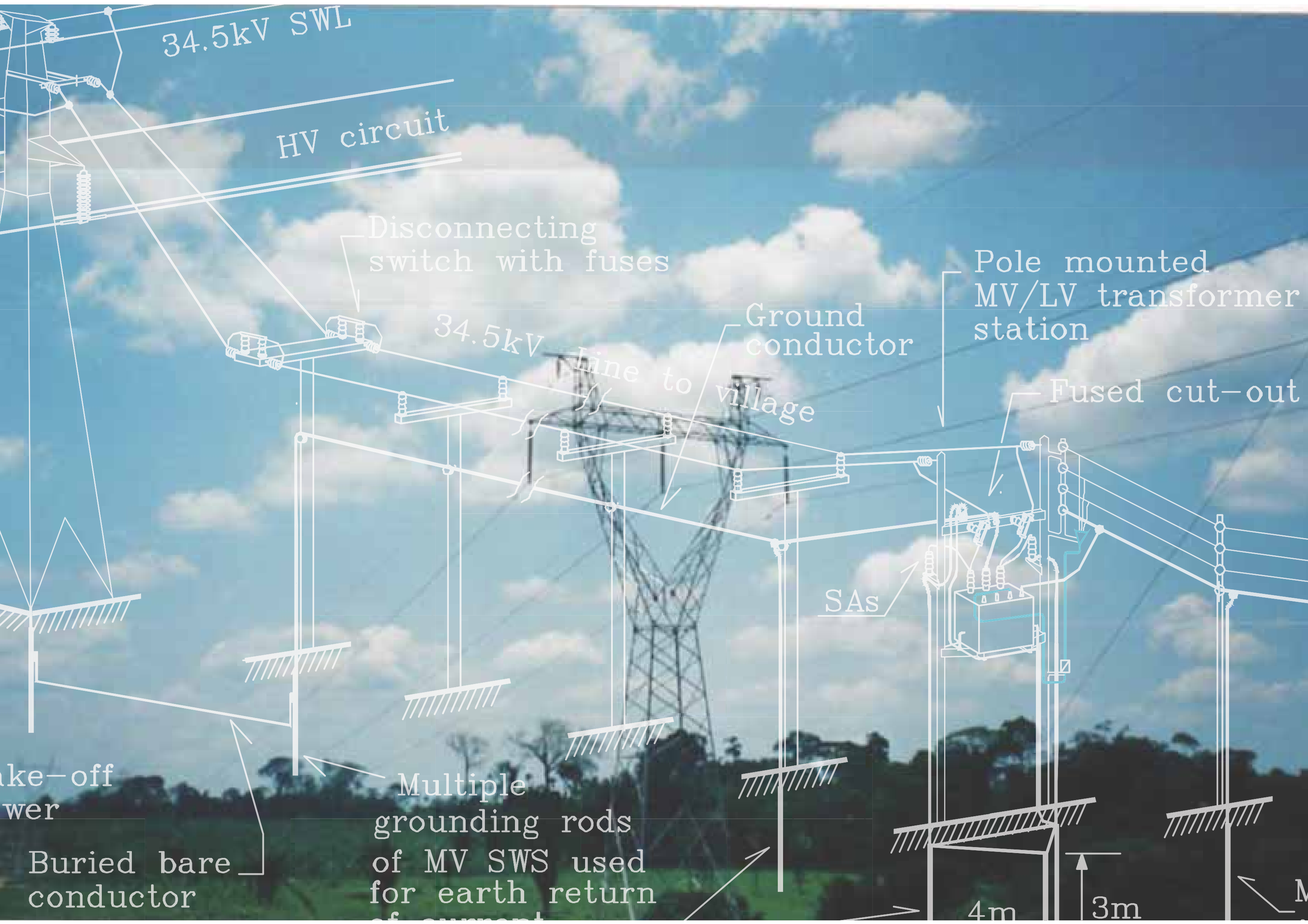


TABLE 22.1

Comparative Summary of the Main Characteristics of the Feasible Shield Wire Schemes

TYPE OF SWS	A. SINGLE-PHASE EARTH-RETURN	B. SINGLE-PHASE METALLIC-RETURN	3-PHASE WITH 2 SWS C1	3-PHASE WITH 2 SWS C2	3-PHASE WITH 2 SWS “V”	3-PHASE WITH 3 SWS
Number of required insulated shield wires (SWs)	1	2	2	2	2	3 (see details in Chapter 14)
Type of loads that can be served	Single-Phase	Single-Phase	3-Phase up to 100 %		A small % only can be 3-Phase	3-Phase up to 100%
Use of earth as a conductor	Yes	No	Yes		Yes	No
Load distribution capacity	Same of equivalent conventional single phase MV lines	Same of equivalent conventional single phase MV lines	Same of equivalent conventional 3-Phase MV lines		60–70% of equivalent conventional 3-Phase MV lines	Same of equivalent conventional 3-Phase MV lines
Quality of service to consumers	Same of equivalent conventional single phase MV lines	Same of equivalent conventional single phase MV lines	Same of equivalent conventional 3-Phase MV lines		Does not allow supply of important 3-Phase loads	Same of equivalent conventional 3-Phase MV lines
Phase-to-Ground (f-to-Gr) insulation levels of MV apparatuses of SWSs	Same as conventional MV lines of same f-to-Gr rated voltage	Same as conventional MV lines of same f-to-f rated voltage	10–15% higher than in conventional MV lines of same rated voltage		Same as conventional MV lines of same rated voltage	Same as conventional MV lines of same rated voltage
Specification and procurement of MV equipment	Conventional single-phase equipment	Same as conventional 3-Phase MV lines of same rated voltage	Use equipment with nominal voltage 10–15% higher than the SWL operation voltage		Same as conventional 3-Phase MV lines of same rated voltage	Same as conventional 3-Phase MV lines of same rated voltage
Environmental impact of SWL	Negligible (SWL right-of-way is not required)	Negligible (SWL right-of-way is not required)	Negligible (SWL right-of-way is not required)		Negligible (SWL right-of-way is not required)	Negligible (SWL right-of-way is not required)
SWL supply by an independent transformer (IT) or a dedicated tertiary winding of an HV/MV step-down transformer	IT is necessary only when available MV is too low for supply of long SWLs	IT is necessary only when available MV is too low for supply of long SWLs	Necessary: IT | tertiary winding (See details in Section 16.4 for choice)		Usually not necessary	IT is necessary only when available MV is too low for supply of long SWLs
Use of an optical ground wire (OPGW) in the HV TL	Feasible with commercial OPGWs and accessories	Feasible with commercial OPGWs and accessories	Feasible with commercial OPGWs and accessories		Feasible with commercial OPGWs and accessories	Feasible with commercial OPGWs and accessories

TABLE 22.1 continued

Comparative Summary of the Main Characteristics of the Feasible Shield Wire Schemes

TYPE OF SWS	A. SINGLE-PHASE EARTH-RETURN	B. SINGLE-PHASE METALLIC-RETURN	3-PHASE WITH 2 SWS C1 / C2	"V"	3-PHASE WITH 3 SWS
Protection against faults	As for conventional equivalent radial MV-LV distribution system	As for conventional equivalent radial MV-LV distribution system	As for conventional equivalent radial MV-LV distribution system	As for conventional equivalent radial MV-LV distribution system	As for conventional equivalent radial MV-LV distribution system
Investment cost of MV SWLs in HV TLs (inclusive of supply bay in HV/MV station)	8–12% of cost of an equivalent MV conventional line	13–16% of cost of an equivalent MV conventional line if TL is protected by two SWs	12–15% of cost of an equivalent conventional MV line if TL is protected by two SWs (for SWLs of 100km)	10–13% of cost of an equivalent conventional MV line if TL is protected by two SWs	25–30% of cost of an equivalent conventional MV line if TL is protected by two SWs
Investment cost of MV-LV distribution networks supplied by the SWLs	Same as for equivalent MV-LV conventional networks	Same as for equivalent MV-LV conventional networks	Same as for equivalent MV-LV conventional networks	Same as for equivalent MV-LV conventional networks	Same as for equivalent MV-LV conventional networks
Power losses of SWLs in comparison with conventional equivalent MV lines	Somewhat lower	Same	Somewhat lower	Somewhat lower	Same
Maintenance of SWSs in comparison with conventional equivalent MV-LV distribution systems	i. SWLs: very low ii. MV-LV networks supplied by the SWLs: same	i. SWLs: very low ii. MV-LV networks supplied by the SWLs: same	i. SWLs: very low ii. MV-LV networks supplied by the SWLs: same	i. SWLs: very low ii. MV-LV networks supplied by the SWLs: same	i. SWLs: very low ii. MV-LV networks supplied by the SWLs: same
Practical feasibility of SWSs in existing HV lines	Generally feasible	Generally feasible if the HV TL is protected by two SWs	Generally feasible if the HV TL is protected by two SWs	Generally feasible if the HV TL is protected by two SWs	Practically not feasible
Applicability of SWLs in low-income countries	In 110kV to 330kV single-circuit and double-circuit TLs	In 110kV to 330kV single-circuit and double-circuit TLs	In 110kV to 330kV single-circuit and double-circuit TLs	Applicable (but not recommended)	In 110kV to 330kV single-circuit and double-circuit new TLs

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ANNEX A | TECHNICAL SPECIFICATIONS FOR THE COMPONENTS OF THREE-PHASE ILICETO SHIELD WIRE SCHEMES USING THE EARTH AS THE CONDUCTOR OF ONE PHASE

CONTENTS

A.1 INTRODUCTION

These technical specifications are applicable to the components of the two-SW three-phase Iliceto shield wire schemes (ISWSs) that use the earth as a phase conductor. The specifications are written for the rated voltage of 34.5 kV; however, they can be applied with minor adjustments for lower rated voltages, in particular for 30 kV with the lower test voltages of equipment specified in the technical data sheets (see Annex B).

Concerning the prospective three-shield wire (SW) three-phase SWSs described in chapter 14 of the manual, most of the components are three-phase standard apparatuses applied in conventional medium-voltage (MV) distribution networks of the same rated voltage. However, the following special components must be included: a three-phase fast automatically-closing grounding switch and power factor correction capacitors. The capacitor bank is to be specified three-phase, symmetrical, star connected with neutral solidly grounded, and continuously in service. Other characteristics of these two components are as specified in the manual for the two-SW three-phase ISWS and three-SW three-phase SWS.

The technical specifications in this Annex for the medium-voltage/low-voltage distribution transformers and for the MV/MV interposing transformers or tertiary winding of high-voltage/medium voltage step-down transformers, are also applicable for three-SW three-phase SWSs.

A.2 ENVIRONMENTAL DATA

The following table summarizes the climatic information to be used for the design of the equipment.

	UNIT	VALUE
Maximum ambient temperature	°C	
Minimum ambient temperature	°C	
Mean maximum daily temperature	°C	
Mean minimum daily temperature	°C	
Annual average temperature	°C	
Maximum solar radiation (worst case)	W/m^2	
Average number of stormy days per year		
Altitude	m	
Maximum wind - Height above ground 0–30 m - Height above ground 30–50 m	 m/s m/s	
Relative humidity, average	% rel.	
Average rainfall annually	mm/year	

A.3 GROUNDING RESISTOR-REACTOR

Detailed characteristics of the grounding resistor-reactor are specified in table B.4 in Annex B. Supplementary requirements and clarifications are provided below.

The resistor shall be fabricated with special stainless steel: steel-chrome-aluminum with low increase of resistance versus temperature. The elements should be expanded mesh; however, edge-wound coils may also be accepted, subject to written approval by the employer/engineer.

If the proposed form of elements has built-in non-negligible inductance (edge-wound coils), the total reactance shall be calculated and deducted from the specified reactance of the reactor in series with the resistor, such as to obtain the specified impedance $Z = R + jX$. If the specified reactance is nil, the use of expanded mesh elements will be mandatory.

The tenderers shall state in the bids the proposed type of special stainless steel, the form of the elements, and their inherent inductance, if any.

The resistor will be housed in a steel kiosk (minimum wall thickness 2 mm). The kiosk shall be hot-dip galvanized, or stainless steel. The kiosk shall be provided with adequate openings in the bottom and sides, to allow abundant air flow for natural cooling (use of fans is not permitted). The housing will be designed such as to prevent water inlet.

The series reactor, where required in series with the resistor, should preferably be of air core type. If an indoor reactor is proposed, it may be housed in a section of the kiosk adjacent to the section housing the resistor. If an air-core outdoor reactor is proposed, it will be supported by an independent structure with minimum height of 2.25 m. Insulation of the reactor (cast resin or conventional insulation of winding wire) shall be suitable for the conditions of operation inside the kiosk (temperature, humidity, etc.) or outside, according to the proposed type.

The reactor and resistor shall be connected in series, as shown in figure 7.1, panels a and b.

If the reactor is installed externally to the kiosk housing the resistor, the connection between the reactor and resistor can be made with an insulated cable.

One terminal of the resistor shall be connected to the grounding system of the substation where it is installed via a current transformer (see table B.4 in Annex B).

One terminal of the reactor shall be connected to one of the 34.5 kV terminals of the interposing transformer, by means of an insulated cable or via an overhead bare aluminum pipe.

The roof of the kiosk shall be shaped such as to prevent water stagnation.

The openings in the bottom for cooling air inlet shall be small (or shall be protected by mesh) so as to prevent insects from entering the kiosk.

Insulators inside the kiosk shall be made of porcelain or alumina (resin insulators are not accepted).

The resistor shall be responsive to IEEE standards 32 of 1972, unless otherwise specified. The reactor shall be responsive to IEC standards 60076-6 of 2008, unless otherwise specified.

Protection of enclosure IP23 (to IEC Publ. 529) is deemed sufficient for outdoor installation.

The total mass of the active resistor elements and maximum temperature reached in normal operation, and after circulation of the specified short circuit current for 3 s, shall be informed in the bids.

A.4 FAST-CLOSING GROUNDING SWITCHES

The switches must be bipolar outdoor type, for installation in a tropical environment. The switches are required for fast grounding (no more than 200 ms) of the shield wire line, by using the energy stored in the springs, to be loaded by an electrical motor during the opening maneuver. A sturdy mechanical construction is required, suitable for frequent maneuvering in operation.

Bidders shall describe in detail the offered equipment and inform previous similar applications for reliable fast grounding.

A.5 CAPACITORS

The capacitors shall be in conformity with IEC standards 60871 Part 1-2, 1997 edition (Shunt Capacitors for A.C. Power Systems Having a Rated Voltage above 1000V), unless otherwise specified.

Standard MV p.f. correction capacitor units are appropriate, with the following special requirements (that are included in table B.18 in Annex B).

- The insulation level and test voltages are higher than required by the IEC standards, owing to the special application. The capacitor units have a rated voltage of 24 kVrms and associated test voltages (51,6 kVrms at 50 Hz; 125 kV with 1.2/50 μs atmospheric impulse). However, the capacitors are normally operated de-rated at 34.5/2 = 17.25 kV, so that, if one unit fails, the other series-connected unit can be operated temporarily over-rated at 34.5 kVrms.
- External fuses are not accepted. Fully un-fused capacitors, or capacitors with internal fuses, are acceptable.
- A routine acceptance test of the capacitor units shall be performed at AC-50 Hz, with applied voltage of 51.6 kVrms for 10 s. The DC routine test shall not be accepted.

Insulation of the capacitor elements is the standard all-polyethylene film, impregnated with non-PCB biodegradable synthetic oil.

Bushings of the capacitor units and support insulators of the capacitor units shall be made of porcelain.

Typical installation drawings of capacitor banks are shown in figures C.1a and C.1b in Annex C and in photos of the installation (in Annex D).

A.6 LOAD-BREAK SWITCHES AND FUSED CUT-OUTS

Installation of a load-break switch or fused cut-outs is to be made in the take-off structures from the HV line (see figure C.2 in Annex C). Fused cut-outs will be installed in all the pole-mounted and ground-mounted MV/LV transformer stations.

This equipment is the same as used in normal 34.5 kV distribution systems; however, it is bipolar and the phase-to-ground insulation levels shall be somewhat higher than usually specified for the 36 kV equipment, as specified in table 5.2 (chapter 5).

The insulation across open contacts of load-break switches and fused cut-outs shall be the same as for normal 36 kV equipment.

A.7 PROTECTION RELAYS AND CONTROL PANEL

The interposing transformers (ITs) that may have to be installed in some substations shall be protected by the protection relays available in the existing MV metal clad supply switchgears, to be properly checked, set, and, if necessary, supplemented. Protection will include as a minimum: an instantaneous overcurrent relay, a definite time delay overcurrent relay, and a Buchholz relay.

As shown in the typical single-line diagram of the ISWS bay (see figure 7.1, panel b), there will be no circuit breaker (CB) between the secondary winding of the IT and the SWL. The IT and SWL will be switched on and off and protected, as one block, by the CB on the MV primary side of the IT.

The protection relays of the SWL will be supplied by the two CTs to be installed in the new bay of the 34.5 kV SWL. Protection of the SWL will consist of:

- An instantaneous overcurrent relay.
- An inverse time delay overcurrent relay, with choice of various current-time curves.
- A current unbalance relay, sensing the percentage difference of the current flow on the two insulated shield wires. This relay will be set to trip with time delay (adjustable up to 10 s) if the current imbalance exceeds a certain value (adjustable from 20% to 50%). This protection is aimed at sensing high resistance to ground faults not detected by the overcurrent protection. It can be realized by means of a relay sensitive to the percentage negative sequence current, of the type used to protect the generators.
- Automatic high speed (0.5 to 2 s delay) and slow speed (15 to 180 s delay) three-phase re-closures (two-wire SWL re-closure) with a four-position pre-selector (re-closure excluded; high-speed single shot; low-speed single shot; high + low speed).

Overcurrent relays in existence in the MV supply bay may be used for protecting the SWL if their characteristics are suitable.

The overcurrent relay shall be a digital type, with capacity to record the pick-up currents and measure the actual currents.

Metering of the SWL will include:

- Voltages, currents, and active and reactive power on the primary side of IT (generally available in the MV supply switchgear)
- Voltage and currents on the 34.5 kV outgoing SWL.

Voltage on SWL side will be measured between the two insulated phases only. Currents on the SWL side will be measured in the two insulated wires and in the ground connection of the reactor-resistor (three-phase measurement).

The contractor shall design, manufacture, test, and transport a control panel for each SWL, to be housed in the space available in the control rooms of the substations. The panel will conform as far as possible in dimensions, design, color, and functionality with the line control panels in existence in the control rooms. The panel shall house the protection relays, auto-re-closing apparatuses, and auxiliary relays; the metering instruments, transducers, control circuits, and interlockings; and the mimic diagram of the SWL with command of the MV supply CB of the IT and of 34.5 kV grounding switch, alarm panel, and other devices and functions to conform with the standards applied for other MV and HV lines.

A.8 34.5 KV T-OFF SLACK SPANS FROM TYPICAL 132 KV DOUBLE-CIRCUIT AND 230 KV SINGLE-CIRCUIT LINES

Typical down lead arrangements are shown in figure C.3 in Annex C.

The T-off structure may be a lattice steel galvanized structure, as shown in figure C.2 in Annex C. Alternatively, the contractor may propose the use of a galvanized steel pole of adequate strength and same height aboveground (12 m), or a gantry consisting of two concrete or wooden poles with steel brackets, of the same height aboveground and adequate mechanical strength. A single concrete pole could also be used, if available with adequate height and strength.

The following equipment shall be installed on the T-off structure:

- N° 4 tension glass insulator rigid strings (see figure 5.1 in chapter 5, and figures C.9a and C9b in Annex C) or conventional strings formed by four cap-and-pin glass insulators (diameter = 254 mm; spacing = 127 mm)
- N° 1 2-pole load break switch provided with fuses, with manual operating mechanism (with an insulated handle at 1.5 m above ground level), if the spur MV line is long
- Alternatively to the previous bullet, if the spur line is short, N° 2 one-pole fused cut-outs with fuse holders and fuse links of specified current rating (figure C4 in Annex C)
- Where specified, power factor correction, balancing, anti-ferroresonance capacitors shall also be supported by the T-off structure (see section A.5 in Appendix A and Table B.18 in Appendix B)
- N° 2 post-type porcelain insulators for insulation and support of connecting conductors (see Figure C.2 in Annex C); not required if a two-pole concrete gantry structure is proposed
- Grounding leads and grounding rod as specified for the 34.5 kV poles (see section A.10), with a buried counterpoise connection to the grounding system of the HV tower

Surge arresters are not required at T-offs, except in the T-offs where the capacitor banks are installed.

The technical characteristics of the load-break switches and fused cut-outs are provided in tables B16 and B17 in Annex B.

If the total length of 34.5 kV lateral line does not exceed 2 km, the load break switch is not required, because energization and de-energization of the lateral line can be performed by the fused cut-outs after disconnection of all the MV/LV distribution transformers supplied by the spur line, by means of the relevant fused cut-out(s).

If the 34.5 kV spur line is very short (say, no longer than 250 m) and supplies only one MV/LV transformer, it is sufficient to install a fused cut-out in the Tee-off structure, to be used for protection of the lateral line and transformer, and for energization/de-energization of the lateral line and transformer after opening the fuse-switches on the LV side of transformer.

A.9 EARTHING SYSTEMS FOR GROUND RETURN OF CURRENT AND LV NETWORKS

A9.1 Earthing System in the HV Supply Substations of the ISWSs

In the HV supply substations, the existing earthing system is generally considered to be satisfactory. In fact, by assuming a ground resistance of 1 Ω and SWL(s) loaded at about 5 MVA, the step and touch voltages are expected to be very small, generally lower than 10 Vrms, and of no concern. Thermal stability will not pose problems.

Measurements of step and touch voltages and potential to remote earth will be performed in the dry season after commissioning of the ISWSs (see Annex E).

A.9.2 Villages

In the villages, the basic grounding principle is multiple grounding. The general arrangement is shown in figure 3.2 in section 3.2 of the manual. The concept is to connect in parallel the grounding rods of the MV/LV transformer station (see figures C.5a, C.5b, and C.5c in Annex C), with one or some other grounding rod(s) via the ground conductor installed underneath the 34.5 kV conductors in the spur lines. In particular, if the spur MV line is short, the paralleling shall be made with the grounding system of take-off HV tower connected with a galvanized steel counterpoise to the grounding rod of T-off structure (see figure 3.2 in chapter 3), and with the grounding rods at every third pole of the 34.5 kV spur line and 34.5 kV reticulation lines in the villages, if any. The following conditions shall be separately fulfilled by the above-described multiple grounding systems in the dry season:

a) The potential to remote earth shall not exceed 30 Vrms with the actual peak loads.

b) The ground resistance shall not exceed the value specified in subsection 3.2.2 (in chapter 3 of the manual) for each grounding system according to the intensity of the earth-return current to be injected.

c) Special attention shall be given to the grounding system where the shunt capacitors are installed, because an important current is injected continuously in the grounding system.

When the lateral line is longer than 600 to 700 m, only a stretch of about 600 m adjacent to the first MV/LV transformer station of the village and the 34.5 kV lines supplying other transformers in the village, if any, should be equipped with the third ground conductor, to be grounded at every second or third pole (see section A.10). The rest of the spur lines shall be equipped with only two wires, insulated for operation at 34.5 kV phase-to-Gr. Each of the resulting multiple earthing systems shall comply with requirements a) and b) above.

If the soil resistivity is very high, lowering of resistance at villages to the specified values (items a) and b) above) can be achieved in a simple and economical manner by installing some additional grounding rods in selected close-by places where soil has low resistivity, if available (in proximity of rivers or creeks, or fountains; in marshy land; in cultivated land where fertilizers are used; etc.). It should not be overlooked that a grounding rod in soil with resistivity of 50 or 100 Ωm has a ground resistance 20 times smaller than the same rod in soil with resistivity of 1,000 or 2,000 Ωm, respectively.

A.9.3 Neutral of LV Networks

The neutral of LV networks shall not be grounded at the supply MV/LV transformer station. An independent multiple grounding will be realized with grounding rods at some poles along the LV lines. The induced potential on the neutral of LV networks should be less than 5% of the measured value of potential to remote earth of the MV grounding system used for earth return of current. Separation by one LV span is usually sufficient.

A.10 EARTHING OF CONCRETE POLES OF 34.5 kV SPUR LINES

Where three wires are applied (spur lines with 2 MV insulated wires and one ground wire), the ground wire will be earthed at about every third pole. Earthing rods can be of galvanized steel rods (minimum 600 gr of zinc per sqm) with diameter ≥ 18 mm and minimum length of 3 m.

The earthing leads on poles can be copper clad conductors of adequate cross-section, protected against contacts and mechanical damage up to 2.7 m aboveground by a sturdy plastic pipe. A removable bolted link may be provided at 2.7 m above ground level, to enable the earthing rod separation for measurement of earth resistance.

The ground wire shall be supported on one side of the poles underneath the 34.5 kV energized wires (see figure C.6a, C.6b, and C6c in Annex C), by means of a shackle-type glass or porcelain insulator (insulation class 1 kV). This provision is aimed at avoiding the use of concrete or steel poles as earth conductors.

Steel stays of poles shall be insulated at a height of at least 3 m above ground level by means of a reel-type porcelain insulator.

A.11 DISTRIBUTION TRANSFORMERS

A.11.1 General Information

This part of the specifications covers the design, manufacture, factory testing, delivery, and transport to the site of installation, if required by the employer.

The latest issues of Recommendations of the International Electrotechnical Commission (IEC standards), in particular IEC 60, IEC 71, IEC 60076, IEC 137, IEC 214, IEC 296, IEC 354, IEC 542, IEC 551, IEC 567, IEC 60599, IEC 722, and IEC 815, shall apply. Supplementary standards are the German standards DIN and VDE, the British standards BS or their subsequent EURONORMs, the American standards, or specific national standards in the above-mentioned sequence, if there are no relevant IEC standards existing or if explicitly asked for in these tender documents.

Moreover, the tender shall include typical dimensional and sectional drawings of the transformers and accessories, such as the off-load tap changers, bushings, cable boxes, control cabinet, etc.

As far as practicable, equipment for all the transformers to be delivered under this part of the specifications, such as insulation oil, bushings, accessories, etc. shall be compatible and interchangeable with each other (subject to approval), so that operation, maintenance, and replacements are as simple as possible for the employer.

Each item necessary for proper completion of the work, whether especially specified in the tender documents or not, is to be included in the tender price.

A.11.2 General Design Conditions and Data

The design of the transformers shall be based on the following conditions and requirements:

- The design shall be based on site and service conditions as specified herein.
- The transformers shall be capable of operating continuously at any tap position within their specified temperature rise limits.
- The transformers shall be capable of withstanding the electrodynamic forces caused by external short circuits. The thermal duty shall be at least 3 seconds after all loading conditions as specified in IEC 354.
- Neutral points shall be brought out and shall be solidly grounded.

All specific technical data are stipulated in the technical data sheets. The transformers shall be designed and tendered in full compliance with all further applicable sections, articles, and drawings of these specifications.

A.11.3 Windings

Electrolytic copper of a high conductivity (class A, in accordance with IEC) and insulation material of high quality shall be used. The insulation material of the windings and connections shall be free from insulation compositions subject to softening, shrinking, or collapsing during service. Moreover, none of the material used shall disintegrate, carbonize, or become brittle under the action of hot oil, under all load conditions.

The coils must be capable of withstanding movement and distortion caused by all operating conditions as specified in IEC 354. Adequate barriers shall be provided between the windings and the core as well as between high-voltage and low-voltage windings.

LV windings shall be designed for at least LI: 20 kV/AC: 8 kV.

All leads or bars from the windings to the terminal boxes and bushings shall be rigidly supported. Stresses on coils and connections must be avoided.

A.11.4 Magnetic Core

The magnetic core shall be made of laminations of non-ageing, cold-rolled, grain-oriented, silicon steel of high permeability without burrs. Each lamination shall be insulated with high-quality insulation coating. The core and its clamping plates shall form a rigid unit structure, which shall maintain its form and position under the severe stresses encountered during shipment, installation, and short circuits.

Care shall be taken to secure uniformly distributed mechanical pressure over all the laminations to prevent setting the core and to limit noise and vibrations to a minimum under service conditions.

The maximum magnetic flux density in the legs and yokes of the core shall not exceed 1.65 Tesla at rated voltage and frequency in mean tap position.

A.11.5 Transformer Tank

The transformer tank shall be of the upper flange type with **bolted cover** and shall be preferably equipped with corrugated sheet steel–type radiators incorporated with the tank. Cooling fins shall be welded, if appropriate, with round stiffening rods to prevent vibration during operation of the transformers.

Only hermetically sealed tanks completely filled with oil shall be provided. Transformer tanks filled with nitrogen above the oil level are not acceptable. A suitable gauge for checking the oil level shall be provided for each transformer.

Gaskets shall be oil resistant and made of such a material that no serious deterioration will occur under service conditions. Rubber gaskets used for flange connections of the various oil compartments shall be laid in grooves. Gaskets of such material, which can be easily damaged by over-pressing (for example, any kind of impregnated/bonded cork), are not acceptable.

Lifting lugs shall be provided on the cover as well as rigid traverses under the bottom as a mounting base. Bi-directional wheels with blocking facilities shall be provided for the ground-mounted station supply transformers. Distribution transformers other than the station supply transformers shall be equipped with appropriate pole-mounting facilities of an approved design. The pole-mounting facilities to be delivered with the transformers shall be complete in every respect and shall be properly coordinated for each transformer type with the manufacturers of the pole and crossarms.

Two earthing terminals of adequate size shall be provided and installed diagonally at the bottom of the transformer tank.

A.11.6 Cooling

The transformers shall be provided with a self-cooled type of cooling system (ONAN).

A.11.7 Terminals

A.11.7.1 Bushings

Bushings shall be of the outdoor type, designed for areas with a heavily polluted atmosphere. They shall also correspond to IEC 137, shall be free from defects, and shall be thoroughly vitrified. Insulators shall be of top quality electrical grade porcelain, homogenous and non-porous, and in one piece. The glaze shall not be depended upon for insulation and shall be of a uniform shade of brown, completely covering all exposed parts of the insulator. The bushings shall be arranged on the tank cover. Uncovered HV bushings shall be equipped with adjustable removable protective gaps.

The clearances in air between live parts of the bushings and against the ground shall be not lower than specified in IEC 60076-3-1. This is applicable for all outdoor arranged bushings.

A.11.7.2 Terminal Boxes

If specified in the technical data sheets, air-filled cable connecting boxes of protection class IP55 equipped with outdoor bushings, suitable for connections of cables with outdoor sealing ends up to Um = 36 kV, shall contain the winding ends and the neutral. The bushings for the station supply transformers shall also be equipped with rigidly fixed solid gas stoppers (subject to approval).

This box, if required, shall also contain internal busbars connected to the bushings to which the corresponding connecting cables for the switchgear will be attached. The cable terminal boxes, if required, shall also be equipped with metal cable glands and shall accommodate the cable sealing ends. Suitable grounding studs with cadmium plated bolts and washers for earthing of the cable sheaths shall also be provided.

The level and design of the insulation shall comply with that of the related bushings. In case of reduced clearances and insulation barriers being provided for the HV terminals, the HV windings are subject to full wave lightning impulse tests with positive as type tests under witness of the employer and/or engineer.

A suitable hand-hole for checking the oil tightness of the bushings shall be provided in the boxes at an easily accessible location. Ingress of dust and other foreign substances, and formation of condensate in the cable boxes must be prevented by a silicagel breather connected to the cable box. The containers for the dehydrating agent and the oil trap shall not be of transparent plastics. The silicagel shall be blue colored when dry, pink colored when wet.

Connecting boxes are not required for the distribution transformers to be used in the 34.5 kV Iliceto shield wire schemes.

MV/LV distribution transformers with rated power up to 800 kVA shall be without terminal boxes.

A.11.8 Off-Circuit Tap Changers

Manually operated off-circuit tap changers shall be supplied for the distribution transformers, and shall be capable of withstanding voltage surges and 180% continuous loading without damage or excessive heating, and short circuits without injury.

The selector switch shall be operated with the transformer de-energized by a handle located on the transformer cover.

Position "1" of the tap-changer is related to the maximum high voltage.

A.11.9 Transformer Oil

The transformers shall be supplied and shipped with their initial oil filling. The insulation oil shall be pure uninhibited naphtenic-based mineral oil free from additives and shall be acid-refined with properties complying with IEC 296, class II.

The contractor is held responsible to prove the dryness and all other properties of the oil before utilization.

A.11.10 Piping and Valves

The piping required for the connection/filling of the various parts of the transformers as well as the valves required for oil draining/sampling, filling, venting, etc. are to be included.

Station supply transformers shall also be equipped with drain and filter valves with adapters of R1½″ male thread fitted with cap.

A.11.11 Measuring and Monitoring Equipment

A combined protection device for monitoring of functions as specified below shall be provided for **transformers above 1,000 kVA and below 2.5 MVA**:

- Dial-type thermometer for oil temperature with adjustable alarm and trip contacts
- Monitoring device for oil leakage and gas formation with trip contact
- Monitoring device for sudden pressure with trip contact
- Oil level gauge.

A suitable terminal box (protection class IP55) for connection of measuring and monitoring devices shall be attached to the transformer tank.

The wiring and cabling shall be of stranded copper and shall be furnished with slip-over ferrules at both ends. The wiring shall also have crimped termination. The minimum cross-section of the wiring shall be 2.5 mm^2. Termination of two conductors at one terminal point shall be made by suitable bridges and links of the terminal.

All the cables that connect the monitoring equipment, as specified previously, to the terminal boxes, shall be steel armored or laid in flexible conduit steel pipes and shall be rigidly fastened to the tank by non-corrosive metal ties or clamps.

All wiring to alarm and trip devices shall include an insulated separate protection earth conductor ("green/yellow" colored) of at least the same cross-section as the line conductor. Suitable grounding conductors shall be provided between the terminal box and related cover. Insulated grounding conductors shall be "green/yellow" colored.

A.11.12 Name Plates and Other Designation Plates

Plates made of corrosion-proof material rigidly supported shall be supplied as specified herein. Outdoor arranged plates shall be of polished stainless steel of top quality only (background clear, engraving black, depth of engraving 0.5 mm). Plates arranged inside the marshalling box, if any, may be of material in accordance with the manufacturer's standard, for example, fiberglass reinforced synthetic resin (subject to approval).

- A rating plate according to IEC 60076.
- A diagram plate showing in an approved manner the internal connections and the voltage vector relationship of the several windings in accordance with IEC 76 and, in addition, a plan view of the transformer giving the correct physical relationship of the terminals.
- For the station supply transformers, a plate showing measuring and monitoring circuits and terminal blocks. This plate shall be located inside the terminal box.

A.11.13 Drawings and Documents

Where applicable, the following drawings and documents shall be submitted for approval as a minimum requirement:

- Technical data sheets
- Painting procedure
- Specification of the insulation oil
- Outline drawing with parts list
- Circuit diagram for auxiliary wiring
- Rating plate and connection diagram
- Termination boxes

- Bushings
- Factory test procedure
- Factory test report (submitted after witness tests)
- Operation and maintenance manual.

A.11.14 Inspections and Tests

The transformers shall be subject to acceptance tests to be performed at the contractor's premises to verify their conformity with the guaranteed and other design data.

The tests shall be performed in accordance with the latest issues of the Recommendations of the International Electrotechnical Commission (IEC-standards), in particular IEC60076, supplemented by these specifications.

The contractor is obliged to submit a detailed test program for approval in due time, prior to the tests (at the latest two months before testing). A detailed time schedule showing exactly when the tests will be carried out (maximum 12 hours per working day) shall be submitted along with the test program above.

The following tests shall be performed in the presence of the employer/engineer in a number of units of each type of transformer as required by the employer/engineer:

- Measurement of voltage ratio at all tap positions
- Check of vector group by voltmeter method
- Measurement of winding resistance at all tap positions
- Measurement of impedance voltage at principal tap and extremes
- Measurement of no-load losses
- Measurement of load losses at principal tap and extremes
- Measurement of insulation resistance (R15, R60, R180,) at 2,500 V, DC
- Induced overvoltage withstand test
- Separate source overvoltage withstand test
- Applied overvoltage test at 2,000 V, AC on auxiliary wiring (if any)
- Short circuit test.

For duplicate units, test reports of tests to be performed as specified above shall be submitted.

A.11.15 Painting

A.11.15.1 General

Due to the unfavorable atmospheric conditions, particular attention should be given to the protection of all ironwork. The methods proposed and the means adopted should be fully described in the tender proposal.

All surfaces shall be thoroughly cleaned of rust, scale, grease and dirt, and other foreign matter and all imperfections shall be removed by means of approved methods.

The following treatments shall be applied:

A.11.15.2 External Surfaces

All steel surfaces shall be sand-blasted in accordance with DIN 55928 Part 4 (equivalent to SIS 055900), and shall then be painted in the following sequence:

COAT	KIND	LAYER THICKNESS
One (1) primer coat	Two-component epoxy zinc-phosphate	60 µm
One (1) intermediate coat	Two-component epoxy micaceous iron oxide	60 µm
One (1) top coat	Two-component polyurethane	40 µm
Total coating thickness (dry-film)		160 µm

The final coat of painting shall be of pore-free and homogeneous quality and shall be a uniform shade of code RAL 7032 (silica-grey).

In case of ordinary stainless steel or aluminum, one primer coat may be omitted.

If any hot-dip galvanized steel parts will be provided, the same painting method shall be applied; however, instead of two primer coats, one adhesive coat and one base coat shall be applied. In this case, the mean thickness of galvanizing shall be 70 µm.

Mechanical damage shall be repaired at the site with the original paint as above.

A.11.15.3 Internal Surfaces (Not Required for MV/LV Distribution Transformers)

Inside the transformer/reactor vessel, sand-blasting shall be performed in accordance with DIN 55928 Part 4, (equivalent to SIS 055900). After that, an oil-resistant insulating coating shall be applied to all steel surfaces in contact with the oil (for example, the tank, cover, core steel plates, etc.).

The minimum dry film thickness shall be 35 µm (color code RAL 9010 white or equivalent).

A.11.16 Capitalization of Losses

When evaluating the individual tenders received from the various bidders, the transformer losses will be capitalized as follows, unless otherwise specified elsewhere in the bidding documents:

No-load losses	$5,000.00 per kW
Load losses	$3,000.00 per kW

The auxiliary power losses (if any) will be added to the load losses.

Transformers with guaranteed losses exceeding the specified values will not be considered for the award of contract.

A.11.16.1 Guaranteed Values and Penalties

The guaranteed values tendered by the contractor in the technical data sheets will be strictly observed by the contractor and the employer.

For the guarantee data not mentioned herein, tolerances in accordance with IEC60076 shall apply.

A.11.16.2 Losses

- If the no-load losses of distribution transformers exceed the guaranteed value, the sum of the no-load losses in excess of all ordered distribution transformers of this type will be considered and an amount of **$5,000.00** for each full kW in excess will be deducted from the contract price.
- If the load losses of distribution transformers exceed the guaranteed value, the sum of the load losses in excess of all ordered distribution transformers of this type will be considered and an amount of **$3,000.00** for each full kW in excess will be deducted from the contract price.
- It is thereby understood that values of 0.5 kW and above will be rounded up to the next full kW.

A.11.16.3 Rated Power

If the test of temperature rise carried out on any transformer should reveal that the temperature rise of the transformer exceeds the values guaranteed, the rated power of the transformer will have to be down-rated to such a degree as to obtain the temperature rise guaranteed.

For each **kVA** of the actual transformer rating below the guaranteed output, an amount of **$200.00** will be deducted from the contract price of this transformer and all those transformers of the same design unless the contractor, at his own expense, modifies the transformers and gives evidence that those transformers fulfill the guaranteed values.

A.11.16.4 Noise Level

Should the noise level measured at the specified distance exceed the required values for power transformers the employer will penalize the excess at a rate of 1% of the price of the transformers per dB(A). It is hereby is understood that values of 0.5 dB(A) and above will be rounded up to the next full dB(A).

A.11.17 Rejection

The employer shall have the right to reject any transformer if the actual values are in excess of the guaranteed values by more than the margins specified hereunder (including the tolerances).

No-load losses	+15%
Load losses	+15%
Total losses	+15%
Temperature rise	0%
Noise level	+3 dB(A)
Rated power	–5%

For all of the other values, the margins stated in the IEC standards are applicable.

A.11.18 Special Requirements for the 34.5/0.4 kV Distribution Transformers of ISWSs

The general characteristics specified in the previous paragraph of this section for conventional distribution transformers are applicable, unless otherwise specified herein and/or in tables B.9 to B.15 in Annex B. These "Technical Data Sheets" shall therefore prevail in case of conflict with the previous paragraphs of this section and/or with the IEC standards.

It should be noted that the shield wire lines energized at 34.5 kVrms phase-to-ground require somewhat increased insulation levels of the MV/LV transformers (50 Hz-60 s of 82.5 kVrms and lightning impulse of 200 kV peak, instead of 70 kVrms and 170 kV peak of conventional 33 kV equipment, respectively).

The 34.5 kV and 0.4 kV bushings shall be made of brown porcelain. The arcing horns on 34.5 kV bushings shall have adjustable distance and shall be removable.

Distribution transformers shall be hermetically sealed for life. Only this alternative is therefore to be considered for bidding in tables B.9 to B.15 of the Technical Data Sheets (Annex B).

The engineer's and/or employer's inspectors shall witness the routine tests of all the transformers of the ISWS, or part of each lot selected by the inspector at the time of the factory acceptance tests.

The following types of tests will be performed in one unit of each type of transformers to be delivered for the ISWS, and will be witnessed by the engineer's and/or employer's inspector:

- Temperature rise test
- Measurement of acoustic noise level
- Lightning impulse test.

At the discretion of the engineer/employer, a short circuit type test shall be performed in one unit or a few units at the time of acceptance, to prove the transformers withstand capacity to the short circuit electrodynamic forces. The test shall be performed in accordance with IEC standards 60076-5 (last edition) in a laboratory of internationally recognized reputation. The units to be tested shall be selected by the engineer/employer.

A separate price shall be quoted only for the short circuit–type test. The price shall not be paid if the test is waived.

A.11.19 Transport

All the distribution transformers to be used in the 34.5kV Iliceto shield wire schemes shall be shipped filled with oil, with all the accessories fitted in the transformers.

A.12 34.5/0.4-0.231 KV AND 30/0.4 – 0.231 TRANSFORMER STATIONS

A.12.1 Pole-Mounted Transformers

The pole-mounted three-phase transformer stations should be built in accordance with the design in figure C.5a (dead-end station) and figure C.5b (intermediate station) in Annex C.

The gantry structure will be realized by means of two 11 m concrete poles or equivalent wooden poles of the type in general use in the 34.5 kV (or 30 kV) lines, and with galvanized steel brackets. A stay may be applied in the dead-end stations.

The standard design shall allow installation of three-phase transformers rated up to 400 kVA.

Protection against overvoltages of the three-phase transformers with rated power ≥ 200 kVA and single-phase transformers with rated power ≥ 100 kVA shall be ensured by two and one MOV surge arrester(s) (SA(s)), respectively. Three-phase transformers with rated power < 200 kVA and single-phase transformers with rated power < 100 kVA will be protected only by arcing horns. The distance between the arcing horns will be set at 145 mm and 125 mm for the 34.5 kV and 30 kV transformers, respectively. Where SAs are installed, the arcing horns will be removed or distance will be increased so as to avoid interference with the operation of the SAs.

Switching of transformers and protection of transformers against short circuits will be performed by fused cut-outs. Rated current of K-type fuse links shall be 3A, 5A, 10A, and 15A for three-phase 34.5 kV and 30 kV transformers rated at 50, 100, 200, 315, and 400 kVA, respectively. A check will be made with the manufacturer to ensure that the fuse links are not melted by the transformer inrush currents.

The minimum air clearance between live parts, phase-to-ground and phase-to-phase, shall be 50 cm.

The grounding leads along the poles shall be copperweld wire AWG7. All structural metal parts shall be bonded and effectively grounded. One of the 34.5 kV terminals of the transformer will be connected to the incoming ground conductor and connected to the grounding lead. An independent lead shall be used to connect the SAs to the buried grounding system.

It is mandatory to connect to the grounding system one of the 34.5 kV (or 30 kV) terminals of each transformer via at least 2 (two) independent grounding leads, to avert the danger for people in the case that one lead were cut. In addition to the lead installed in the MV/LV stations, the grounded 34.5 kV (or 30 kV) terminal shall be connected to the ground wire of the supply 34.5 kV (or 30 kV) line (see Figures C.5a, C.5b, and C.5c in Annex C).

The grounding system of each MV/LV transformer station shall consist, as a minimum, of three galvanized steel rods (minimum 600 gr of zinc per sqm) with diameter ≥ 18 mm and length of 3 to 4 m, driven at the corners of a triangle with minimum side of 4 m (see figures C.5a, C.5b, and C.5c in Annex C).

On the LV side, the protection and switching of 0.4-0.231 LV lines shall be performed by three-phase pole-mounted fused cut-outs rated according to the load current of the line, one set for each line.

Connections between the four LV terminals of the three-phase transformer and LV fused cut-outs, and between the latter and the LV overhead lines, will be made with single-core aluminum or copper insulated conductors of adequate cross-section.

The neutral of the LV network shall not be connected to the grounding system of the MV/LV station (see section A.9.3).

Anti-climbing devices shall be installed below the transformer support brackets.

A.12.2 Ground-Mounted Transformers

The ground-mounted transformer stations shall be built in accordance with the design in figure C.5c in Annex C, with transformers rated at 630 kVA or 800 kVA.

The electrical requirements for the 34.5 kV (or 30 kV) equipment shall be as specified in subsection A12.1; however, K-type fuse links rated at 25 A and 30 A shall be used for the 630 kVA and 800 kVA transformers, respectively.

If switching on-load of transformers rated at 630 kVA and 800 kVA is required, a manually operated load break switch with fuses shall be used instead of the fused cut-outs.

On the LV side, the protection, switching, and metering of the 0.4/0.231 kV lines will be installed in a separate LV switchboard.

Access to the transformer by un-authorized persons shall be prevented by a galvanized steel earthed fence, as shown in figure C.5c in Annex C, with height not less than 2 m. The gate shall be provided with a padlock.

A.13 INTERPOSING TRANSFORMER

A.13.1 Scope

This specification covers the design, manufacturing, testing, supply, and transport of typical three-phase power interposing transformers for the 34.5 kV three-phase Iliceto shield wire scheme (ISWSs).

A.13.2 General

A.13.2.1 Transformer Type

The primary MV supply is assumed to be 33 kV. However, the MV may be different depending on local availability (say, 10 kV, 15 kV, or 20 kV, etc.).

Transformers shall be three-phase, 50 Hz with no-load ratio 33/35.5 kV ±2 × 3.75%, oil immersed outdoor type, natural air cooled, and provided with an off-load tap changer.

The transformer shall be able to sustain the over-excitation conditions mentioned herein.

The transformer shall be provided with bushing-type current transformers, for measurement and protection as specified elsewhere in these specifications.

A.13.2.2 Service Conditions

The altitude above sea level will not exceed 2,000 m.

Air temperatures are:

- Maximum +45°C
- Annual mean not exceeding +25°C
- Minimum +0°C

The equipment is exposed to tropical conditions and therefore is subject to high sun radiation and heavy moisture condensation during the nighttime.

The area is subject to heavy storms and frequent lightning strikes.

Earthquake conditions to be taken into account shall allow for a horizontal peak ground acceleration level of 0.2 g; 80% of this value will be assumed for the vertical ground acceleration.

A.13.2.3 Standards

Unless otherwise specified herein, the transformers shall be designed and manufactured in accordance with the standards and documents listed below:

- IEC Publ. 60076-1, 2000 "Power Transformers -Part 1: General" (edition 2.1)
- IEC Publ. 60076-2, 2011 "Power Transformers - Part 2: Temperature Rise for Liquid Immersed Transformers" (3rd edition)
- IEC Publ. 60076-3, 2000 "Power Transformers - Part 3: Insulation Levels, Dielectric Tests and External Clearances in Air" (2nd edition)
- IEC Publ. 76-4, 1976 "Power Transformers - Part 4: Tappings and Connections"
- IEC Publ. 60076-5 "Power Transformers - Part 5: Ability to Withstand Short-Circuit" (last edition)

•	IEC Publ. 296	"Specification for Unused Mineral Insulating Oils for Transformers and Switchgear" (2nd edition)
•	IEC Publ. 60076-7, 2009	"Power Transformers –Part 7: Loading Guide for Oil-Immersed Power Transformers"
•	IEC Publ. 60076-10, 2001	"Power transformers. Part 10: Determination of Sound Levels" (1st edition)
•	IEC Publ. 137, 1995	"Insulated bushings for Alternating Voltages Above 1000 V" (4th edition)
•	IEC Publ. 60044, 2000	"Current Transformers"
•	IEC Publ. 567, 1992	"Guide for the Sampling of Gases and Oil from Oil Filled Electrical Equipment, and for the Analysis of Free and Dissolved Gases" (2nd edition)
•	IEC Publ. 60599, 1999	"Mineral oil Impregnated Electrical Equipment in Service. Guide for the Interpretation of Dissolved and Free Gases Analysis" (2nd edition)
•	IEC Publ. 60076-4, 2002	"Power Transformers. Part 4: Guide for the Lightning Impulse and Switching Impulse Testing - Power Transformers and Reactors" (1st edition)
•	IEC Publ. 60076-8, 1997	"Application Guide for Power Transformers"
•	IEC Publ. 616, 1978	"Terminals and Tapping Markings for Power Transformers"
•	IEC Publ. 600694	"Common Specifications for High Voltage Switchgear and Control Gear Standards" (last edition)
•	IEC Publ. 529, 1989	"Degrees of Protection Provided by Enclosures (IP Code)"
•	EN 50216	"Accessories for Power Transformers and Reactors" Parts 1 through 6

Electrical accessories (such as motors. switches, relays, cables, etc.) shall comply with the relevant IEC standards even if not expressly mentioned in this clause.

Chemical, physical, dielectric, and mechanical characteristics of materials to be used for manufacturing transformers shall comply with the requirements given by ASTM (American Society for Testing and Materials) or DIN (Deutshes Institute for Normung) or British standards.

Should it occur that during the manufacturing of the transformers the above-mentioned standards are revised, it shall be understood that, unless otherwise expressly requested or authorized in writing by the engineer, these standards shall be considered valid regardless of the revisions.

A.13.2.4 Technical Documentation Required with Tender

The following technical documentation shall be submitted with the tender:

- A technical description including information on materials, guaranteed values, type and disposition of windings, type of core, and type of insulation and impregnation used

- A preliminary drawing with the overall dimensions and weights of the transformer, including all the accessories
- A report including information on short circuit tests carried out on similar transformers, if available
- A summary of calculations for earthquake strengths; the calculations shall show the design stresses and safety factors used and the relevant types of failure
- A preliminary drawing of the proposed gaskets for the main flange
- One drawing with transport dimensions, weights, and other relevant information
- Facilities available for testing and Inspection (see section A.13.5)
- Tap changer description with photographs or drawings
- Quantity of oil (kg).

A.13.2.5 Documentation to be Furnished by the Contractor

- Outline drawings showing overall dimensions, location of terminals and cubicles, and weights and details of the under-base as necessary for the foundation design
- Electrical diagrams for all the control, protective, signaling, and alarm equipment mounted on the transformers
- Drawings of transformer transportation, with fittings for road transport and without fittings for sea transport
- Drawings of terminal blocks
- Installation and maintenance instructions.

A13.2.6 Installation and Maintenance Instructions

The contractor shall provide a manual concerning the erection, dismantling, and maintenance of transformers. In particular, this manual shall include:

- Information on handling the different parts in which transformers may be sub-assembled
- Cautions to be taken during installation
- Characteristics of all protective, signaling and alarm equipment mounted on the transformers
- Procedure for on-site treatment of the insulating oil of the transformers
- All applicable drawings
- Information on periodic measurements, checks, and maintenance
- Any other useful information
- The manual shall be in English.

A.13.2.7 Evaluation of Losses

For the purpose of comparing tenders and penalty application, the guaranteed losses of the transformers will be evaluated as listed below, unless otherwise specified elsewhere in the bidding documents:

- No-load loss at rated voltage — $5,000/kW
- Load loss at rated kVA — $3,000/kW

No credit shall be granted for characteristics that are found to be better than the guaranteed value. The total losses will be evaluated as listed below:

$$L_{11} = (2L_{12} + L_{13} + 0.5L_{23})/3.5$$

where:

L_{12} (kW) are load losses at mean voltage ratio

L_{13} (kW) are load losses at the highest voltage ratio

L_{23} (kW) are load losses at the lowest voltage ratio.

It is hereby understood that values of 0.5 KW and above will be rounded up to the next full KW.

A.13.3 Main Technical Characteristics

A.13.3.1 Specified Ratings

Transformers shall comply with the following characteristics, which shall be the minimum requirements.

Phases:	Three
Windings:	Two
Rating with:	
Cooling type ONAN	3 MVA – 4.5 MVA - 6 MVA (alternative to be selected)
Rated frequency	50 Hz
Rated voltage	
• Primary winding	33 kV or another MV available in the HV/MV station of installation
• Secondary winding	35.5 kV (31 kV for 30 kV Iliceto shield wire schemes)
Tap changing	Off-load (off-voltage)
Voltage regulation	35.5 kV (31 kV) ±2 × 3.75%
Connections of phases:	
• Primary winding	Delta
• Secondary winding:	Star connected, with one terminal permanently grounded, (directly or via an R-X circuit)

Connection symbol: DY5

Cooling method: Natural cooling by means of radiators fitted on the main tank suitable for the nominal ONAN ratings

Insulation:

- Primary winding Uniform
- Secondary winding Uniform

The insulation levels shall be as follows:

WINDING (KV)	INSULATION LEVELS	
	POWER FREQUENCY	LIGHTNING IMPULSE WITHSTAND VOLTAGE
	Line terminals (kV rms)	Line terminals (kV crest)
35.5 kV[a]	95	250
33 kV	70	170

[a]*One terminal of the 35.5 kV winding will be operated permanently grounded, directly or via a resistor-reactor circuit. The other two terminals shall thus be operated at a potential of 35.5 kV rms phase-to-ground. This justifies the specification of the test voltages as for the 52 kV rated voltage.*

Impedance voltage (base-rated power): 6% for 3 MVA rated power

6.5% for 4.5 MVA rated power

7% for 6 MVA rated power.

Temperature-rise limits:

- Windings (average): not exceeding 60°C
- Top oil: not exceeding, 55°C
- Winding hot spot: not exceeding 70°C
- Core surface: not exceeding 75°C.

The above temperature rises shall not be exceeded with the transformers operating with one radiator out of service and the tap-changer in any position.

A.13.3.2 Particular Operating Conditions

The transformers shall be able to sustain, without any danger an exceptional over-excitation causing the flux to increase, up to 1.33 times the normal flux for a duration up to 10 seconds.

The transformers shall also be able to operate continuously with the primary (33 kV) winding energized at 36.5 kV.

Maximum short circuit power of the feeding system (to be considered for the short circuit test): infinite.

A.13.3.3 Current Transformers (Optional, to Be Quoted with Separate Price)

If required in the order, current transformers shall be mounted on the 35.5 kV bushings. The electrical characteristics shall be as follows:

•	Highest system voltage	≥ 0.6 kV rms		
•	Ratio for transformers rated at:	3 MVA	4.5 MVA	6MVA
		60/5/5 A	90/5/5 A	120/5/5 A
•	Cores	1 for measuring, 1 for protection		
•	Rated continuous thermal current	1.2 rated current		
•	Rated short-time thermal current	as per IEC standards		
•	Rated dynamic current	as per IEC standards		
•	Burden	≥ 10 VA for measuring		
		≥ 10 VA for protection		
•	Accuracy class	1 for measuring		
		5 P for protection		
•	Accuracy limit factor	20 for protection.		

A.13.3.4 Tolerances

Unless specified elsewhere, transformers will be considered to comply with these specifications when the guaranteed characteristics are within the following tolerances:

	For penalty Application	For rejection
• Voltage ratio at no-load on any tapping	-	±0.5%
• Impedance voltage		
– Principal tapping	-	±5%
– On extreme taps		±10%
• No-load losses at rated voltage and at rated frequency	0	+15%
• No-load losses at 1.1 rated voltage and frequency	-	+15%
• Load-losses calculated with formula in subsection A.13.2.7	0	+15%
• No-load current at rated voltage and frequency	-	+30%
• No-load current at 1.1 rated voltage and at rated frequency	-	+30%
• Temperature rise	0	0
• Audible sound level		As per IEC Standards

A.13.4 Construction Requirements

A.13.4.1 General

Materials used shall be new, of first class quality, and free from defects and imperfections.

The contractor shall submit to the engineer a list of the proposed sub-suppliers for the main components (such as copper, insulating materials, core laminations, bushings, tap-changer, and current transformers). Said list is subject to acceptance by the engineer before the suborders are placed.

A.13.4.2 Magnetic Circuits

The core shall be of the three-legged type. The core shall be made of cold-rolled oriented-grain silicon steel, of the best quality, suitably annealed to minimize losses. Joints shall be cut at 45 degrees to facilitate flux flow from legs to yokes.

Core construction shall be sturdily clamped by means of yoke clamping structures made of fabricated steel. Upper and lower yokes shall be connected by plates of tie-rods mechanically secured to the yoke frames only, to avoid mechanical stresses on the laminations. The resulting structure shall be capable of retaining its shape under the most severe stresses met during shipment, handling, and under short-circuit conditions.

In particular, the unit is designed to withstand the acceleration induced by the earthquake levels mentioned elsewhere in these specifications and to sustain an inclination of 10 degrees.

Insulation of the core frame from the core shall be able to withstand a voltage of 2 kV rms 50 Hz for 1 minute.

Means shall be adopted to avoid hot spots.

The core shall be connected to the yoke frames and to ground at one point only by means of a copper strap, having a minimum cross-section of 160 mm^2, accessible through a hand hole. Copper bridges shall also be provided across cooling ducts (if any).

A.13.4.3 Windings

Conductors shall be made of electrolytic copper insulated by pure cellulose paper.

All weldings in windings shall be brazed.

The windings shall be conceived to sustain thermal and dynamic stresses occurring in short circuit conditions.

The primary winding (33 kV or other) shall be external. The 35.5 kV (secondary) winding shall be internal (close to the core). This requirement is justified because there will be no circuit breaker on the 35.5 kV (line) side. The transformer will be switched on and off from the primary terminals, in one block with the 34.5 kV shield wire line (SWL) connected to the 35.5 terminals. The SWL could occasionally happen to be affected by a short circuit, thereby causing, in the switched-on primary winding, the superposition of the inrush currents and short circuit currents. The transformer must be guaranteed to withstand this severe switching condition.

A.13.4.4 Tank

The tank shall be made with stiffened welded steel plates so that the transformer can be lifted, completely assembled with oil, without permanent deformation or oil leakages.

The tank is capable of withstanding without permanent deformation practically a complete vacuum (less than 1 mm Hg absolute pressure). The permissible loss of vacuum shall not exceed 6 mm Hg in 6 hours.

The tank shall also withstand a steady-state overpressure test of 1 kg/sqcm measured at tank bottom, with duration of 24 hours, without permanent deformation and leaks.

The cover shall be of the bolted type. Sufficient openings will be provided, if appropriate, to provide access to the internal connections of the bushings, when it is necessary to dismount the bushings, and also to provide access to the grounding links.

The gaskets shall be 0-ring type of synthetic rubber, seated in on-purpose milled and turned grooves or on grooves made by means of two steel bars continuously welded all around the flange, to avoid over-compression of the gaskets. Details on the gaskets and the arrangement of the gaskets shall be submitted for approval together with suitable reference to previous experience.

The tank and the cover are designed so as to leave no external pockets in which water can lodge, and no internal pockets in which oil remains when draining the tank or in which air can be trapped when filling the tank. Venting pipes, if appropriate, shall connect to gas relay all points in which air/gas may collect.

All bolts shall be made of galvanized or stainless steel.

Steel plates for jacking lugs shall be located near the corners of the base, as well as lugs for lifting the completely assembled transformer with oil, and core-coils only.

Pulling eyes near the base shall be mounted for dragging the transformer.

Two grounding terminals shall be provided near the base in the middle of the long sides

The tank bottom shall be provided with skids under the base for movement on a flat concrete surface. In addition, standing feet shall be provided for permanent stationing of the transformer.

The tank is provided with filtering, drain, and sampling valves and fittings for connection to vacuum pumps, as specified herein.

Suitable electric bridges shall ensure that all parts of the tank and all fitting frames are at the same potential.

A.13.4.5 Bushings

The bushings shall comply with IEC publication 137, 1995. The color of the porcelain shall be brown.

The primary and secondary terminals will be of the flag type, in accordance with DIN standards. The type shall be approved by the engineer.

Toroidal current transformers shall be mounted on the 35.5 kV bushings as specified elsewhere in these specifications.

A.13.4.6 Off-Load Tap-Changer

The tap-changer shall be of the rotating type. Rated current shall be not lower than 1.5 times the rated current of the 35.5 kV winding. It shall be impossible to leave the winding open or short circuited when the operating handle is placed in a locked position.

- No. of positions: 5
- Rated voltage to ground: ≥ 52 kVrms
- Insulation level to ground:
  - Power frequency: 95 kVrms
  - Lightning impulse: 250 kV peak

A.13.4.7 Oil Conservator

The oil conservator shall be located on the tank cover.

The size of conservator shall be suitable for a temperature range of 0°C to 100°C. A removable end for cleaning, or approved inspection holes, otherwise arranged, shall be provided.

The conservator shall be provided with a filling cap and draining plug, connection pipes to the gas actuated (Buchholz) relay (with suitable disconnecting valves), and to the tank (such pipes protruding at least 1 in. inside the conservator and having a slope of about 2 degrees), and with an oil level indicator with low-level alarm contact easily readable at eye level. The dial shall indicate minimum, 30°C, and maximum levels. Silicagel breather will be fitted at eye level and connected to the conservator.

A.13.4.8 Cooling

ONAN cooling shall be adopted with the rating limits specified in subsection A.13.3. The cooling equipment shall be vibration-free and oil-leak free, whatever the wind speed and atmospheric conditions.

Natural cooling shall be ensured by pressed steel radiators or tubes welded to suitably shaped headers. Radiators shall be mounted on tank walls; one stand-by radiator shall be provided; temperature rise as per subsection A.13.3 above shall not be exceeded with the stand-by radiator cut out.

Each radiator shall be connected via butterfly valves to the tank so that each radiator can be removed without putting the transformer out of service. Each radiator shall also be provided with vent and drain plugs and fitted with means to lift it.

Radiators shall be of sturdy construction and shall be securely fastened.

A.13.4.9 Control Cabinet, Terminal Blocks, and Wiring

One control cabinet shall be provided. The cabinet shall be of rigid construction and weather-, dust-, and vermin-proof and protected according to IEC publication 144, degree IP55.

If appropriate, the cabinet shall have a door with a clear glass window and shall be equipped with a heating element controlled by an adjustable thermostat to avoid condensation. Suitable natural ventilation shall also be provided.

Terminal blocks used for internal wiring of the equipment and for control, protective, and alarm wiring shall be of the modular type and made of material that is self-extinguishing or flame propagation resistant.

Terminal blocks shall be mounted on metal guides, spring retained. The guides shall be separated at least 15 cm from each other. Each row assembly shall have at least 20% spare terminal blocks for future use. Each terminal block shall have a removable marking strip.

The insulation degree of the cables shall be not lower than three (tested at 2 kVrms against earth), sheath quality R2, and shall be of type resistant to flame propagation and to the temperature that occurs in the position immediately adjacent to the tank.

All wiring terminations adjacent to the terminal blocks shall be equipped with ferrules for proper identification.

Alarm and tripping circuits shall be independent.

All the electrical external connections shall be laid in conduits. Cables shall be colored as follows:

- Red, yellow, blue — A.C. phase connections
- Black — A.C. neutral connections
- Green — Ground connections
- Grey — D.C. circuits

Circuit insulation shall be as follows:

- Power frequency withstand voltage — 2 kV rms
- Atmospheric impulse withstand voltage — 5 kV peak

A.13.4.10 Auxiliary Supplies

The auxiliary supply voltages shall be the following:

- For control circuits and space heaters, if applicable — one phase, 220 V ±10%, 50 Hz (to be confirmed in the order)
- For tripping, alarm and signaling circuits — 125 V –20% to + 10%, D.C. (to be confirmed in the order)

A.13.4.11 Oil

The supply shall include the transformer oil, plus 10% spare oil. This oil shall be new, non-inhibited, and shall meet the requirements for Class I according to IEC publication 296, 1982.

The oil shall be obtained from naphthenic crudes and shall not contain PCB.

In any case, the contractor shall submit to the engineer for approval the characteristics of the oil the contractor intends to use.

A.13.4.12 Painting

All parts of the transformer made of corrodible metals shall be painted. The surfaces inside the transformer tank (including the oil conservator) shall be protected by rust inhibiting paint of proven insolubility in hot oil (at 100°C).

The external metal surfaces shall be treated as follows:

a) Surface preparation: prior to painting, all surfaces shall be subjected to white metal blast-cleaning according to specification SSPC-SP 5-63 of the Steel Structure Painting Council. The primer shall not be applied later than 24 hours after sand blasting, and in any case before the sandblasted surfaces start rusting.

b) First coat (primer): catalyzed epoxy paints with anticorrosion pigments shall be used as a primer for the tank and radiators; synthetic paints may also be used for the radiators.

c) Finishing coat: the finishing coats for the tank and radiators shall be based on paints belonging to one of the following categories:

- Polyurethane paints
- Alkyd and silicone-based paints (30% silicone-copolymer)
- Modified vinyl paints

Intermediate coats between the priming and finishing coats may be selected by the contractor. The various coats of paint should be of contrasting colors to permit their prompt identification. The color of the finishing paint shall be subject to approval by the engineer. The minimum thickness of the paint shall be not less than 150 microns on any point of painted outdoor surfaces.

The contractor shall submit for approval the painting method the contractor intends to adopt, in particular the contractor shall specify the nominal value of the thickness of each coat. Painting of the transformers shall be completed before the routine tests. Finished painted surfaces shall be properly protected against possible damage during transport and installation. The contractor shall supply a sufficient quantity of touch-up paint to repair damaged parts.

A.13.4.13 Accessories

- 1 Buchholz relay with two floats and two independent contacts for alarm and tripping for the oil of the transformer tank with two disconnecting valves and circuit testing device
- 1 oil sampling device vacuum-tight at eye level connected with the above relay
- 1 flanged pipe for the above relay to allow removal of same
- 1 hot oil thermometer, dial type with two resettable contacts (alarm and tripping), mounted on the tank wall at a suitable level

- 1 bronze plug vacuum-tight with screwed cap for sampling oil from the main tank
- 2 bronze valves in opposite sides of the main tank (located at convenient height) for oil treatment The valves shall be vacuum-tight, threaded 1.5 in., and fitted with screwed cap. The lower valve will be used for oil draining.
- 1 valve as above for the vacuum pump
- Blind flanges to be fitted on butterfly valves of radiators (see subsection A.13.4.8)
- 2 thermometer pockets with captive screw caps
- 1 safety overpressure valve with alarm contacts
- Nameplate with transformer diagram
- Other accessories, such as lugs, valves, etc., as listed in subsections A.13.4.4, A.14.4.7, and A.13.4.8

A.13.4.14 Labels and Plates

The transformer shall be provided with one rating plate affixed in one long side of the tank. Relays and all other apparatus as well as cable and wiring terminations shall have identifying labels. All labels and plates shall be of stainless steel or other approved non-corrodible metal, shall be fitted with stainless steel screws and lettering shall not deteriorate with time. All inscriptions shall be in English and subject to approval by the engineer.

The rating plates shall show all the indications specified in IEC publication 60076-1 (plus the indication that the tank is suitable for lifting the transformer full of oil).

A.13.5 Tests

A.13.5.1 Tests on Components

Before being fitted to the transformers, all components (bushings, tap-changer, radiators, relays, etc.) shall be subjected to routine tests required by the relevant standards at the supplier's or sub-supplier's factory.

A detailed test report, proving the successful passing of such tests, shall be provided.

A.13.5.2 Acceptance Tests

The following tests shall be performed at the contractor's works prior to shipment:

TYPE TESTS:

- Temperature-rise test
- Short-circuit test (optional, at discretion of the engineer)

- Measurement of the harmonics in the no-load current
- Measurement of acoustic noise level
- Vacuum test on the tank and assembled fittings
- Leakage test on the tank and assembled fittings under oil pressure

ROUTINE TESTS:

- Measurement of voltage ratio
- Check of voltage vector relationship
- Measurement of the winding resistances
- Separate-source power-frequency withstand test
- Impulse test
- Induced overvoltage withstand test
- Measurement of no-load losses and current
- Measurement of short circuit impedance and load losses
- Measurement of loss angle
- Measurement of insulation resistance
- Checks of breakdown voltage of insulating oil
- Operation test of tap-changer
- Fitting inspection and operational check
- Check of paint protection
- Test on components

The routine tests shall be made on each transformer supplied.

The type tests shall be made on one transformer, after the routine tests.

Unless otherwise specified, the tests shall be carried out in accordance with IEC recommendations.

A.13.5.3 Type Tests

TEMPERATURE-RISE TEST

The test shall be carried out with the short-circuit test method in accordance with the procedure laid down in IEC publication 60076-2, 2011.

The test shall be continued until the requirements of the relevant clauses of IEC publication 60076-2, 2011 have been met. The winding temperature shall be ascertained by using the resistance method. The maximum inaccuracy of the measurements shall not exceed ±0.5%.

SHORT-CIRCUIT TESTS

To be carried out in accordance with the procedure laid down in IEC publication 60076-5 (last edition), unless otherwise specified herein.

Each tenderer shall inform the test station or laboratory where the short circuit test will be performed, and will quote the total cost of the test, including transport of the transformer to and from the test site.

If the tenderer has performed a short circuit test on a transformer of the same design and equivalent power rating, a test certificate shall be submitted with the tender.

The final decision whether to perform the short circuit type test shall be notified by the engineer at the time of the acceptance tests, at the engineer's discretion. A test waiver, if considered by the engineer, will in no way relieve the manufacturer of its obligation under the contract. Should the test be waived, the relevant price will not be paid.

The thermal ability to withstand short circuit shall be demonstrated by calculations while the dynamic ability shall be proved by tests.

For the latter purpose, nine short circuits will be applied as follows:

WINDING CONDITIONS	TAP-CHANGER POSITION	CURRENT IN PHASES A, B, C, AS PERCENTAGE OF SHORT-CIRCUIT CURRENT		
		A	B	C
Primary terminals (33 kV or other): Supply input: 35.5 kV (31 kV) terminals: short circuited	–7.5%	100%	consequent	consequent
	–7.5%	100%	consequent	consequent
	–7.5%	100%	consequent	consequent
	0	consequent	100%	consequent
	0	consequent	100%	consequent
	0	consequent	100%	consequent
	+7.5%	consequent	consequent	100%
	+7.5%	consequent	consequent	100%
	+7.5%	consequent	consequent	100%

The duration of each short-circuit shall be 0.5 seconds with a tolerance of ±10%.

The calculation of the short circuit first peak current and rms current shall be made by considering nil (zero) the equivalent impedance of the supply network. This compensates for the fact that the supply voltage in operation can be higher than the rated voltage (for example, 33 kV instead of 30 kV). Tolerances on peak and rms currents shall be as per IEC standards.

The testing scheme shall be one of those permitted by the IEC standards. However, the test procedures and scheme shall be discussed and approved by the engineer prior to the test.

Nine short circuit tests shall be carried out with the 35.5 kV (secondary winding) terminals short circuited (that is, with pre-set short circuit): three tests shall be in mean tap; three in highest tap; and three in lowest tap. Test procedures shall warrant that the specified peak values of the test current shall flow three times in each phase:

- When the test is made with the three-phase scheme, this is obtained by synchronizing the closing time of the short-circuiting breaker
- When a single-phase scheme is applied, this is obtained by changing cyclically the phase under test

During the test, the following measurements and checks shall be carried out:

a) Oscillographic record of applied voltages and currents to check values and duration

b) Measurement of transformer short circuit inductance before and after each test (with the bridge method, to ensure reproducibility within ±0.1%)

c) Record of the capacitive currents induced in the 35.5 kV windings, by zero-sequence repetitive impulses applied at the 33 kV terminals, before and after each test

After completion of all the short circuit tests, the following checks will be made:

a) Check of insulation by repeating the induced overvoltage and 50 Hz applied voltage tests, and by performing the atmospheric impulse test, all at 100% of specified test value

b) Visual inspection of the untanked transformer; a comparison with photos made before the tests shall also be made to check that no deformation of the connections has occurred

The test is deemed successful if:

a) The star equivalent inductance values measured before and after the tests do not differ more than 1% (one percent)

b) The insulation tests are all successful

c) Visual inspection and photos of the untanked machine provide evidence that no failures or defects have occurred (no deformation or displacement of windings, connections, support structures; no incipient flashovers; etc.)

The axial compression of the windings shall also be checked, for comparison with the compression applied before the short circuit test.

During the test, the relief valve and Buchholz relay shall not intervene. The tank and bushings shall stand the overpressure and vibrations, without any damage and any oil leak.

If the star equivalent inductance values measured before and after the short circuit test differ by more than 1% but less than 2% (two percent), the transformer could be accepted, at the engineer's discretion, only if the inspection of the completely disassembled transformer (including the windings) does not show any deformation, failure, or displacement of windings, connections, support structures, etc.

If the star equivalent inductance values measured as specified differ by 2% or more, the transformer shall be rejected straightaway and the test shall be repeated on a new or modified prototype.

MEASUREMENT OF THE HARMONICS IN THE NO-LOAD CURRENT

To be carried out according to the procedure laid down in clause 8.6 of IEC publication 60076-1, 2000.

MEASUREMENT OF ACOUSTIC NOISE LEVEL

To be carried out in accordance with the procedure laid down in IEC publication 60076-10, 2001.

VACUUM TEST ON TANK AND ASSEMBLED FITTINGS

This test shall be carried out on the tank without oil, but with core-and-coil assembly and fittings, which are mounted directly on the tank.

The test pressure (absolute pressure) in the tank shall be less than or equal to 1 mm Hg. The connection to the vacuum pump shall then be isolated to check on compliance with subsection 13.4.4.

During this test, the magnitude of any eventual permanent deformation of the tank shall be noted.

LEAKAGE TEST ON TANK AND ASSEMBLED FITTINGS UNDER OIL PRESSURE

The test shall be carried out with the transformer filled with warm oil and shall be performed at the end of the temperature-rise test.

During this test, the magnitude of any permanent deformation of the tank shall be noted.

A.13.5.4 Routine Tests

Unless otherwise agreed, tests shall be carried out in the order specified herein.

Tests shall be performed at any temperature between 10°C and 40°C.

MEASUREMENT OF VOLTAGE RATIO

To be carried out in accordance with the procedure laid down in IEC publication 76-4, 1976.

CHECK OF VOLTAGE VECTOR RELATIONSHIP

To be carried out in accordance with the procedure laid down in IEC publication 76-4.

MEASUREMENT OF THE WINDING RESISTANCES

To be carried out in accordance with the procedure laid down in IEC publication 60076-2. For the 35.5 kV winding, the measurement shall be carried out on principal and extreme tappings.

The accuracy of measurement shall be ±0.5% or better.

SEPARATE-SOURCE POWER-FREQUENCY WITHSTAND TEST

To be carried out in accordance with the procedure laid down in clause 10 of IEC publication 60076-3, 2000.

IMPULSE TEST

To be carried out in accordance with the procedure laid down in clause 12 of IEC publication 60076-3, 2000.

The position of tap-changer shall be chosen by the inspector of the engineer attending the tests. Of the N°9 1.2/50 µs impulses to be applied to the 35.5 kV terminals, three will be applied with the tap-changer in the middle position, three in the higher position, and three in the lower position.

INDUCED OVERVOLTAGE WITHSTAND TEST

To be carried out in accordance with the procedure laid down in clause 11 of IEC publication 60076-3, 2000.

MEASUREMENT OF NO-LOAD LOSSES AND CURRENT

To be carried out in accordance with the procedure laid down in clause 8.5 of IEC publication 60076-1, 2000.

The measurement of losses shall be performed using three wattmeters for low power factor, class of accuracy at least 0.5; error corrections shall be made. Voltages and currents shall be measured by instrument transformers of class 0.2 or better; errors shall be known with an accuracy of ±0.2% or better.

MEASUREMENT OF SHORT CIRCUIT IMPEDANCE AND LOAD LOSSES

To be carried out in accordance with the procedure laid down in clause 8.4 of IEC publication 60076-1, 2000.

Measurements shall be made by employing instruments and instrument transformers having the same requirements as above stated for measurement of no-load losses. The measurement shall be performed on principal and extreme tappings.

MEASUREMENT OF LOSS ANGLE (TAN DELTA OR COSINE PHI)

To be carried out between windings and between every winding and tank, by means of the Schering bridge or Doble test apparatus (with record of atmospheric conditions and correction of results to 20°C).

The same measurements shall also be carried out for terminal bushings.

MEASUREMENT OF INSULATION RESISTANCE

To be carried out between windings and between every winding and tank (at 0, 15, 30, 45, and 60 seconds) on the oil filled transformer by 5,000 V motor-driven Megger (with records of oil and atmospheric conditions and correction of results to 20°C).

OPERATION TEST OF OFF-LOAD TAP-CHANGER

To be carried out in accordance with the procedure laid down in IEC applicable standards.

FITTINGS INSPECTION AND OPERATIONAL CHECK OF ITS OPERATION

Correct operation of all fittings, mounted on the transformer during the acceptance test and unmounted, shall be checked. This check, with all accessories mounted, shall be repeated at the site.

The insulation test of the auxiliary wiring shall be carried out in accordance with the procedure laid down in clause 9 of IEC publication 60076-3, 2000.

CHECKS OF BREAKDOWN VOLTAGE OF INSULATING OIL

To be carried out in accordance with the procedure laid down in IEC publication 296, 1982.

The breakdown voltage of oil shall be not less than 60 kV for all samples drawn from the transformers. In case the oil used during the acceptance tests at works differs from the oil used at the site, this test will be performed at the site only.

CHECK OF PAINT PROTECTION

To be carried out by checking both thickness and adhesion of the film.

The measurement of the paint thickness shall be performed by employing a "paint inspection gauge." In particular, it shall be made by the direct measurement of total film thickness as well as the thickness of individual coats. Ten points shall be chosen at random on the painted surface of the transformer (radiators included); the mean of the values of each coat shall not be lower than the nominal value declared by the contractor. No value shall be lower than the minimum thickness specified by the contractor.

Film adhesion shall be verified by the cross-cut method according to DIN standard 53151-1970. The test shall be made on 10 points chosen at random on the painted surface of the transformer. The degree of alteration shall not be higher than Gtl.

A.13.5.5 Criteria for the Acceptance of Transformers

TESTS ON COMPONENTS AT THE FACTORY

All routine tests shall have a positive result within the tolerance allowed, when applicable.

The negative result of one test shall not imply the rejection of the supply, but only of the failing component, if the contractor is in a position to remedy said defect within a reasonable period of time.

FINAL TESTS ON THE TRANSFORMER AT THE FACTORY BEFORE SHIPMENT

The negative result of a type test, if considered by the engineer as essential for reliable operation of the transformers, may involve rejection of all transformers of the same type in the supply. The engineer will accept the repetition of the test if the contractor proposes to modify the design of the transformers within a reasonable period of time and to repeat, at the contractor's own expense, all type tests listed in subsection A.13.5.2.

All routine tests shall have a positive result within the tolerances allowed, when applicable.

If the negative result of a test is prejudicial to the operation of the transformer, the transformer shall be replaced or repaired at the full expense of the contractor.

A negative result of the control of paint application entitles the engineer to require, at no charge, the repainting of transformer.

FAILURE TO MEET GUARANTEES

If tests on the transformer show that the characteristics fail to meet the guaranteed values, the engineer is entitled to reject the transformer in case the tolerances stipulated in subsection A.13.3 are exceeded. If no-load and/or load losses exceed the guaranteed values, the following penalties shall be applied:

a) An amount calculated at the rate of $4,000 for every full kilowatt by which the no-load losses at rated voltage and frequency exceed the guaranteed value.

b) An amount calculated at the rate of $2,500 for every full kilowatt by which the load losses, calculated with the formula in subsection A.13.2.7, exceed the guaranteed value.

No credit shall be granted for characteristics that are found to be better than the guaranteed values.

A.13.6 Transport

Transformers shall be designed for rail, sea, and road transport.

From the contractor's works to the installation site, the transformer will be transported by rail/road/sea filled with oil and bushings. Radiators and conservator will be transported separately. All openings (including those of radiators) shall be closed by means of blind flanges.

The ship shall be trimmed so as to avoid damage to the transformer in case of rough seas.

The fittings (radiators and conservator) shall be packed with the greatest care and transported, if possible, by container.

A.13.7 Spare Parts

A list of recommended spare parts, with unit prices, for necessary maintenance of the power transformers shall be furnished with the tender.

The list shall include, but not be limited to, the following:

- One set of gaskets
- One bushing for the 33 kV winding terminals
- One bushing for the 35.5 kV winding terminals
- One oil temperature indicator
- One Buchholz relay.

Spare parts shall be interchangeable with and have the same characteristics and quality as those mounted on the transformers.

All spare parts shall be treated and packed as required to preserve them against deterioration for indefinite storage. Each spare part shall be suitably identified by a metal label.

A.14 TERTIARY WINDING OF HV/MV STEP-DOWN TRANSFORMERS

The addition of a tertiary winding to an HV/MV step-down transformer is an economic alternative to the interposing transformer (IT) for the supply of the two-SW three-phase SWLs (see the single-line diagram in figure 7.1, panel a, in chapter 7 of the manual), and also for the supply of the three-SW three-phase SWLs when needed (see chapter 14 and figure 16.1, panel a, in chapter 16 of the manual). Specification of tertiary winding is part of specification of the HV/MV step-down transformer, however it shall be in compliance with the following main characteristics:

• Rated voltage:	35.5 kV ± 2 × 3.75% (or 31 kV ± 2 × 3.75%)
• Voltage regulation:	with off-voltage tap changer
• Connection:	delta
• Rated power:	4 or 6 or 8 MVA, in any case ≥ 20% of the rated,
• power of the HV winding	
• Impedance voltage between HV and tertiary winding:	8% to 10%, on basis of rated power of tertiary winding (from 4 to 8 MVA), respectively
• Withstand capability to electrodynamic forces caused by external short circuits:	As specified in subsection A.13.5.3 of this Annex for the IT and table B.21 in Annex B

SPECIAL TECHNICAL REQUIREMENT

The tertiary winding supplies long 30-34.5 kV SWLs which are frequently struck by lightning, causing short circuits (flashover across the arcing horns of the SW insulators). It is therefore mandatory to warrant the tertiary winding withstand capability to the ϕ-to-ϕ and 3-ϕ short circuits in close proximity to the transformer terminals.

The tertiary winding shall therefore be of compact and sturdy design, in particular if the winding is proposed to be located internally to the HV winding (that is, exposed to centripetal forces). The design shall be submitted to the purchaser for approval prior to the start of manufacturing.

The bidder shall quote with separate price the transformer short circuit tests as per the last edition of IEC publication 60076-5 and as specified for the IT in this Annex. Bidders shall also specify the name of an independent internationally reputed laboratory where the test will be performed.

The employer shall notify the manufacturer if the short circuit test will be performed when the first unit of the supply will be ready for the factory acceptance tests. If the test will be waived by the employer, the relevant price will not be paid.

ANNEX B | TECHNICAL DATA SHEETS FOR THE EQUIPMENT FOR THREE-PHASE ILICETO SHIELD WIRE SCHEMES USING THE EARTH AS THE CONDUCTOR OF ONE PHASE, WITH RATED VOLTAGES OF 34.5 kV AND 30 kV

CONTENTS

ABBREVIATIONS AND ACRONYMS

Ω	ohm
μf	microfarad
μs	microsecond
ϕ-to-ϕ	phase-to-phase
ϕ-to-Gr	phase-to-ground
3-ϕ	three-phase
°C	degrees Celsius
A	ampere
AC	alternating current
Al	aluminum
ANSI	American National Standards Institute
Arms	root mean square amperes
cm	centimeter
CO	close-open
Cu	copper
daN	deca Newton
dB(A)	decibel
DC	direct current
DIN	Deutsches Institute for Normung
Dyn	delta-star with neutral
f	frequency
g	gram
HV	high-voltage
Hz	hertz
IEC	International Electrotechnical Commission
IP	protection degree
ISWS	Iliceto Shield Wire Scheme
k	kilo (1,000 times)
kA	kilo ampere
kArms	root mean square kilo ampere
kg	kilogram
kJ	kilojoule
kN	kilonewtons
kV	kilovolt
kVA	kilovolt-ampere
kVAR	kilovolt-ampere reactive
kVrms	root mean square kilovolt
kW	kilowatt
LV	low-voltage
m	meter
MCOV	maximum continuous operating voltage
MHz	megahertz
mm	millimeter
ms	millisecond
mV	millivolt
MVA	megavolt ampere
MW	megawatt
N	Newton
NC	Normally Closed
nF	nanofarad
NO	Normally Open
ONAN	oil-natural air-natural
pC	pico coulomb
p.u.	per unit
R	resistance
R.I.V.	radio interference voltage
rms	root mean square
s	second
SF6	esa fluoride of sulphur
SWL	shield wire line
SWS	shield wire scheme
V	volt
VA	volt-ampere
V-I	voltage-current
W	watt
X	reactance

INTRODUCTION

The equipment insulation requirements and the characteristics of the surge arresters have been justified and specified in subsection 5.3.4 of the manual for two-shield-wire (SW) three-phase Iliceto shield wire schemes (ISWSs) with rated voltage of 34.5 and 30 kilovolts (kV).

The switching and protection apparatuses with rated voltage of 36 kV that meet the requirements of International Electrotechnical Commission (IEC) standard 60694, Series I-European Practice, that are available in all the manufacturing countries, can be applied in two-SW "three-phase" ISWSs with operation voltage of 30 kV.

The operation voltage at 34.5 kV requires switching equipment with phase-to-ground test voltages of the 38 kV class, in accordance with the IEC standards 60694, Series II – North American Practice, which may not be available in the catalogues of manufactures in Europe and of some countries in Asia.

In this Annex, the specified data in brackets are applicable to two-SW "three-phase" ISWSs operated at 30 kV. Where only one value is specified (that is, not followed by a value in brackets), the value is applicable for the 34.5 and 30 kV operation voltages.

LIST OF APPLICABLE STANDARDS

IEC 60099-4	"Metal-oxide surge arresters without gaps for alternative current systems"
IEC 60289	"Reactors"
IEC 62271-102	"High-Voltage alternating current disconnectors and grounding switches"
IEC 62271-100	"High-voltage alternating current circuit breakers"
IEC 61869-2	"Current transformers"
IEC 61869-3	"Inductive voltage transformers"
IEC 255	"Electrical relays"
IEC 60076-1 to 10	"Power transformers"
IEC 296	"Specification for unused mineral insulating oil for transformers and switchgear"
IEC 137	"Insulated bushings for alternating voltages above 1000 V"
IEC 62271-105	"High-voltage alternating current switch-fuse combination"
IEC 62271-103	"High-voltage switches for rated voltage above 1kV and less than 52kV"
IEC 60871-1 and 2	"Shunt capacitors for a.c. power systems having a rated voltage above 1kV"
IEC 60383-1	"Insulators for overhead lines with a nominal voltage above 1 kV – Part 1 – Ceramic or glass insulators"
IEC 720	"Characteristics of line post insulators"

TABLE B.1

Metal Oxide Surge Arresters

METAL-OXIDE SURGE ARRESTERS	REQUIRED	TENDERED
Manufacturer's name and country		
Type designation		
Standard applicable	IEC 60099-4	
Rated frequency (Hz)	50	
Rated voltage (kVrms)	47 (42)	
Max. continuous operation voltage (MCOV) (kVrms)	≥38 (≥33)	
TOV capability for 1s (kVrms)	≥55 (≥48)	
Max residual voltage - With switching surges (500 A crest; front time >30 μs) (kV crest) - With lightning surges (kV crest): • with 5kA – 8/20 μs wave • with 10 kA – 8/20 μs wave	 ≤100 (≤90) ≤120 (≤110) ≤130 (≤115)	
Energy capability(kJ/kV of rated voltage)	≥3,5	
Line discharge class as per IEC	Minimum 2	
High current operation duty (4/10 μs wave; kA crest)	100	
Housing • Material • Creepage length (mm) • Ultimate cantilever strength (kN)	 Brown porcelain or polymeric ≥1050 (≥950) —	
External insulation (housing) • 50 Hz – 1' power frequency, wet (kVrms) • 1.2/50 μs lightning impulse (kV peak)	 ≥82.5 ≥200	
Pressure relief type, if applicable	—	
Counter and leakage current indicator	Not required	
Overall dimensions (mm) • Width • Height		
Mass (kg)		

TABLE B.2

Fast-Closing Grounding Switches

FAST-CLOSING GROUNDING SWITCH	REQUIRED	TENDERED
Manufacturer's name and country	—	
Type designation	—	
Standards applicable	IEC 62271-102	
Number of poles	2	
Type of construction	Outdoor	
Rated frequency(Hz)	50	
Rated voltage	52 (38)	
Closing time (ms)	≤200	
Closing mechanism	Spring type	
Opening mechanism	Motor operated	
Short circuit current duty: • Making capacity (kA peak) • 3 s momentary current rating (kA rms)	≥12.5 ≥5	
Insulation levels, phase-to-ground, between phases and across the insulating distance • 50 Hz-1 minute, wet (kVrms) • Lightning impulse 1.2/50 µs (kV crest)	95 (≥ 80) 250 (≥ 200)	
Insulators Material/color • Type • Creepage distance (mm)	Porcelain/brown C8-250 ≥ 1050 (≥ 950)	
Closing coil voltage (V-DC)	To be specified in the order	
Opening motor voltage (V-DC or V-AC)	To be specified in the order	
Emergency manual operation with individual crank	Included	
Housing of operating mechanism and control circuits	Stainless steel, IP – 55	
Auxiliary contacts	5 NO + 5 NC	
Anticondensation resistance (AC)	Included	
Overall dimensions (mm) • Length • Width • Height		
Mass (kg):		

TABLE B.3

Circuit Breaker (If Applicable)

CIRCUIT BREAKER	REQUIRED	TENDERED
Manufacturer's name and country		
Manufacturer's type designation		
Standard in force	IEC 62271-100	
Number of poles	2	
Type of circuit breaker	SF6	
Installation	Outdoor	
Rated duty cycle	0–0.3 s-CO-3 min-CO 0–0.3 s-CO-15s-CO	
Operating functions	High speed 2-pole reclosure	
Rated frequency (Hz)	50	
Rated voltage (kVrms)	52 (38)	
Highest continuous operation voltage phase-to-ground (kVrms)	38.5 (33)	
Rated current (Arms)	≥400	
Breaking capacity • Symmetrical (kArms) • Asymmetrical (kA peak)	 ≥8 ≥20	
Rated short circuit making current (kA peak)	≥20	
Short time withstand current (3 s) (kArms)	≥8	
Insulation levels, phase-to-ground and between phases • 50 Hz-1 minute wet (kVrms) • Lightning impulse 1.2/50 μs (kV peak)	 95 (≥ 80) 250 (≥ 200)	
Across open contacts • 50 Hz-1 minute wet (kVrms) • Lightning impulse 1.2/50 μs (kV peak)	 95 (≥ 80) 250 (≥ 200)	
Creepage distance of insulators, phase-to-ground (mm)	1,050 (≥ 950)	
Creepage distance of insulators, across open contact (mm)	≥900	
Make break time (ms)	—	
Opening time (mechanical) (ms)	—	
Arcing time (ms)	—	
Critical current and arcing time at critical current (A and ms)	—	

CIRCUIT BREAKER	REQUIRED	TENDERED
Max break time from 10% to 100% of rated interrupting current (tolerance nil) (ms)	60	
Max tripping delay (s)	—	
Max closing time (ms)	—	
Dead time for auto-reclosing (s)	0.3–2	
Maintenance-free interruptions: • At rated breaking current (N◦) • At 50% breaking current (N◦) • At rated nominal current (N◦)	 — — —	
Power required at rated voltage to re-load the operating mechanism (W)	—	
Rated DC voltage and operating range of trip coil (V)	To be informed in the order	
Rated DC voltage and operating range of closing coil (V)	To be informed in the order	
Power consumption of closing coil (W)	—	
Power consumption of trip coil (W)	—	
Number of trip coils	2	
Number of closing coils	1	
Supply voltage of motor (V)	—	
Power consumption of motor (W)	—	
Number and type of spare auxiliary contacts per pole:	—	
Make contacts	≥ 6	
Break contacts	≥ 6	
Closing capacity of spare contacts (A)	—	
Opening capacity of spare contacts (A)	—	
Supply voltage of heating resistors (V) (AC-50 Hz-single phase)	220	
Power consumption of heating resistors (W)		
Material of insulators	Porcelain, brown	
Reference number of drawing of insulator profile	—	

(*continued*)

TABLE B.3

Circuit Breaker (If Applicable) (*continued*)

CIRCUIT BREAKER	REQUIRED	TENDERED
Contact temperature rise: • Silver faced (°C) • Non-silver faced (°C)	 — —	
Characteristics of SF6 - Rated pressure at 20°C (bar) - Lower and higher limits of gas pressure for rated making capacity (bar) - Lower and higher limits of gas pressure for rated breaking capacity (bar) - Lower and higher limits of gas pressure causing lock-out or safety valve operation (bar) - Total capacity of circuit breaker local gas receivers. - Min time from commissioning date to first refilling (subject to formal guarantee) - Mass (kg) - Rate of escape (%) per year	 — — — — — >5 years — <1%	
Breaker drive mechanism: - Type	 Spring operated	
Type and dimensions of rollers	—	
Earthquake acceleration withstand capacity: - Horizontal - Vertical	 0.2 g 0.16 g	
Overall dimensions (mm): • Length • Width • Height	 — — —	
Net mass in operating condition (including operation mechanism) (kg)	—	

TABLE B.4

Grounding Resistors-Reactors

GROUNDING RESISTOR-REACTOR	REQUIRED	TENDERED
Manufacturer's name and country		
Type designation		
Standards applicable for resistors	IEEE-32	
Number of phases	1	
Connection:	Earthing of one 34.5 kV (30 kV) terminal of interposing transformer feeding the shield wire line	
Type of installation	Outdoor	
Rated frequency (Hz)	50	
Max. ambient temperature °C	+45	
Rated impedance, at + 20°C, R + jX (ohm): To be specified for each ISWS, on the basis of the results of the steady-state operation analysis, to be performed with the ad hoc computer program.		
Resistance variation range of each resistor by means of bolted connections: - Above rated value (Ω) - Below rated value (% of rated resistance)	 + 4 Ω, in at least 3 steps Down by –40%, in at least 4 steps	
Rated continuous current (Arms): To be specified for each ISWS, as equal to the current corresponding to the long term (say, 15–20 years ahead) load forecast.		
3 second overcurrent capacity (Arms):	To be specified, according to the calculated short circuit current	
Connection of resistor and reactor	In series (resistor on earth side)	
V-I characteristics of reactor (if reactor is required)	Linear up to at least 130% of rated current	
Insulation class of resistor and reactor (kVrms)	17.5	
Insulation type of resistor	Graded	
Material of resistor elements	Steel chrome-aluminum alloy	
Total resistance variation from no-load to rated current	≤ 4%	
Temperature of resistor elements at rated current and max. ambient temperature (°C)	380	
Max. temperature permissible of resistor elements following a 3 s 850 Arms overcurrent starting from continuous operation at rated current (°C)	≤ 780	

(*continued*)

TABLE B.4

Grounding Resistors-Reactors (*continued*)

GROUNDING RESISTOR-REACTOR	REQUIRED	TENDERED
Characteristics of HV bushing, if applicable: - Withstand test voltages • 50 Hz 1 minute wet (kVrms) • Lightning impulse 1.2/50 µs (kV crest) - Creepage distance (mm) - Material/color	 38 95 ≥ 450 Porcelain/brown	
Cooling	Natural	
Housing: • Type • Material • Protection degree • Paint color	 Self-supporting free-standing kiosk Galvanized steel with stainless steel doors IP 23 will be informed in the order	
Standards applicable for reactors	IEC 60289	
Current transformer		
Location	On connection to ground of resistor	
Type		
Rated voltage (kVrms)	3	
Ratio (A/A)	60 – 90 – 120/5/5 (to be informed in the order)	
Number of cores: • For metering • For protection	 1 1	
Burden (VA): • For metering • For protection	 ≥ 10 ≥ 10	
Accuracy class: • For metering • For protection • Accuracy limit factor for protection	 0.5 5 P 10	
Overall dimensions of resistor (mm): • Length • Width • Height	 — — —	
Overall dimensions of reactor, where applicable (mm): • Length • Width • Height	 — — —	
Mass: • Active mass of resistor material (kg) • Total mass (kg)	 — —	

TABLE B.5

Line Isolators

LINE ISOLATOR	REQUIRED	TENDERED
Manufacturer's name and country		
Type designation		
Standards applicable	IEC 62271-102	
Number of poles	2	
Installation	Outdoor	
Opening/closing	Hand operated	
Rated frequency (Hz)	50	
Rated voltage (kVrms)	52 (38)	
Highest continuous operation voltage, phase-to-ground (kVrms)	38.5 (33)	
Rated current (Arms)	≥250	
Rated short time (1 s) current (kArms)	≥8	
Rated peak current (kA crest)	≥20	
Auxiliary contacts	4 NO+4 NC	
Insulation levels, phase-to-ground and phase-to-phase		
• 50 Hz-1 minute, wet (kVrms)	95 (≥ 80)	
• Lightning impulse 1.2/50 μs (kV crest)	250 (≥ 200)	
Insulation levels, across open contacts		
• 50 Hz-1 minute, wet (kVrms)	≥85 (≥ 80)	
• Lightning impulse 1.2/50 μs (kV crest)	≥200	
Creepage distance of insulators (mm)	≥1,050 (≥ 950)	
Material/color	Porcelain/brown	
Overall dimensions (mm) • Length • Width • Height	 — — —	
Mass (kg):	—	

TABLE B.6

Current Transformers

CURRENT TRANSFORMERS	REQUIRED	
Manufacturer's name and country		
Type designation		
Standards applicable	IEC 61869-2	
Installation	Outdoor	
Rated voltage (kVrms)	52 (38)	
Highest continuous operation voltage, phase-to-ground (kVrms)	38.5 (33)	
Rated frequency (Hz)	50	
Rated primary current (Arms)	120-90-60 (to be confirmed in the order)	
Rated secondary current (Arms)	5	
Number of cores	2	
Burdens (VA) • Measuring core • Protection core	 ≥ 15 ≥ 10	
Accuracy class • Measuring core • Protection core	 0,5 5 P	
Accuracy limit factor (protective core only)	20	
Continuous thermal current rating (p.u. of rated current)	1.2	
Short time current ratings: • Thermal, 1 s (kArms) • Dynamic (kA peak)	 8 20	
Insulation level of primary winding: • Power frequency I minute withstand voltage, wet (kVrms) • Lightning impulse withstand voltage, 1.2/50 µs (kV crest)	 95 (≥ 80) 250 (≥ 200)	
Insulation level of secondary windings • Power frequency 1 minute withstand voltage (kVrms)	 5	
Internal partial discharges at 150% of rated voltage (pC)	<10	
Min. creepage distance (mm)	1,050 (950)	
Overall dimensions (mm) • Length • Width • Height	 — — —	
Mass (kg):	—	

TABLE B.7

Voltage Transformers

VOLTAGE TRANSFORMER	REQUIRED	TENDERED
Manufacturer's name and country		
Type designation		
Standards applicable	IEC 61869-3	
Type	Inductive	
Installation	Outdoor	
Rated system voltage (kVrms)	34.5 (30)	
Highest continuous operation voltage, phase-to-phase and phase-to-ground (kVrms)	38.5 (33)	
Rated frequency (Hz)	50	
Rated primary voltage (kVrms)	34.5 (30)	
Rated secondary voltage (Vrms)	100	
Rated voltage factor (p.u): • continuous • 30 s duration	 1.2 1.6	
Burdens (VA): • Measuring winding • Protection winding	 100 100	
Accuracy class: • Measuring winding • Protection winding	 0.5 3 P	
Insulation level of primary winding: • Power frequency 1 minute withstand voltage wet (kVrms) • Lightning impulse withstand voltage, 1.2/50 μs (kV crest)	 95 (≥ 80) 250 (≥ 200)	
Insulation level of secondary windings: • Power frequency 1 minute withstand voltage (kVrms)	 5	
34.5 kV bushings: • Number • Rated voltage (kVrms) • Material • Creepage length (mm)	 2 52 Porcelain, brown ≥1,050 (≥950)	
Dimensions (mm) • Height • Length • Width	 — — —	
Total mass (kg)	—	

TABLE B.8

Protection Relays and Control Panel

PROTECTION RELAYS AND CONTROL PANEL	REQUIRED	TENDERED
Manufacturer's name and country	—	
Type designation		
Standards applicable	IEC 255	
Installation	Indoor	
Characteristics of relays	See technical specifications	
Characteristics of metering instruments	See technical specifications	
Dimensions (mm) • Height • Length • Width	 — — —	
Total mass (kg)	—	

BOX B.1

Standards Applicable for Distribution Transformers (IEC, Latest Edition)

- IEC 60076: Parts from 1 to 10 - Power Transformers
- IEC 296: Specifications for unused mineral insulating oil for transformers and switchgears

TABLE B.9

Three-Phase Distribution Transformer, 100 kVA

THREE-PHASE DISTRIBUTION TRANSFORMER – 100 kVA	REQUIRED	TENDERED
Manufacturer's name and country	—	
Type designation	—	
Type	Oil immersed	
Installation	Outdoor	
Rated power (ONAN cooling) (kVA)	100	
Number of phases	3	
Rated frequency (Hz)	50	
Rated voltages (at no-load):		
• Primary winding (kV)	34.5 (30)	
• Secondary winding (kV)	0.400–0.231	
Tappings on primary winding	± 2 × 2.5%	
Number of tapping positions	5	
Type of tap changer	Off-voltage	
Max. continuous operation voltage of windings:		
• Primary winding (kV)	36.5 (33)	
• Secondary winding (kV)	Value consistent with primary side	
Connection group:	Dyn 11	
• Primary winding	Delta connected, with one terminal permanently grounded	
• Secondary winding	Star, with neutral grounded	
Number of windings	2	
Impedance voltage on principal tapping at 75°C (%)	4	
No-load losses (W)	≤250	
No-load current (%)	≤1,5	
Load losses at 75°C (W)	≤1,400	
Sound level [power] (dB(A))	< 48	
Insulation class	A	
Cooling method	ONAN	

(*continued*)

TABLE B.9

Three-Phase Distribution Transformer, 100 kVA (*continued*)

THREE-PHASE DISTRIBUTION TRANSFORMER – 100 kVA	REQUIRED	TENDERED
Insulation levels, primary winding • Highest system voltage (kVrms) • Power frequency withstand voltage (kVrms) • Lightning impulse withstand voltage (1.2/50 µs) (kV peak)	 36.5 (33) 82.5 200	
Insulation levels, secondary winding • Highest system voltage (kVrms) • Power frequency withstand voltage (kVrms) • Lightning impulse withstand voltage (1.2/50 µs) (kV peak)	 (3.6) 10 20	
Induced withstand voltage of HV winding with tap-changer in intermediate position (34.5 kV) (kVrms)	82.5 (70)	
Temperature rises • Windings (average) (°C) • Top oil (°C) • Winding hot spot (°C) • Core surface (°C)	 ≤60 ≤55 ≤70 ≤75	
The transformer must withstand the short circuit special test as per IEC standard 60076 part 5, on units selected at random by the employer's inspector from each lot submitted to acceptance test. Execution of short circuit tests	Yes Will be decided at employer's discretion, after manufacturing of each lot of transformers	
Short circuit test reports performed on similar transformers in an independent test laboratory	Shall be enclosed to the offer	
Short circuit power of 34.5 kV supply network for short circuit test	Infinite	
Construction		
Characteristics of windings:		
Material:		
• Primary	Cu	
• Secondary	Cu, or Al to be informed in the tender	
• Cross section	Uniform	
• Current density in copper (A/mm^2)	HV: ≤ 3; LV: ≤ 3	
Magnetic core		
Type	3 legged	
Material	Cold rolled grain oriented silicon steel	
Flux density at rated voltage and frequency, with mean tap (tesla)	≤ 1.65	
Bushings characteristics	IEC 137	
Type	Porcelain	

THREE-PHASE DISTRIBUTION TRANSFORMER – 100 kVA	REQUIRED	TENDERED
Primary bushings		
Rated voltage as per IEC 60694 (kV)	38	
Rated current (A)	≥ 250	
Withstand test voltage		
• 50 Hz-1 minute wet (kVrms)	≥ 82.5	
• Lightning impulse (1.2/50 μs) (kV crest)	≥ 200	
Creepage distance (mm)	≥ 1,050 (≥ 950)	
Secondary bushings		
• Insulation level (kV)	1.1	
Rated current (Arms)	≥ 400	
Withstand test voltage		
• 50 Hz-1 minute (kVrms)	10	
• Lightning impulse 1.2/50 μs (kV crest)	20	
Bushings number		
• Primary	3	
• Secondary	4	
Tank	Rib type	
Valves and bolts	Made of corrosion resistant material	
Painting		
• Internal surfaces, including the conservator	Protected against hot oil at a temperature of 105°C	
• External surfaces	For tropical environment, as specified in detail in the order	
Accessories required • Conservator • Oil level indicator • Oil filling plug • Pocket thermometer dial type • Skid • Filling and draining valves • Lifting eyes • Hitching holes • Rating plate	Yes	

(*continued*)

TABLE B.9

Three-Phase Distribution Transformer, 100 kVA (*continued*)

THREE-PHASE DISTRIBUTION TRANSFORMER – 100 kVA	REQUIRED	TENDERED
Overall dimensions (mm) • Height • Length • Width		
Mass • Total mass (kg) • Oil (kg)		
Alternative bid for tank hermetically sealed, for life:		
Tank	With corrugated walls completely full of oil	
Max. internal pressure between 0°C and 110°C (bar)	0,3	
Endurance test	5,000 cycles, with the oil volume variation between 0°C and 110°C	
Functions of the integrated protection relay	Gas; over temperature (alarm and trip); over pressure	

TABLE B.10

Three-Phase Distribution Transformer, 200 kVA

THREE-PHASE DISTRIBUTION TRANSFORMER – 200 kVA	REQUIRED	TENDERED
Manufacturer's name and country	—	
Type designation	—	
Type	Oil immersed	
Installation	outdoor	
Rated power (ONAN cooling) (kVA)	**200**	
Number of phases	3	
Rated frequency (Hz)	50	
Rated voltages (at no-load):		
• Primary winding (kV)	34.5 (30)	
• Secondary winding (kV)	0.400–0.231	
Tappings on primary winding	$\pm 2 \times 2.5\%$	
Number of tapping positions	5	
Type of tap changer	Off-voltage	

THREE-PHASE DISTRIBUTION TRANSFORMER – 200 kVA	REQUIRED	TENDERED
Max. continuous operation voltage of windings:		
• Primary winding (kV)	36.5 (33)	
• Secondary winding (kV)	Value consistent with primary side	
Connection group;	Dyn 11	
• Primary winding	Delta connected, with one terminal permanently grounded	
• Secondary winding	Star, with neutral grounded	
Number of windings	2	
Impedance voltage on principal tapping at 75°C (%)	4	
No-load losses (W)	≤440	
No-load current (%)	≤1.2	
Load losses at 75°C (W)	≤2,200	
Sound level [power] (dB(A))	< 51	
Insulation class	A	
Cooling method	ONAN	
Insulation levels, primary winding • Highest system voltage (kVrms) • Power frequency withstand voltage (kVrms) • Lightning impulse withstand voltage (1.2/50 μs) (kV peak)	 36.5 (30) 82.5 200	
Insulation levels, secondary winding • Highest system voltage (kVrms) • Power frequency withstand voltage (kVrms) • Lightning impulse withstand voltage (1.2/50 μs) (kV peak)	 (3.6) 10 20	
Induced withstand voltage of HV winding with tap-changer in intermediate position (34.5 kV) (kVrms)	82.5 (70)	
Temperature rises • Windings (average) (°C) • Top oil (°C) • Winding hot spot (°C) • Core surface (°C)	 ≤60 ≤55 ≤70 ≤75	
The transformer must withstand the short circuit special test as per IEC standard 60076 part 5, on units selected at random by the employer's inspector from each lot submitted to acceptance test. Execution of short circuit tests	Yes Will be decided at the employer's discretion, after manufacturing of each lot of transformers	

(*continued*)

TABLE B.10

Three-Phase Distribution Transformer, 200 kVA (*continued*)

THREE-PHASE DISTRIBUTION TRANSFORMER – 200 kVA	REQUIRED	TENDERED
Short circuit test reports performed on similar transformers in an independent test laboratory	Shall be enclosed to the offer	
Short circuit power of 34.5 kV supply network for short circuit test	Infinite	
Construction		
Characteristics of windings:		
Material:		
• Primary	Cu	
• Secondary	Cu, or Al, to be informed in the tender	
• Cross section	Uniform	
• Current density in copper (A/mm^2)	HV: ≤ 3; LV: ≤ 3	
Magnetic core		
Type	3 legged	
Material	Cold rolled grain oriented silicon steel	
Flux density at rated voltage and frequency, with mean tap (tesla)	≤ 1.65	
Bushings characteristics	IEC 137	
Type	Porcelain	
Primary bushings		
Rated voltage as per IEC 60694 (kV)	38	
Rated current (A)	≥ 250	
Withstand test voltage		
• 50 Hz-1 minute wet (kVrms)	≥ 82.5	
• Lightning impulse (1.2/50 μs) (kV crest)	≥ 200	
Creepage distance (mm)	≥ 1,050 (≥ 950)	
Secondary bushings • Insulation level (kV)	1.1	
Rated current I (A)	≥ 630	
Withstand test voltage		
• 50 Hz-1 minute (kVrms)	10	
• Lightning impulse (1.2/50 μs) (kV crest)	20	

THREE-PHASE DISTRIBUTION TRANSFORMER – 200 kVA	REQUIRED	TENDERED
Bushings number		
• Primary	3	
• Secondary	4	
Tank	Rib type	
Valves and bolts	Made of corrosion resistant material	
Painting		
• Internal surfaces, including the conservator	Protected against hot oil at a temperature of 105°C	
• External surfaces	For tropical environment, as specified in detail in the order	
Accessories required • Conservator • Oil level indicator • Oil filling plug • Pocket thermometer dial type • Skid • Filling and draining valves • Lifting eyes • Hitching holes • Rating plate	Yes	
Overall dimensions (mm) • Height • Length • Width		
Mass • Total mass (kg) • Oil (kg)		
Alternative bid for tank hermetically sealed, for life:		
Tank	With corrugated walls completely full of oil	
Max. internal pressure between 0°C and 110°C (bar)	0.3	
Endurance test	5,000 cycles, with the oil volume variation between 0°C and 110°C	
Functions of the integrated protection relay	Gas; over temperature (alarm and trip); over pressure	

TABLE B.11

Three-Phase Distribution Transformer, 315 kVA

THREE-PHASE DISTRIBUTION TRANSFORMER – 315 kVA	REQUIRED	TENDERED
Manufacturer's name and country	—	
Type designation	—	
Type	Oil immersed	
Installation	Outdoor	
Rated power (ONAN cooling) (kVA)	315	
Number of phases	3	
Rated frequency (Hz)	50	
Rated voltages (at no-load):		
• Primary winding (kV)	34.5 (30)	
• Secondary winding (kV)	0.400–0.231	
Tappings on primary winding	$\pm 2 \times 2.5\%$	
Number of tapping positions	5	
Type of tap changer	Off-voltage	
Max. continuous operation voltage of windings:		
• Primary winding (kV)	36.5 (33)	
• Secondary winding (kV)	Value consistent with primary side	
Connection group:	Dyn 11	
• Primary winding	Delta connected, with one terminal permanently grounded	
• Secondary winding	Star, with neutral grounded	
Number of windings	2	
Impedance voltage on principal tapping at 75°C (%)	4	
No-load losses (W)	≤ 620	
No-load current (%)	≤ 1	
Load losses at 75°C (W)	$\leq 3{,}000$	
Sound level [power] (dB(A))	< 53	
Insulation class	A	

THREE-PHASE DISTRIBUTION TRANSFORMER – 315 kVA	REQUIRED	TENDERED
Cooling method	ONAN	
Insulation levels, primary winding • Highest system voltage (kVrms) • Power frequency withstand voltage (kVrms) • Lightning impulse withstand voltage (1.2/50 μs) (kV peak)	 36.5 (33) 82.5 200	
Insulation levels, secondary winding • Highest system voltage (kVrms) • Power frequency withstand voltage (kVrms) • Lightning impulse withstand voltage (1.2/50 μs) (kV peak)	 (3.6) 10 20	
Induced withstand voltage of HV winding with tap-changer in intermediate position (34.5 kV) (kVrms)	82.5 (70)	
Temperature rises • Windings (average) (°C) • Top oil (°C) • Winding hot spot (°C) • Core surface (°C)	 ≤ 60 ≤ 55 ≤ 70 ≤ 75	
The transformer must withstand the short circuit special test as per IEC standard 60076 part 5, on units selected at random by the employer's inspector from each lot submitted to acceptance test. Execution of short circuit tests	Yes Will be decided at the employer's discretion, after manufacturing of each lot of transformers	
Short circuit test reports performed on similar transformers in an independent test laboratory	Shall be enclosed to the offer	
Short circuit power of 34.5 kV supply network for short circuit test	Infinite	
Construction		
Characteristics of windings:		
Material:		
• Primary	Cu	
• Secondary	Cu, or Al, to be informed in the tender	
• Cross section	Uniform	
• Current density in copper (A/mm^2)	HV: ≤ 3; LV: ≤ 3	

(*continued*)

TABLE B.11

Three-Phase Distribution Transformer, 315 kVA (*continued*)

THREE-PHASE DISTRIBUTION TRANSFORMER – 315 kVA	REQUIRED	TENDERED
Magnetic core		
Type	3 legged	
Material	Cold rolled grain oriented silicon steel	
Flux density at rated voltage and frequency, with mean tap (tesla)	≤ 1.65	
Bushings characteristics	IEC 137	
Type	Porcelain	
Primary bushings		
Rated voltage as per IEC 60694 (kV)	38	
Rated current (A)	≥ 250	
Withstand test voltage		
• 50 Hz-1 minute wet (kVrms)	≥ 82.5	
• Lightning impulse (1.2/50 μs) (kV crest)	≥ 200	
Creepage distance (mm)	≥ 1,050 (≥ 950)	
Secondary bushings • Insulation level (kV)	1.1	
Rated current I (A)	≥ 800	
Withstand test voltage		
• 50 Hz-1 minute (kVrms)	10	
• Lightning impulse (1.2/50 μs) (kV crest)	20	
Bushings number		
• Primary	3	
• Secondary	4	
Tank	Rib type	
Valves and bolts	Made of corrosion resistant material	
Painting		
• Internal surfaces, including the conservator	Protected against hot oil at a temperature of 105°C	
• External surfaces	For tropical environment, as specified in detail in the order	

THREE-PHASE DISTRIBUTION TRANSFORMER – 315 kVA	REQUIRED	TENDERED
Accessories required • Conservator • Oil level indicator • Oil filling plug • Pocket thermometer dial type • Skid • Filling and draining valves • Lifting eyes • Hitching holes • Rating plate	Yes	
Overall dimensions (mm) • Height • Length • Width		
Mass • Total mass (kg) • Oil (kg)		
Alternative bid for tank hermetically sealed, for life:		
Tank	With corrugated walls completely full of oil	
Max. internal pressure between 0°C and 110°C (bar)	0.3	
Endurance test	5,000 cycles, with the oil volume variation between 0°C and 110°C	
Functions of the integrated protection relay	Gas; over temperature (alarm and trip); over pressure	

TABLE B.12

Three-Phase Distribution Transformer, 630 kVA

THREE PHASE DISTRIBUTION TRANSFORMER – 630 kVA	REQUIRED	TENDERED
Manufacturer's name and country	—	
Type designation	—	
Type	Oil immersed	
Installation	Outdoor	
Rated power (ONAN cooling) (kVA)	630	
Number of phases	3	
Rated frequency (Hz)	50	

(*continued*)

TABLE B.12

Three-Phase Distribution Transformer, 630 kVA (*continued*)

THREE PHASE DISTRIBUTION TRANSFORMER – 630 kVA	REQUIRED	TENDERED
Rated voltages (at no-load):		
• Primary winding (kV)	34.5 (30)	
• Secondary winding (kV)	0.400–0.231	
Tappings on primary winding	$\pm 2 \times 2.5\%$	
Number of tapping positions	5	
Type of tap changer	Off-voltage	
Max. continuous operation voltage of windings:		
• Primary winding (kV)	36.5 (33)	
• Secondary winding (kV)	Value consistent with primary side	
Connection group:	Dyn 11	
• Primary winding	Delta connected, with one terminal permanently grounded	
• Secondary winding	Star, with neutral grounded	
Number of windings	2	
Impedance voltage on principal tapping at 75°C (%)	6	
No-load losses (W)	$\leq$ 900	
No-load current (%)	$\leq$ 0.8	
Load losses at 75°C (W)	$\leq$ 5,600	
Sound level [power] (dB(A))	$<$ 56	
Insulation class	A	
Cooling method	ONAN	
Insulation levels, primary winding • Highest system voltage (kVrms) • Power frequency withstand voltage (kVrms) • Lightning impulse withstand voltage (1.2/50 µs) (kV peak)	 36.5 (33) 82.5 200	
Insulation levels, secondary winding • Highest system voltage (kVrms) • Power frequency withstand voltage (kVrms) • Lightning impulse withstand voltage (1.2/50 µs) (kV peak)	 (3.6) 10 20	
Induced withstand voltage of HV winding with tap-changer in intermediate position (34.5 kV) (kVrms)	82.5 (70)	

THREE PHASE DISTRIBUTION TRANSFORMER – 630 kVA	REQUIRED	TENDERED
Temperature rises • Windings (average) (°C) • Top oil (°C) • Winding hot spot (°C) • Core surface (°C)	 ≤ 60 ≤ 55 ≤ 70 ≤ 75	
The transformer must withstand the short circuit special test as per IEC standard 60076 part 5, on units selected at random by the employer's inspector from each lot submitted to acceptance test. Execution of short circuit tests	Yes Will be decided at the employer's discretion, after manufacturing of each lot of transformers	
Short circuit test reports performed on similar transformers in an independent test laboratory	Shall be enclosed to the offer	
Short circuit power of 34.5 kV supply network for short circuit test	Infinite	
Construction		
Characteristics of windings:		
Material:		
• Primary	Cu	
• Secondary	Cu, or Al, to be informed in the tender	
• Cross section	Uniform	
• Current density in copper (A/mm^2)	HV: ≤ 3; LV: ≤ 3	
Magnetic core		
Type	3 legged	
Material	Cold rolled grain oriented silicon steel	
Flux density at rated voltage and frequency, with mean tap (tesla)	≤ 1.65	
Bushings characteristics	IEC 137	
Type	Porcelain	
Primary bushings		
Rated voltage as per IEC 60694 (kV)	38	
Rated current (A)	≥ 250	

(*continued*)

TABLE B.12

Three-Phase Distribution Transformer, 630 kVA (*continued*)

THREE PHASE DISTRIBUTION TRANSFORMER – 630 kVA	REQUIRED	TENDERED
Withstand test voltage		
• 50 Hz-1 minute wet (kVrms)	≥ 82.5	
• Lightning impulse (1.2/50 μs) (kV crest)	≥ 200	
Creepage distance (mm)	≥ 1,050 (≥ 950)	
Secondary bushings • Insulation level (kV)	1.1	
Rated current I (A)	≥ 1,250	
Withstand test voltage		
• 50 Hz-1 minute (kVrms)	10	
• Lightning impulse (1.2/50 μs) (kV crest)	20	
Bushings number		
• Primary	3	
• Secondary	4	
Tank	Rib type	
Valves and bolts	Made of corrosion resistant material	
Painting		
• Internal surfaces, including the conservator	Protected against hot oil at a temperature of 105°C	
• External surfaces	For tropical environment, as specified in detail in the order	
Accessories required • Conservator • Oil level indicator • Oil filling plug • Pocket thermometer dial type • Skid • Filling and draining valves • Lifting eyes • Hitching holes • Rating plate	Yes	
Overall dimensions (mm) • Height • Length • Width		

THREE PHASE DISTRIBUTION TRANSFORMER – 630 kVA	REQUIRED	TENDERED
Mass • Total mass (kg) • Oil (kg)		
Alternative bid for tank hermetically sealed, for life:		
Tank	With corrugated walls completely full of oil	
Max. internal pressure between 0°C and 110°C (bar)	0.3	
Endurance test	5,000 cycles, with the oil volume variation between 0°C and 110°C	
Functions of the integrated protection relay	Gas; over temperature (alarm and trip); over pressure	

TABLE B.13

Three-Phase Distribution Transformer, 800 kVA

THREE-PHASE DISTRIBUTION TRANSFORMER – 800 kVA	REQUIRED	TENDERED
Manufacturer's name and country	—	
Type designation	—	
Type	Oil immersed	
Installation	Outdoor	
Rated power (ONAN cooling) (kVA)	800	
Number of phases	3	
Rated frequency (Hz)	50	
Rated voltages (at no-load):		
• Primary winding (kV)	34.5 (30)	
• Secondary winding (kV)	0.400–0.231	
Tappings on primary winding	$\pm 2 \times 2.5\%$	
Number of tapping positions	5	
Type of tap changer	Off-voltage	
Max. continuous operation voltage of windings:		
• Primary winding (kV)	36.5	
• Secondary winding (kV)	Value consistent with primary side	

(*continued*)

TABLE B.13

Three-Phase Distribution Transformer, 800 kVA (*continued*)

THREE-PHASE DISTRIBUTION TRANSFORMER – 800 kVA	REQUIRED	TENDERED
Connection group:	Dyn 11	
• Primary winding	Delta connected, with one terminal permanently grounded	
• Secondary winding	Star, with neutral grounded	
Number of windings	2	
Impedance voltage on principal tapping at 75°C (%)	6	
No-load losses (W)	≤ 1,100	
No-load current (%)	≤ 0.75	
Load losses at 75°C (W)	≤ 7,200	
Sound level [power] (dB(A))	< 58	
Insulation class	A	
Cooling method	ONAN	
Insulation levels, primary winding • Highest system voltage (kVrms) • Power frequency withstand voltage (kVrms) • Lightning impulse withstand voltage (1.2/50 μs) (kV peak)	 36.5 (33) 82.5 200	
Insulation levels, secondary winding • Highest system voltage (kVrms) • Power frequency withstand voltage (kVrms) • Lightning impulse withstand voltage (1.2/50 μs) (kV peak)	 (3.6) 10 20	
Induced withstand voltage of HV winding with tap-changer in intermediate position (34.5 kV) (kVrms)	82.5 (70)	
Temperature rises • Windings (average) (°C) • Top oil (°C) • Winding hot spot (°C) • Core surface (°C)	 ≤ 60 ≤ 55 ≤ 70 ≤ 75	
The transformer must withstand the short circuit special test as per IEC standard 60076 part 5, on units selected at random by the employer's inspector from each lot submitted to acceptance test. Execution of short circuit tests	Yes Will be decided at the employer's discretion, after manufacturing of each lot of transformers	
Short circuit test reports performed on similar transformers in an independent test laboratory	Shall be enclosed to the offer	
Short circuit power of 34.5 kV supply network for short circuit test	Infinite	

THREE-PHASE DISTRIBUTION TRANSFORMER – 800 kVA	REQUIRED	TENDERED
Construction		
Characteristics of windings:		
Material:		
• Primary	Cu	
• Secondary	Cu, or Al, to be informed in the tender	
• Cross section	Uniform	
• Current density in copper (A/mm^2)	HV: ≤ 3; LV: ≤ 3	
Magnetic core		
Type	3 legged	
Material	Cold rolled grain oriented silicon steel	
Flux density at rated voltage and frequency, with mean tap (tesla)	≤ 1.65	
Bushings characteristics	IEC 137	
Type	Porcelain	
Primary bushings		
Rated voltage as per IEC 60694 (kV)	38	
Rated current (A)	≥ 250	
Withstand test voltage		
• 50 Hz-1 minute wet (kVrms)	≥ 82.5	
• Lightning impulse (1.2/50 µs) (kV crest)	≥ 200	
Creepage distance (mm)	≥ 1,050 (≥ 950)	
Secondary bushings • Insulation level (kV)	1.1	
Rated current I (A)	≥ 1,600	
Withstand test voltage		
• 50 Hz-1 minute (kVrms)	10	
• Lightning impulse (1.2/50 µs) (kV crest)	20	

(*continued*)

TABLE B.13

Three-Phase Distribution Transformer, 800 kVA (*continued*)

THREE-PHASE DISTRIBUTION TRANSFORMER – 800 kVA	REQUIRED	TENDERED
Bushings number		
• Primary	3	
• Secondary	4	
Tank	Rib type	
Valves and bolts	Made of corrosion resistant material	
Painting		
• Internal surfaces, including the conservator	Protected against hot oil at a temperature of 105°C	
• External surfaces	For tropical environment, as specified in detail in the order	
Accessories required • Conservator • Oil level indicator • Oil filling plug • Pocket thermometer dial type • Skid • Filling and draining valves • Lifting eyes • Hitching holes • Rating plate	Yes	
Overall dimensions (mm) • Height • Length • Width		
Mass • Total mass (kg) • Oil (kg)		
Alternative bid for tank hermetically sealed, for life:		
Tank	With corrugated walls completely full of oil	
Max. internal pressure between 0°C and 110°C (bar)	0.3	
Endurance test	5,000 cycles, with the oil volume variation between 0°C and 110°C	
Functions of the integrated protection relay	Gas; over temperature (alarm and trip); over pressure	

TABLE B.14

Single-Phase Distribution Transformer, 50 kVA

SINGLE PHASE DISTRIBUTION TRANSFORMER – 50 kVA	REQUIRED	TENDERED
Manufacturer's name and country	—	
Type designation	—	
Type	Oil immersed	
Installation	Outdoor	
Rated power (ONAN cooling) (kVA)	50	
Number of phases	1	
Rated frequency (Hz)	50	
Rated voltages (at no-load): • Primary winding (kV) • Secondary winding (kV) • Between the two energized terminals of secondary winding (kV)	 34.5 (30) 0.231 – 0 – 0.231 0.462	
Tappings on primary winding	± 2 × 2.5%	
Number of tapping positions	5	
Type of tap changer	Off-voltage	
Max. continuous operation voltage of windings • Primary winding (kV) • Secondary winding (kV)	 36.5 (33) Values consistent with HV side	
Number of windings • HV • LV	 1 or 2 in parallel, according to design type 2	
Impedance voltage on principal tapping, at 75°C (%) (to be measured at half power on each of the two secondary windings with the other open)	4	
No-load losses (W)	≤ 150	
No-load current (%)	≤ 1.9	
Load losses at 75°C (W)	≤ 850	
Sound level [power] (dB(A))	< 46	
Insulation class	A	
Cooling method	ONAN	

(*continued*)

TABLE B.14

Single-Phase Distribution Transformer, 50 kVA (*continued*)

SINGLE PHASE DISTRIBUTION TRANSFORMER – 50 kVA	REQUIRED	TENDERED
Insulation levels, primary winding • Highest system voltage (kVrms) • Power frequency withstand voltage (kVrms) • Lightning impulse withstand voltage (1.2/50 µs) (kV peak)	 36.5 (33) 82.5 200	
Insulation levels, secondary winding • Highest system voltage (kVrms) • Power frequency withstand voltage (kVrms) • Lightning impulse withstand voltage (1.2/50 µs) (kV peak)	 (3.6) 10 20	
Induced withstand voltage of HV winding with tap-changer in intermediate position (34.5 kV) (kVrms)	82.5 (70)	
Temperature rises • Windings (average) (°C) • Top oil (°C) • Winding hot spot (°C) • Core surface (°C)	 ≤ 60 ≤ 55 ≤ 70 ≤ 75	
The transformer must withstand the short circuit special test as per IEC standard 60076 part 5, on units selected at random by purchaser inspector from each lot submitted to acceptance test.	Yes	
Execution of short circuit tests as per previous clause	Will be decided, at the employer's discretion, after manufacturing of each lot of transformers	
Short circuit test reports performed on similar transformers in an independent test laboratory	Shall be enclosed to the offer	
Short circuit power of 34.5 kV supply network for short circuit test	Infinite	
Winding configuration	To ensure stable secondary voltages with one secondary winding at full load and the other at no-load	
Characteristics of windings:		
Material: • Primary • Secondary • Cross section • Current density in copper (A/mm^2)	 Cu Cu or Al, to be informed in tender Uniform HV: ≤ 3; LV: ≤ 3	
Magnetic core		
Type	Stacked or wound	
Material	Cold rolled grain oriented silicon steel	
Flux density at rated voltage and frequency, with mean tap (tesla)	≤ 1.65	
Bushings characteristics • Standards • Type	 IEC 137 Porcelain	

SINGLE PHASE DISTRIBUTION TRANSFORMER – 50 kVA	REQUIRED	TENDERED
Primary bushings • Rated voltage as per IEC 60694 (kV) • Rated current (A) • Withstand test voltage - 50 Hz-1 minute wet (kVrms) - Lightning impulse (1.2/50 µs) (kV crest) • Creepage distance (mm)	 38 ≥ 250 ≥ 82.5 ≥ 200 ≥ 1,050 (≥ 950)	
Secondary bushings • Insulation level (kV) • Rated current, I (A)	 1.1 ≥ 400	
Withstand test voltage • 50 Hz-1 minute (kVrms) • Lightning impulse (1.2/50 µs) (kV peak)	 10 20	
Bushings number • Primary • Secondary	 2 3	
Tank	Rib type	
Valves and bolts	Made of corrosion resistant material	
Painting		
• The internal surfaces including the conservator, shall be protected against hot oil at a temperature of 105°C	Yes	
• The external surfaces shall be painted with a cycle suitable for heavy environment conditions.	Yes	
Accessories required		
• Conservator • Oil level indicator • Oil filling plug • Pocket thermometer dial type • Skid • Filling and draining valves • Lifting eyes • Hitching holes • Rating plate	Yes	
Overall dimensions (mm) • Length • Width • Height		
Mass • Total (kg) • Oil (kg)		

(*continued*)

TABLE B.14

Single-Phase Distribution Transformer, 50 kVA (*continued*)

SINGLE PHASE DISTRIBUTION TRANSFORMER – 50 kVA	REQUIRED	TENDERED
Alternative bid for tank hermetically sealed for life:		
• Tank	With corrugated walls completely full of oil	
• Max. internal pressure between 0°C and 110°C (bar)	0.3	
• Endurance test	5,000 cycles, with the oil volume variation between 0°C and 110°C	
• Functions of the integrated protection relay	Gas; over temperature (alarm and trip); over pressure	

TABLE B.15

Single-Phase Distribution Transformer, 100 kVA

SINGLE-PHASE DISTRIBUTION TRANSFORMER – 100 kVA	REQUIRED	TENDERED
Manufacturer's name and country	—	
Type designation	—	
Type	Oil immersed	
Installation	Outdoor	
Rated power (ONAN cooling) (kVA)	100	
Number of phases	1	
Rated frequency (Hz)	50	
Rated voltages (at no-load) • Primary winding (kV) • Secondary winding (kV) • Between the two energized terminals of secondary winding (kV)	 34.5 (30) 0.231 – 0 – 0.231 0.462	
Tappings on primary winding	$\pm 2 \times 2.5\%$	
Number of tapping positions	5	
Type of tap changer	Off-voltage	
Max. continuous operation voltage of windings • Primary winding (kV) • Secondary winding (kV)	 36.5 (33) Values consistent with HV side	
Number of windings • HV • LV	 1 or 2 in parallel, according to design type 2	
Impedance voltage on principal tapping, at 75°C (%) (to be measured at half power on each of the two secondary windings with the other open)	4	

SINGLE-PHASE DISTRIBUTION TRANSFORMER – 100 kVA	REQUIRED	TENDERED
No-load losses (W)	≤ 250	
No-load current (%)	≤ 1.5	
Load losses at 75°C (W)	≤ 1,400	
Sound level [power] (dB(A))	< 48	
Insulation class	A	
Cooling method	ONAN	
Insulation levels, primary winding • Highest system voltage (kVrms) • Power frequency withstand voltage (kVrms) • Lightning impulse withstand voltage (1.2/50 µs) (kV peak)	 36.5 (33) 82.5 200	
Insulation levels, secondary winding • Highest system voltage (kVrms) • Power frequency withstand voltage (kVrms) • Lightning impulse withstand voltage (1.2/50 µs) (kV peak)	 (3.6) 10 20	
Induced withstand voltage of HV winding with tap-changer in intermediate position (34.5 kV) (kVrms)	82.5 (70)	
Temperature rises • Windings (average) (°C) • Top oil (°C) • Winding hot spot (°C) • Core surface (°C)	 ≤ 60 ≤ 55 ≤ 70 ≤ 75	
The transformer must withstand the short circuit special test as per IEC standard 60076 part 5, on units selected at random by the purchaser inspector from each lot submitted to acceptance test.	Yes	
Execution of short circuit tests as per previous clause	Will be decided, at the employer's discretion, after manufacturing of each lot of transformers	
Short circuit test reports performed on similar transformers in an independent test laboratory	Shall be enclosed to the offer	
Short circuit power of 34.5 kV supply network for short circuit test	Infinite	
Winding configuration	To ensure stable secondary voltages with one secondary winding at full load and the other at no-load	

(*continued*)

TABLE B.15

Single-Phase Distribution Transformer, 100 kVA (*continued*)

SINGLE-PHASE DISTRIBUTION TRANSFORMER – 100 kVA	REQUIRED	TENDERED
Characteristics of windings:		
Material: • Primary • Secondary • Cross section • Current density in copper (A/mm²)	 Cu Cu or Al, to be informed in the tender Uniform HV: ≤ 3; LV: ≤ 3	
Magnetic core		
Type	Stacked or wound	
Material	Cold rolled grain oriented silicon steel	
Flux density at rated voltage and frequency, with mean tap (tesla)	≤ 1.65	
Bushings characteristics • Standards • Type	 IEC 137 Porcelain	
Primary bushings • Rated voltage as per IEC 60694 (kV) • Rated current (A)	 38 ≥ 250	
• Withstand test voltage - 50 Hz-1 minute wet (kVrms) - Lightning impulse (1.2/50 μs) (kV crest)	 ≥ 82.5 ≥ 200	
• Creepage distance (mm)	≥ 1,050 (≥ 950)	
Secondary bushings • Insulation level (kV) • Rated current, I (A)	 1.1 ≥ 800	
• Withstand test voltage - 50 Hz-1 minute wet (kVrms) - Lightning impulse (1.2/50 μs) (kV crest)	 10 20	
Bushings number • Primary • Secondary	 2 3	
Tank	Rib type	
Valves and bolts	Made of corrosion resistant material	

SINGLE-PHASE DISTRIBUTION TRANSFORMER – 100 kVA	REQUIRED	TENDERED
Painting		
• The internal surfaces, including the conservator, shall be protected against hot oil at a temperature of 105°C	Yes	
• The external surfaces shall be painted with a cycle suitable for heavy environment conditions.	Yes	
Accessories required		
• Conservator • Oil level indicator • Oil filling plug • Pocket thermometer dial type • Skid • Filling and draining valves • Lifting eyes • Hitching holes • Rating plate	Yes	
Overall dimensions (mm) • Length • Width • Height		
Mass • Total (kg) • Oil (kg)		
Alternative bid for tank hermetically sealed for life:		
• Tank	With corrugated walls completely full of oil	
• Max. internal pressure between 0°C and 110°C (bar)	0.3	
• Endurance test	5,000 cycles, with the oil volume variation between 0°C and 110°C	
• Functions of the integrated protection relay	Gas; over temperature (alarm and trip); over pressure	

TABLE B.16

Fused Cut-Outs

FUSED CUT-OUTS	REQUIRED	TENDERED
Manufacturer's name and country	—	
Manufacturer's type designation	—	
Standards	IEC 62271-105 or corresponding ANSI Standards	
Rated voltage (kV rms)	38 (36)	
Highest operation voltage (kV rms)	36.5 (33)	
Rated current (A rms)	≥100	
Rated frequency (Hz)	50	
Number of poles	1	
Operating device	Manual, with insulating stick	
Short time current rating • 1 s momentary rating (kArms) • dynamic (kA, peak)	 ≥ 5 ≥ 12.5	
1 min power frequency withstand voltage, wet (rain at ANSI standards): • Phase-to-ground (kVrms) • Across the isolating distance (kVrms)	 85 (70) 88 (80)	
Lightning impulse 1.2/50 μs withstand voltage, dry: • Phase-to-ground (kV peak) • Across isolating distance (kV peak)	 200 (170) 195	
Insulators • Material • Creepage length, phase-to-ground and between terminals (mm) • Insulators' arrangement	 Porcelain, brown ≥ 1,050 (≥ 950) as per technical specification	
Fuse holder type	Drop-out if fuse is melted	
Fuse link current – time characteristic	K type	
Fuse links rated current (Arms)	Shall be informed in the order (3, 5, 10, 15, 20, 25, 30)	
Mechanical terminal load (daN)		
Reference drawing	Attached to tender	
Weight of complete cut out (kg)	—	

TABLE B.17

Load Break Interrupters

LOAD BREAK DISCONNECTOR	REQUIRED	TENDERED
Manufacturer's name and country	—	
Manufacturer's type designation	—	
Standards	IEC 62271-103	
Rated voltage (kV rms)	38 (36)	
Highest operation voltage (kV rms)	36.5 (33)	
Rated frequency (Hz)	50	
Number of poles	Bipolar	
Rated current (A rms)	400	
Rated breaking currents (Arms) • Load and loop current • Line capacitive current • Transformer no-load current	 400 ≥ 10 ≥ 10	
Short time current rating • 1 s momentary rating (kA rms) • dynamic (kA, peak)	 8 20	
Operating mechanism • Type	 Spring type, manual level, free tripping	
• Height of installation on poles above ground level (m)	Up to 9	
• Installation	Horizontal or vertical	
Power frequency withstand voltage, wet (rain at ANSI standards): - Phase-to-ground, phase-to-phase (kVrms) - Across the isolating distance (kVrms)	 85 (70) 88 (80)	
Lightning impulse 1.2/50 μs withstand voltage, dry: • Phase-to-ground and phase-to-phase (kV peak) • Across open contacts (kV peak)	 200 (170) 195	
Insulators • Material • Creepage distance (mm)	 Porcelain, brown ≥1,050 (≥ 950)	
Mechanical terminal load (daN)	—	
Reference drawing	Attached to tender	
Weight of complete cut out (kg)	—	

BOX B.2

Capacitor Banks

Capacitor banks are intended to be used for the following purposes:

- To avoid ferroresonance phenomena
- For power factor correction
- To balance the shunt capacitances of the shield wire line.

TABLE B.18

Capacitor Banks

CAPACITOR BANKS	REQUIRED	TENDERED
Manufacturer's name and country	—	
Type designation	—	
Standard applicable	IEC 60871 - Parts 1 and 2	
System ratings		
Rated operation voltage (kV)	34.5 (30)	
Rated frequency (Hz)	50	
Number of system phases	3 (2 insulated; 1 grounded)	
Max. continuous operation voltage (kV)	36.5 (33)	
A. Characteristics of single-phase capacitor banks		
Electrical ratings		
Rated voltage (kV)	48 (42)	
Rated capacitance (nF): C_{WW} = capacitance of each bank connected between the two shield wires C_{WG} = capacitance of each bank connected between each shield wire and ground To be specified for each ISWS, on the basis of the results of the operation analyses performed with the ad-hoc computer program		
Rated frequency (Hz)	50	
Number of phases	1	

CAPACITOR BANKS	REQUIRED	TENDERED
Capacitor banks output at system rated voltage of 34.5 (30) kV (kVAr): To be specified for each ISWS, on the basis of the results of the operation analyses performed with the ad-hoc computer program		
Number of single-phase banks to be supplied: To be specified for each rated kVAr (and capacitance) on the basis of the results of the computer analyses	— —	
Insulation levels of capacitor banks		
• Highest system voltage	52 (45)	
• Power frequency withstand voltage, 1 minute (wet test for supporting insulator) (kVrms)	95	
• 1.2/50 μs impulse withstand voltage for supporting insulator (kV crest)	250	
Installation	Outdoor	
Construction		
Each single-phase bank is composed of: • 2 capacitor units connected in series (see figure C.1a and C.1b in Annex C) with the characteristics specified in section B of this table. • 1 support frame made of hot-dip galvanized steel or aluminum alloy • 1 support insulator	Yes Yes Yes	
B. Characteristics of capacitor units		
• Electrical ratings		
• Rated voltage (kV)	24 (21)	
• Max. continuous operation voltage of units (kVrms)	18.25 (16.5)	
• Rated frequency (Hz)	50	
Rated capacitances of C^1_{WW}/C^1_{WG}: To be specified for each ISWS on the basis of the results of the computer analyses		
Unit outputs at rated voltage of 24 kV (kVAr): To be specified for each ISWS on the basis of the results of the computer analyses		
Unit outputs at normal operation voltage of 34.5/2 kV (30 kV/÷2 kV) (kVAr): To be specified for each ISWS on the basis of the results of the computer analyses		
Tan delta max. %	0.02	

(*continued*)

TABLE B.18
Capacitor Banks (*continued*)

CAPACITOR BANKS	REQUIRED	TENDERED
Temperature category (°C)	–25/+45	
AC routine voltage test between terminals (50 Hz, 10 s) (kVrms)[a]	51.6 (45)	
Insulation level of capacitor units		
• Rated voltage (kV)	24 (21)	
• Power frequency withstand voltage, 1 minute (wet test for capacitor bushing) (kVrms)	50	
• 1.2/50 μs lightning impulse withstand voltage (kV crest) (only on capacitor bushing)	125	
Installation	Outdoor	
Construction		
Type of construction	1 bushing	
Hermetically sealed case	Stainless steel	
Fuses: • External • Internal	 Not allowed Acceptable, not mandatory	
Internal discharge resistors	Required	
Dielectric	All polypropylene film	
Max dielectric stress (V/μ)	60	
Oil, biodegradable, and nontoxic	PCB free	
Overall dimensions of capacitor bank (mm) • Length • Width • Height		
Mass		
- Total (kg)		....

[a]*This routine test cannot be replaced by the direct current alternative test foreseen in the IEC standards.*

TABLE B.19

Rigid Insulator Strings: Alternative A

RIGID INSULATOR STRINGS	REQUIRED	TENDERED
Manufacturer's name and country	—	
Type	Rigid string with protective arcing horns	
Highest operation voltage, phase-to-ground (kV rms)	36.5 (33)	
Material and coupling:		
• Insulator discs • Cap and pin • Coupling	Toughened glass — Rigid	
Number of glass insulators per string	4	
Diameter of glass discs (mm)	255	
Spacing between discs: • Altitude ≤ 1,000 m above sea level (mm) • Altitude of 1,000 to 2,200 m above sea level (mm)	 108 120	
Creepage distance (mm)	1,200	
Length of insulator string (from coupling with tower U bolt and coupling with suspension clamp) (see figure C.9.a of Annex C) • Disc spacing of 108 mm • Disc spacing of 120 mm	 550 585	
Dry lightning impulse withstand voltage, without arcing horns: • Disc spacing of 108 mm (kV peak) • Disc spacing of 120 mm (kV peak)	 270 295	
Dry power frequency withstand voltage without arcing horn: • Disc spacing of 108 mm (kVrms) • Disc spacing of 120 mm (kVrms)	 190 200	
Wet power frequency withstand voltage, without arcing horn (rain at ANSI standards): • Disc spacing of 108 mm (kVrms) • Disc spacing of 120 mm (kVrms)	 130 143	
Electromechanical and mechanical failing load	≥ 50	
Gap distance between arcing horns, adjustable: • Disc spacing of 108 mm, range (mm) • Disc spacing of 120 mm, range (mm)	 200 to 360 240 to 400	
Additional requirement for tension strings	Bird anti-perching spike (see figure C.9a in Annex C)	
Weight of rigid string • Suspension set (kg) • Tension set (kg)		
Standards in force	IEC 60381-1	

BOX B.3

Cap and Pin 34.5 kV Insulator Strings: Alternative B applicable in the spur lines which supply the villages from the SWLs

The glass or porcelain cap and pin tension insulator strings used in the conventional 33 kV lines, formed by three units of type U70BL, are applicable as an alternative to the rigid insulator strings (table B.19), in the spur and reticulation 30 to 34.5 kV lines and in the 30 to 34.5/0.4 kV transformer stations.

TABLE B.20

Pin Type 30 to 34.5 kV Insulators

PIN TYPE 30 TO 34.5 kV INSULATORS	REQUIRED	TENDERED
Manufacturer's name and country	—	
Type designation	—	
Standards	IEC 720	
Material • Insulator • Fittings	 Porcelain, brown, Galvanized steel	
Minimum cantilever strength (kN)	6	
Dry 1.2/50 μs lightning impulse withstand voltage (kV peak)	≥250	
60 s power frequency withstand voltage • Dry (kVrms) • Wet (kVrms)	 ≥175 ≥125	
Creepage distance (mm)	≥1,050 (≥ 950)	
Puncture voltage (kVrms)	—	
Dimensions of insulator (mm) • Height • Radius of top groove • Spindle diameter • Spindle length	 >500 — —	
Max R.I.V. at 1 MHZ (mV)	—	
Net weight (kg)	—	

TABLE B.21

Interposing Transformer

INTERPOSING TRANSFORMER	REQUIRED	TENDERED
Manufacturer's name	—	
Manufacturer's type designation	—	
Service conditions - Altitude above sea level (m) - Ambient temperature (°C) • Maximum • Yearly average • Minimum	 ≤ 1,000 + 45 + 20 0	
Standards applicable (with reservations as per technical specifications)	IEC 60076 – Parts 1 to 10	
Type of transformer	Oil immersed	
Rated power (MVA)	3 – 4.5 – 6[a]	
Number of phases	3	
Rated frequency (Hz)	50	
Rated voltages (kV)		
- Primary winding	33	
- Secondary winding	35.5 (31)[b]	
Tappings on secondary winding	± 2 × 3.75%	
Number of tapping positions	5	
Regulation	Off-voltage	
Tapping power	Rated power for all taps	
Max. continuous operation voltage of windings - Primary winding (kV) - Secondary winding (kV)	 36 36.5 (33)	
Connection group - Primary winding - Secondary winding	dY5 Delta connected Star with one terminal (phase) permanently grounded	
Number of windings	2	
Impedance voltages at 75°C, base rated power (MVA): • 33 kV/35.5 (31) kV (%) • 33 kV/35.5 (31) kV + 7.5% (%) • 33 kV/35.5 (31) kV – 7.5% (%)	3 – 4.5 – 6 6.5 – 7 – 7 6.8 – 7.3 – 7.3 6.2 – 6.7 – 6.7	

(*continued*)

TABLE B.21

Interposing Transformer (*continued*)

INTERPOSING TRANSFORMER	REQUIRED	TENDERED
No-load losses - At rated voltage and 50 Hz (kW) - At 1.1 rated voltage and 50 Hz (kW)	MVA: 3; — 4.5 — 6 ≤ 3.5; ≤ 4.75; ≤ 5.7 —/—/—	
No-load current - At rated voltage and 50 Hz (%) - At 1.1 rated voltage and 50 Hz (%)	MVA: 3 – 4.5 - 6 ≤ 0.3; ≤ 0.25; ≤ 0.2;	
Load losses (at 75°C), at ratios: - 33/35.5 (31) kV (kW) - 33 kV/35.5 (31) kV + 7.5% (kW) - 33 kV/35.5 (31) kV – 7.5% (kW)	MVA: 3 – 4.5 - 6 ≤ 24; ≤ 29; ≤ 36; ≤ 23; ≤ 28; ≤ 35; ≤ 25; ≤ 30; ≤ 38;	
Sound level [power] (dB)	≤ 55	
Insulation class	A	
Cooling method	ONAN	
Insulation levels • Highest system voltage (kVrms) - Primary - Secondary • 1 minute 50 Hz withstand voltage (kVrms) - Primary - Secondary • Lightning impulse 1.2/50 µs withstand voltage (kV crest) - Primary - Secondary	 36 36.5 (33) 70 95 170 250	
Induced withstand voltage on primary Winding (kV_{rms})	72	
Temperature rises (with one radiator out of service) - Windings (average) (°C) - Top oil (°C) - Winding hot spot (°C) - Core surface (°C)	 ≤60 ≤55 ≤70 ≤75	
Can transformer withstand the short circuit special test as per IEC standard 60076 – Part 5	Yes, with energization from the 33 kV terminals and the 35.5 kV (31 kV) terminals in pre-set short circuit[c]	
Short circuit test	Optional test, will be decided by purchaser after manufacturing. The supplier should submit with tender a test certificate on a similar transformer performed by an independent test laboratory, if available.	
Short circuit power of 33 kV supply network	Infinite	

INTERPOSING TRANSFORMER	REQUIRED	TENDERED
Construction		
Characteristics of windings: - Material - Current density (A/mm²): • Primary winding • Secondary winding • Regulation winding - Insulating material	 Cu ≤ 3 ≤ 3 ≤ 3 Kraft paper	
Arrangement of windings: - 35.5 kV winding - 33 kV winding	 Internal (close to core)[c] External	
Core - Type - Material	 3-legged Cold rolled grain oriented silicon steel	
- Flux density at principal tapping at rated voltage and frequency (tesla)	≤1.65	
Bushings characteristics		
- Type	Porcelain, brown DIN standard	
Primary (33 kV) bushings - Rated voltage (kV) - Rated current (A) - Withstand test voltages a) 50 Hz-1 minute wet (kVrms) b) Lightning impulse (1.2/50 µs) (kV_{crest}) - Creepage distance (mm)	 36 ≥250 70 170 ≥900	
Secondary 35.5 (31) kV bushings - Rated voltage (kV) - Rated current (A) - Withstand test voltages a) 50 Hz-1 minute wet (kVrms) b) Lightning impulse (1.2/50 µs) - Creepage distance (mm)	 52 ≥ 250 95 250 ≥ 1,050 (≥ 950)	
Bushings number:		
- Primary	3	
- Secondary	3	
Tank type	Bolted cover	
Cooling	Radiators (see technical specification)	
Valves and bolts	Of corrosion resistant material	

(*continued*)

TABLE B.21

Interposing Transformer (*continued*)

INTERPOSING TRANSFORMER	REQUIRED	TENDERED
Painting		
Internal surfaces including the conservator	Protected against hot oil at a temperature of 105°C	
External surfaces	Painted with a cycle suitable for tropical environment conditions.	
Ability to withstand vacuum	See technical specification	
Overpressure test	See technical specification	
Accessories		
- Off-voltage tap changer on 35.5 (31) kV winding	Yes	
- Conservator with filling and drainage valves	Yes	
- Buchholz relay with two contacts	Yes	
- Pressure relief device	Yes	
- Dial type thermometer for oil, with two contacts	Yes	
- Oil level indicator with two contacts	Yes	
- Silica gel air drier	Yes	
- Set of valves for radiators	Yes	
- Radiator draining and venting devices	Yes	
- One vacuum pump connection	Yes	
- One sampling device	Yes	
- Lugs for lifting removable part and whole transformer	Yes	
- Earthing terminals	Yes	
- Swivel wheels	Yes (optional)	
- Marshalling box	Yes	
- First filling oil	Yes	
Weight of part to be havened out of tank (tons)		
Weight of filling oil (tons)		
Net weights (tons) - Core and coils - Tank and fittings - Complete unit (excluding oil)		

INTERPOSING TRANSFORMER	REQUIRED	TENDERED
Gross weight for transportation of heaviest part including oil (tons)		
Gross weight of complete unit (tons) - Without oil - With oil		
Approximate dimensions - Overall height (m) - Height over tank (m) - Length (m) - Width (m)		
Dimensions for transportation of the heaviest parts - Height (m) - Length (m) - Width (m)		

[a]Alternative offers are required for rated power of 3, 4.5, and 6 MVA.

[b]Final rated voltage (in range 30–35.5 kV) will be specified in the order.

[c]This requirement is justified because there will be no circuit breaker on the 35.5 (31) kV (line) side. The transformer will be switched from the 33 kV terminals, in one block with the 35.5 (31) kV shield wire line, which occasionally could be affected by a short circuit.

ANNEX C | TYPICAL DRAWINGS OF SPECIAL EQUIPMENT AND INSTALLATION OF THE 30–34.5 kV THREE-PHASE ILICETO SHIELD WIRE SCHEME USING THE EARTH AS THE CONDUCTOR OF ONE PHASE

(Some drawings are also applicable to other types of iliceto shield wire schemes)

CONTENTS

Figures

Table

FIGURE C.1.A

Lattice Pole-Mounted Capacitor Bank for “Three-Phase” ISWS

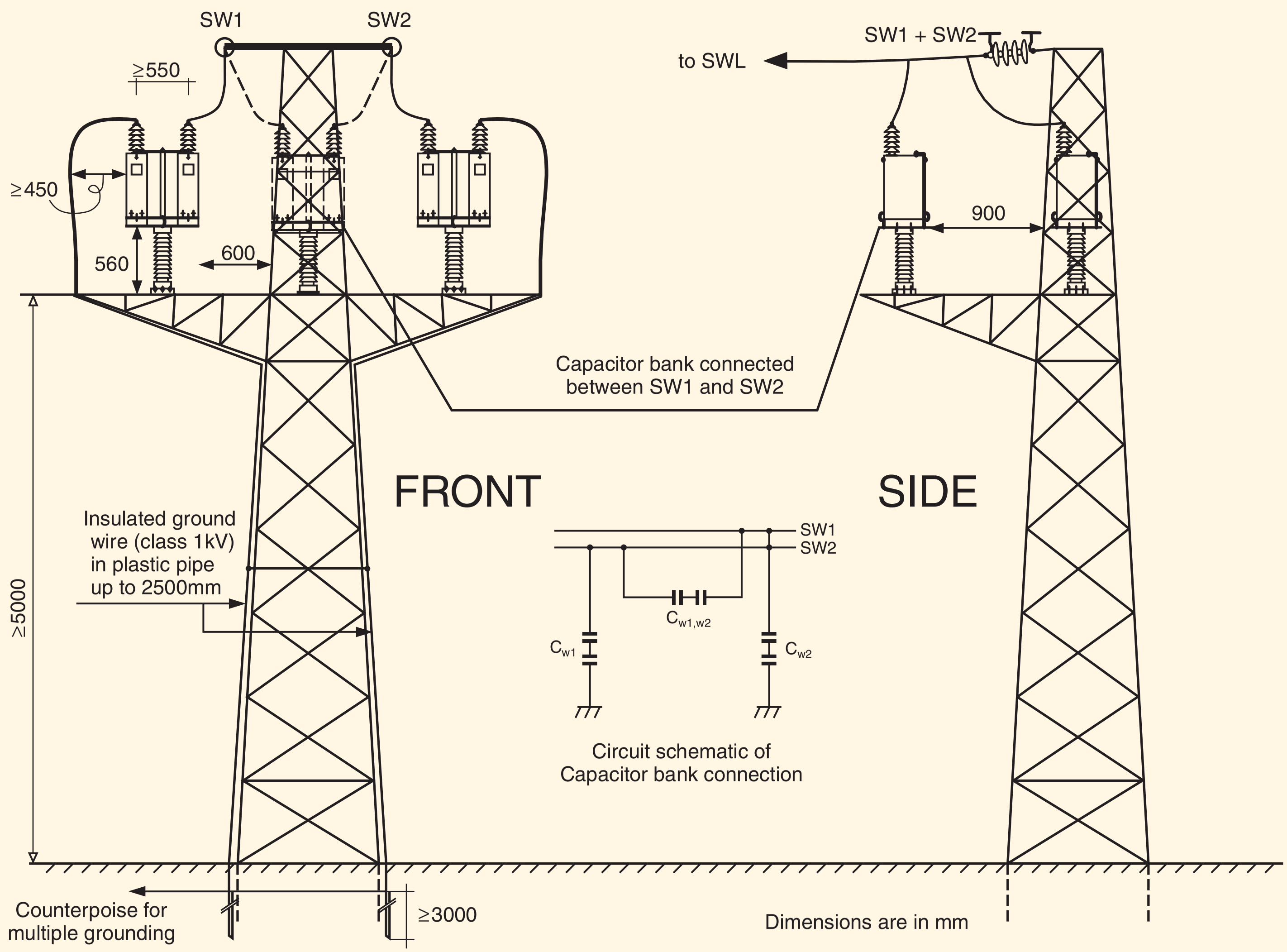


FIGURE C.1.B

Ground Mounted Capacitor Bank: Front and Side Cross-Sections

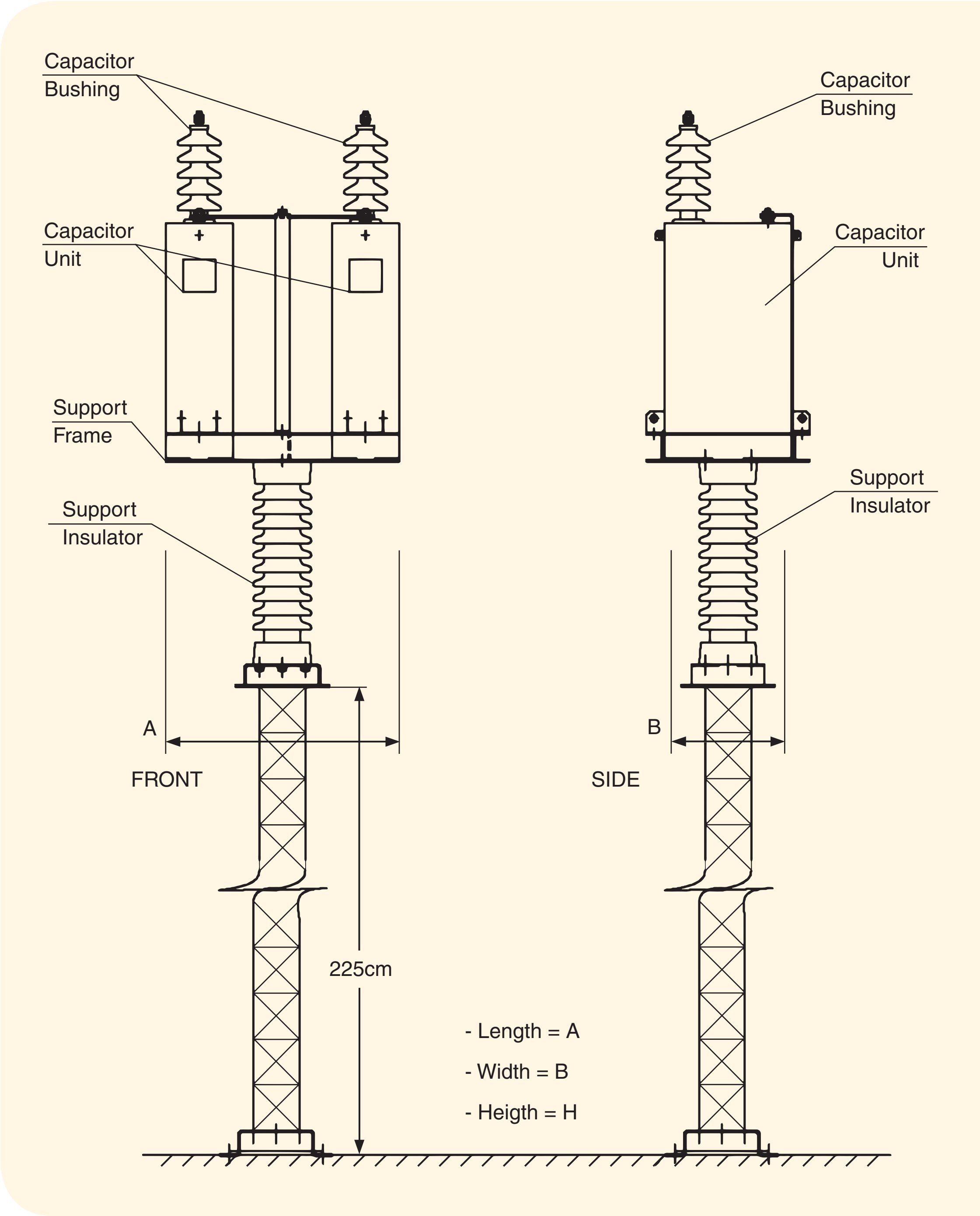
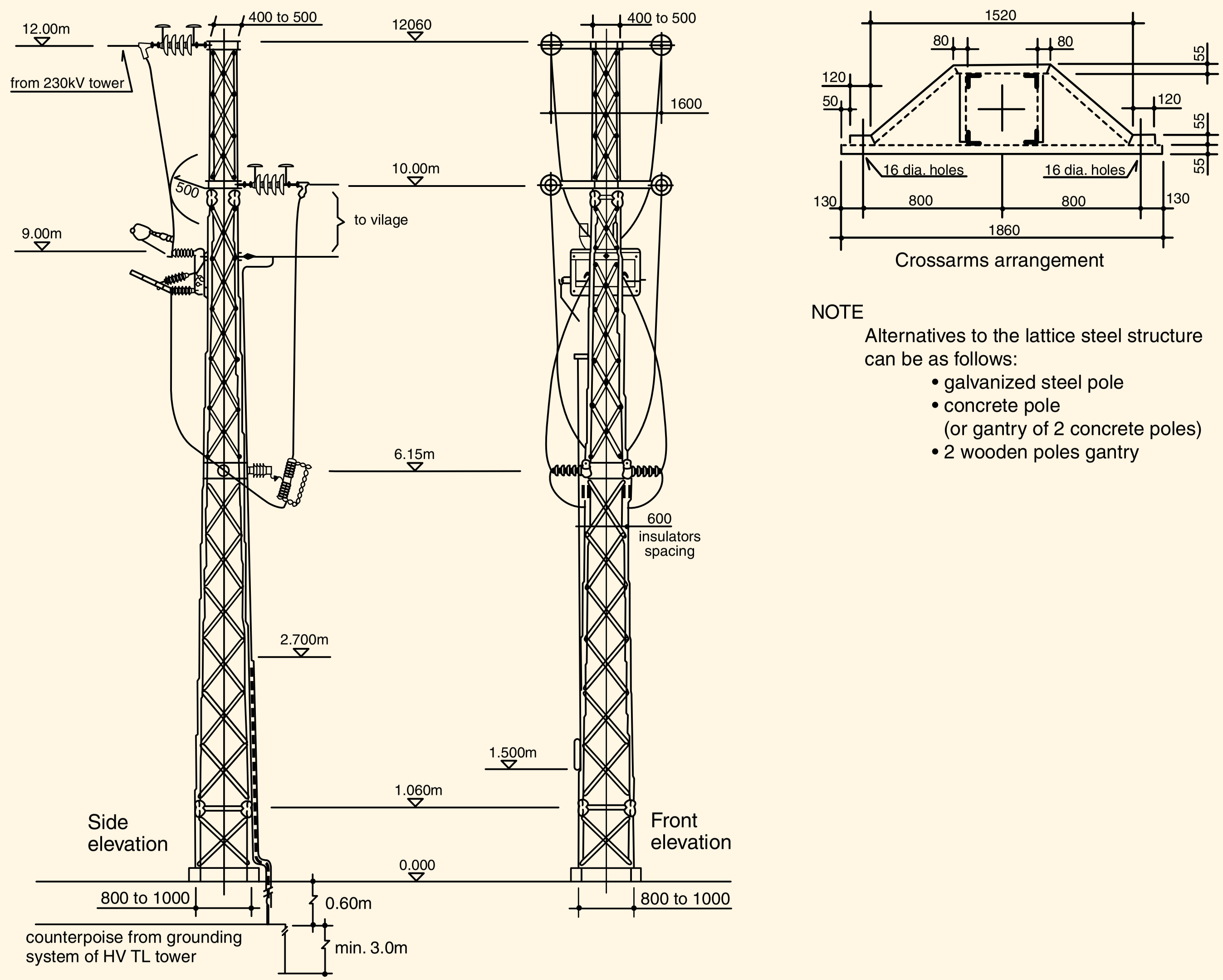


FIGURE C.2

Typical Tee-Off from the Insulated Shield Wires of a High-Voltage Line: Lattice Tower Arrangement



NOTE

Alternatives to the lattice steel structure can be as follows:

- galvanized steel pole
- concrete pole (or gantry of 2 concrete poles)
- 2 wooden poles gantry

FIGURE C.3.A

34.5 kV Tee-Off from the Shield Wires of a 132 kV Double-Circuit Line: Connection Span from a Suspension Tower

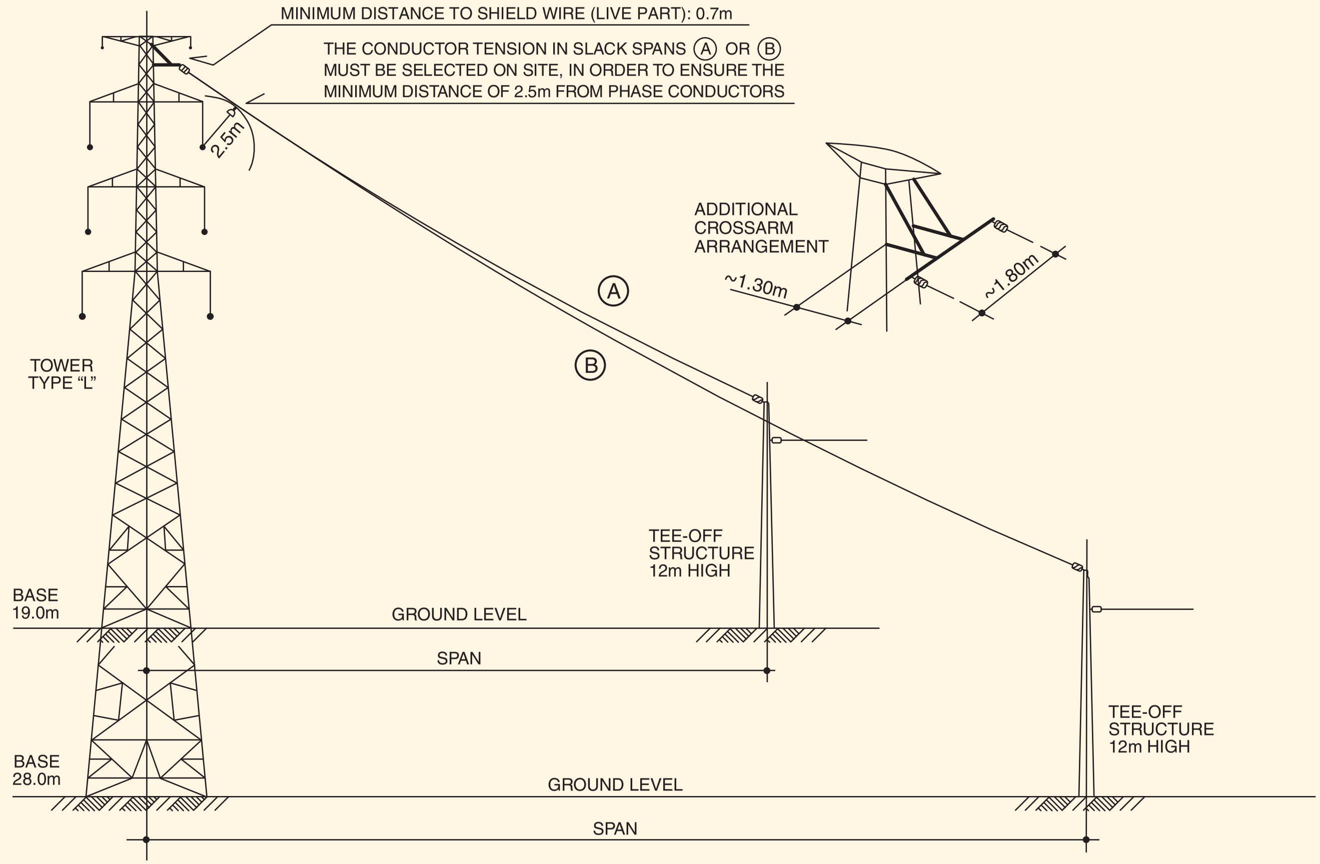


FIGURE C.3.B

34.5 kV Tee-Off from the Shield Wires of a 132 kV Double-Circuit Line: Connection Span from a Tension Tower

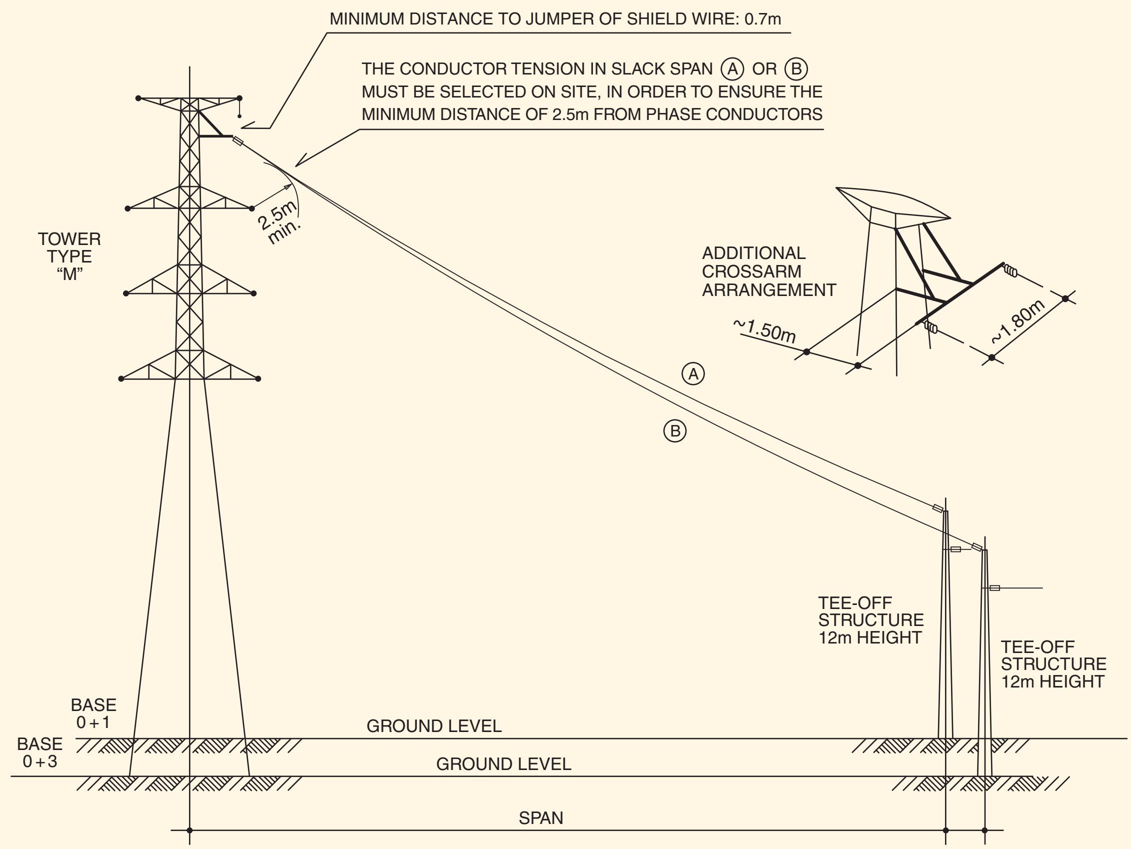


FIGURE C.3.C

34.5 kV Tee-Off from the Shield Wires of a Single-Circuit 230 kV Line: Connection Span from a Suspension Tower on the Side with One Phase Conductor

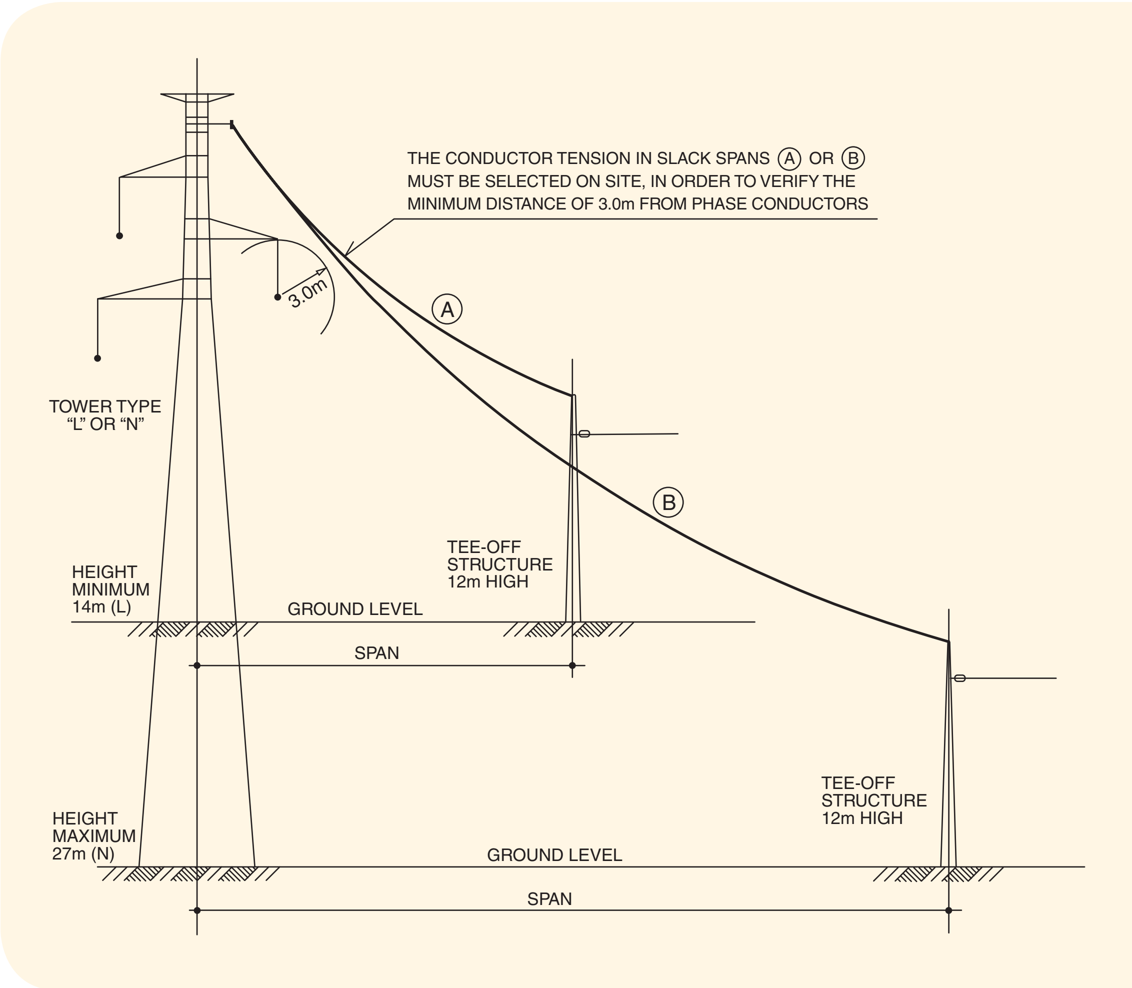


FIGURE C.3.D

34.5 kV Tee-Off from the Shield Wires of a Single-Circuit 230 kV Line: Connection Span from a Suspension Tower on the Side with Two Phase Conductors

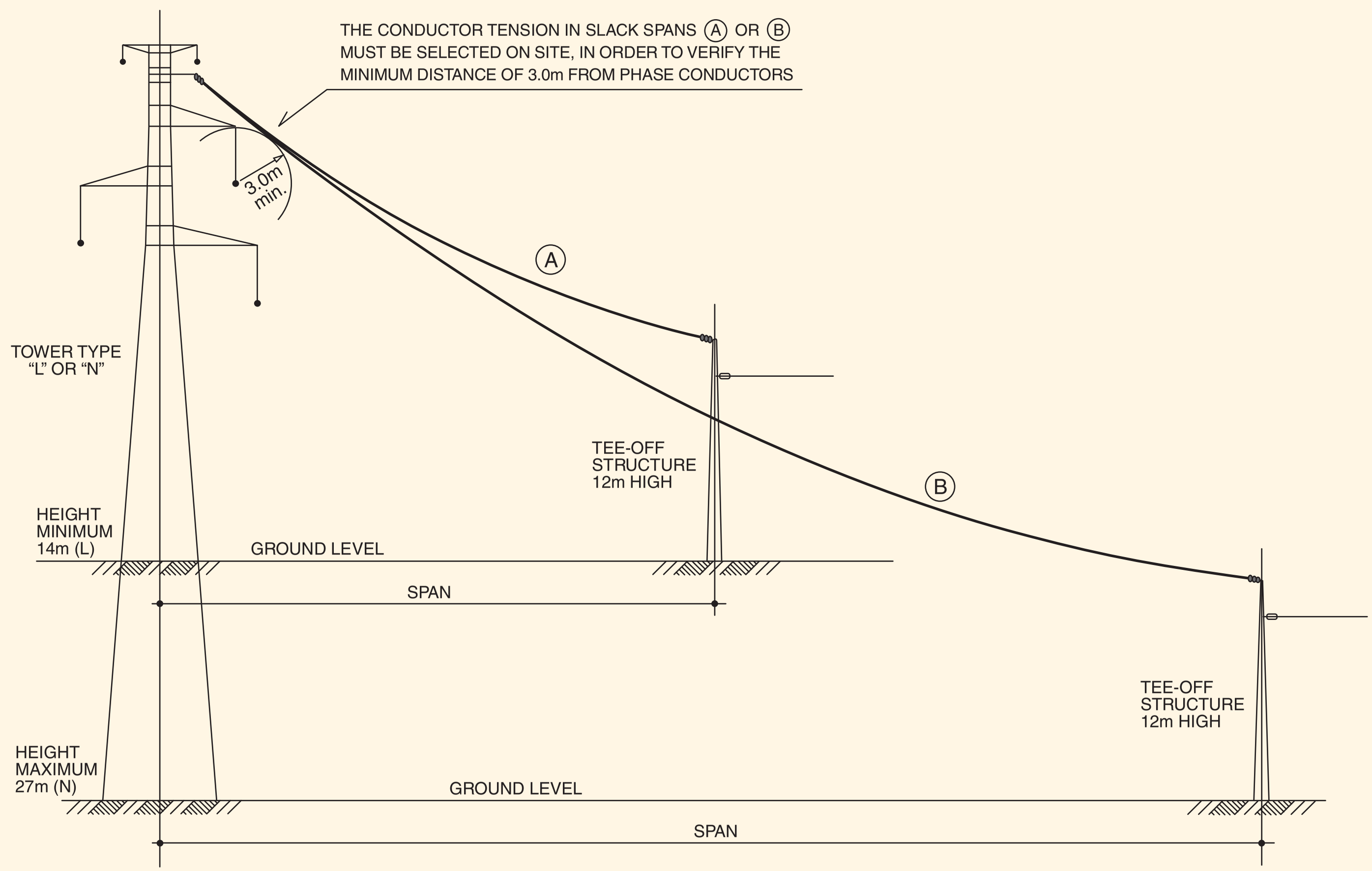
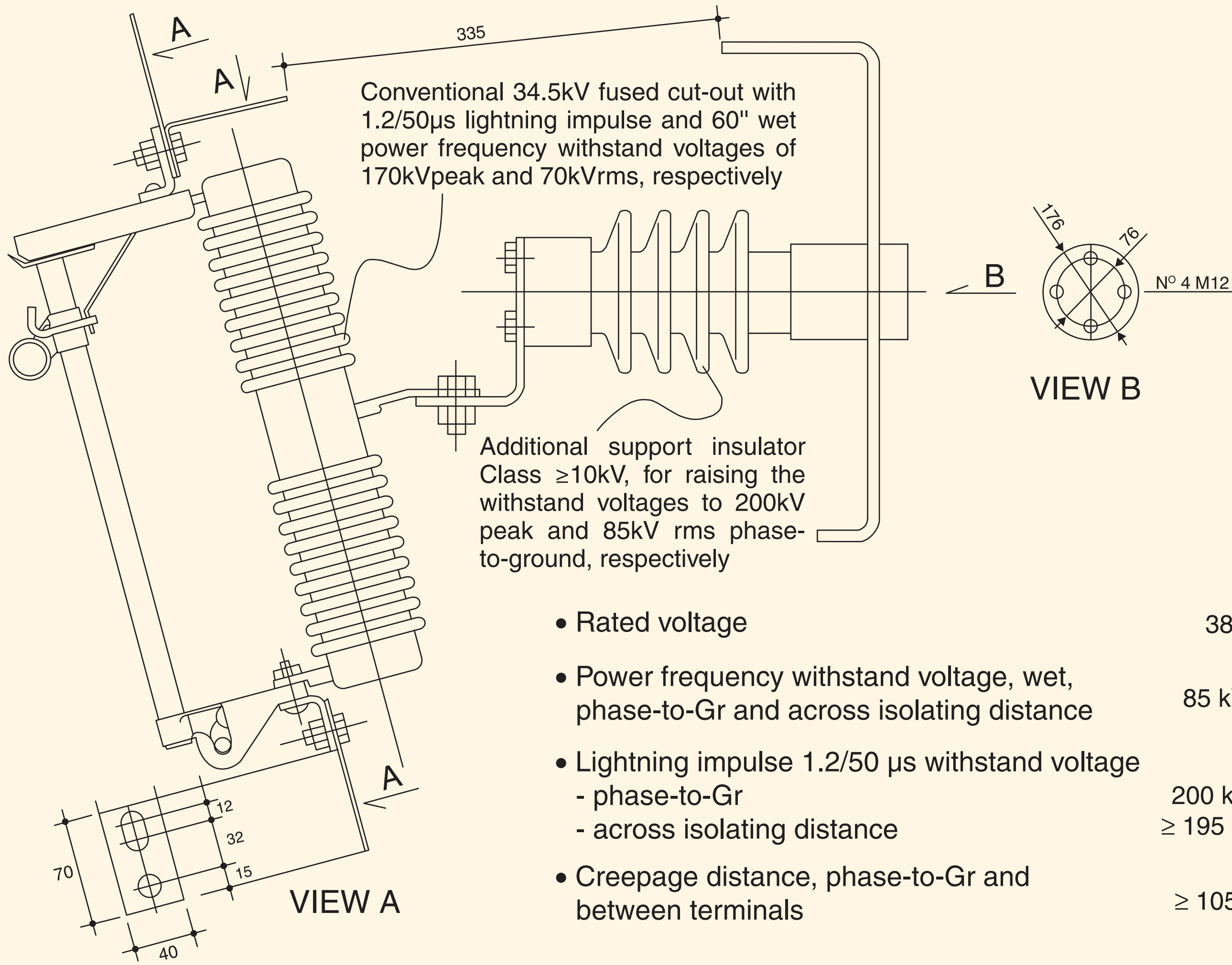


FIGURE C.4

Fused Cut-Out for a 34.5 kV Iliceto Shield Wire Scheme



• Rated voltage	38 kV
• Power frequency withstand voltage, wet, phase-to-Gr and across isolating distance	85 kVrms
• Lightning impulse 1.2/50 μs withstand voltage	
- phase-to-Gr	200 kV peak
- across isolating distance	≥ 195 kV peak
• Creepage distance, phase-to-Gr and between terminals	≥ 1050 mm

FIGURE C.5.A

Pole Mounted 34.5/0.4 kV Transformer Station (100–400 kVA): Dead-end Station Arrangement

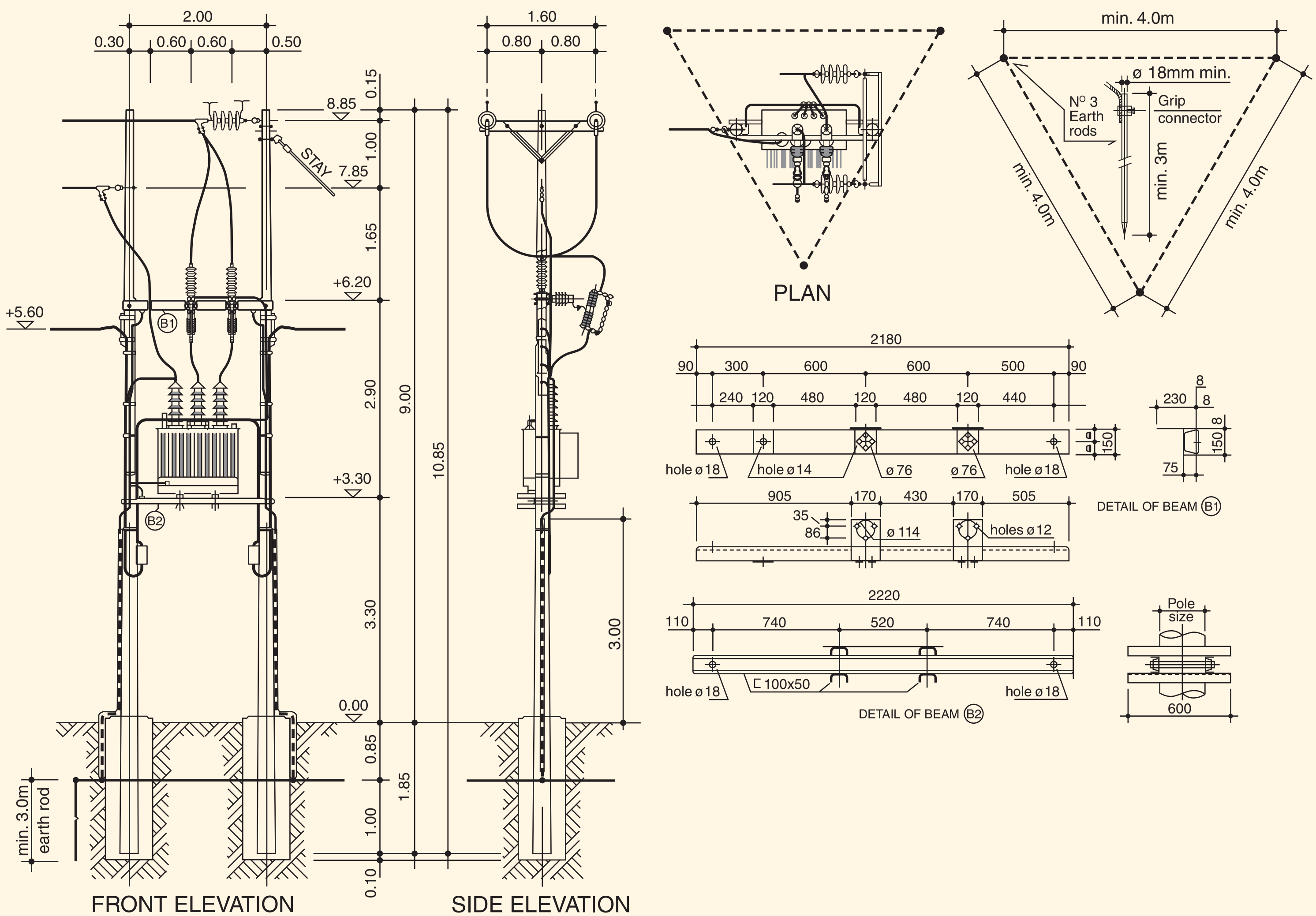


FIGURE C.5.B

Pole Mounted 34.5/0.4 kV Transformer Station (100–400 kVA): Intermediate Station Arrangement

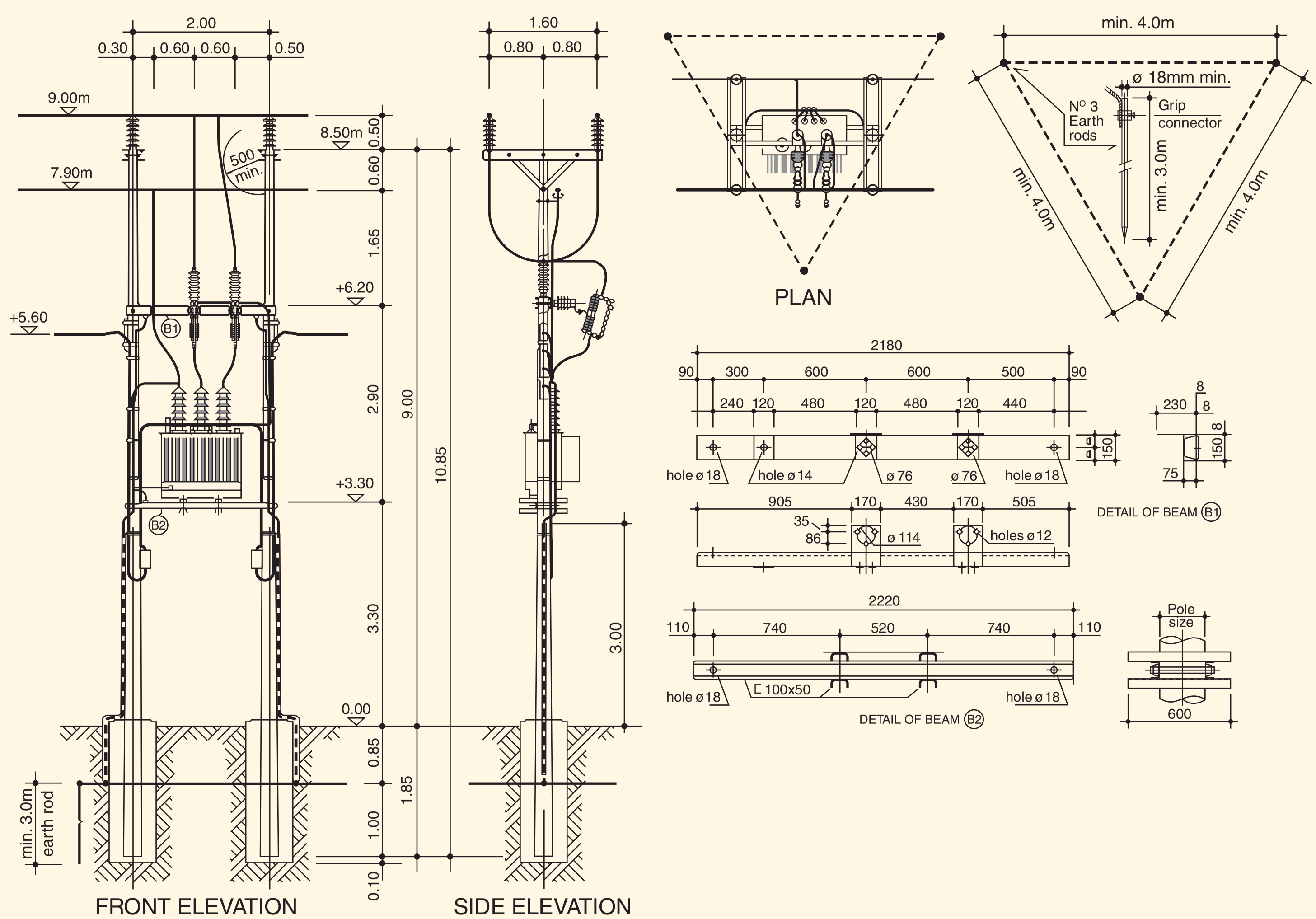


FIGURE C.5.C

Ground Mounted 34.5/0.4 kV Transformer Station (630–800 kVA): Dead-end Station Arrangement

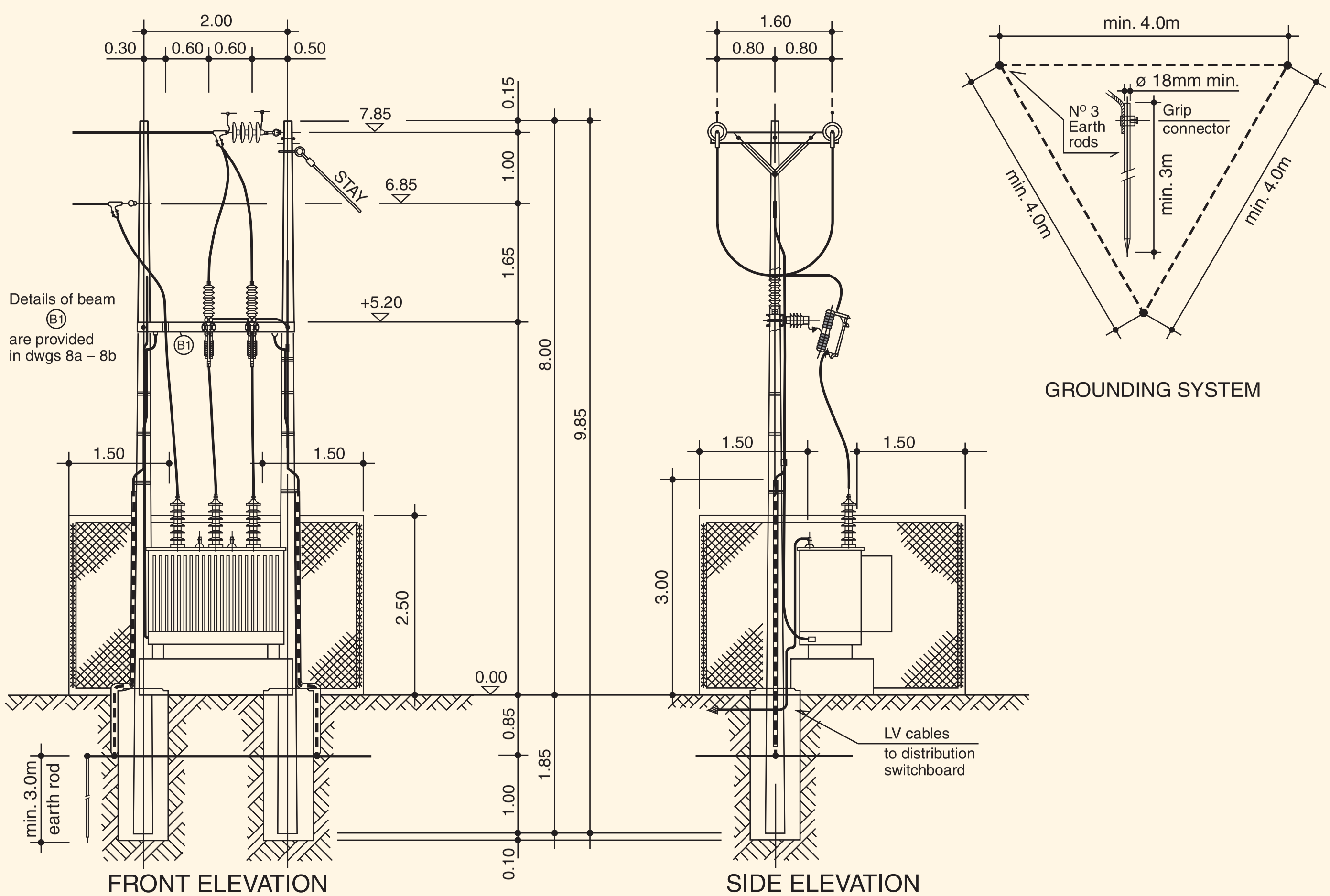
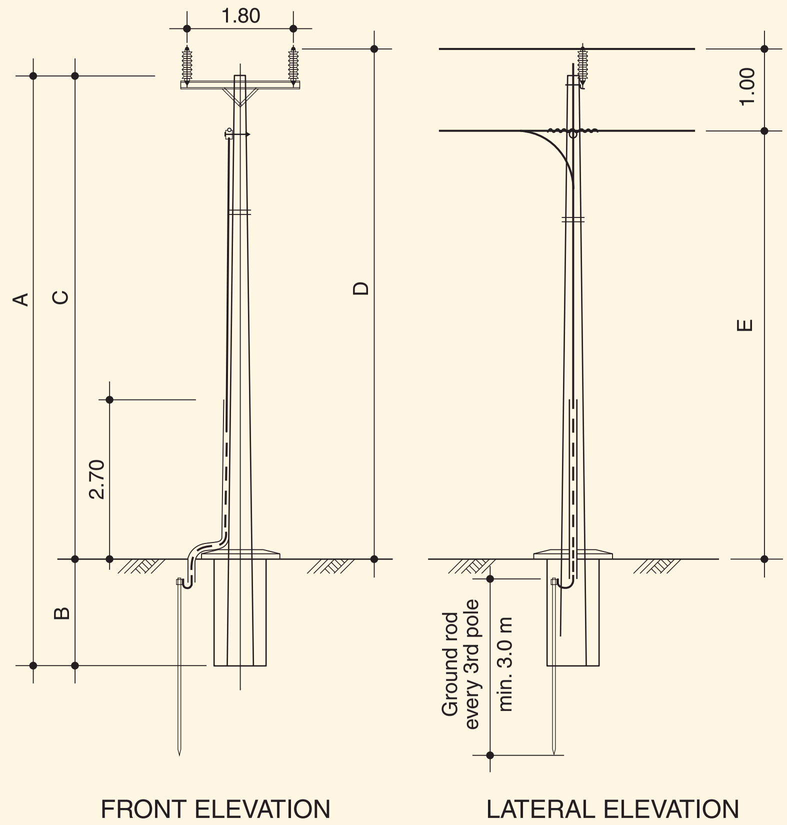


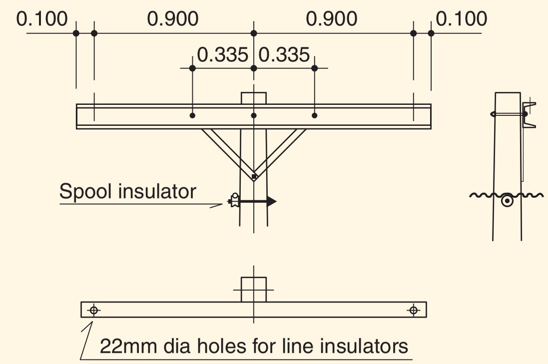
FIGURE C.6.A

34.5 kV Spur Line for a Two-Shield-Wire Three-Phase Iliceto Shield Wire Scheme with a Ground Conductor: Concrete Poles with Pin Type Insulators



A [m]	B [m]	C [m]	D [m]	E [m]	Span [m] α = 0	Span [m] α = 3°	Sag*) [m]
10	1.80	8.20	8.60	7.60	110		2.06
11	1.80	9.20	9.60	8.60	140		2.87
12	1.85	10.15	10.55	9.55	150		3.17
13	1.90	11.10	11.50	10.50	150		3.17
14	1.95	12.05	12.45	11.45	150		3.17

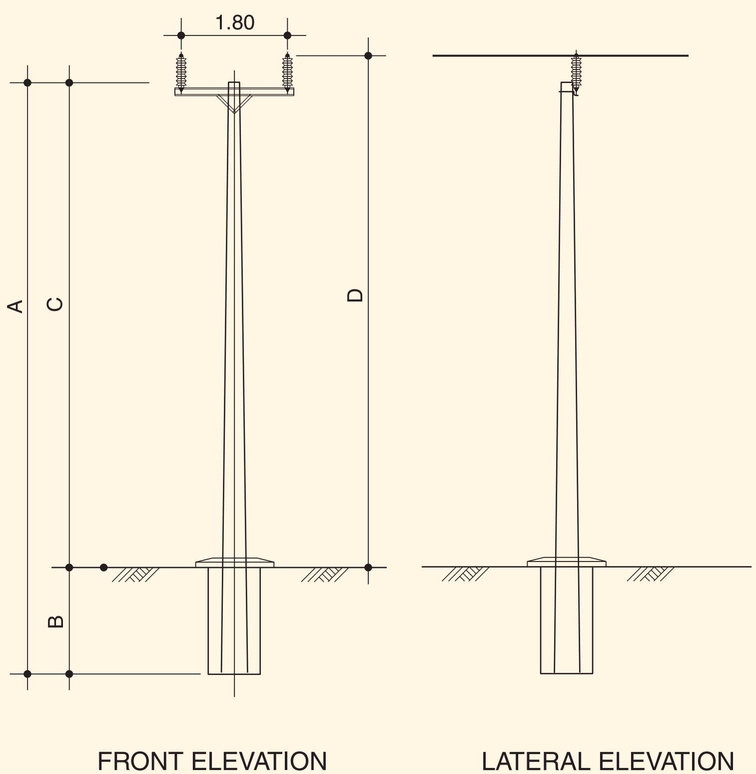
*) at +70°C, in still air



Dimensions are in meters

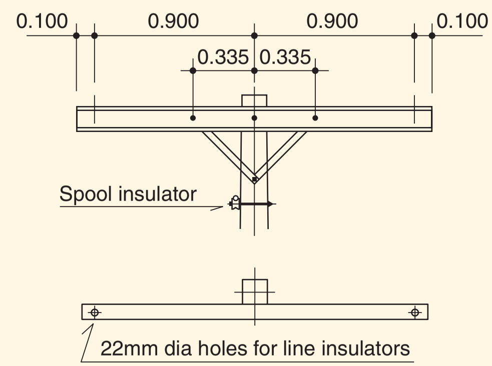
FIGURE C.6.B

34.5 kV Two-Wire Spur Line for a Two-Shield-Wire Three-Phase Iliceto Shield Wire Scheme: Concrete Poles with Pin Type Insulators



A [m]	B [m]	C [m]	D [m]	Span [m] α = 0	Span [m] α = 3°	Sag*) [m]
10	1.80	8.20	8.60	110		2.06
11	1.80	9.20	9.60	140		2.87
12	1.85	10.15	10.55	170		3.79
13	1.90	11.10	11.50	200		4.82
14	1.95	12.05	12.45	210		5.19

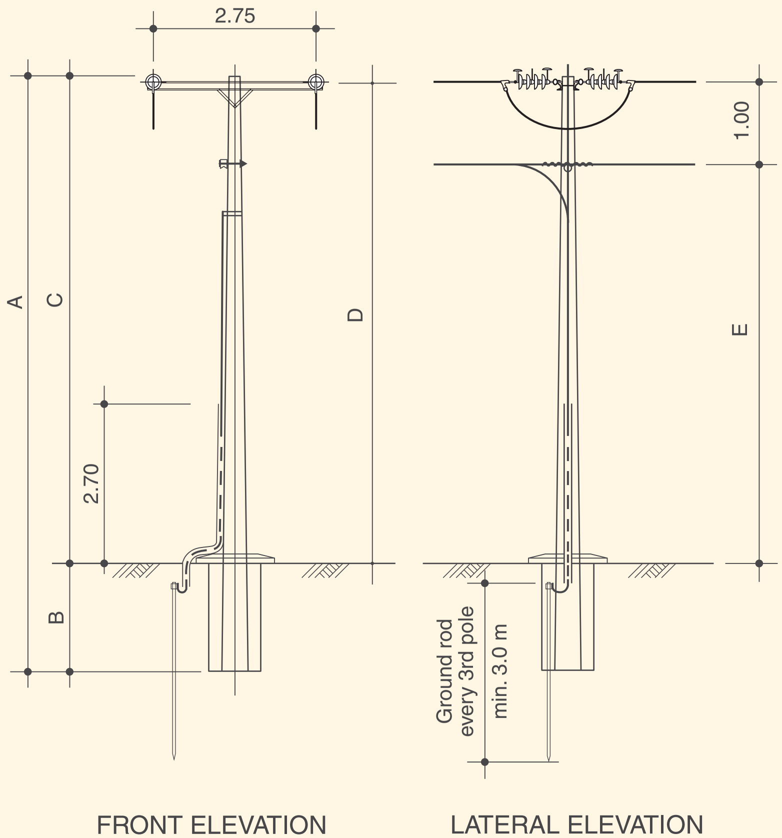
*) at +70°C, in still air



Dimensions are in meters

FIGURE C.6.C

34.5 kV Spur Line for a Two-Shield-Wire Three-Phase Iliceto Shield Wire Scheme with a Ground Conductor: Concrete Pole with Tension Insulator Strings



A [m]	B [m]	C [m]	D [m]	E [m]	Span [m] α = 0	Span [m] α = 60°	Sag*) [m]
10	1.80	8.20	8.10	7.10	100		1.82
11	1.80	9.20	9.10	8.10	130		2.59
12	1.85	10.15	9.15	9.05	150		3.17
13	1.90	11.10	10.10	10.00	150		3.17
14	1.95	12.05	11.05	10.95	150		3.17

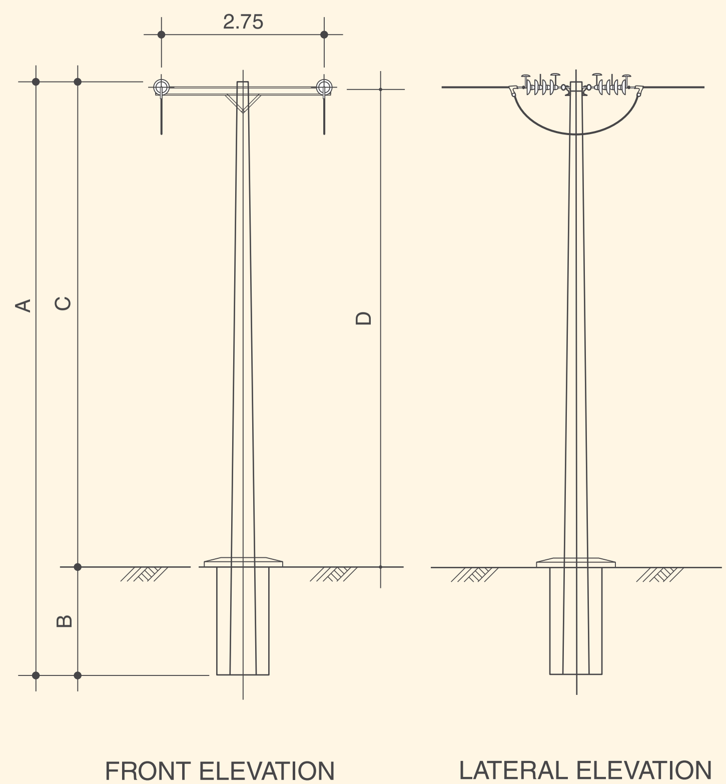
*) at +70°C, in still air

NOTE

- Heights of poles are the same as the ones of poles with line pin type insulators
- Insulator strings are formed by N° 4 cap and pin toughened glass insulators U 70 BL with disc diameter of 254 mm and spacing of 127 mm, protected by arcing rods and provided with bird antiperching devices
- Angle poles are strengthened by a galvanized steel stay
- Dimensions are in meters

FIGURE C.6.D

34.5 kV Two-Wire Spur Line for a Two-Shield-Wire Three-Phase Iliceto Shield Wire Scheme: Concrete Pole with Tension Insulator Strings



A [m]	B [m]	C [m]	D [m]	Span [m] α = 0	Span [m] α = 60°	Sag*) [m]
10	1.80	8.20	8.10	100		1.82
11	1.80	9.20	9.10	130		2.59
12	1.85	10.15	10.05	160		3.47
13	1.90	11.10	11.00	190		4.47
14	1.95	12.05	11.95	200		5.19

*) at +70°C, in still air

NOTE

- Heights of poles are the same as the ones of poles with line pin type insulators
- Insulator strings are formed by N° 4 cap and pin toughened glass insulators U 70 BL with disc diameter of 254 mm and spacing of 127 mm, protected by arcing rods and provided with bird antiperching devices
- Angle poles are strengthened by a galvanized steel stay
- Dimensions are in meters

TABLE C.1

Sag and Tension Calculation Characteristics of a Typical Conductor

• Type	AAAC 50
• Material	Aldrey alloy (Almelec)
• Cross section	48.48 mm^2
• Diameter	9 mm
• Ultimate tensile strength (UTS)	>11.635 kN
• Weight	0.1376 kg/m
• Modulus of elasticity	57000 N/mm^2
• Linear expansion coefficient	23×10^{-6} °C^{-1}
• Wind speed, v	135 km/h
• Every day stress at +20°C (referred to a UTS of 11.635 kN)	18.333%

	t = +20°C; v = 0		t = +70°C; v = 0		t = –5°C; v = 135 km/h[+)]	
SPAN (m)	T (kN)	SAG (m)	T (kN)	SAG (m)	T (kN)	SAG (m)
50	2.13	0.198	0.553	0.76	4.344	0.50
100	2.13	0.79	0.928	1.82	5.269	1.65
110	2.13	0.96	0.990	2.06	5.441	1.94
120	2.13	1.14	1.047	2.32	5.608	2.23
130	2.13	1.34	1.101	2.59	5.771	2.55
140	2.13	1.55	1.152	2.87	5.927	2.87
150	2.13	1.78	1.199	3.17	6.078	3.22
160	2.13	2.03	1.244	3.47	6.224	3.58
170	2.13	2.29	1.286	3.79	6.364	3.95
180	2.13	2.56	1.326	4.12	6.501	4.33
190	2.13	2.86	1.364	4.47	6.632	4.73
200	2.13	3.16	1.399	4.82	6.758	5.15
210	2.13	3.49	1.432	5.19	6.880	5.57

[+)] Assumed wind pressure on conductor projection is 765 N/m^2

FIGURE C.7.A
Single-Line Diagram of the 30–34.5 kV Supply Bay of Two-Shield-Wire Three-Phase Shield Wire Lines from Tertiary Winding of the High Voltage/Medium Voltage Transformer

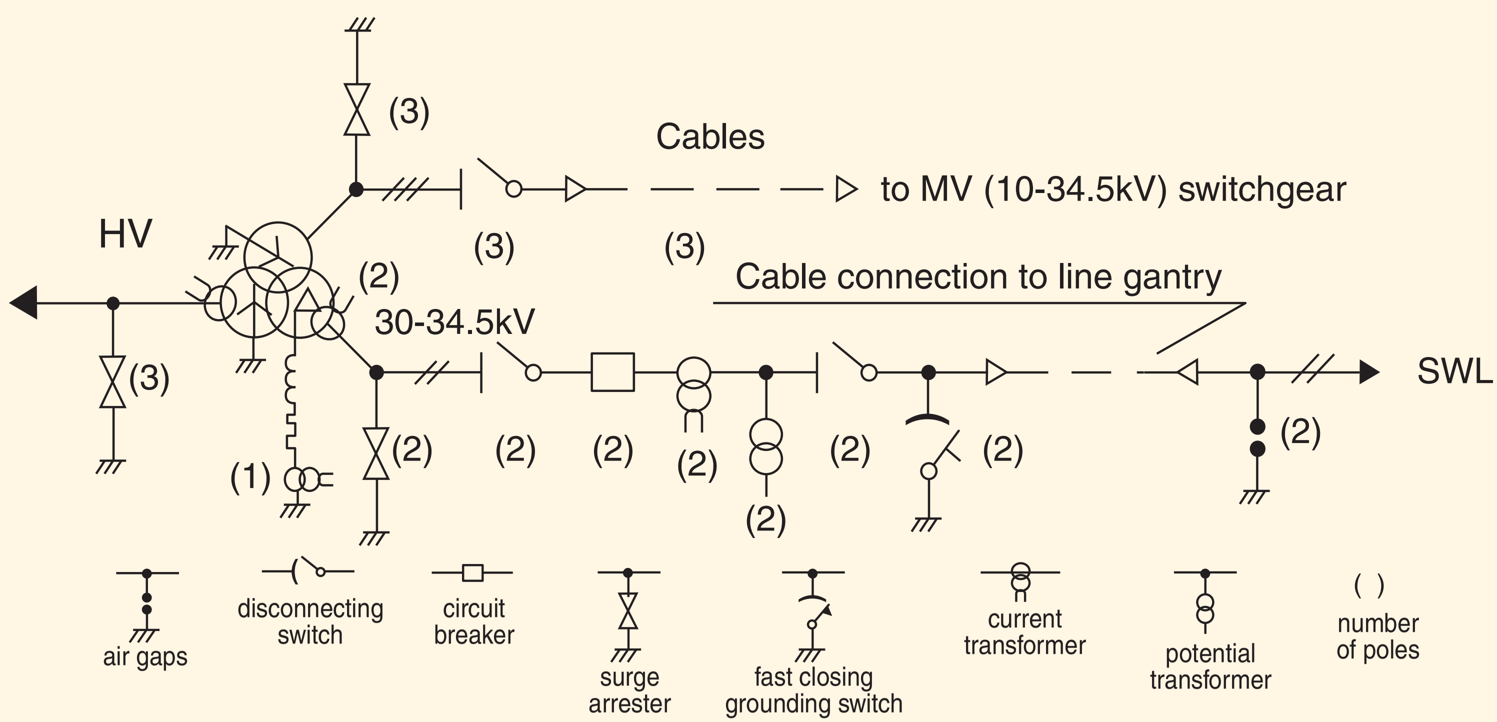


FIGURE C.7.B

Single-Line Diagram of the 30–34.5 kV Supply Bay of Two-Shield-Wire Three-Phase Shield Wire Lines from an Interposing Transformer

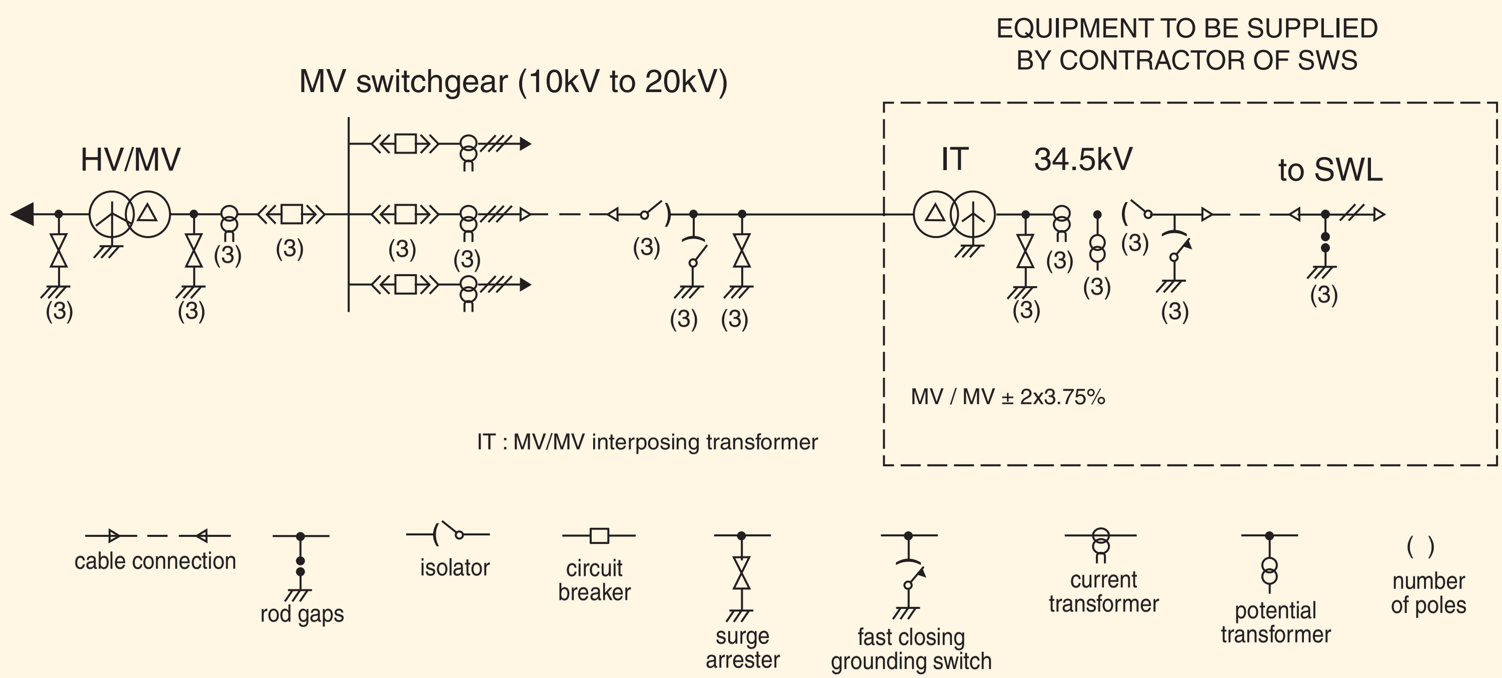
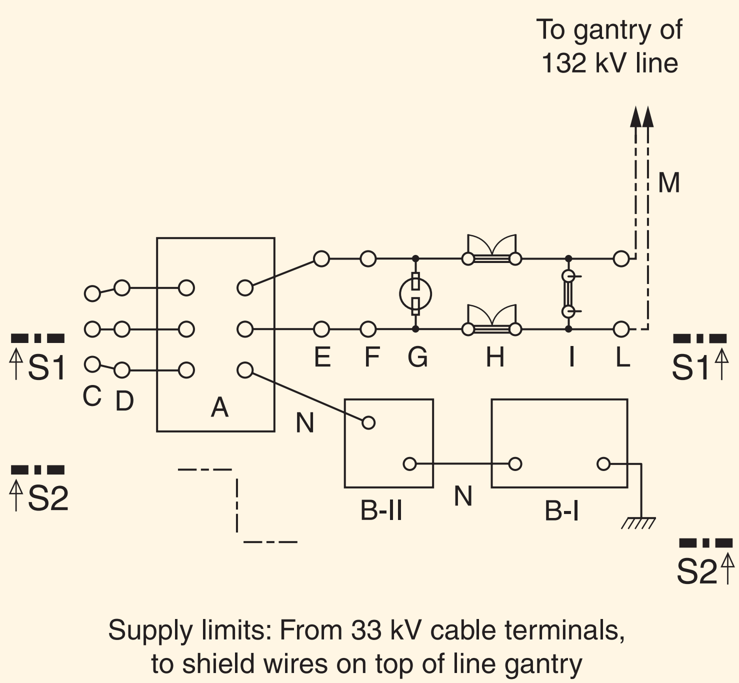


FIGURE C.8.A

Typical Preliminary Layout of the 34.5 kV Supply Bay of a Two-Shield-Wire Three-Phase Ilíceto Shield Wire Scheme: Plan



Legend

A - 33 / 34.5 kV Interposing Transformer

B - Grounding Resistor (B-I) and Reactor (B-II) if applicable

C - 33 kV supply cable terminals

D - Existing Surge Arresters (3 N°)

E - 48 kV Surge Arresters (2 N°)

F - Current Transformers (2 N°)

G - 34.5 / 0.1 kV Potential Transformer (1 N°)

H - 34.5 kV Bipolar Isolator (1 N°)

I - 34.5 kV fast closing Bipolar Grounding Switch (1 N°)

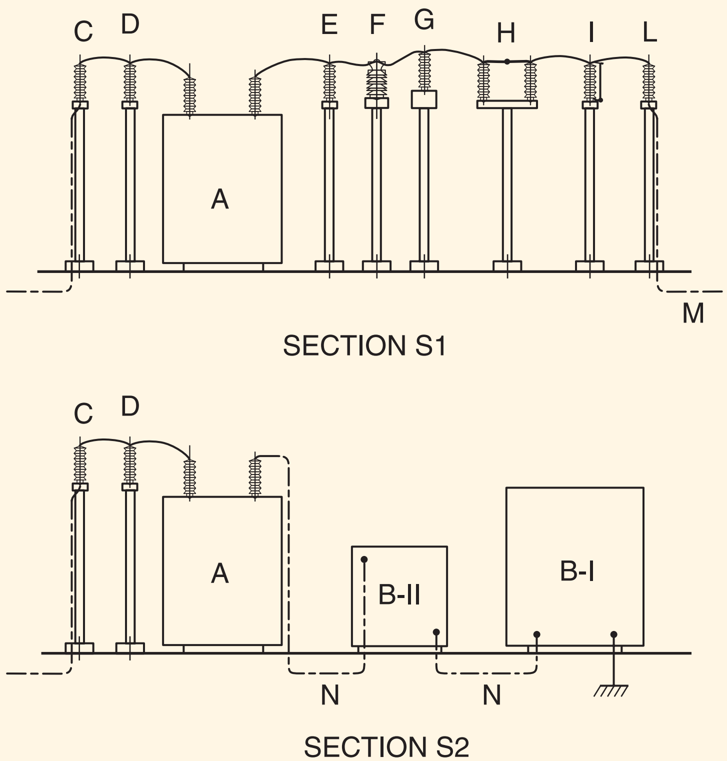
L - 34.5 kV cable terminals (2 N°)

M - Single-core cable connections to shield wires on HV line gantry (2 N°)

N - Single-core cable connections

FIGURE C.8.B

Typical Preliminary Layout of the 34.5 kV Supply Bay of a Two-Shield-Wire Three-Phase Iliceto Shield Wire Scheme: Sections



Legend

A - 33 / 34.5 kV Interposing Transformer

B - Grounding Resistor (B-I) and Reactor (B-II) if applicable

C - 33 kV supply cable terminals

D - Existing Surge Arresters (3 N°)

E - 48 kV Surge Arresters (2 N°)

F - Current Transformers (2 N°)

G - 34.5 / 0.1 kV Potential Transformer (1 N°)

H - 34.5 kV Bipolar Isolator (1 N°)

I - 34.5 kV fast closing Bipolar Grounding Switch (1 N°)

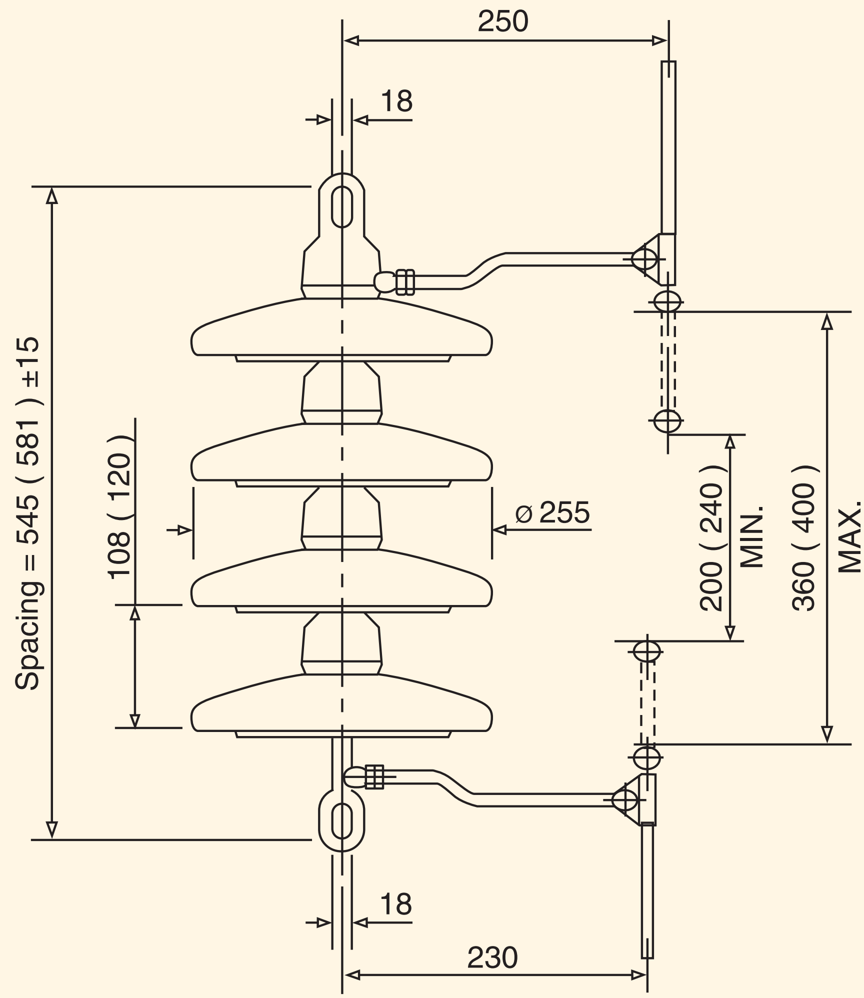
L - 34.5 kV cable terminals (2 N°)

M - Single-core cable connections to shield wires on HV line gantry (2 N°)

N - Single-core cable connections

FIGURE C.9.A

Rigid Toughened Glass Insulator String for a 34.5 kV Three-Phase Iliceto Shield Wire Scheme



- Dimensions are in millimeters
- Dimensions and withstand voltages in brackets apply for disc spacing of 120 mm
- Wet 50 Hz-60 s withstand voltage __________ 130 (143) kVrms +)
- Dry 1.2 / 50 μs impulse withstand voltage ___ 270 (295) kVpeak +)
- Creepage distance _______________________ 1200 mm
- Electromechanical falling load _____________ ≥50 kN

+) without arcing horns

FIGURE C.9.B

Typical Installation Arrangement of the Rigid Toughened Glass Insulator String for a 34.5 kV Three-Phase Shield Wire Line

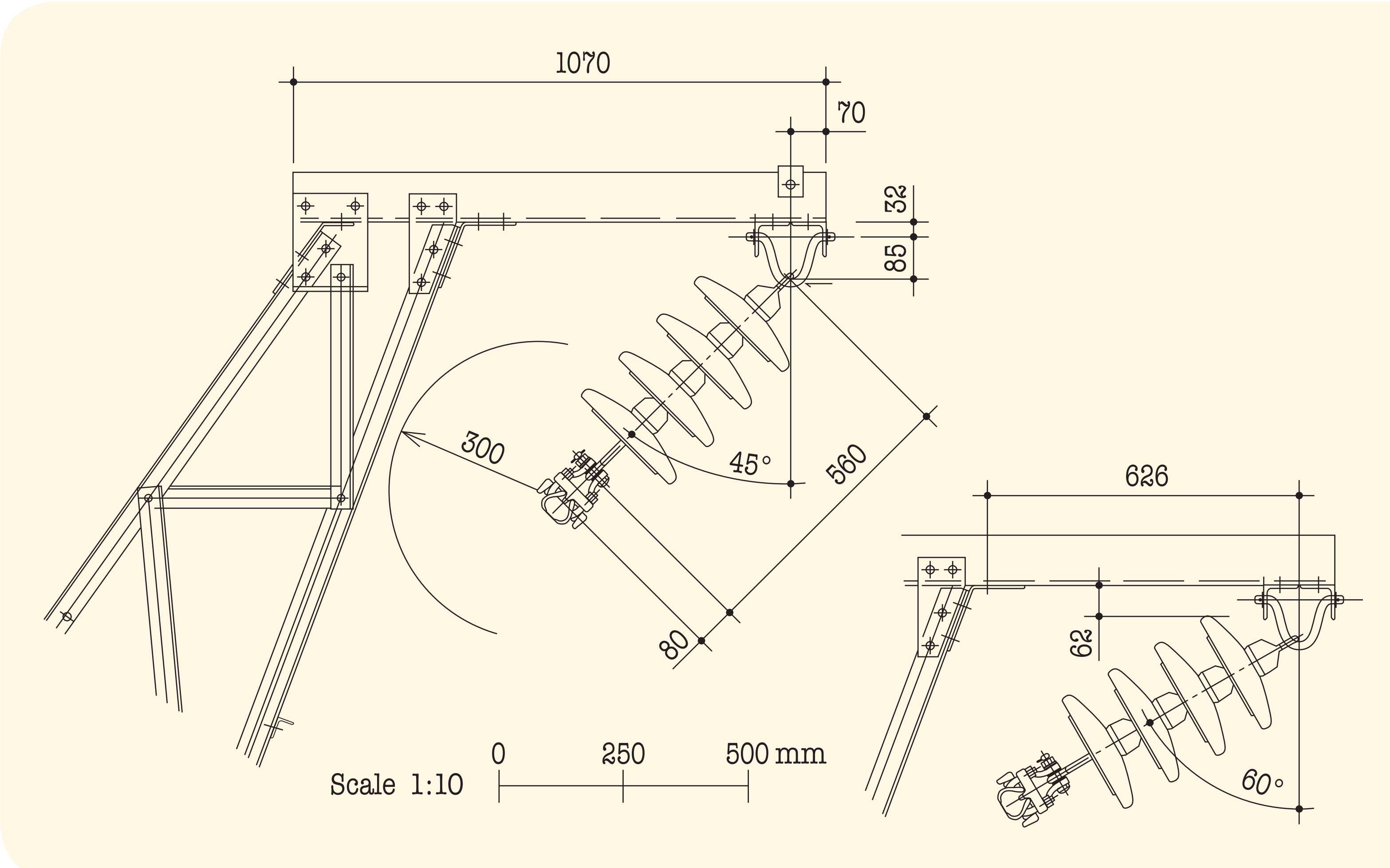


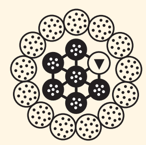
FIGURE C.10.A

Specifications for a Typical Optical Ground Wire Applicable as One Shield Wire of the Shield Wire Lines

ALCATEL CABLE	SPECIFICATION FOR SELF SUPPORTING OPTICAL FIBRE AERIAL CABLE	Telecom Product Line Product Group Optical Aerial Cables

Cable Type ASLH-D(S)bb 1 x 12 E9/125 (AA/ACS 52/30 - 7.4)

Cross Section



Design	Center	1 ACS - Wire		2,60 mm
	Layer 1	5 ACS - Wires		2,50 mm
	+	1 Steel Tube with 12 E9/125	2,10 /	2,50 mm
	Layer 2	13 AA - Wires		2,25 mm
	stranded, core and layer 1 greased			
	Cable Diameter			12,1 mm
	Cable Weight			367 kg/km
Technical Data	according to IEC standards			
	Supporting Cross Section			81,5 mm²
	Rated Tensile Strength			52,0 kN
	Modulus of Elasticity			95,4 kN/mm²
	Thermal Elongation Coefficient			16,8 10^{-6}/K
	Permissible Maximum Working Stress			267,9 N/mm²
	Everyday Stress (16% RTS)			102,0 N/mm²
	Ultimate Exceptional Stress			459,2 N/mm²
	DC Resistance			0,529 Ω/km
	Continuous Current		(Tmax=80°C; v=0,6m/s; To=35°C)	257 A
	Short Time Current		(1,0s, 20-200°C)	7,4 kA
	Maximum Permissible Installation Force			21,8 kN
	Minimum Bending Radius			182 mm
	Normal Delivery Length			4000 m
Temperature Range	Installation			-10 to +50°C
	Transportation and Operation			-40 to +80°C
Remarks	All Sizes and Values are Nominal Values Maximum Fibre Capacity per Steel Tube: 16			

FIGURE C.10.B

Typical Suspension Insulated Splicing and Post-type Terminal Coupling Unit of Optical Ground Wire

Accessoires pour conducteur à fibres optiques – ∅ 14,0 mm

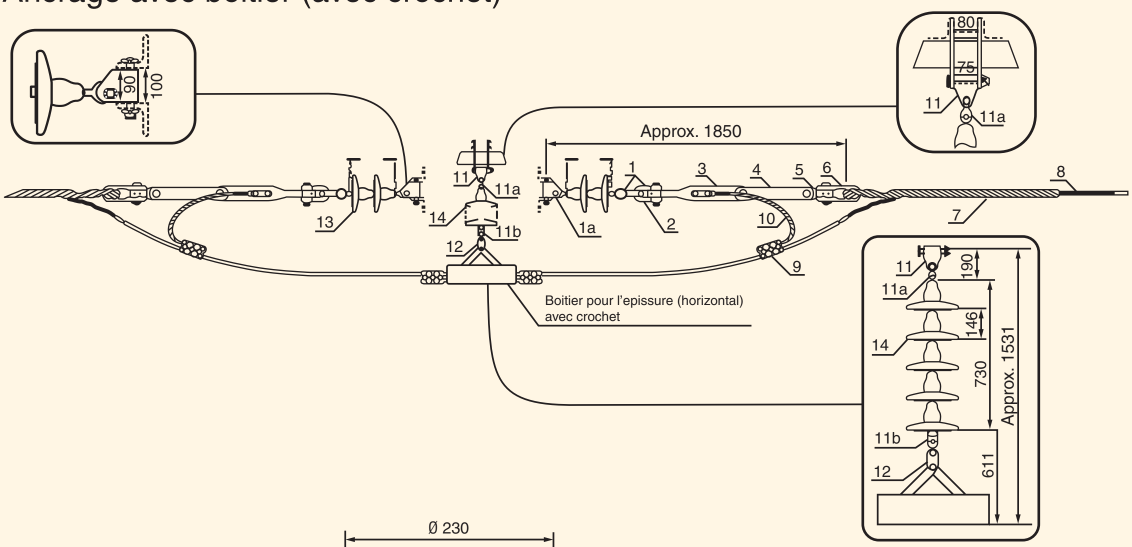
Client : nkt cables GmbH — 16.01.09

Projet : Burkina Faso – Lot 1 (Afrique)

OPPC : 74-AL3/37-A20SA – 24xG.652 – 66,1kN – 10,0kA – 14,0 mmØ
(Couche exterieure a droite)

Ancrage (33 x)

Ancrage avec boitier (avec crochet)



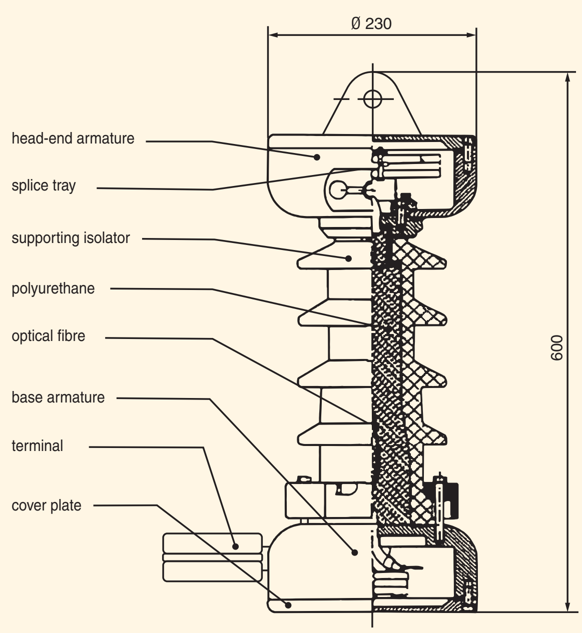
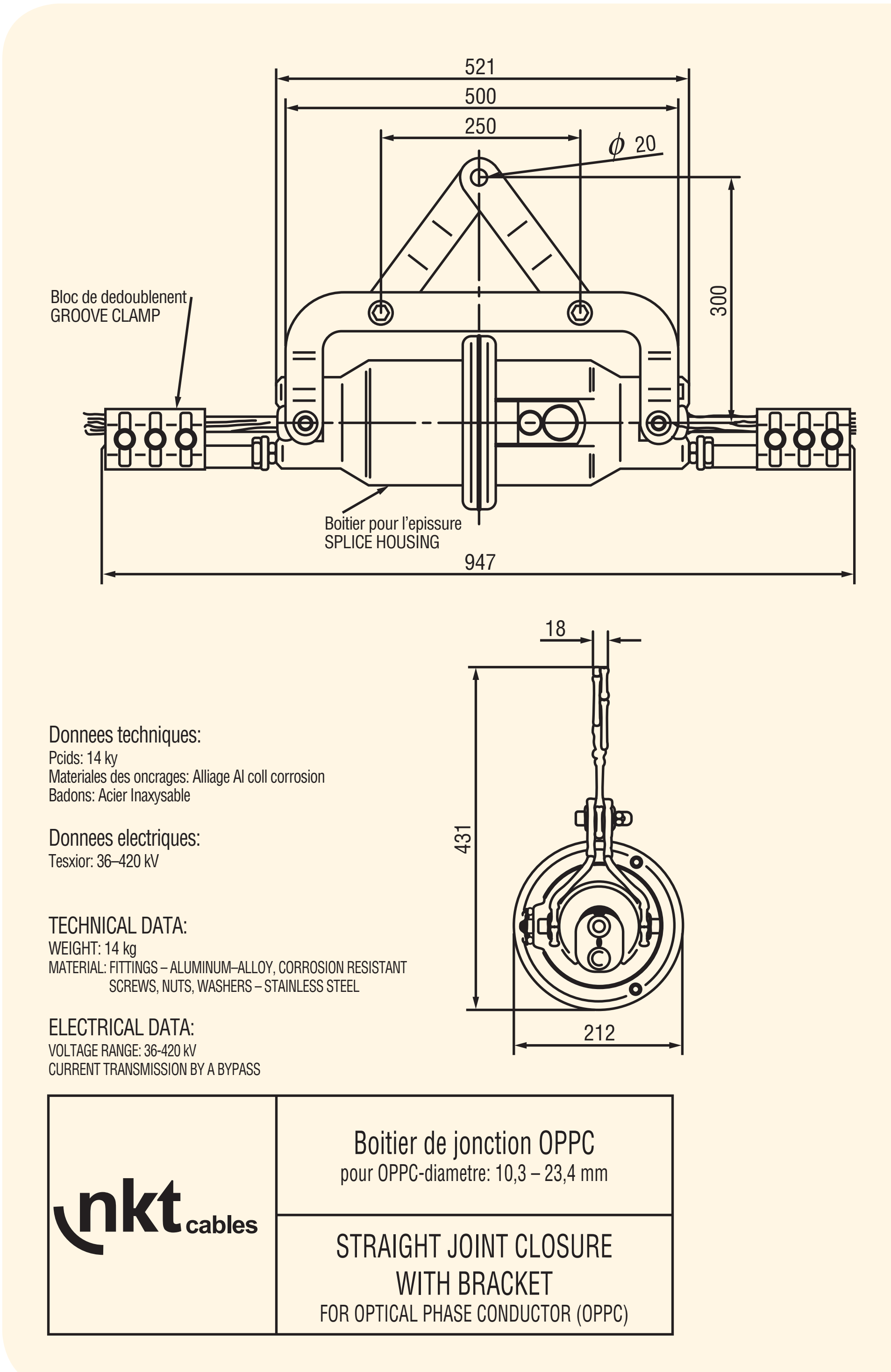


FIGURE C.10.C

Example of the Suspended Straight Splicing of the Fiber Optics and Electrical Joint of a Shield Wire



ANNEX D | SINGLE-LINE DIAGRAMS AND PHOTOGRAPHS OF ILICETO SHIELD WIRE SCHEMES IN OPERATION

CONTENTS

INTRODUCTION: INFORMATION ON ILICETO SHIELD WIRE SCHEMES

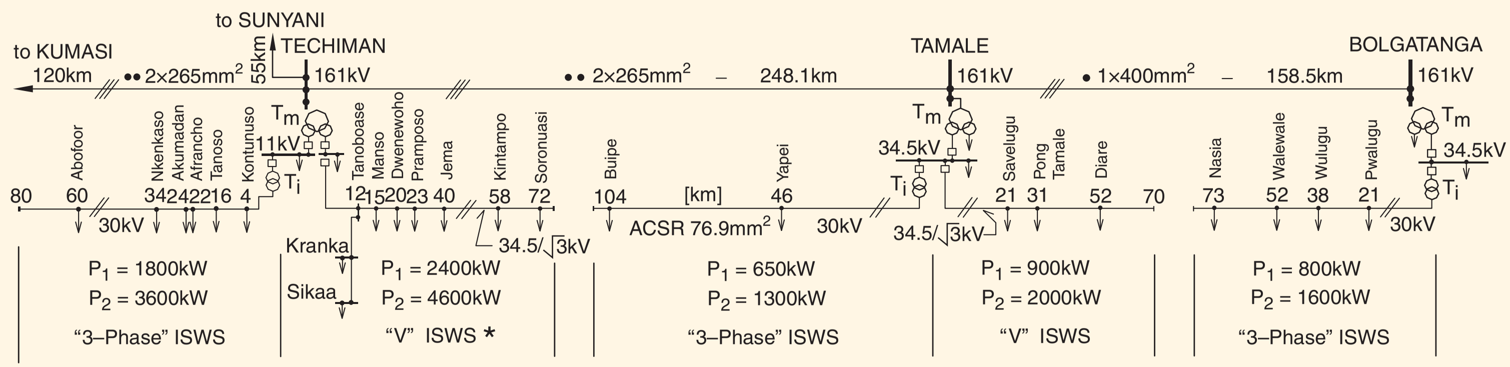
This Annex reports the single-line diagrams of the so far implemented Iliceto shield wire schemes (ISWSs) as originally planned and built. A set of available photographs of the equipment of the ISWSs is also provided.

For several ISWSs all the villages and other loads shown in the single-line diagrams were electrified from the beginning. In some ISWSs the construction of the spur MV lines and LV networks of the villages have been staged in accordance with a priority plan. Information are provided also on the present status of operation of the ISWSs as known by the writer.

- **Ghana:** About 1,000 kilometers (km) of 161 kilovolt (kV)–50 hertz (Hz) transmission lines have been equipped with shield wire lines. The 30-34.5 kV ISWSs shown in figure D.1 have been in operation since 1989, with all the villages electrified. As of 2015, all the ISWSs shown in figure D.1 are in operation, except the Bolgatanga-Nasia ISWS that has been recently replaced by conventional 34.5 kV lines. The recovered materials are used as spare parts.
- **Brazil:** Three-phase 34.5 kV ISWSs were put in operation in 1995 in a 230 kV-60 Hz line (figure D.2).
- **Lao People's Democratic Republic:** Three Single-phase earth-return 25 kV ISWSs have been put in operation in 1996 along 190 km of 115 kV-50 Hz transmission lines. Five Three-phase 34.5 kV ISWSs have been commissioned in 2002–03 with all the villages electrified, along 335 km of 115 kV transmission lines (figure D.3) and are reported to be in operation at the time of writing. The author has no information on the current status of the single-phase earth-return SWSs.
- **Sierra Leone:** A three-phase 34.5 kV ISWS has been in operation since 2010 in the first built 161 kV-50 Hz line of the country (figure D.4). The ISWS supplies at the remote end the town of Makeni (~80,000 inhabitants) and, with a spur MV line from Makeni, the town of Magburaka (not shown in figure D.4). The ISWS Freetown-Lunsar shown in figure D.4 has not been realized due to the outbreak of a civil war in the country.
- **Ethiopia:** Three single-phase earth-return 34.5 kV ISWSs were built in the late 1990s along 200 km of 132 kV-50 Hz transmission lines (figure D.5). Reportedly, they have been replace by conventional 3-phase MV lines for supplying 3-phase motors.
- **Togo:** Three-phase 34.5 kV ISWSs are in operation along 261 km of 161 kV-50 Hz lines (figure D.6). One of the shield wires is an insulated optical ground wire (OPGW). So far 19 villages have been electrified from the ISWSs.
- **Burkina Faso:** Three-phase 34.5 kV ISWSs are in operation along 330 km of 225 kV-50 Hz transmission lines (figure D.7). One insulated shield wire is an OPGW. So far only part of the villages have been electrified from the ISWSs.

FIGURE D.1

Single-Line Diagram of an Insulated Iliceto Shield Wire Scheme in Ghana, 1989



T_m – 161kV+8×1.25%/34.5kV/11kV – 20/12.5/12.5MVA

T_i – Interposing transformer

– MV circuit breaker

P_1 = Year 1999 peak load

P_2 = Year 2010 estimated load

* = To be transformed into "3–Phase" SWS in 1999

FIGURE D.2

Single-Line Diagram of the 34.5 kV 60 Hz Three-Phase Shield Wire Line in Mato Grosso, Brazil, 1995

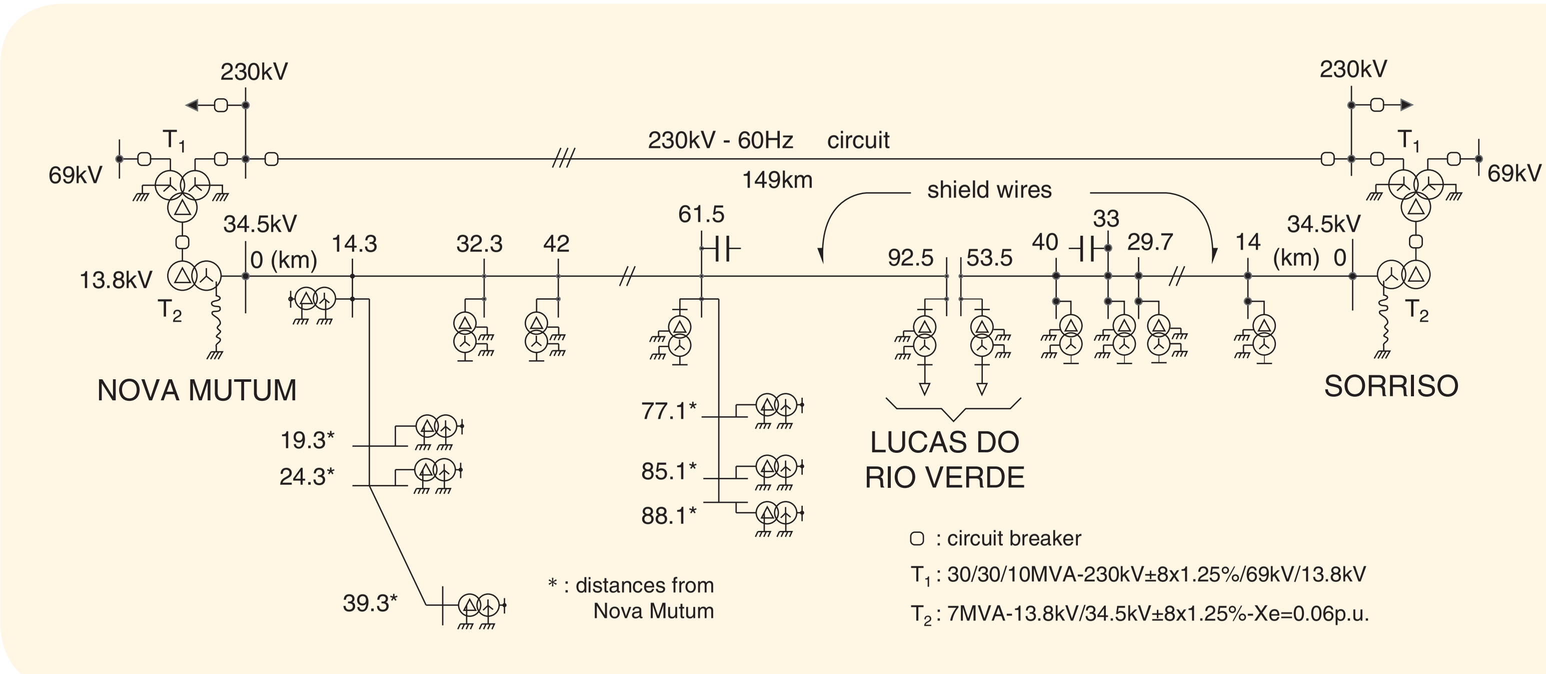


FIGURE D.3

Single-Line Diagrams of 34.5 kV Three-Phase Iliceto Shield Wire Schemes in the Lao People's Democratic Republic, 2002-3

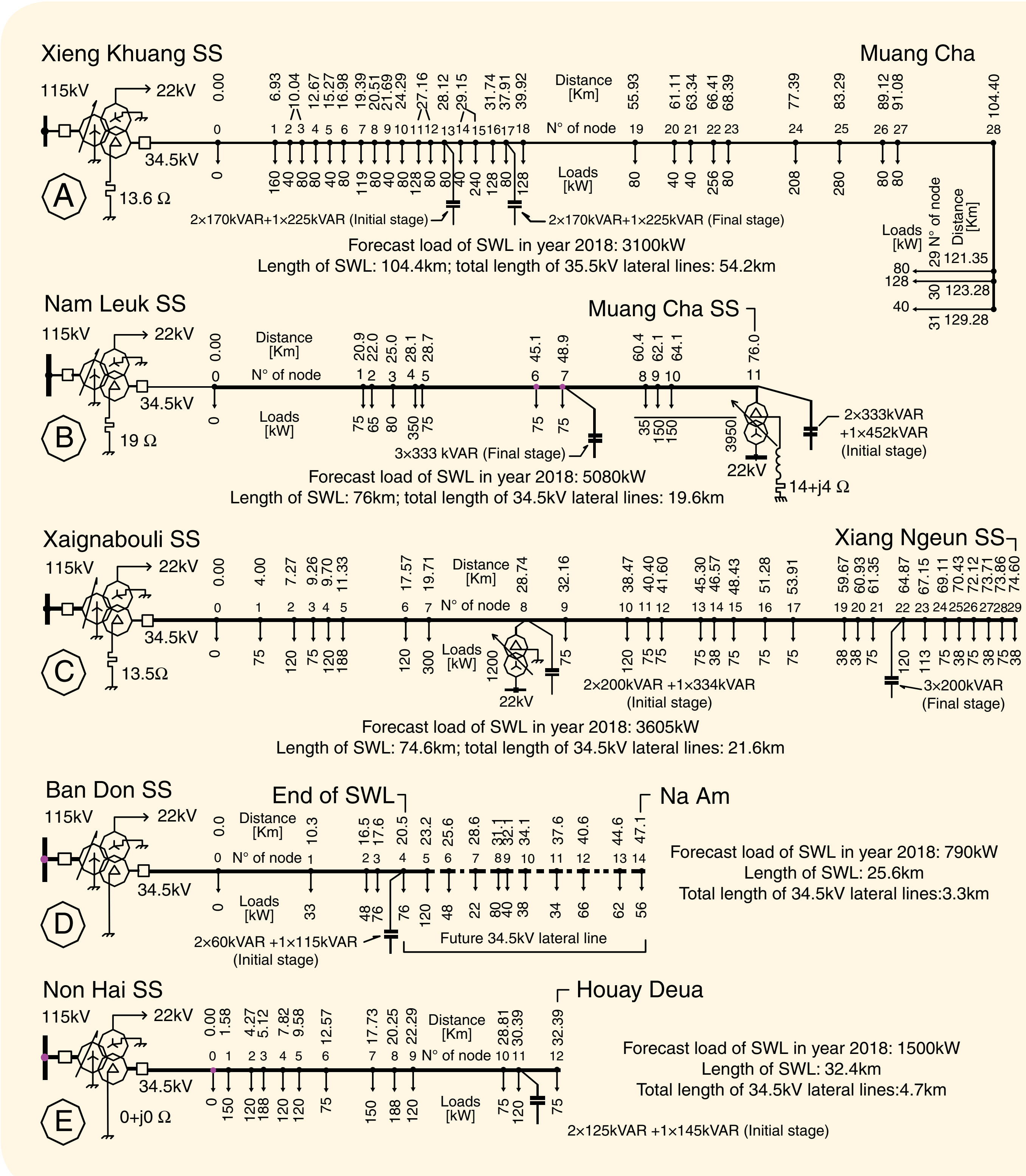
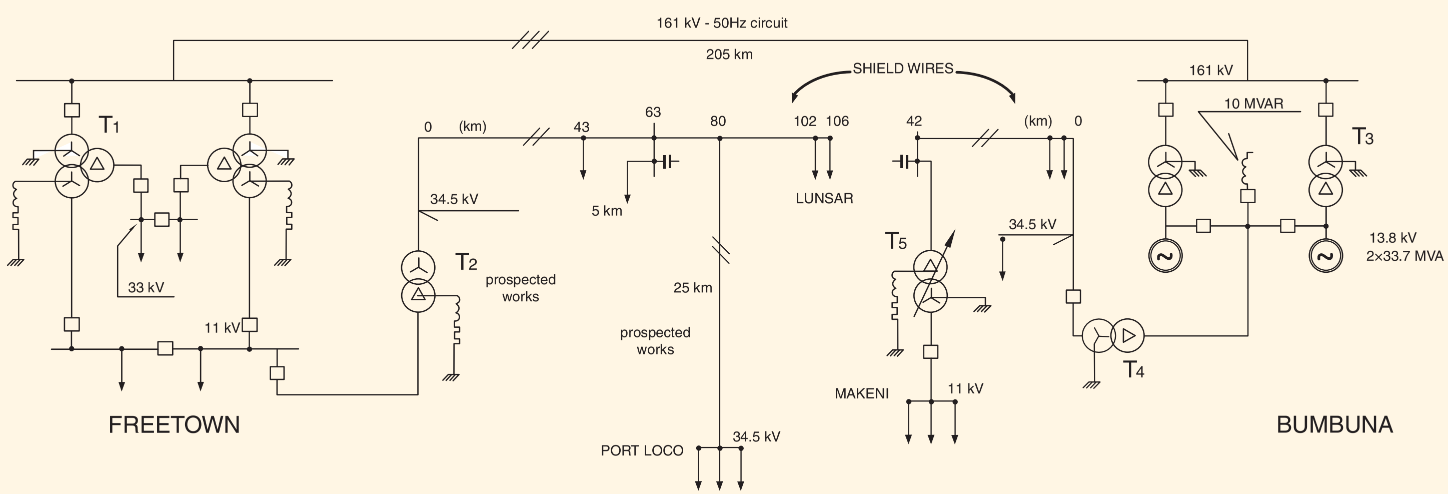


FIGURE D.4

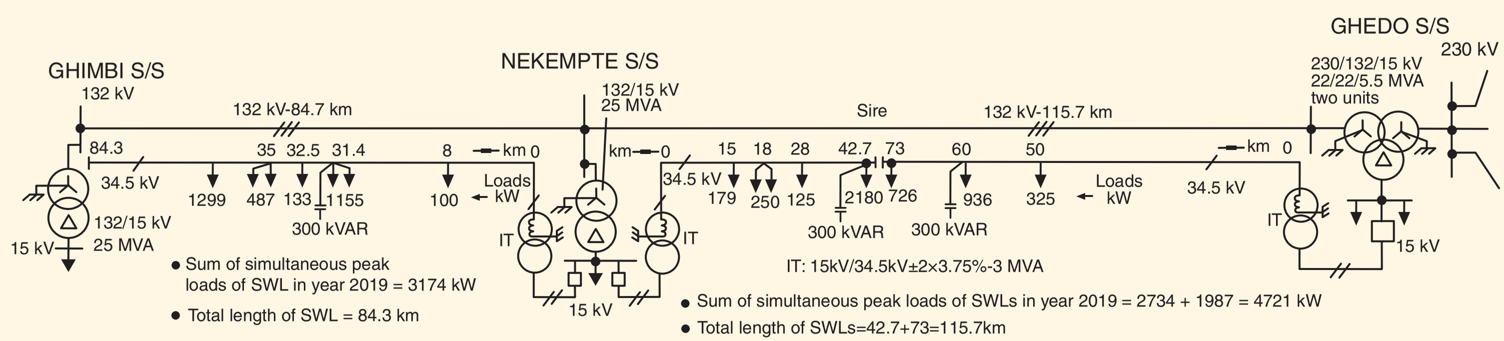
Single-Line Diagram of a 34.5 kV Three-Phase Iliceto Shield Wire Scheme in Sierra Leone, 2010



□ : circuit breaker
T_1 : 45/35/15 MVA - 161kV±10×1.25%/11.5kV/34.5kV
T_2 : 5 MVA - 11kV±2×2.5%/35.5kV-X_e=0.06 p.u. (prospected works)
T_3 : 33.7 MVA - 13.8kV/165kV±2×3.75%
T_4 : 5 MVA - 13.8kV±2×2.5%/35kV-X_e=0.06p.u
T_5 : 4 MVA - 34.5kV/11.5kV±8×1.25%-X_e=0.06p.u
T_6 : 35/35/15 - three windings, to be defined

FIGURE D.5

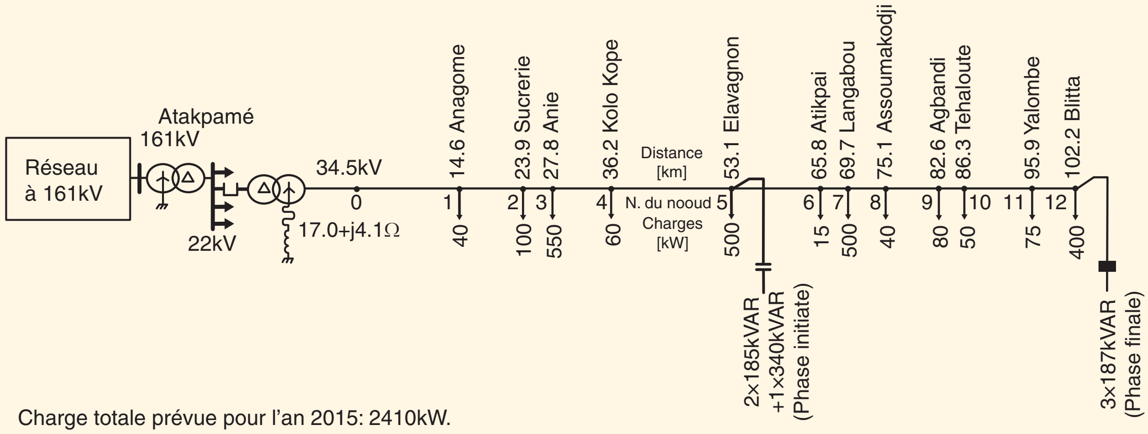
Single-Line Diagrams of a 34.5 kV Single-Phase Earth-Return Iliceto Shield Wire Scheme in Ethiopia, 2000



Note | *The operation has been discontinued.*

FIGURE D.6

Single-Line Diagrams of 34.5 kV Three-Phase Iliceto Shield Wire Schemes in Togo

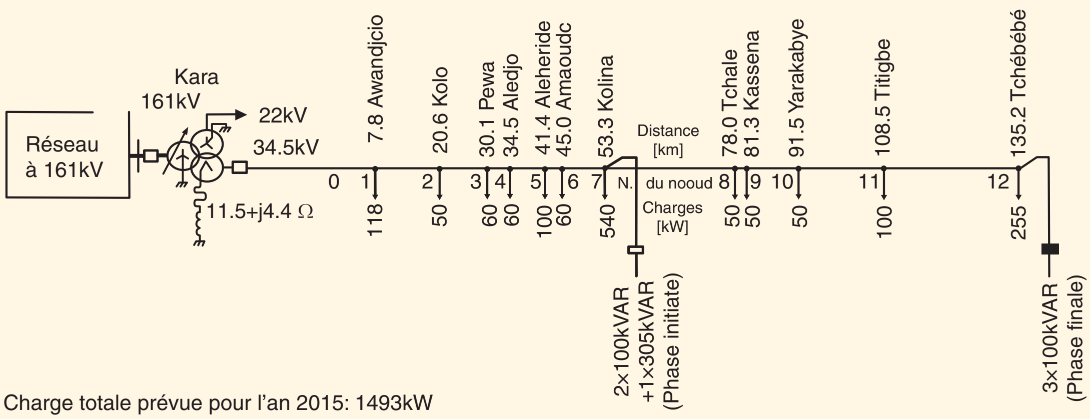


Charge totale prévue pour l'an 2015: 2410kW.

Charge maximale considérée: 3615kW (150% de la prévision de l'an 2015).

Longueur totale: 102.2km.

CDGI Al./Ac. de diametre 12.2mm.

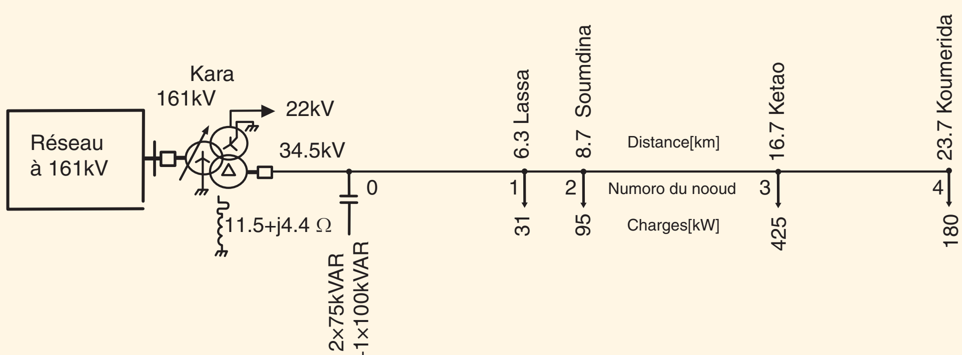


Charge totale prévue pour l'an 2015: 1493kW

Charge maximale considérée: 2239kW (150% de la prévision de l'an 2015).

Longueur totale: 135.2km.

CDGI Al./Ac. de diametre 12.2mm.



Charge totale prévue pour l'an 2015: 731kW

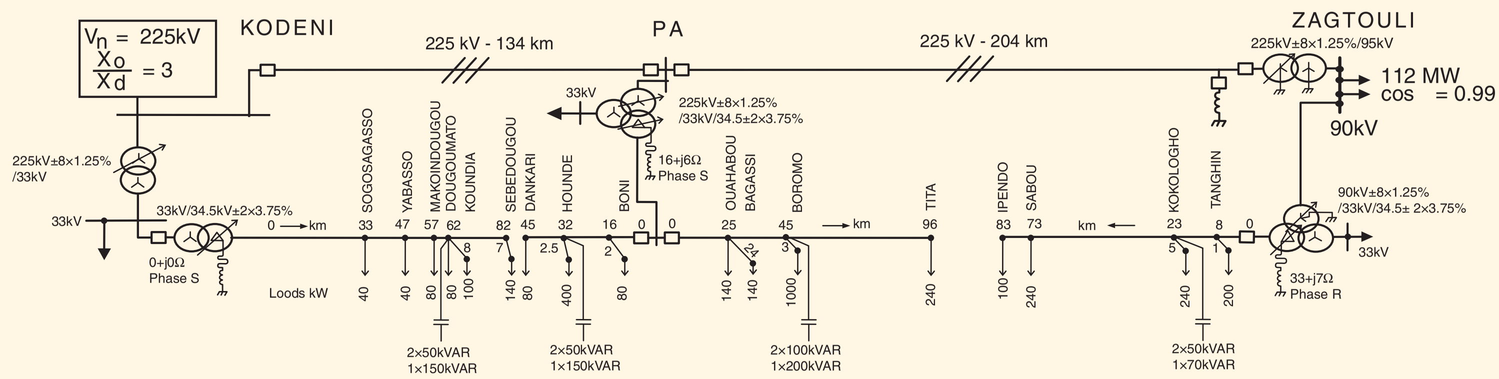
Charge maximale considérée: 1096kW (150% de la prévision de l'an 2015).

Longueur totale: 23.7km.

CDGI Al./Ac. de diametre 12.2mm.

FIGURE D.7

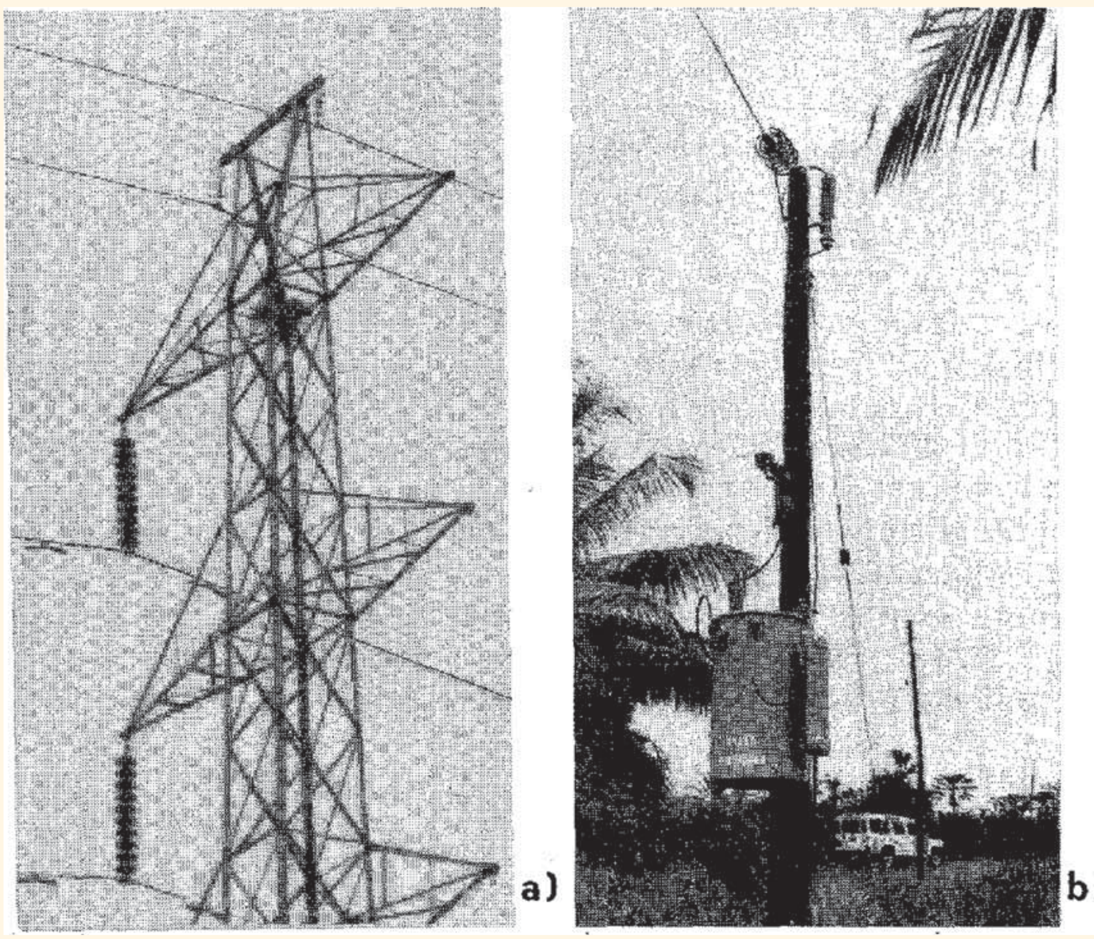
Single-Line Diagram of a 34.5 kV Three-Phase Iliceto Shield Wire Scheme in Burkina Faso



Burkina Faso - Electrification along the Bobo Dioulasso - Ouagadougou 225 kV transmission line with the "3-Phase" Iliceto Shield Wire Schemes. Loads: 200% of loads informed by Sogreah Consultants

PHOTOGRAPH D.1

Pilot 33 kV Iliceto Shield Wire Scheme Built in Ghana, 1985



a) Suspension tower with insulated shield wires; b) 100 kVA single-phase ground-return transformer station in Atabadzi. Photographed by Prof. Francesco Iliceto.

PHOTOGRAPH D.2

Suspension Tower of a 161 kV 248 km Transmission Line with Two Insulated Shield Wires, Ghana

Photographed by Prof. Francesco Iliceto.

PHOTOGRAPH D.3

Typical 30 kV Spur Line for Supply of a Village with a Three-Phase Iliceto Shield Wire Scheme, Ghana

Note | A ground conductor is strung under the two insulated phase conductors, for multiple earthing. Photographed by Prof. Francesco Iliceto.

PHOTOGRAPH D.4

Typical Intermediate Pole-Mounted Transformer Station for Public Distribution with the Three-Phase Iliceto Shield Wire Scheme, Ghana

Photographed by Prof. Francesco Iliceto.

PHOTOGRAPH D.5

Typical Terminal Pole-Mounted Medium Voltage/Low Voltage Transformer Station for Public Distribution with the Three-Phase Iliceto Shield Wire Scheme, Ghana

Photographed by Prof. Francesco Iliceto.

PHOTOGRAPH D.6

Transformer Station Supplying a Water Pumping Station, Ghana

Note | *The photo shows a 30 kV/415-240 V 3 I 5 kVA pole mounted transformer supplying a water pumping station equipped with six pumps. Photographed by Prof. Francesco Iliceto.*

PHOTOGRAPH D.7

Motors Rated at 75 kW at the Water Pumping Station of photograph D.6, Ghana

Photographed by Prof. Francesco Iliceto.

PHOTOGRAPH D.8

Transformer Station and Associated Oil Pumping Station, Ghana

Top: 30 kV/415-240 V 315 kVA transformer station supplied from a three-phase Iliceto shield wire scheme; Bottom: associated oil pumping station. Photographed by Prof. Francesco Iliceto.

PHOTOGRAPH D.9

Suspension Tower of a 230 kV 60 Hz Transmission Line with Two Insulated Shield Wires, Brazil

Photographed by Prof. Francesco Iliceto.

PHOTOGRAPH D.10

Suspension Tower of a 161 kV 200 km Transmission Line with Two Insulated Shield Wires, Sierra Leone

Photographed by Stefano Galantino/Pietrangeli S.r.l. Consultants.

PHOTOGRAPH D.11

Side View of the 34.5/10 kV 4 MVA Transformer Station That Supplies the Town of Makeni from the Iliceto Shield Wire Scheme, Sierra Leone

Photographed by Stefano Galantino/Pietrangeli S.r.l. Consultants.

PHOTOGRAPH D.12

Three-Phase Capacitor Bank, Makeni, Sierra Leone

Note | The capacitor bank was installed as shown in figure C.1b in Annex C. Photographed by Stefano Galantino/Pietrangeli S.r.l. Consultants.

PHOTOGRAPH D.13

Supply Bay of the Bumbuna-Makeni 34.5 kV Shield Wire Line through a 13.8/35.5 kV Interposing Transformer, Sierra Leone

Photographed by Stefano Galantino/Pietrangeli S.r.l. Consultants.

ANNEX E | MEASUREMENT OF GROUNDING RESISTANCE AND STEP AND TOUCH VOLTAGES OF GROUNDING SYSTEMS FOR EARTH RETURN OF CURRENT IN ILICETO SHIELD WIRE SYSTEMS

CONTENTS

E.1 INTRODUCTION

Measuring the potential to remote earth of grounding electrodes, V_{re}, and the step and touch voltages is easy when the Iliceto shield wire scheme is in operation, because there is a continuous current flow from the grounding system to the earth. Therefore, there is no need to use a temporary power supply and circuit arrangement to create a ground current flow. During the measurements, as much as possible, local loads should be switched-on for increasing the current flow on the earth.

E.2 POTENTIAL TO REMOTE EARTH. GROUNDING IMPEDANCE

The potential to remote earth, V_{re}, of the grounding systems is simply measured with a multimeter.

An insulated wire (cross section of 1 to 1.5 square millimeters is sufficient) is needed with a length of at least 10 times the maximum dimension of the grounding system. If this is a single grounding rod with length of 3 meters (m), a wire preferably 40 to 50 m long should be used. If the grounding system is formed by several grounding rods and/or buried conductors in an area with maximum diameter D, a wire with length about 10 D should be used.

The wire will be laid on the ground, starting from the grounding electrode (figure E.1) in the direction of the maximum expected electric field. Measurements can be repeated in two or three directions to identify the direction of the highest electric field, if this is not evident from the location of the grounding systems of the local spur medium-voltage (MV) lines and/or high-voltage (HV) transmission line (TL). At the other end of the wire, a small auxiliary electrode (of the type normally used for ground resistance measurements) shall be driven into the ground and connected to the wire. The multimeter shall then be connected between the grounding system to be checked and the wire. The multimeter reading provides the potential to remote earth, V_{re}.

If measurement of V_{re} is performed for the grounding mesh of a substation, the insulated wire should be laid in a direction orthogonal to the HV TLs provided with shield wires grounded in all the towers and/or with buried continuous counterpoise. The wire will be extended up to a distance for which V_{re} does not appreciably increase further.

Measurement of current injected into the grounding system, I_g, is usually carried out with a clamp-on ammeter on the connection to ground of one MV terminal of the medium-voltage/low-voltage (MV/LV) transformers (single-phase in figure E.1), or a capacitor bank, or the MV winding of the shield wire line supply transformer in the HV/MV station. The measurement of V_{re} and I_g allows calculation of the power frequency (50 or 60 hertz) impedance of the grounding system as follows:

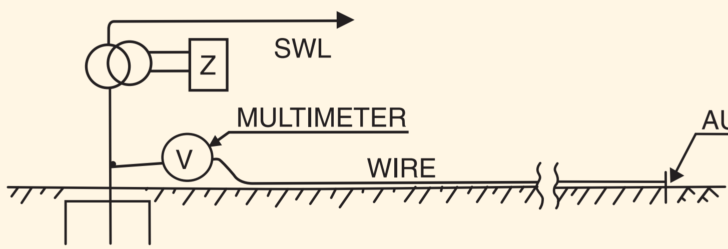
$$Z_g = \frac{V_{re}}{I_g} (\Omega) \tag{E.1}$$

Normally, Z_g is close to the resistance of the grounding system, R_g. However, in the case of use of multiple grounding electrodes distributed along an MV line, the following points should be considered:

i) Z_g can be higher than R_g, due to the importance of inductance of the ground wire supported by the poles of the MV line and connecting the various grounding electrodes (multiple grounding).

FIGURE E.1

Circuit Schematic for Measuring Potential to Remote Earth with Use of a Multimeter in an MV/LV Transformer Station



ii) The ground resistance measurement would be misleading if the measurement is performed with instruments making use of high-frequency test voltage. In fact, what is measured with an instrument using a high frequency is the impedance (**Z** = R+j2ΠfL). This can yield values considerably higher than the value of Z_g calculated with formula E.1 (at 50 hertz).

iii) The value of Z_g may differ depending on the point where the current is injected along multiple electrodes interconnected via an overhead ground wire. Ground impedance measurements should be performed with current injected in the site of installation of the MV/LV transformers and capacitor banks.

iv) *Measurement of V_{re} and calculation of Z_g with formula E.1, as described above, is the correct procedure.*

E.3 STEP AND TOUCH VOLTAGES

The step and touch voltages, V_s and V_t, can be measured with a multimeter by applying standard methods. The resistance of the human body can be considered very high and disregarded. This precautionary assumption simplifies the measurements. The assumption may yield step and touch voltages a little overestimated for the cases when the human body resistance is low.

Touch voltage is measured at a distance of 1 m from any metallic structure that can go in potential, in particular at 1 m from the structures connected to the grounding system for earth return of current, with continuous current flow. A multimeter (preset for alternating current voltage) shall be connected from the structure and a small auxiliary electrode in the ground at 1 m distance. Measurement of step voltage requires use of two auxiliary electrodes at 1m distance, radially located from the ground electrode. Step and touch voltages should be measured in various directions, to find the highest values.

In some cases, it may be difficult to measure the current injected in the earth, when the current flows to the earth via several parallel paths (for example, via the multiple grounding rods along an MV spur line).

Summation of currents measured on various electrodes can be made. If the local load is a power factor correction capacitor of known capacitance, the current can be readily calculated by dividing the shield wire to ground voltage by the capacitor impedance. Comparison of measured and calculated currents is an indicator of the integrity of the capacitor.

The measured step and touch voltages refer to the actual current, I_g, injected in the grounding system.

The step and touch voltages vary in proportion to the current flowing into the earth, and can thus be calculated for any expected current value, I_g max, when a measurement has been performed for an actual current value, I_g. The maximum step and touch voltages are the actual measured values multiplied by the ratio I_{gmax}/I_g.

E.4 ACCEPTABLE VALUES OF V_{RE}, V_S, AND V_T

To avert the risk of thermal instability (temperature run-away) of the grounding system operated for earth return of current, at the design stage the potential to remote earth, V_{re}, must be checked so that it does not exceed the value allowed by the Ollendorff formula (Equation 3.4 in chapter 3 of the manual).

V_{re} should be periodically measured in operation (at least every five years), particularly in the critical locations, during the dry season. Two requirements should be complied with:

i) V_{re} should be not higher than the maximum value allowed by the Ollendorff formula.

ii) The value of V_{re} measured for the grounding systems of the MV/LV transformer stations and capacitor banks generally should not exceed 30 V. A value up to a maximum of 50 V can be accepted only in exceptional locations.

The measured values of the step and touch voltages, V_g and V_t, are usually not higher than $0.33V_{re}$, that is, generally not higher than 10 V.

According to some national regulations, the maximum allowed value of the step and touch voltages with continuous persistence is 25 V.

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