MULTIQUIP®

GENERATOR SHORT-CIRCUIT CURRENT

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50
YEARS
ESTABLISHED 1973

2023

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Introduction

Power generation systems are designed to be free of short-circuit through careful engineering design and quality control during the manufacturing process. However, with these precautions a short-circuit can still occur within the electrical system. Some of the causes are loose connections, voltage surges, deterioration of insulation, contaminants, improper maintenance, accidental contact, and improper installation to name a few. When a short-circuit occurs within a power system several bad things happen:

- Arcing and burning at the short-circuit location.
- Current flows to the short-circuit location from various sources (parallel generators).
- Equipment and components exposed to the short-circuit are subject to thermal and mechanical stress and damage.
- Voltage drop in the system is proportional to the magnitude of the short-circuit current. The maximum voltage drops occurs at the point of the fault (can drop close to zero for maximum short-circuit current)

Overcurrent protective devices when correctly sized and maintained are designed to quickly open the circuit when a short-circuit occurs with minimum stress and damage to the system. The devices must be capable of interrupting the maximum available fault current that can be imposed at the short-circuit location. The maximum available fault current is based on the size and capacity of the power source. The larger the capacity of the power source the greater the available fault current. The most common power source is utility (transformer) and the second is a generator.

The determination of available short-circuit current from a power source is imperative in determining proper circuit protection, and to ensure the design of equipment and components are sufficient to withstand fault current imposed based on duration of time before the fault is removed by the overcurrent protective device. The determination of available fault current is a crucial factor of electrical safety and fire prevention.

Determining available fault current of a generator especially a mobile rental generator can be a challenging endeavor. The flow of available fault current from a generator to the short-circuit location is limited only by the impedance of the alternator which primarily consists of reactance and is not one simple value as a cable or transformer. Generator available short-circuit current is complex and varies with time. The current starts at a high value and rapidly decays due to alternator reactance. Explaining the change in current based on time when a short-circuit is initiated can be complicated and requires complex equations involving time as one of the variables.

The purpose of this short paper is to:

- Review the requirements for calculating available short-circuit current in an electrical system.
- Review a simple method of calculating fault current at different points within an electrical system.
- Demonstrate how to calculate available short-circuit current at different points within a temporary electrical system when the power source is a generator.
- Explain the behavioral characteristics of a generator when a short-circuit occurs.
- Explain the different reactance values assigned to generators for the purpose of calculating short-circuit current at a specific time.
- Discuss symmetrical and asymmetrical short-circuit current and for the sake of simplification use basic equations to calculate short-circuit current at the generator terminals.
- Review a generator short-circuit curve (decrement curve).

Requirements for Calculating Available Short-Circuit Current Within an Electrical System

Determining available fault current at different points within an electrical system is a requirement of the 2020 and 2023 National Electrical Code (NEC). It must be determined at each electrical device, such as motors, contactors, switchgear. panelboards, motor control centers (MCC), industrial control panels, etc. Equipment and devices must have a short-circuit current rating (SCCR) equal to or greater than the available fault current in the system otherwise potential damage can be catastrophic should a short-circuit occur. Some of the NEC requirements for calculating available short-circuit current in at electrical system are listed below:

110.10 *The overcurrent protective devices, total impedance, the equipment short-circuit current rating, and other characteristics of the circuit to be protected shall be selected and coordinated to permit the circuit protective devices used to clear faults to do so without extensive damage to the electrical equipment of the circuit.*

110.24 (A) *Service equipment at other than dwelling units shall be legibly mark in the field with available fault current. The field marking(s) shall include the date the fault current calculation was performed and be of sufficient durability to withstand the environment involved. The calculation shall be documented and made available to those authorized to design, install, inspect, maintain, or operate the system.*

408.6 *Switchboards, switchgear and panelboards (includes temporary) shall have a short-circuit current rating not less than the available fault current. In other than one- and two-family dwelling units, the available fault current and the date the calculation was performed shall be field marked on the enclosure at the point of supply.*

409.22 *An industrial control panel shall not be installed where the available fault current exceeds its short-circuit current rating as marked in accordance with 409.110 (4).*

(B). If an industrial control panel is required to be marked with a short-circuit current rating in accordance with 409.110(4), the available fault current at the industrial control panel and the date the available fault current calculation was performed shall be documented and made available to those authorized to inspect, install, or maintain the installation.

430.83 (F) *A motor controller shall not be installed where the available fault current exceeds the motor controllers's short-circuit current rating.*

430.99 *Motor control center (MCC) shall have the available fault current calculated and the date the calculation was performed documented and made available to those authorized to inspect, install, or maintain the installation.*

440.10 (A) *(Air conditioning and refrigeration equipment) Motor controllers or industrial control panels of multi-motor and combination-load equipment shall not be installed where the available fault current exceeds its short-circuit current rating as marked in accordance with 440.4(B).*

(B) When the motor controllers or industrial control panels of multi-motor or combination-load equipment are required to be marked with a short-circuit current rating, the available fault current and the date the available fault current calculation was performed shall be documented and made available to those authorized to inspect, install, or maintain the installation.

Note: Article 445.11, *The information required by the NEC to be provided with the generator is what is used to model the short-circuit current behavior of the generator. It also used to calculate the available fault current at time of installation of the generator (power source).*

670.5 (A) *Industrial machinery shall not be installed where the available fault current exceeds its short-circuit rating as marked in accordance with 670.3(A)(4).*

(B) Industrial machinery shall be legibly marked in the field with available fault current. The field marking(s) shall include the date the available fault current calculation was performed and be of sufficient durability to withstand the environment involved.

Determining available short-circuit current and overcurrent device clearing times are major factors in short-circuit current studies and hazard assessments for calculating incident energy, arcing current, protective approach boundaries and personal protective equipment (PPE) levels to minimize employee exposure to electrical hazards as outlined in the National Fire Protection Association (NFPA) 70E Standard for Electrical Safety in the Workplace. The Informational note 1# at the bottom of NEC article 110.24 states the available fault-current marking (s) addressed in 110.24 is related to NFPA 70E and provides guidance in determining the severity of potential exposure, planning safe work practices, and selecting PPE equipment. Determining available fault current at each point in an electrical system is crucial to electrical safety and equipment protection and it all starts with performing short-circuit current study of the electrical system whether it be a permanent or temporary electrical installation.

Sources of Short-Circuit Current

When calculating short-circuit current in an electrical system it imperative to consider all sources of short-circuit current and their impedance characteristics. All sources in a system can contribute available short-circuit current into a short-circuit fault. There are four sources of short-circuit current:

1. Electric Utility
2. Induction Motors
3. Synchronous Motors
4. Generators

Electric utility is the most common source of short-circuit current in an electrical system. Transformers connected to a utility system or generator are often mistakenly considered a source of short-circuit current. A transformer merely delivers the short-circuit current from the utility or generator. Transformers are designed to change system voltage and magnitude of current but generate neither. The short-circuit current is determined by the impedance of the generator and/or system to the terminals of the transformer. Typically, when available fault current at the primary terminals of the transformer is unknown the transformer secondary voltage and impedance values are used to calculate short-circuit current. Unlike transformers, generators and motors can generate short-circuit current.

Generators and synchronous motors have similar short-circuit behaviors both have field excitation by direct current and alternating current flow from the stator windings. The amount of short-circuit current is limited by their impedance. In a synchronous motor if a short-circuit occurs the voltage on the system is reduced which causes the synchronous motor to stop delivering energy to the mechanical load however the inertia of the load and motor rotor drives the synchronous motor, and the motor becomes a generator. The motor based on its impedance can deliver short-circuit current to the point of fault for several cycles.

Induction motors react to a short-circuit in a similar manner. The field of an induction motor is produced from the stator rather than DC field windings. The induction motor does not have DC field winding but there is magnetic flux in the motor during normal operation which acts like the flux produced by DC field windings in a synchronous motor. The rotor flux remains normal as long as a voltage is applied however when the external voltage suddenly drops or is removed when a short-circuit occurs the flux in the rotor cannot change instantly. Because of the inertia of the rotating parts and the fact the rotor flux cannot decay a voltage is generated in the stator windings. This causes the available short-circuit current to flow to the short-circuit location until the rotor flux decays to zero. The short-circuit current can lasts up to approximately three to four cycles. The flux can last long enough to produce a high enough level of short-circuit current to influence the momentary duty of overcurrent protective devices.

The magnitude of short-circuit current depends on the impedance of the motor. Depending on the size of the motor it can be a significant contribution to the available short-circuit current that will flow to short-circuit location. Consequently, the initial value of available short-circuit current from an inductive motor when a short occurs is approximately equal to the locked rotor starting current. Hence, the short-circuit current produced by inductive motors can contribute current to a short-circuit location in an electrical system and therefore must be considered in system short-circuit studies.

Symmetrical and Asymmetrical Current

Symmetrical and asymmetrical describe the shape of the AC wave form about the zero axis of a sine wave. Symmetrical refers to a current wave that is symmetric to a fixed reference axis see figure #1.

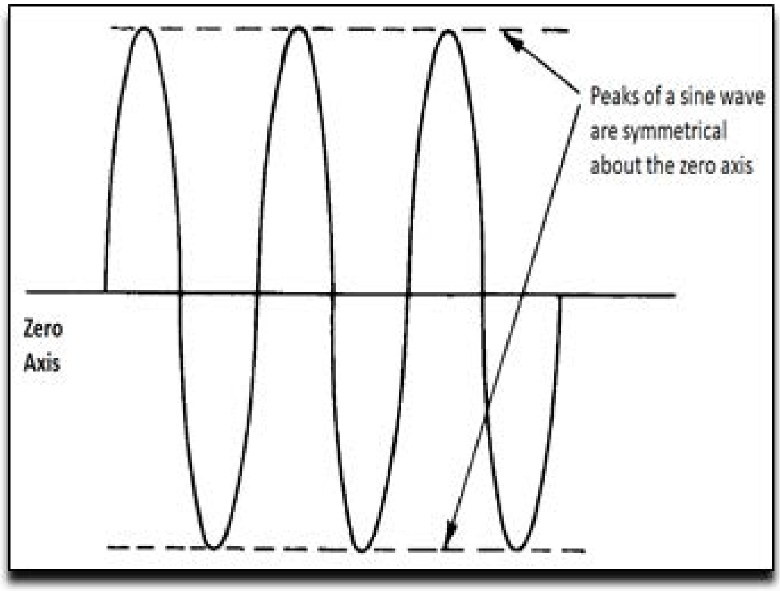


Figure #1 Symmetrical AC Sine Wave

Asymmetrical refers to a current that is not centered to a fixed reference axis and contains a direct current (DC) component which is based on the resistance in a circuit. When a current sine wave is asymmetrical it contains a combination of both symmetrical current and DC current components and is typically a lot higher than symmetrical current see figure #2

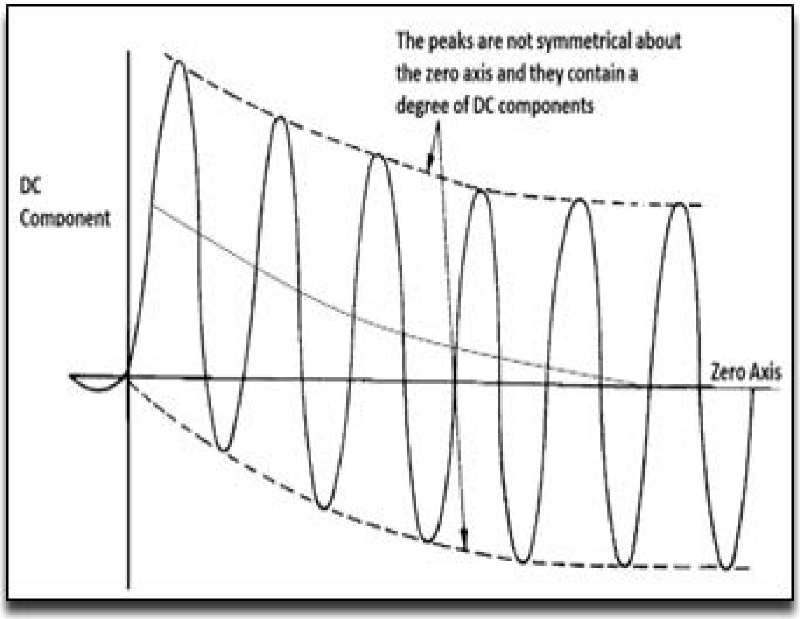


Figure #2 Asymmetrical Current Sine Wave

The point in time at which the short circuit in the system occurs determines if the resultant current is initially symmetrical or asymmetrical or a combination of both. If the short-circuit occurs when the voltage sine wave is crossing the zero-axis line, the current will be asymmetrical. If the short-circuit occurs when the voltage is at a positive or negative peak, the resultant fault current will be symmetrical. A fault occurring at any point in time between zero crossing, and the positive or negative peak will produce a lesser asymmetrical current. Most short-circuit currents are nearly always asymmetrical during the first few cycles after the fault occurs. The asymmetrical current decays rapidly and symmetrical becomes the significant current.

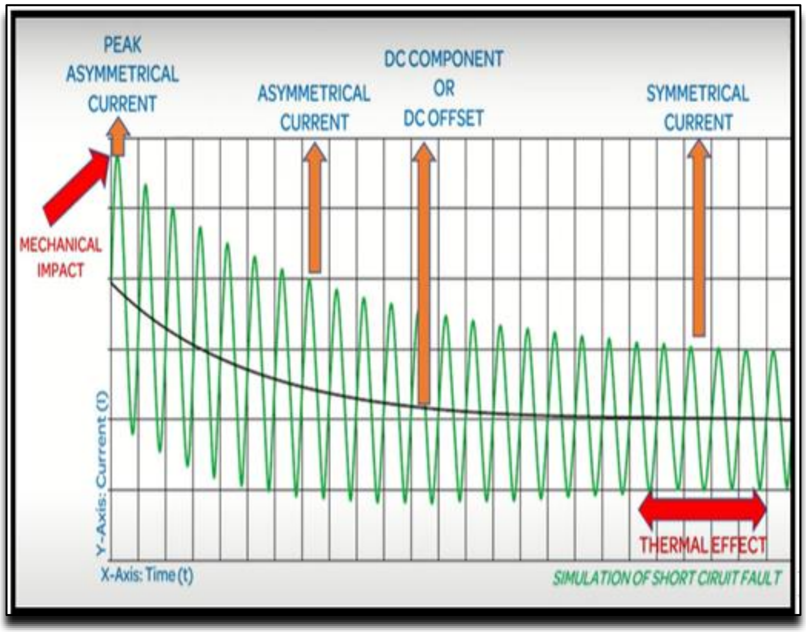


Figure #3 Behavior of Short-Circuit

To better illustrate the typical behavior of a short circuit in an electrical system refer to figure #3.

- DC Component: Depends on the X/R ratio of the of the source of fault current.
- Symmetrical Current: Symmetry around time-axis that has no DC component.
- Asymmetrical Current: Asymmetry around time-axis and is the sum of symmetrical and DC components.
- Peak Asymmetrical Current: Highest value of asymmetrical current at the peak which occurs at the 1st half cycle based on at point in the cycle the fault occurs.

Asymmetrical current is significate for two important reasons. First, the electromagnetic force exerted on parts of the systems that carry current and secondly is the amount of thermal energy content of the short-circuit which is dissipated as power I^2R. The amount of both mechanical force and thermal heat are at their highest peak when the short circuit is initiated which can create both mechanical and thermal damage and stress to equipment.

The impedance, or combined reactance and resistance, control the flow of current in an alternating current circuit. **X/R ratio** is the relationship of the resistance and reactance of a circuit. Resistance of a circuit is low compared with the reactance. The degree of asymmetry depends on the ratio of resistance to reactance. The short-circuit current in a circuit typically decays to a steady state value due to the apparent change in reactance during the short-circuit. With a degree of resistance in a circuit the DC component will also rapidly decay to zero as the energy is dissipated as heat or I^2R power in the circuit.

Ohmic Method of Calculating Available Fault Current in an Electrical Circuit

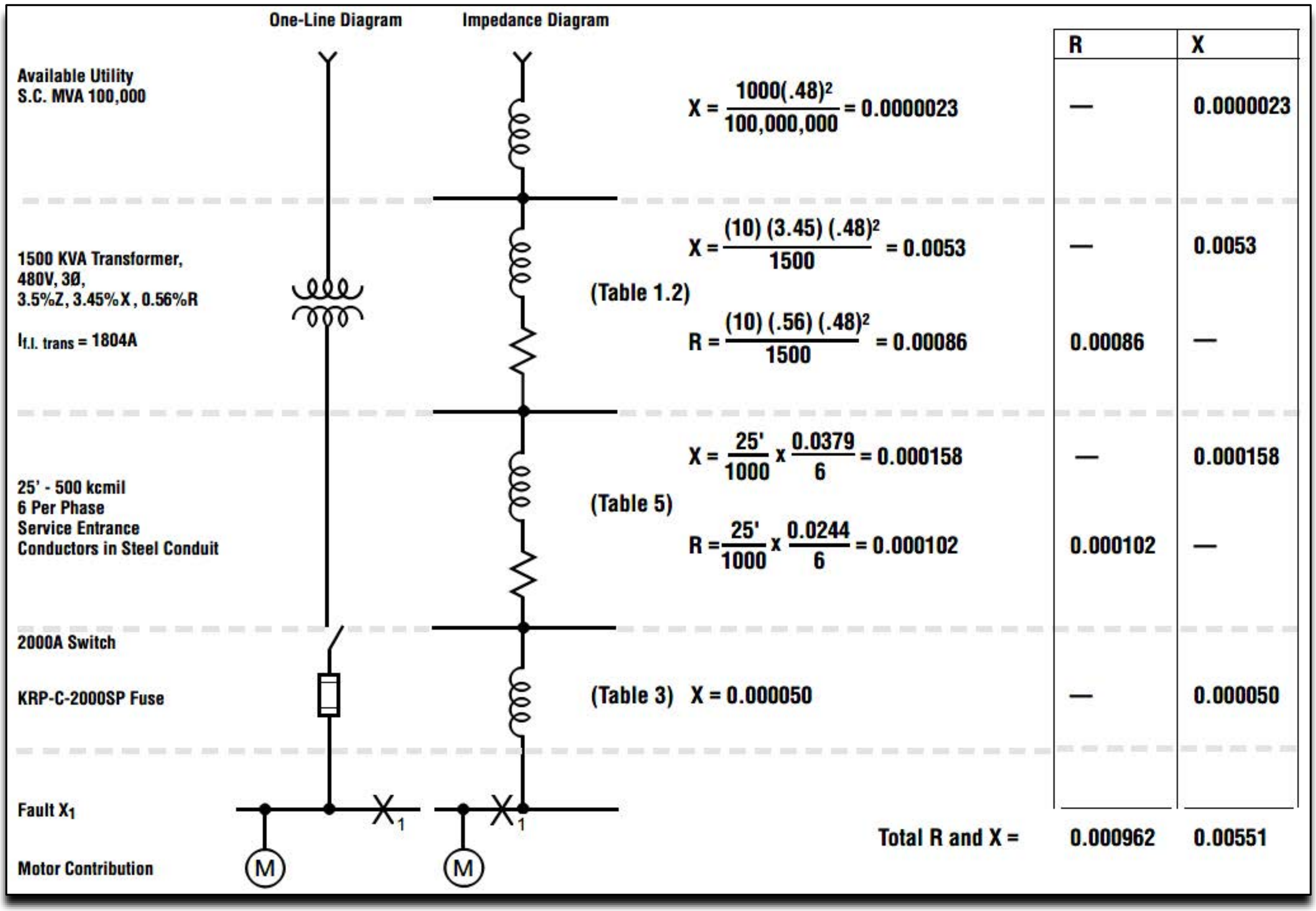


Figure #4 Combined One-Line Electrical System & Impedance Diagram

Available short-circuit current can be calculated down to the point of the short-circuit within an electrical system by using the *ohmic* method and the tables found in pages 31-33. Using the single line drawing / impedance diagram in figure #4 the available fault current can be calculated for both symmetrical and asymmetrical current at each point.

To find the available fault current at X1 in the system the first step is to find the impedance of X1

Impedance (Z) = $\sqrt{R^2 + X^2}$

$$\sqrt{0.000962^2 + 0.00551^2} = 0.0056\ ohms$$

Use Ohms law to find RMS symmetrical fault current.

$\frac{480V}{\sqrt{3}\cdot(0.0056\ ohms)} =$ 49,489A RMS Symmetrical current

Motor contribution is approximately equal to the lock rotor current of the motor.

For this example, the full load current of the motor is 1804A

Motor contribution is 1804 x 5 = 9020A RMS symmetrical.

49,489 + 9020 = 58,509A RMS symmetrical current at fault location marked X1.

The power factor of a short-circuit is determined by the series resistance and reactance of the system from point of short-circuit back to the source. The power factor can be used to determine the multiplier to calculate asymmetrical current.

Example: total resistance and reactance at fault location marked X1, R=0.000962, X=0.00551. The power factor is 17.1% determined by the following formula,

PF = R/Z (100), PF$_{SC}$= $\left(\frac{R}{\sqrt{R^2+X^2}}\right)100$

The relationship of the resistance and reactance is expressed in terms of the X/R Ratio.

(X) 0.00551 /(R) 0.000962 = 5.727 X/R ratio.

Short-circuit power factor can also be determined by the following equation. PF$_{SC}$ = cos $(tan^{-1}(X/R)) * 100$

Asymmetrical current can be calculated based on the ohmic method for calculating short-circuit current in a system and utilizes the short-circuit power factor and/or the X/R ratio. For this method you must use the table 8# provided on page 32 to determine the multiplier.

The power factor is 17.1% and the X/R ratio is 5.727.

The Asymmetrical multiplier can be found in table 8, use the column marked Mm which will provide the worst-case scenario of asymmetrical current in the first ½ cycle.

49,489A Symmetrical x 1.295 = 64,088.25A Asymmetrical

Motor contribution: 5 x 1804 = 9,020A

Total current 64,088.25A + 9,020A = 73,108A asymmetrical short-circuit current at fault location marked X1.

Based on the X/R ratio the current will lag the voltage by less than 90° see figure #5.

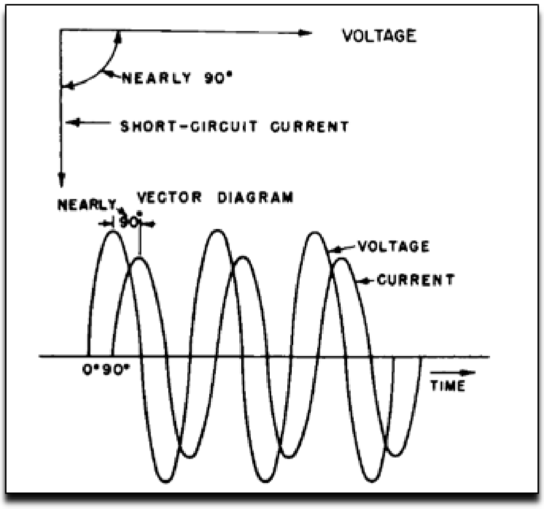


Figure #5 Phase Relationship between Voltage & Short-Circuit Current

If we look at the available fault current at different points within the electrical system, we can see based on the sum of the impedance at different points the available short-circuit current drops the further we get from the power source.

Transformer secondary terminals:	51,613A sym.
Fuse:	49,563A sym.
At terminals of the Motor	49,489A Sym.

Motor contribution to short-circuit current must be added to each point.

Asymmetrical current also referred to as total current has both AC & DC components. You can calculate the asymmetrical current based on time. For practical purposes it can be express as

$$I_{sc\ asym} = I_{sc\ sym}\sqrt{1 + 2\left(\frac{DC\%}{100}\right)^2} \qquad e^{\frac{-\omega t}{X/R}} \times 100 = DC\%$$

$\omega = 2\pi 60$, t = time (1 cycle = .017), X/R ratio = 5.727. RMS symmetrical current = 56,706A.

If we look at the Isc asym. at a half of a cycle based on the equation the DC% is 59% so the asymmetrical current is 73,883A. At 1 cycle the DC% is 32.65% so the Isc asym. current is 62,462A. As you can see in this example the DC component decays rapidly based on time. The DC component is based on the short-circuit ratio and in this example completely decays in approximately 2 cycles where the current left is symmetrical only. The most mechanical stress on a system from a short-circuit occurs within the first 0.5-1.5 cycles when total current is at its highest point.

The total asymmetrical current is the current that a circuit breaker must interrupt at its contact parting time. Per IEEE C37.04, contact parting time is the sum of ½ cycle, as the minimum relay operation time, and the minimum operating time of the circuit breaker. For example, contact parting time, including ½ cycle for relay operation, is assumed as 1.5 cycles for 2-cycle breaker, 2 cycles for 3-cycle breaker, and 3 cycles for 5-cycle breaker. If the contact parting time is different from the above-mentioned assumed times, for example due to faster or slower relay operation, the required asymmetrical interrupting capability should be adjusted. It very important the overcurrent protective device is sufficiently sized and set to handle the total short-circuit current imposed.

Example, if the short-circuit X/R ratio is 5.727 if the contact parting time (interrupting time) is 1.5 cycles the circuit breaker is required to be able to interrupt a fault current with a $e^{\frac{-0.025\times 377}{5.727}} x 100 =$ 19.2% DC component, and hence the total asymmetrical current that the circuit breaker must be capable of interrupting is $\sqrt{1+2\times(0.192)^2}$ =1.0362 times the specified symmetrical short circuit rating. If the X/R ratio is 32 with a circuit breaker cycle time of 1 cycle the circuit breaker must be capable of handling a DC component of $e^{\frac{-0.025\times 377}{5.727}} x$ 100 = 82.2% and be capable of interrupting asymmetrical current of $\sqrt{1+2*(0.822)^2}$ = 1.53341 times the specified symmetrical short-circuit rating.

Generator Performance during a Short-Circuit

Generators performance during short-circuit is a bit more complex to calculate because the fault current rapidly decays within milliseconds to a steady-state and generator windings have little ability to withstand the sudden heating effects and mechanical stress imposed by a fault. The thermal withstand rating of the winding is around 7 to 10 seconds at 300-400% of rated current for a three-phase bolted faults, 3-6 seconds for line-to-line fault. The terminal damage curve for a ground-fault or single- phase fault is drastically reduced to around 1 to 3 seconds due to magnitude of L-N fault current which does not decay. Plus, generators must be designed to provide adequate fault current to a short-circuit downstream in the electrical system to provide overcurrent protective devices enough time to react.

The amount of available short-circuit current a generator can produce during a short-circuit event is based on the generator voltage, impedance, and the generator excitation support system. When a generator experiences a sudden load increase, such as a starting a motor, or short-circuit the output voltage and speed of the genset drops which causes the voltage regulator to react by increasing the amount of current to field excitation to attempt to stabilize the voltage. The requirements for excitation vary according to the power factor. Therefore, excitation requirements are greatest at lagging power factors and less at leading power factors. Naturally the power factor of a short-circuit is low so the voltage regulator will maximize the amount of field force current which will increase the steady state short-circuit current to approximately 2-4 times the base current depending on the performance characteristics of the voltage regulator and excitation system. Generator excitation support systems such as the open-delta or permanent magnet generator (PMG) excitation system are immune to non-linear loads and provide excitation support during transient load changes. The open delta system is a separate set of auxiliary windings in the alternator separate from main load windings and rely on residual magnetism for voltage buildup.

By design the mutual inductance with the main winding is minimized so not to be affected by non-linear load and allow the voltage regulator to perform under transient load changes such as motor starting or short-circuit.

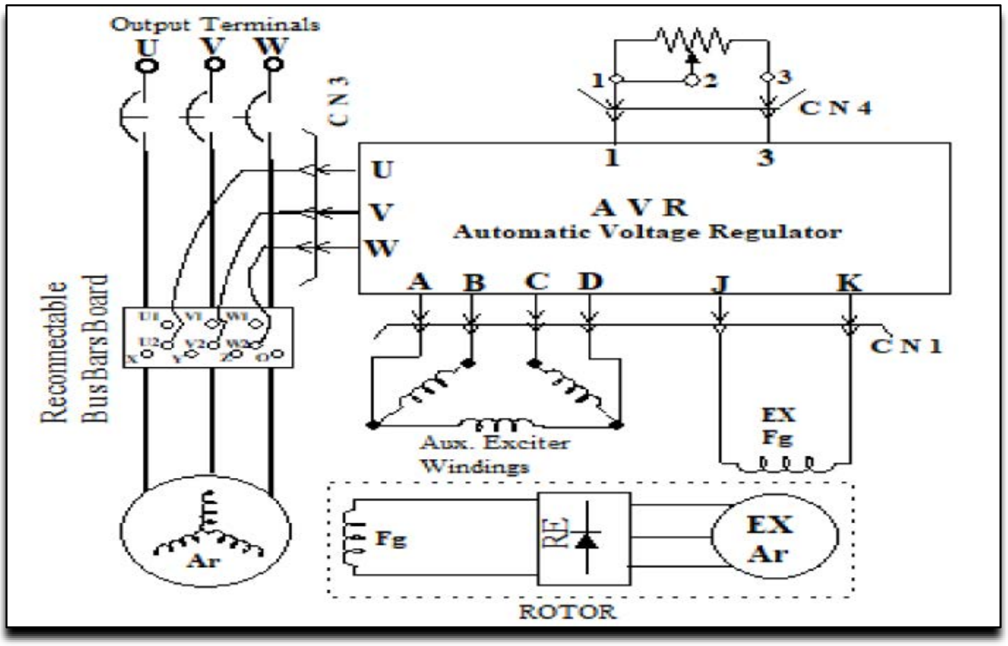


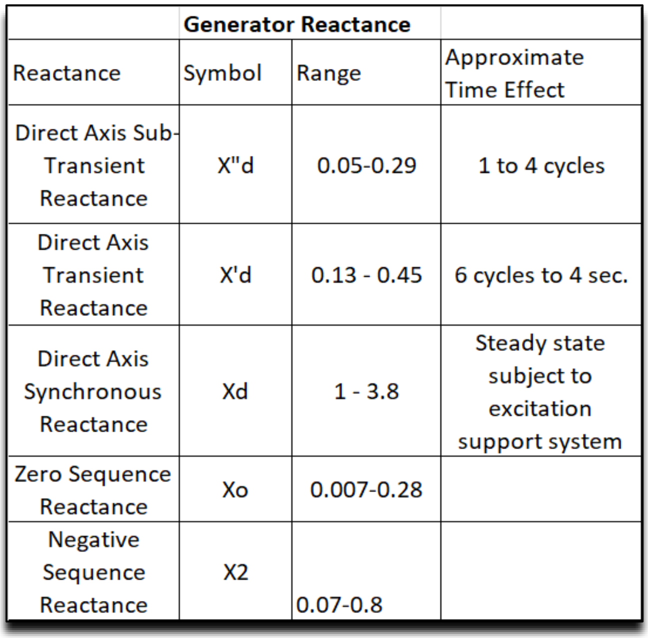
Figure #6 Open Delta Excitation System

The auxiliary windings are coupled to one another in a three-phase series connection or open-delta with two open ends. See figure #6 for an illustration of the open delta exciter system. The four terminal points of the windings connected to the AVR allow for automatic switching between the output points of the open delta winding to provide current support to the field windings as load demand on the generator changes. This multiple output open delta configuration allows the AVR to utilize the first field harmonic to generate power for normal operation, respond to transient loads and motor starting inrush current by utilizing the zero-phase component having the third harmonic obtained through the open ends of the series connected windings.

The employment of the zero-phase component for field control makes it possible for the AVR to have excellent response to motor starting inrush current and short-circuit faults beyond the standard of 300% of base current for short period of time to allow protective devices time to react to a short circuit.

Generator Reactance

The voltage and impedance, or combined reactance and resistance in generators determines the amount of short-circuit current available at the generator terminals. Reactance is such a large part of the total impedance that resistance can be disregarded. The amount of current that will flow because of a ground-fault or short-circuit is determined by the various reactance regions assigned to the generator (assuming constant field current). The effect of armature reaction to the generator air gap flux causes the current to decay over time from an initial high value to a steady state value dependent on the generator reactance. Reactance is dependent on the behavior of the flux in the armature. Figure #7 list the different reactance's that are used to determine the performance behavior of current in a generator.



	Generator Reactance		
Reactance	Symbol	Range	Approximate Time Effect
Direct Axis Sub-Transient Reactance	X"d	0.05-0.29	1 to 4 cycles
Direct Axis Transient Reactance	X'd	0.13 - 0.45	6 cycles to 4 sec.
Direct Axis Synchronous Reactance	Xd	1 - 3.8	Steady state subject to excitation support system
Zero Sequence Reactance	Xo	0.007-0.28	
Negative Sequence Reactance	X2	0.07-0.8	

Figure #7 Generator Reactance Table

Reactance is typically expressed in ohms or per unit. Direct axis synchronous reactance determines steady-state current flows in a generator. When a sudden change from steady state occurs, such as load change due to motor starting or short circuit, other reactance value come into play. This happens because the magnetic flux in the alternator cannot change immediately.

Direct axis sub-transient reactance denoted as X”d is the apparent reactance of the stator winding at the instant a short-circuit occurs, and it determines the maximum current flow during the first few cycles of a short-circuit. The quantity depends on the physical characteristics and construction of the alternator. The sub-transient reactance is a transient effect that is directly related to the electromagnetic relationships between the various physical components of the alternator. The X’d is the primary reactance used in most short-circuit calculation to determine the available fault current within the electrical system. The symmetrical current can reach the equivalent to the full load current multiplied by the reciprocal of the sub-transient reactance when a short-circuit is initiated. Sub-transient is also used to calculate the maximum asymmetrical current to include peak asymmetrical that can be imposed on the generator overcurrent protective device and terminals at the instant a short-circuit occurs.

Direct axis transient reactance denoted as X’d is the follow-though current due to the rapid decay of sub-transient (maximum) current. After the first few cycles of decaying sub-transient current behavior, the alternator’s performance becomes dominated by current based on transient reactance X’d and appropriate time constants. Transient reactance is typically used to determine the motor starting capability of a generator and is also used in determining circuit breaker set points. Direct axis synchronous reactance denoted as Xd is used to determine steady state short-circuit current. Zero-sequence reactance determines neutral currents, and negative phase sequence reactance is used in calculating line-to-line faults. Neither are subject to time limitations.

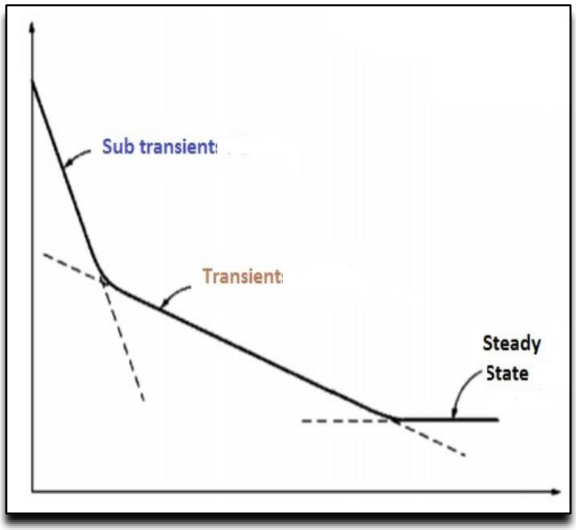


Figure #8 Reactance Regions of a Short-Circuit

Most generators utilize some type of excitation support system capable of supporting steady state short-circuit current in the range of 2 to 4 times rated current for up to 5 to 10 seconds under a three-phase short-circuit condition. Which means based on field forcing of the excitation system, the steady state current will be increase above the value of Xd by 3 to 6 times based on performance characteristics of the excitation system.

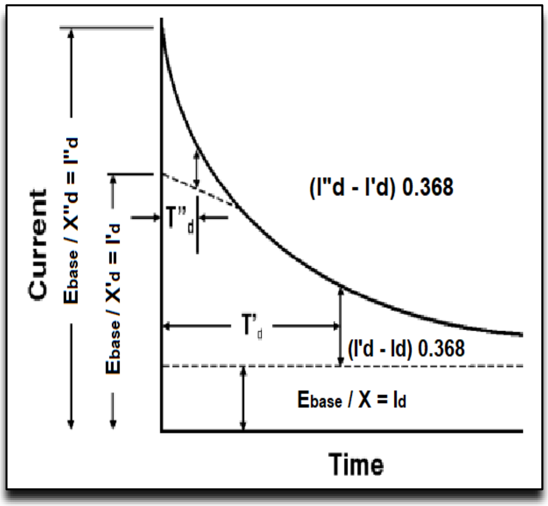


Figure #9 Example of Short-Circuit Time Constant Test based on Percentage of Voltage Drop

The generator time constant is a measurement of the magnetic inertia in a generator and gives an indication of machine performance under short circuit conditions. The factor is determined by conducting a test on the generator output by short-circuiting the terminals and measuring the reaction.

The time elapsed between short circuit and current decline to a specific value is the generator time constant. Normally the decline factor used is 36.8%.

Time constants characterize the length of time current flows during a specific instant. Typical time constants provided by generator manufacture:

- Sub-transient time constant (T"d)
- Short-circuit transient time constant (T'd)
- Short-circuit time constant of armature Windings (Ta)

- Transient Open Circuit Time Constant (T'do)

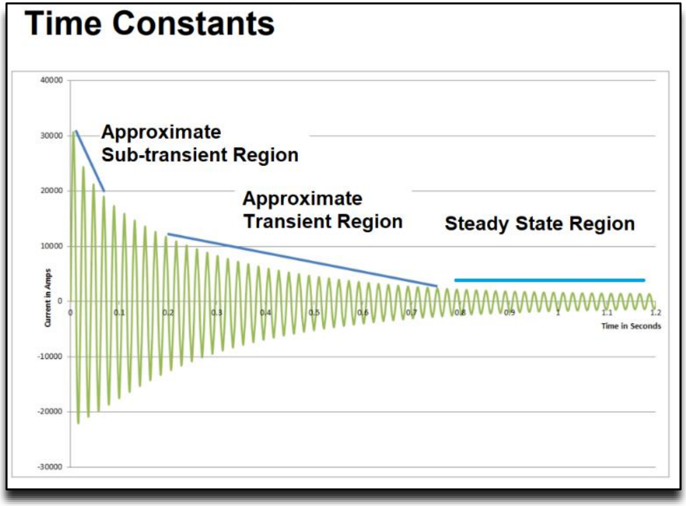


Figure #10 Example – Time Constant

The generator short circuit ratio gives an indication of generator response to a sudden applied load. It is the ratio of the field current required for the rated voltage at open circuit to the field current required for the rated armature current at short circuit. It can be expressed as the reciprocal of the synchronous reactance. This number is usually in the order of 0.3-0.6.

The following examples show how the different reactance values are used to determine what happens in a short-circuit near generator terminals.

Base values of the alternator must first be established. Generator rated at 400kVA, 320kW, power factor 0.8, voltage 480/277V.

$$\text{Ibase} = \frac{400\ x\ 1000}{480\sqrt{3}} = 481\text{A}$$

The maximum amount of available fault current when a short-circuit is initiated is based on the per unit sub-transient reactance (X"d) which rapidly decays within a few cycles. Available short-circuit current is sometimes expressed as a multiplier which is the reciprocal of the per unit sub-transient reactance. If we use a per unit X"d value of 0.087 the short-circuit multiplier is 11.494.

$$X''d = .087\ \text{pu} \qquad \left(\frac{1}{0.087}\right) * 481.121 = \ 5530.12\text{A sym.}$$

Instead of using a multiplier just simply divide the generator rated current by the per unit sub-transient reactance which will give you an RMS symmetrical current of $\frac{481.121}{0.087} = 5530.12$A symmetrical.

Another way to determine symmetrical short-circuit current is to first find the short-circuit impedance of the generator. The following equation can be used. $\frac{\%X"d * kV^2 * 10}{kVA} =$Zsc, $\frac{8.7\% * 0.48^2 * 10}{400} =$0.050112 Ω. After you find the impedance simply apply ohm's law;

$$\frac{480V}{\sqrt{3} * 0.050112\Omega} = 5530.174\text{A} \quad \text{RMS Symmetrical}$$

Note: Generators operating in parallel:

To find Isc symmetrical current of two generators operating in parallel you can simply add the generator Isc-symmetrical current together or you can calculate the impedance and use ohms law to calculate the available short-circuit current. Example: Gen. 1#: 400kVA, 480V, 60Hz, three-phase, X"d of 0.087 pu. Gen. 2#: 300kVA, 480V, 60Hz, three-phase, X"d of 0.079 pu.

Gen 1#: Zsc = $\frac{8.7\% * 0.48^2 * 10}{400} = 0.050112\ \Omega$ Gen 2#: Zsc = $\frac{7.9\% * .48^2 * 10}{300} = 0.060672\ \Omega$

$\frac{1}{\frac{1}{0.050112}+\frac{1}{0.060672}} = 0.027444\ \Omega$ $\frac{480V}{\sqrt{3} * 0.027444} = 10{,}097.8\text{A sym.}$

The point in time at which the short-circuit occurs determines if the current is initially symmetrical or asymmetrical or a combination of both. When the fault is initiated, and the voltage is at the zero axis the current is asymmetrical. If the fault should occur when the voltage is at a positive or negative peak the resulting current is symmetrical. If a fault should occur in between the zero axis and the negative or positive peak the resulting current is a combination of symmetrical and asymmetrical current with a lesser dc component. The asymmetrical current declines at a rate of 1 to 4 cycles and the remaining current is said to be symmetrical. The resistance controls the DC rate of decay. The subtransient and transient time constants determine the AC rate of decay.

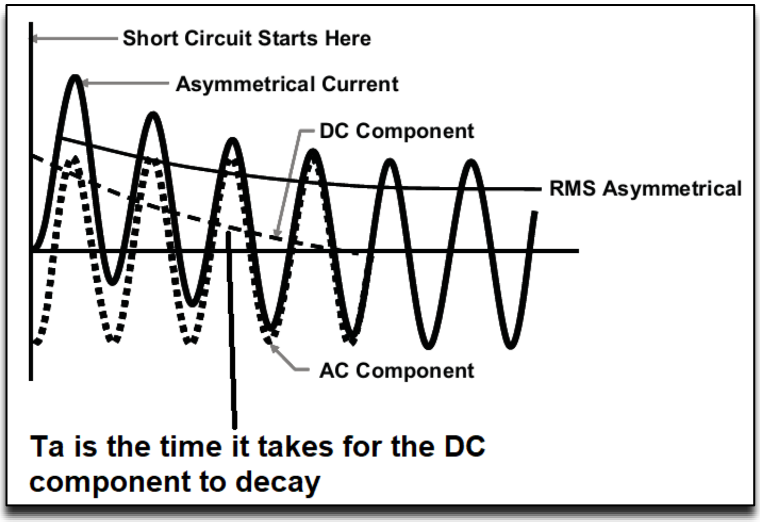


Figure #11 Example of the Rapid Decay of the DC Component in an Asymmetrical Current.

Determining the X/R ratio of a generator is a challenge since reactance changes base on time. X/R ratio is typically based on the reactance (X"d) divided by armature resistance (Ra). You can use the following equation to find armature resistance. Find Ra armature winding resistance: $\frac{Z_{SC}}{2 * \pi * f * Ta} = \text{Ra}$

To determine X/R you have to first convert the sub-transient per unit value to an ohmic value. Generator data: 400kVA, 480V three-phase, base current 481A, sub-transient reactance X"d = 0.087 per unit and transient reactance X'd = 0.227 per unit. Armature time constant is 22ms.

The base voltage line to line must be converted to line to neutral voltage; $\frac{480}{\sqrt{3}} = 277V.$

Convert sub-transient reactance per unit value to an ohmic value use the following equation.

$\frac{L-N\ Voltage}{base\ current} x\ X"d$ = ohms. $\frac{277}{481}x0.087 = 0.050101\Omega$ sub-transient reactance,

$\frac{277}{481}x0.227 = 0.130725\Omega$ transient reactance

Find Ra: Zsc = 0.050112 Ω, Ta = 22ms, f = frequency (60Hz) $\frac{0.050112}{2\pi 60*0.022}$ =0.006042

X/R = 0.050101 / 0.006042 = 8.292 (sub-transient reactance region), 0.130725 / 0.006042 = 21.6 (transient reactance region)

Using X/R ratio to calculate asymmetrical current can be difficult and one thing to keep in mind is it changes with reactance and time. Assuming voltage and frequency is constant the equation shows two variables that change based on time because of the rapid decay of both the AC and DC components. X/R represents the DC component and Isc symmetrical current represents the AC component. Both rapidly decay over time to a steady state current.

Isc symm. (t) $\sqrt{1+2\times\left(e^{\frac{-\omega(t)}{X/R}}\right)}$=Asymmetrical current. 5530$\sqrt{1+2\times\left(e^{\frac{-377*0.001}{8.292}}\right)} = 9435$A

Asymmetrical current at ½ cycle = 5530$\sqrt{1+2\times\left(e^{\frac{-377*0.008}{8.292}}\right)}$= 8549A.

The sub-transient time constant T"d = 0.013, based on time the symmetrical current is less, we are now entering the transient reactance region so the X/R changes to 21.6. At 20ms (0.02) the symmetrical current drops to 3000A applying the same equation the asymmetrical current would drop to 4658A.

$$3000\sqrt{1+2\times\left(e^{\frac{-377*0.02}{21.6}}\right)} = 4658A$$

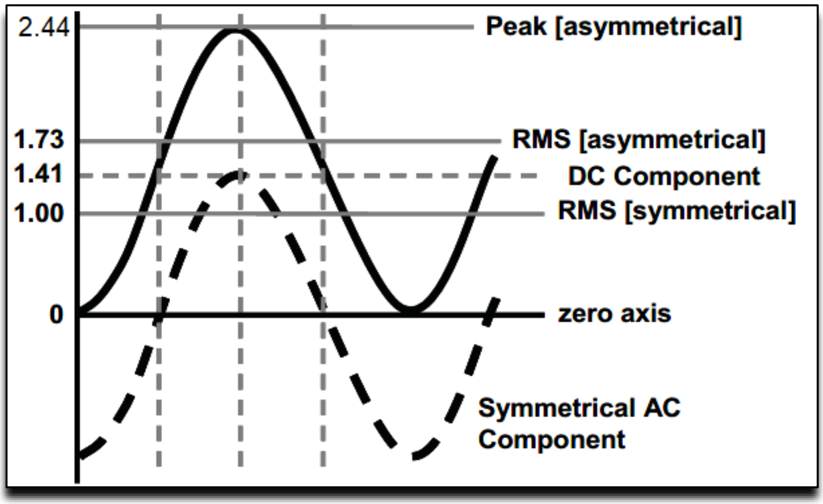


Figure #12 Max Asymmetrical and Peak Multipliers

For practical purposes, maximum asymmetrical RMS current is calculated at RMS symmetrical current multiplied by the $\sqrt{3}$ (1.73). Peak symmetrical instantaneous current is calculated at RMS symmetrical current multiplied by the $\sqrt{2}$ (1.414). Example; Generator data, 400kVA, 480V, base current 481A, X"d = 0.087 per unit. RMS symmetrical current = 481A/0.087 pu = 5530A symm.

5530A * $\sqrt{2}$ = 7821A Peak symmetrical current, 5530A * $\sqrt{3}$ = 9578A Asymmetrical current. 1.732 * 1.414 = 2.44. Peak asymmetrical instantaneous current is RMS symmetrical current multiplied by 2.44. 5530 * 2.44 = 13,493A.

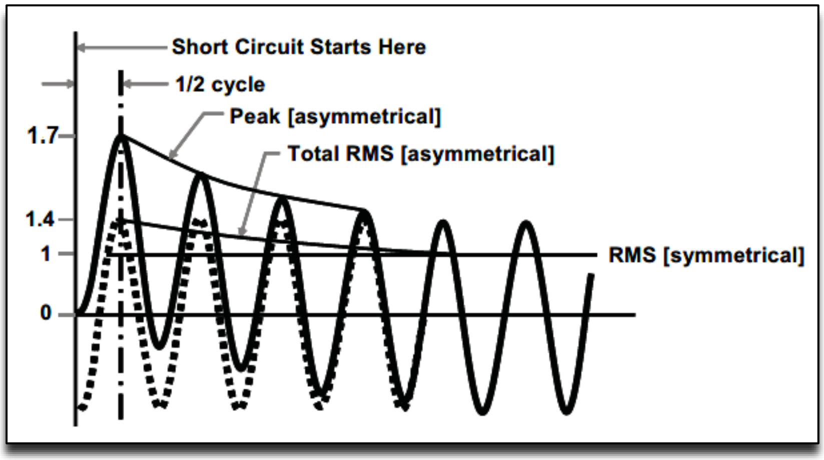


Figure # 13 Peak & Asymmetrical Current Multiplier – ½ Cycle

The accepted practice for calculating asymmetrical and peak instantaneous current is to calculate the current which is available 1/2 cycle after the short circuit starts. A fully offset wave the maximum current occurs at the end of the first half cycle and at this point the DC component has already started to decay. Systems operating at 600 volts or less the multiplier for ½ cycle value for the RMS asymmetrical current is 1.4, and peak asymmetrical instantaneous current is 1.7 times the RMS symmetrical current.

Negative sequence reactance (X2) is an important reactance in determining the fault current in a line to line short-circuit fault at the terminals of a three-phase generator.
400kVA, 60Hz, 480V, three-phase, 481A rated current. X"d = 0.087pu and X2 = 0.1pu

$$\frac{Rated\ current\ x\ \sqrt{3}}{X"d + X2} = \text{RMS symmetrical current}$$

$$\frac{481 \times \sqrt{3}}{0.087 + 0.1} = 4455A\ RMS\ sym$$

Zero sequence reactance is used to determine short-circuit current in a line to neutral or line to ground short-circuit based on the system is neutral-ground bonded systems. X"d = 0.087 pu, Xo = .009pu. X2 = 0.1pu and rated current is 481A. Following equation is used to calculate line to ground RMS symmetrical current:

$$\frac{Rated\ current \times 3}{X"d + X2 + Xo} = \text{Isc sym.} \qquad \frac{481\times3}{0.087+0.10+0.009} = \text{7362A RMS symm.}$$

Line to line or line to ground symmetrical fault current due to a short-circuit are not limited by time constants and cause mechanical and thermal stress on the armature.

Another factor that should be taken into consideration is sub-transient and transient reactance changes when there is a voltage deviation from machine rated voltage. The per unit reactance value changes inversely (rated volts down, reactance up) with is the square of the voltage ratio if the kVA rating remains the same. This can have a direct impact on the amount of available short-circuit current.

Example:

Generator 400kVA, rated voltage 240V, sub-transient reactance X"d is 0.087 pu. Voltage adjusted to 208V, use the following equation to adjust X"d. $(240\ /\ 208)^2\ x\ 0.087 = 0.115\ pu$

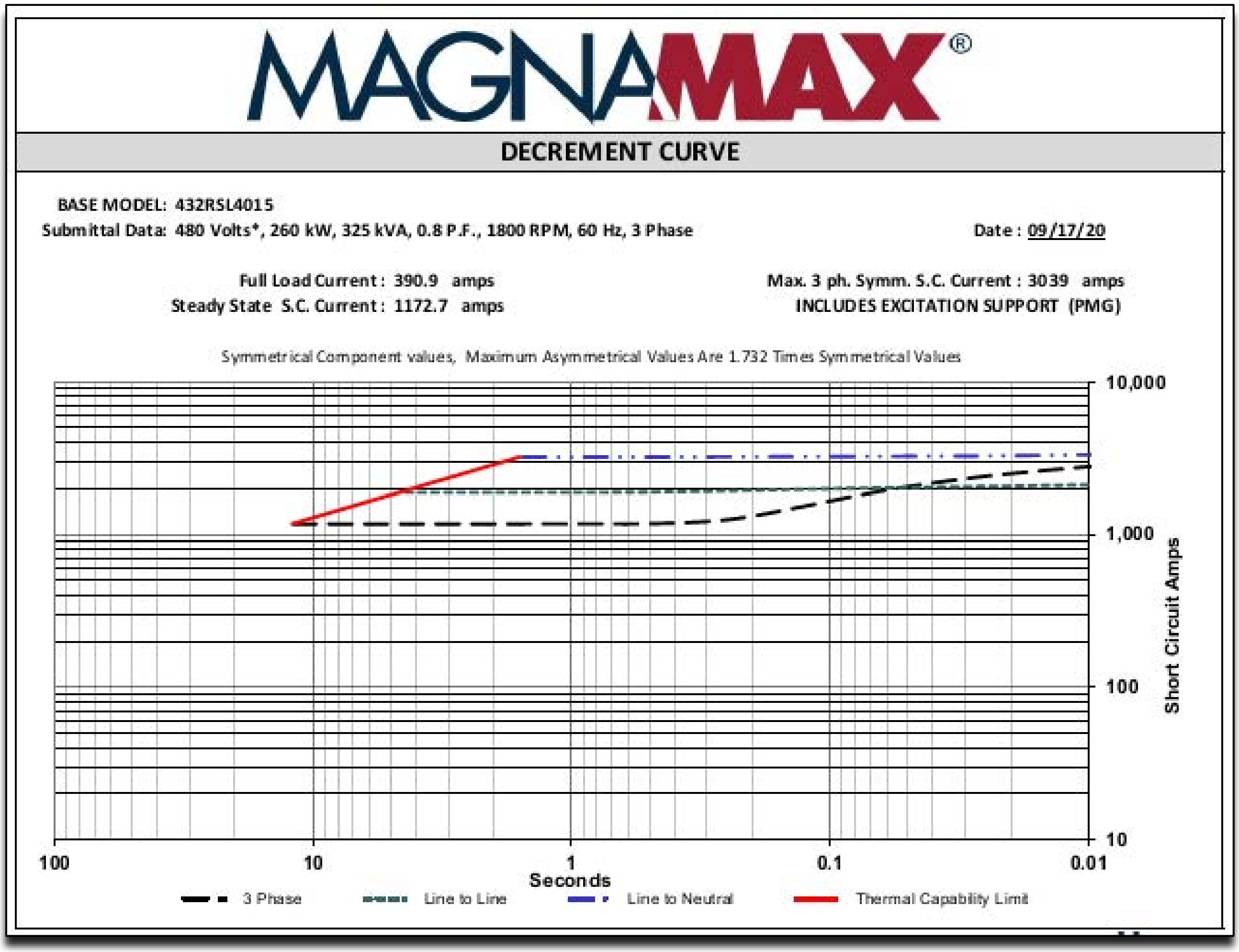
Isc calculated based on using the sub-transient reactance value of 0.087. Generator rated voltage 240/139V, rated current 962A. 962 / 0.087= 11,057A. Voltage adjusted to 208/120V the base current is 1,110A.

1110 / 0.115= 9652A.

Generator Short-Circuit Current Modeling

Most manufactures supply a short-circuit time-curve based on symmetrical RMS current. The purpose of the time current curve is view short-circuit current based on time ensure proper selection and setting of the overcurrent protection device. Each manufacture may use a slightly different method to model generator short-circuit current behavior and excitation support.

The next illustration is generator submittal data and short-circuit current decrement curve provided by Marathon Electric for a 325kVA alternator. The curve shows three-phase RMS short-circuit current symmetrical, Line to line and line to neutral short-circuit current. The steady state current does not reflect the synchronous reactance value Xd listed on the generator submittal data sheet the reason why is the value was replaced to represent 300% PMG excitation support up to 10 seconds.



MAGNAMAX®

DECREMENT CURVE

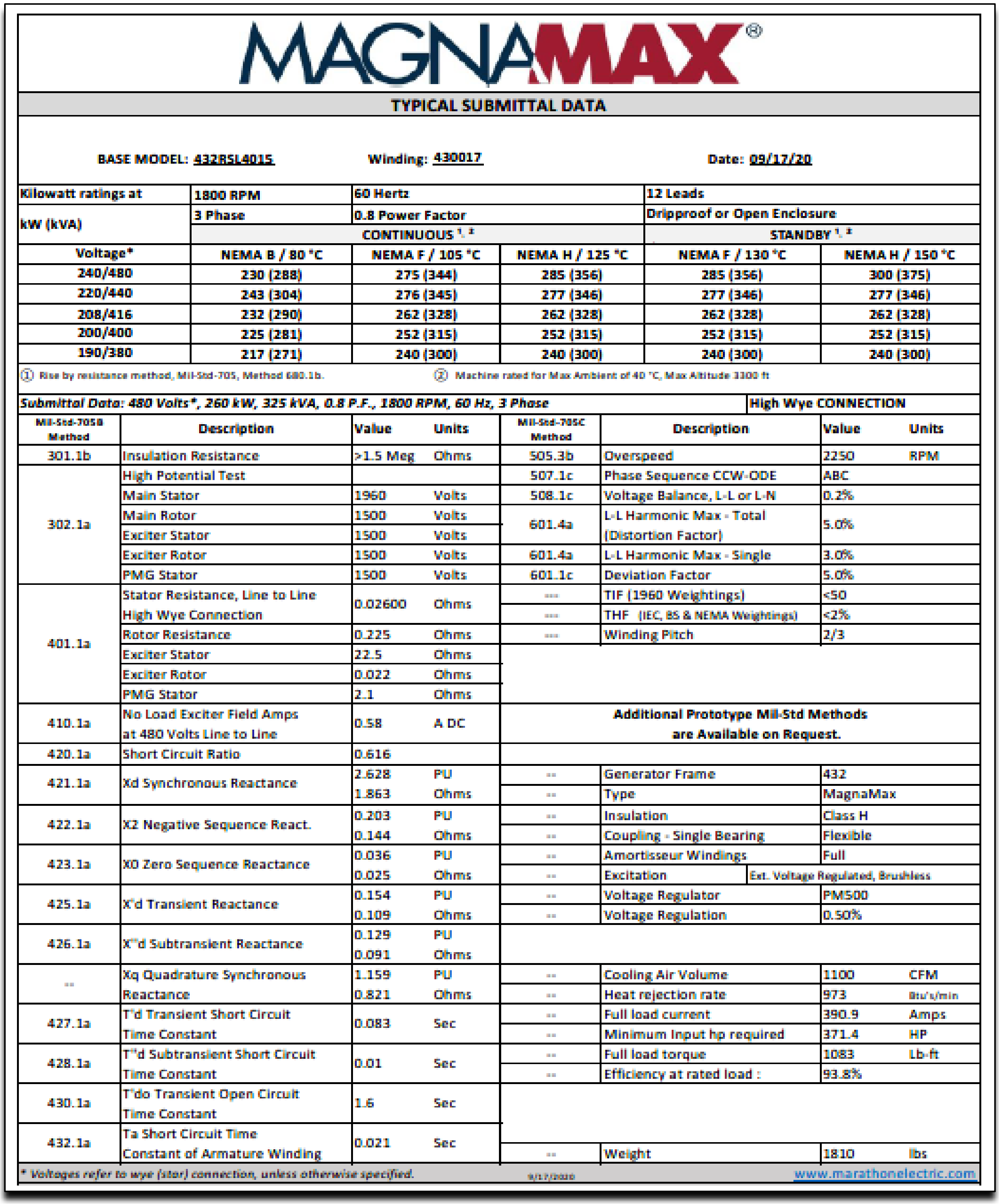
BASE MODEL: 432RSL4015
Submittal Data: 480 Volts*, 260 kW, 325 kVA, 0.8 P.F., 1800 RPM, 60 Hz, 3 Phase
Date : 09/17/20

Full Load Current : 390.9 amps
Steady State S.C. Current : 1172.7 amps

Max. 3 ph. Symm. S.C. Current : 3039 amps
INCLUDES EXCITATION SUPPORT (PMG)

Symmetrical Component values, Maximum Asymmetrical Values Are 1.732 Times Symmetrical Values

Figure # 14 Decrement Curve for 325kVA Alternator (Courtesy of Marathon Electric)



MAGNAMAX®

TYPICAL SUBMITTAL DATA

BASE MODEL: 432RSL4015 **Winding:** 430017 **Date:** 09/17/20

Kilowatt ratings at	1800 RPM	60 Hertz		12 Leads	
kW (kVA)	3 Phase	0.8 Power Factor		Dripproof or Open Enclosure	
	CONTINUOUS [1, 2]			STANDBY [1, 2]	
Voltage*	NEMA B / 80 °C	NEMA F / 105 °C	NEMA H / 125 °C	NEMA F / 130 °C	NEMA H / 150 °C
240/480	230 (288)	275 (344)	285 (356)	285 (356)	300 (375)
220/440	243 (304)	276 (345)	277 (346)	277 (346)	277 (346)
208/416	232 (290)	262 (328)	262 (328)	262 (328)	262 (328)
200/400	225 (281)	252 (315)	252 (315)	252 (315)	252 (315)
190/380	217 (271)	240 (300)	240 (300)	240 (300)	240 (300)

① Rise by resistance method, Mil-Std-705, Method 680.1b. ② Machine rated for Max Ambient of 40 °C, Max Altitude 3300 ft

Submittal Data: 480 Volts, 260 kW, 325 kVA, 0.8 P.F., 1800 RPM, 60 Hz, 3 Phase* | High Wye CONNECTION

Mil-Std-705B Method	Description	Value	Units
301.1b	Insulation Resistance	>1.5 Meg	Ohms
302.1a	High Potential Test		
	Main Stator	1960	Volts
	Main Rotor	1500	Volts
	Exciter Stator	1500	Volts
	Exciter Rotor	1500	Volts
	PMG Stator	1500	Volts
401.1a	Stator Resistance, Line to Line High Wye Connection	0.02600	Ohms
	Rotor Resistance	0.225	Ohms
	Exciter Stator	22.5	Ohms
	Exciter Rotor	0.022	Ohms
	PMG Stator	2.1	Ohms
410.1a	No Load Exciter Field Amps at 480 Volts Line to Line	0.58	A DC
420.1a	Short Circuit Ratio	0.616	
421.1a	Xd Synchronous Reactance	2.628 1.863	PU Ohms
422.1a	X2 Negative Sequence React.	0.203 0.144	PU Ohms
423.1a	X0 Zero Sequence Reactance	0.036 0.025	PU Ohms
425.1a	X'd Transient Reactance	0.154 0.109	PU Ohms
426.1a	X''d Subtransient Reactance	0.129 0.091	PU Ohms
--	Xq Quadrature Synchronous Reactance	1.159 0.821	PU Ohms
427.1a	T'd Transient Short Circuit Time Constant	0.083	Sec
428.1a	T''d Subtransient Short Circuit Time Constant	0.01	Sec
430.1a	T'do Transient Open Circuit Time Constant	1.6	Sec
432.1a	Ta Short Circuit Time Constant of Armature Winding	0.021	Sec

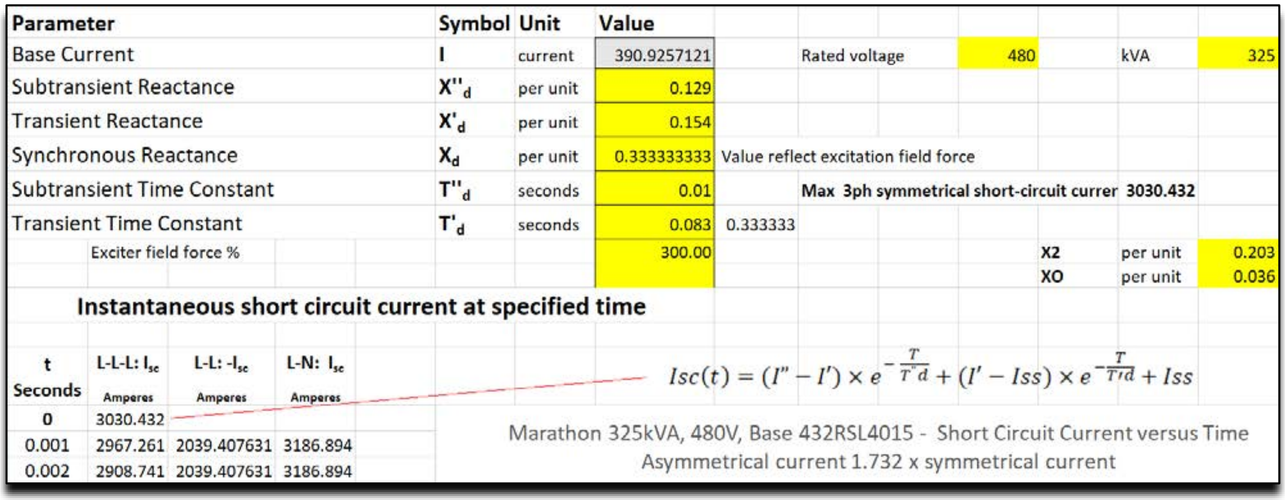
Mil-Std-705C Method	Description	Value	Units
505.3b	Overspeed	2250	RPM
507.1c	Phase Sequence CCW-ODE	ABC	
508.1c	Voltage Balance, L-L or L-N	0.2%	
601.4a	L-L Harmonic Max - Total (Distortion Factor)	5.0%	
601.4a	L-L Harmonic Max - Single	3.0%	
601.1c	Deviation Factor	5.0%	
--	TIF (1960 Weightings)	<50	
--	THF (IEC, BS & NEMA Weightings)	<2%	
--	Winding Pitch	2/3	
	Additional Prototype Mil-Std Methods are Available on Request.		
--	Generator Frame	432	
--	Type	MagnaMax	
--	Insulation	Class H	
--	Coupling - Single Bearing	Flexible	
--	Amortisseur Windings	Full	
--	Excitation	Ext. Voltage Regulated, Brushless	
--	Voltage Regulator	PM500	
--	Voltage Regulation	0.50%	
--	Cooling Air Volume	1100	CFM
--	Heat rejection rate	973	Btu's/min
--	Full load current	390.9	Amps
--	Minimum Input hp required	371.4	HP
--	Full load torque	1083	Lb-ft
--	Efficiency at rated load :	93.8%	
--	Weight	1810	lbs

** Voltages refer to wye (star) connection, unless otherwise specified.* 9/17/2020 www.marathonelectric.com

Figure #15 Marathon Electrical Submittal Data – 325kVA (Courtesy of Marathon Electric)

The basic equation to determine RMS symmetrical short-circuit current versus time is listed below.

$$I_{SC(t)} = (I'' - I') \times e^{-\frac{T}{T''d}} + (I' - Iss) \times e^{-\frac{T}{T'd}} + Iss$$



Parameter	Symbol	Unit	Value				
Base Current	I	current	390.9257121	Rated voltage	480	kVA	325
Subtransient Reactance	X''_d	per unit	0.129				
Transient Reactance	X'_d	per unit	0.154				
Synchronous Reactance	X_d	per unit	0.333333333	Value reflect excitation field force			
Subtransient Time Constant	T''_d	seconds	0.01	Max 3ph symmetrical short-circuit currer	3030.432		
Transient Time Constant	T'_d	seconds	0.083	0.333333			
Exciter field force %			300.00		X2	per unit	0.203
					XO	per unit	0.036

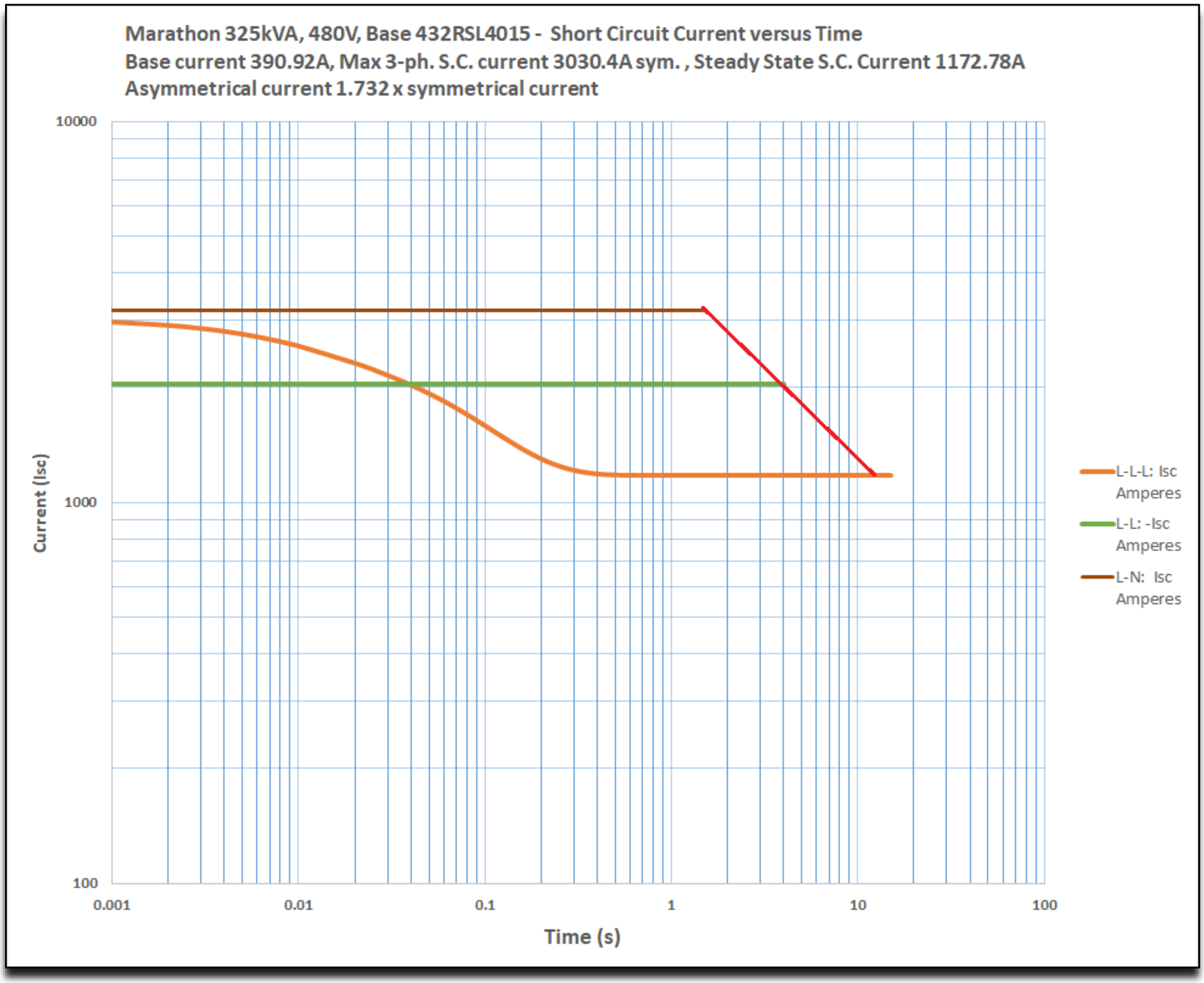
Instantaneous short circuit current at specified time

$$Isc(t) = (I'' - I') \times e^{-\frac{T}{T''d}} + (I' - Iss) \times e^{-\frac{T}{T'd}} + Iss$$

t Seconds	L-L-L: I_{sc} Amperes	L-L: -I_{sc} Amperes	L-N: I_{sc} Amperes
0	3030.432		
0.001	2967.261	2039.407631	3186.894
0.002	2908.741	2039.407631	3186.894

Marathon 325kVA, 480V, Base 432RSL4015 - Short Circuit Current versus Time
Asymmetrical current 1.732 x symmetrical current

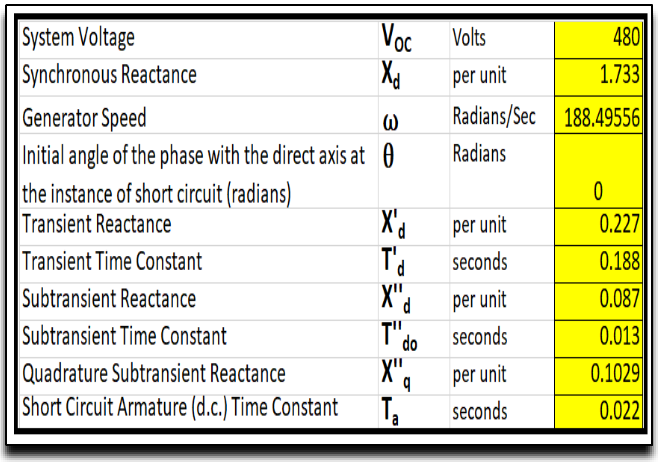
Figure #16 Spreadsheet Data from Marathon Generator Submittal Sheet



Marathon 325kVA, 480V, Base 432RSL4015 - Short Circuit Current versus Time
Base current 390.92A, Max 3-ph. S.C. current 3030.4A sym. , Steady State S.C. Current 1172.78A
Asymmetrical current 1.732 x symmetrical current

Figure #17, 325kVA Short-Circuit Decrement Curve Plotted using Time-Current Equation

Using the current to time equation based on the data in figure #16 a similar graph can be plotted using Excel spreadsheet see figure #17. The 325kVA decrement curve shows three-phase symmetrical short-circuit current, line-to-line and line to neutral short-circuit current. Synchronous reactance value changed to reflect 300% field excitation from a PMG system. In the absent of a short-circuit decrement curve from a manufacture the time-current equation can be used to plot a curve to utilize for the purpose of verifying adequate overcurrent protection and settings.



System Voltage	V_{OC}	Volts	480
Synchronous Reactance	X_d	per unit	1.733
Generator Speed	ω	Radians/Sec	188.49556
Initial angle of the phase with the direct axis at the instance of short circuit (radians)	θ	Radians	0
Transient Reactance	X'_d	per unit	0.227
Transient Time Constant	T'_d	seconds	0.188
Subtransient Reactance	X''_d	per unit	0.087
Subtransient Time Constant	T''_{do}	seconds	0.013
Quadrature Subtransient Reactance	X''_q	per unit	0.1029
Short Circuit Armature (d.c.) Time Constant	T_a	seconds	0.022

Figure #18, 400kVA Generator Data

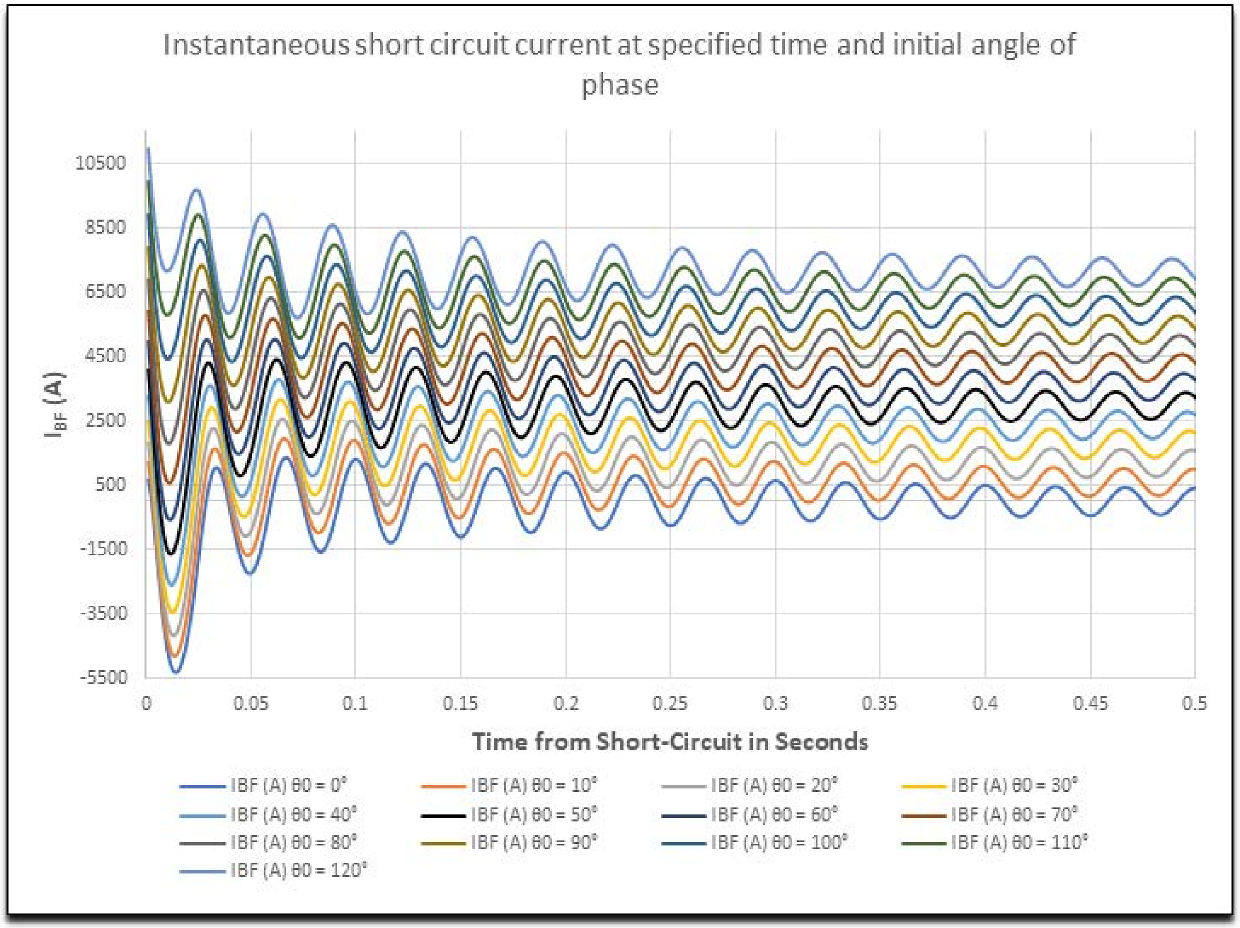


Figure #19 Instantaneous short circuit current at a specified time and angle of phase. Plot calculated by Mukesh Patel, Multiquip, Inc.

Another variable used in conjunction with a current/time equation which provides a more adequate picture of maximum peak asymmetrical current at a point in time is phase angle = θ. Based on the generator data in figure #18 the illustration in figure #19 shows a plot of the instantaneous short-circuit current at a specified point in time and angle of phase. The initial symmetrical fault current is calculated at 5,529A RMS symmetrical. If the fault should occur at θ_0 = 120° based on the plot the peak asymmetrical current is 10,959A. The peak asymmetrical current only last for a fraction of a cycle however it causes the highest amount of mechanical stress and damage to the system.

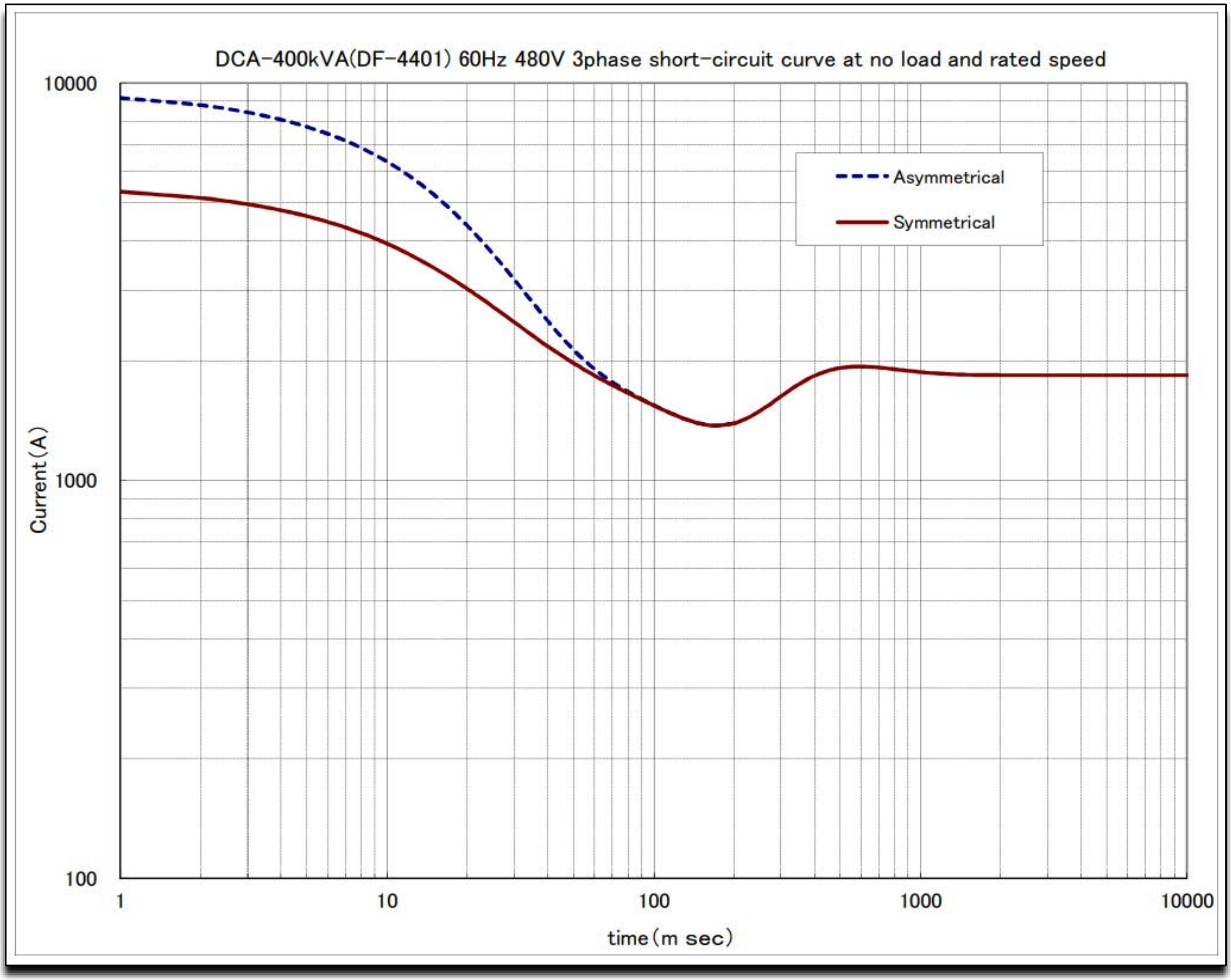


Figure #20 DCA400SSI4F3, 400kVA Generator Short-Circuit Decrement Curve

Figure # 20 is an example of a short-circuit decrement curve for a DCA400SSIU4F3, 400kVA generator. The curve is based on the generator data in Figure #18. The short-circuit curve shows both symmetrical and asymmetrical current based on time. The Xd value in figure#18 does not match the the steady state current value in the decrement curve . The reason is the ploted decrement curve reflects the exciter field force current which is approximately 380% of rated current

The decrement curve can be used as a comparison to the circuit breaker trip curve to verify current reaches the trip time region of the curve to trip the breaker if a short-circuit fault should occur. Figure #21 is an example of a circuit breaker trip curve with generator fault current curve plotted.

The decrement curve was plotted using ABB E-design software. Generator curve plotted based on the data from figure #18 (400kVA). The circuit breaker selected is an ABB - T7S 1000 w/Pr231/LS/I – M motorized circuit breaker.

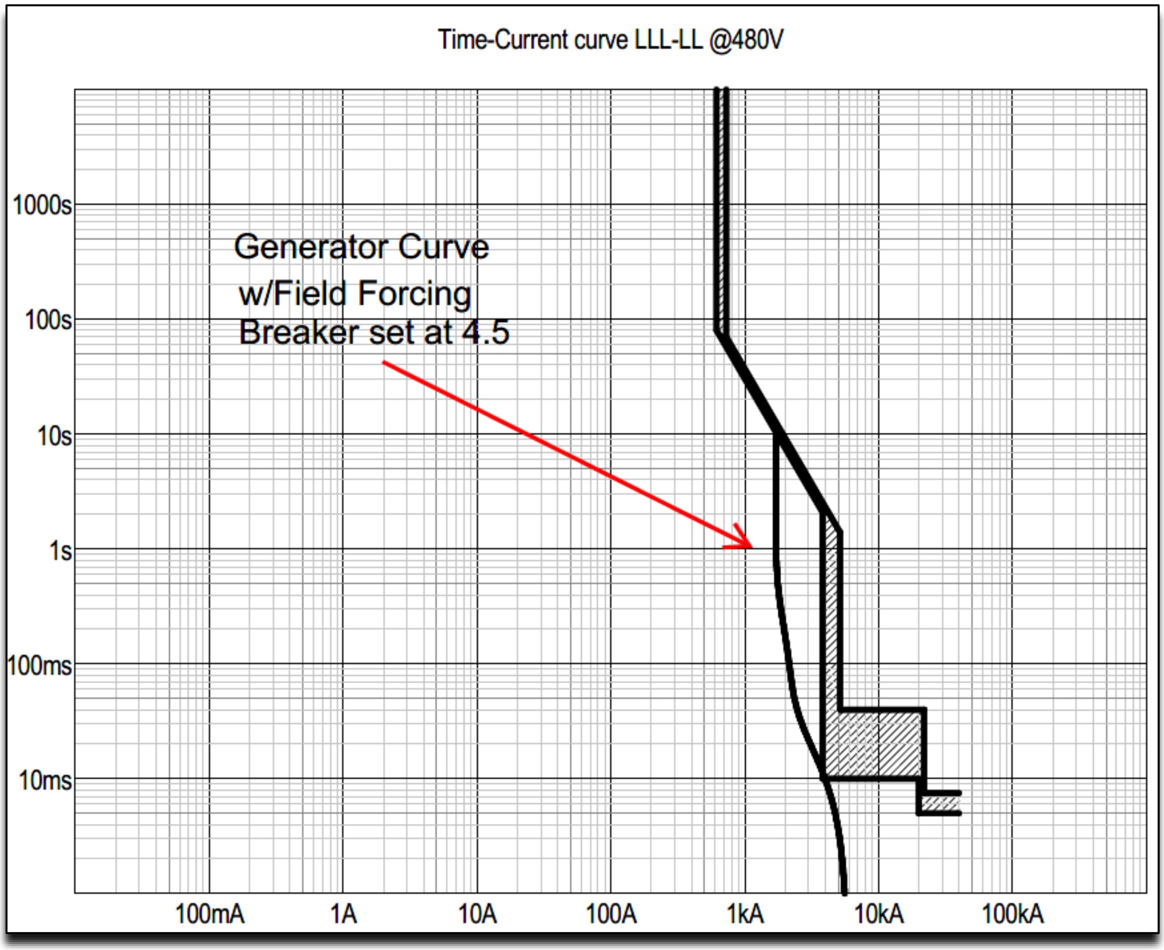


Figure #21 Generator Circuit Breaker Trip Curve

Based on rapid decay of short-circuit current for 480V operations, the circuit breaker would have to be adjusted to 3.5 or 4.5 see ABB time current curve. Generator circuit breaker trip curve shows a maximum amount of short-circuit current of approximately 5530A RMS symmetrical. The current decays to about 4500A and hits the trip region in less than 1 cycle. Current decays to a steady state around 600ms.

Calculate Short-Circuit Current in a Temporary Installation

The method we used to calculate the available fault current within the electrical system in figure #4 can also be used to calculate the available short-circuit current in a temporary installation. The illustration in figure #22 shows a single line drawing for a temporary installation using a 400kVA generator as the power source.

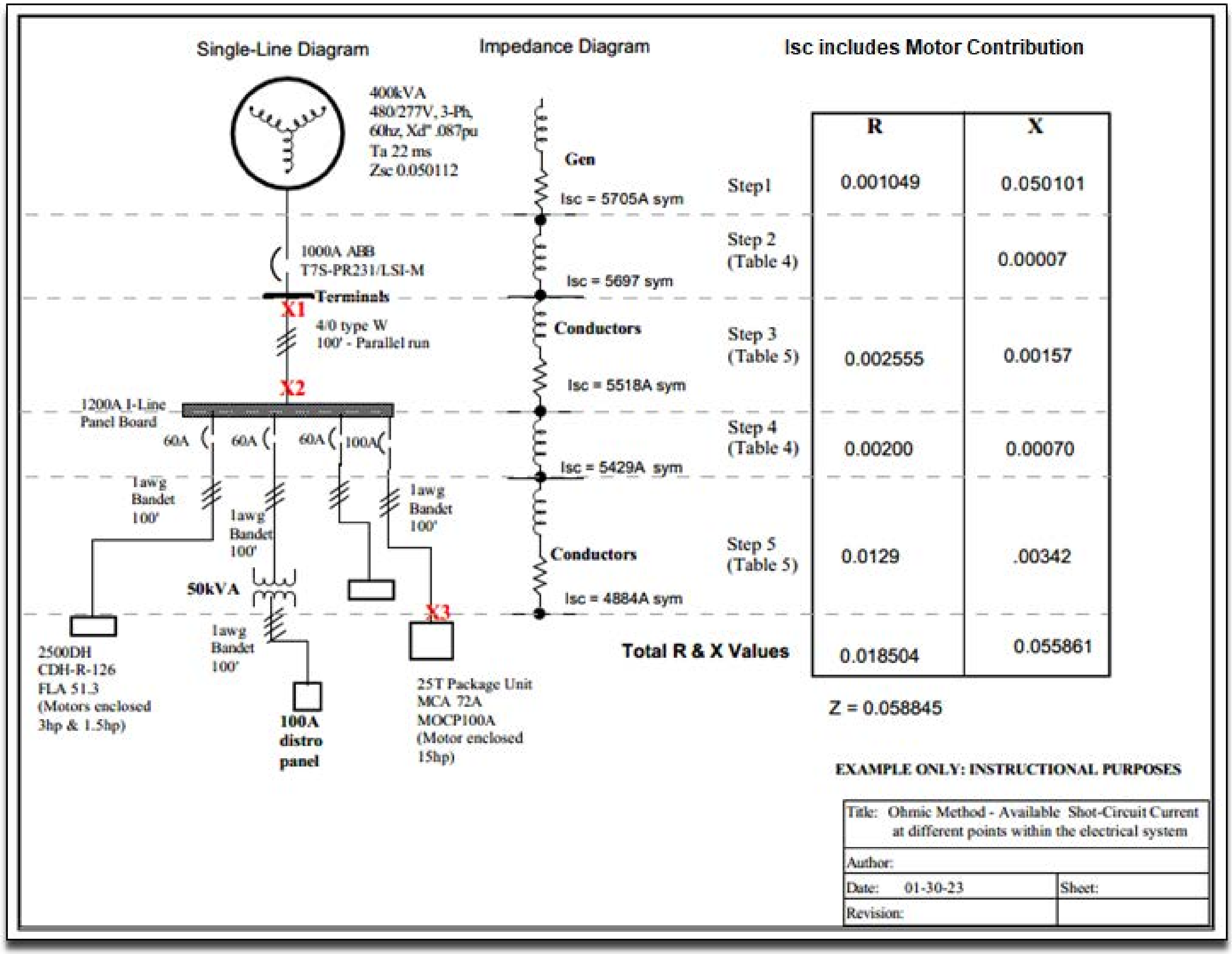


Figure #22, Single-line drawing showing available fault current at different points within the temporary electrical system. Available fault current calculated using the Point-to-Point method.

The values in the example are calculated using the tables on page 31-33. Generator data used is from figure #18.

Step 1:

400kVA generator, 480/277V, 60Hz, three-phase, X"d = 0.087, short-circuit armature time constant Ta = 22ms, rated current at 0.8 PF = 481.125A

Find short-circuit impedance value: $\frac{\%X"d * kV^2 * 10}{kVA}$ =Zsc, $\frac{8.7\% * 0.48^2 * 10}{400}$ =0.050112 Ω

Convert X"d to an ohm value. $\frac{277}{481} \times 0.087 = 0.050101\ \Omega$

Find resistance $= \sqrt{0.050112^2 - 0.050101^2} = 0.001049\ \Omega$

Find the short-circuit current RMS symmetrical: $\frac{480}{\sqrt{3} * 0.050112}$ =5530.174A RMS Symmetrical

Note:

Motor short-circuit current is approximately equal to locked rotor amps. This method an acceptable multiplier to use is 5 times the full load amperage (FLA)of the motor. To find motor short-circuit current contribution add all the motors FLA together and multiply by 5. If the value is significant add the current to the Isc of the power source and at each point in the system.

The motors in the circuit are 11/2 Hp, FLA 4A, 3Hp, FLA 6A and 15Hp, FLA 25A. 4 + 6 + 25 = 35A,

35A * 5 =175A motor short-circuit current contribution.

Add motor short-circuit current contribution. 5530.174A + 175A = 5705.174A sym

Step 2:

Find the reactance of the overcurrent device (1000A circuit breaker). Use table 4. 0.00007 Ω

Add the resistance values together up to this point in the circuit = 0.001049 Ω, Add the reactance values together up to this point in the circuit = 0.050171 Ω

Z = $\sqrt{0.001049^2 + 0.050171^2} =$ 0.050181 Ω

Isc = $\frac{480}{\sqrt{3}x \cdot 0.050181} =$ 5522A sym.

Add motor short-circuit current contribution = 5522 + 175A = 5697.57A sym.

Step 3:

Find the resistance and reactance of the phase conductors. Use table 5.

4/0 type W single conductor 100' – parallel run (free air). Use value for value in table for non-metallic.

R = (length / 1000) x (impedance /number conductors per phase) $\frac{100}{1000} * \frac{0.0511}{2} =$ 0.002555 Ω

X = (length / 1000) x (impedance /number conductors per phase) $\frac{100}{1000} * \frac{0.0314}{2} =$ 0.00157 Ω

Add the resistance values together up to this point in the circuit = 0.001049 + 0.002555 = .003604 Ω, Add the reactance values together up to this point in the circuit = 0.050101 + 0.00007 + 0.00157 = 0.051741 Ω

Z = $\sqrt{0.003604^2 + 0.051741^2} =$ 0.051866 Ω

Isc = $\frac{480}{\sqrt{3}x \cdot 0.051866} =$ 5343A sym.

Add motor short-circuit current contribution 5343A + 175A =5518A sym.

Step 4:

Find the resistance and reactance of the overcurrent device (molded case circuit breaker 100A). Use table 4.

Resistance = 0.00200 Ω, Reactance = 0.00070 Ω

Add the resistance values together up to this point in the circuit = 0.001049 + 0.002555 + 0.00200 = 0.005604 Ω, Add the reactance values together up to this point in the circuit = 0.050101 + 0.00007 + 0.00157 + .00070 = 0.052441 Ω

Z = $\sqrt{0.005604^2 + 0.052441^2} =$ 0.052739 Ω

Isc = $\frac{480}{\sqrt{3}x \cdot 0.052739} =$ 5254AA sym.

Add motor short-circuit current contribution 5254A + 175 = 5429A sym

Step 5:

Find the resistance and reactance of the phase conductors. Use table 5.

1 AWG bandit 3-ph. Conductors, 100' (free air). Use value for value in table for non-metallic.

R = (length / 1000) x (impedance /number conductors per phase) $\frac{100}{1000} * \frac{0.1290}{1} =$ 0.0129 Ω

X = (length / 1000) x (impedance /number conductors per phase) $\frac{100}{1000} * \frac{0.0342}{1} =$ 0.00342 Ω

Add the resistance values together up to this point in the circuit = 0.001049 + 0.002555 + 0.00200 + 0.0129 = 0.018504 Ω, Add the reactance values together up to this point in the circuit = 0.050101 + 0.00007 + 0.00157 + .00070 + .00342 = 0.055861 Ω

Z = $\sqrt{0.018504^2 + 0.055861^2} =$ 0.058845 Ω

Isc = $\frac{480}{\sqrt{3} * 0.058845} =$ 4709A sym

Add motor short-circuit current contribution 4709A + 175A = 4884A sym.

The available short-circuit current drops the further you get from the generator terminals.

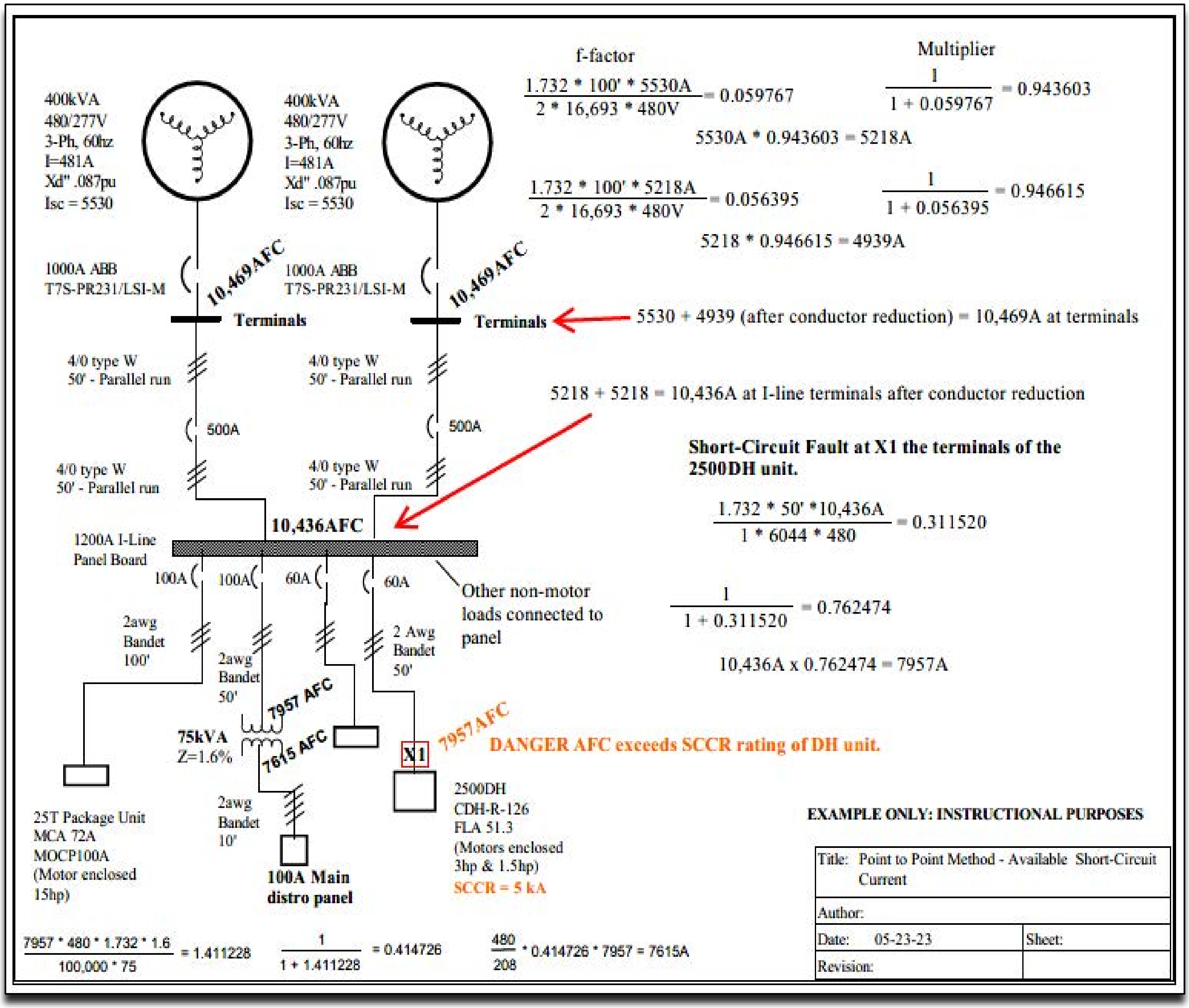


Figure #23 Point to Point Method (Two Generators Operating in Parallel)

Point -to -Point Method of Calculating Available Short-Circuit Current

The Point-to-Point method is a simplified method of calculating available fault current in the field. Recommend reading:

Bulletin EDP-1 (2004) Engineering Dependable Protection for an Electrical Distribution System, Part 1, A Simple Approach to Short- Circuit Calculations. Cooper-Bussmann. Retrieved from; http://www1.cooperbussmann.com/library/docs/EDP-1.pdf

Basic Point-to-Point Calculation Procedure;

Power Source – Determine Isc at the beginning of circuit from the power source. If the power source is utility if Isc is known use it if it unknown assume unlimited primary short-circuit current (infinite bus). If a transformer is the start of the circuit first determine Isc at the secondary windings of the transformer.

GENERATOR SHORT-CIRCUIT CURRENT

Step 1. Determine the 3-phase transformer full load amperes from either the nameplate or the following formulas:

$\frac{kVA \times 1000}{V(L-L)\ X\ \sqrt{3}}$ =Ibase, Find the impedance either on the data plate or use table 1.2. Find the transformer multiplier. 100 / %Z = multiplier. Ibase * multiplier = Isc RMS symmetrical

If the power source is a generator find the base current first then simply divide it by the X"d pu value to find maximum Isc. Figure #23 shows two 400kVA generator operating in parallel, 480V, three-phase, 60Hz, X"d per unit 0.087.

Find the base current first for each generator. $\frac{kVA * 1000}{V(l-l) * \sqrt{3}}$ = Ibase, $\frac{400 * 1000}{480 * \sqrt{3}}$ =481.12A,
Second, calculate the maximum available fault current for each generator in parallel. 481.12A / 0.087 = 5530A RMS symmetrical.

Calculate the AFC at generator terminals you must first determine other generator Isc after F-factor reduction then add the two available short-circuit values together see figure #23 as an example.

Step 2. Calculate the F-Factor (3-phase) $\frac{2 * L * I_{sc}}{N * C * V}$ =F-Factor

L = Length of conductor (feet)
Isc = Available fault current at the beginning of the circuit
N = Number of conductors per phase
C = Constant from Table 6. Temporary application cable on the ground in free air use column for non-metallic.
V = Voltage line to line

Calculate the multiplier (M) = $\frac{1}{1+F-factor} = M$, Isc at the beginning of the circuit multiplied by M = Isc (Available fault current at the point of the terminals)

Note. Motor short-circuit contribution, if significant, may be added to each point in the circuit. A practical estimate of motor short-circuit contribution is to multiply the total motor FLA current by 5.
The motors in the circuit are 11/2 Hp, FLA 4A, 3Hp, FLA 6A and 15Hp, FLA 25A. 4 + 6 + 25 = 35A,

35A * 5 =175A motor short-circuit current contribution. The motor contribution is small, so it was not included in the AFC calculations listed in figure #23.

Procedures for calculating Isc at the terminals of a secondary transformer in circuit.
Three-phase transformer: Find the F-Factor for the transformer first.

$\frac{I_{sc\ primary} * V_{primary} * \sqrt{3} * (\%Z)}{100{,}000 * kVA\ transformer}$ = f Single-phase transformer: $\frac{I_{sc\ primary} * V_{primary}(\%Z)}{100{,}000 * kVA\ transformer}$ = f

Find the multiplier (M): $\frac{1}{1+F-factor} = M$ $\frac{V_{primary}}{V_{secondary}} * M *$ Isc primary = Isc secondary.

Note:
Figure #23 shows an example of a temporary application with two generators of the same size and characteristics operating in parallel. Based on the point-to-point calculations X1 – available fault current (AFC) exceeds the short-circuit current rating (SCCR) of the DH unit. To continue operating in this manner could cause extensive damage to the equipment if a fault should occur. This could also be considered as a violation of NEC article 110.10.

Conclusion

Calculating available fault current in an electrical circuit is a requirement of the NEC code, NFPA 70E and plays important factor in short-circuit studies, coordination, selection of overcurrent protective devices, hazard analysis and PPE assessments to protect people and equipment. As you can tell by the numerous NEC articles requiring short-circuit current calculations, the National Electrical Code is becoming more and more in tune with NFPA 70E, which is mentioned in informational note No.1 in article 110.24. Short-circuit current determination is the first step in performing hazard assessments, calculating arcing current, incident energy and determining arc flash protective boundaries.

Several methods can be used to calculate available short-circuit current. Out of the two methods illustrated in this paper the simplest methods to use in the field is the *Point-to-to-Point* method which provides a level of acceptable accuracy without the use of complex equations and computer software programs.

Generator short-circuit behavior can be a little complex due to the rapid decay of current. Manufacture generator data sheets and short-circuit current behavior modeling such as decrement curves simplifies the process of reviewing short-circuit current behavior based on time. Generator modeling aids in determining circuit breaker instantaneous short-circuit current setpoints. As shown in the point-to-point method maximum available short-circuit current from a generator is calculated based on sub-transient reactance. However always keep in mind the rapid decay which could influence down streams overcurrent protective devices. Hopefully, this short paper took out some of the mystery of calculating available short-circuit current when using a generator as the sole source of power in a temporary application.

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Tables

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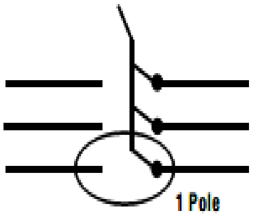
Table 1.2. Impedance Data for Three Phase Transformers

KVA	%R	%X	%Z	X/R
3.0	3.7600	1.0000	3.8907	0.265
6.0	2.7200	1.7200	3.2182	0.632
9.0	2.3100	1.1600	2.5849	0.502
15.0	2.1000	1.8200	2.7789	0.867
30.0	0.8876	1.3312	1.6000	1.5
45.0	0.9429	1.4145	1.7000	1.5
75.0	0.8876	1.3312	1.6000	1.5
112.5	0.5547	0.8321	1.0000	1.5
150.0	0.6657	0.9985	1.2000	1.5
225.0	0.6657	0.9985	1.2000	1.5
300.0	0.6657	0.9985	1.2000	1.5
500.0	0.7211	1.0816	1.3000	1.5
750.0	0.6317	3.4425	3.5000	5.45
1000.0	0.6048	3.4474	3.5000	5.70
1500.0	0.5617	3.4546	3.5000	6.15
2000.0	0.7457	4.9441	5.0000	6.63
2500.0	0.7457	4.9441	5.0000	6.63

Note: UL Listed transformers 25KVA and greater have a ±10% tolerance on their nameplate impedance.

Table 3. Disconnecting Switch Reactance Data (Disconnecting-Switch Approximate Reactance Data, in Ohms*)

Switch Size (Amperes)	Reactance (Ohms)
200	0.0001
400	0.00008
600	0.00008
800	0.00007
1200	0.00007
1600	0.00005
2000	0.00005
3000	0.00004
4000	0.00004



Note: The reactance of disconnecting switches for low-voltage circuits (600V and below) is in the order of magnitude of 0.00008 - 0.00005 ohm/pole at 60 Hz for switches rated 400 - 4000 A, respectively.

*For actual values, refer to manufacturers' data.

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Table 4. Circuit Breaker Reactance Data

(a) Reactance of Low-Voltage Power Circuit Breakers

Circuit-Breaker Interrupting Rating (amperes)	Circuit-Breaker Rating (amperes)	Reactance (ohms)
15,000 and 25,000	15 - 35	0.04
	50 - 100	0.004
	125 - 225	0.001
	250 - 600	0.0002
50,000	200 - 800	0.0002
	1000 - 1600	0.00007
75,000	2000 - 3000	0.00008
100,000	4000	0.00008

(b)Typical Molded Case Circuit Breaker Impedances

Molded-Case Circuit-Breaker Rating (amperes)	Resistance (ohms)	Reactance (ohms)
20	0.00700	Negligible
40	0.00240	Negligible
100	0.00200	0.00070
225	0.00035	0.00020
400	0.00031	0.00039
600	0.00007	0.00017

Notes:

(1) Due to the method of rating low-voltage power circuit breakers, the reactance of the circuit breaker which is to interrupt the fault is not included in calculating fault current.

(2) Above 600 amperes the reactance of molded case circuit breakers are similar to those given in (a)

• For actual values, refer to manufacturers' data.

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Table 5. Impedance Data - Insulated Conductors (Ohms/1000 ft. each conductor - 60Hz)

Size AWG or kcM	Resistance (25C) Copper Metal	NonMet	Aluminum Metal	Nonmet	Reactance - 600V - THHN Single Conductors Mag.	Nonmag.	1 Multiconductor Mag	Nonmag.
14	2.5700	2.5700	4.2200	4.2200	.0493	.0394	.0351	.0305
12	1.6200	1.6200	2.6600	2.6600	.0468	.0374	.0333	.0290
10	1.0180	1.0180	1.6700	1.6700	.0463	.0371	.0337	.0293
8	.6404	.6404	1.0500	1.0500	.0475	.0380	.0351	.0305
6	.4100	.4100	.6740	.6740	.0437	.0349	.0324	.0282
4	.2590	.2590	.4240	.4240	.0441	.0353	.0328	.0235
2	.1640	.1620	.2660	.2660	.0420	.0336	.0313	.0273
1	.1303	.1290	.2110	.2110	.0427	.0342	.0319	.0277
1/0	.1040	.1020	.1680	.1680	.0417	.0334	.0312	.0272
2/0	.0835	.0812	.1330	.1330	.0409	.0327	.0306	.0266
3/0	.0668	.0643	.1060	.1050	.0400	.0320	.0300	.0261
4/0	.0534	.0511	.0844	.0838	.0393	.0314	.0295	.0257
250	.0457	.0433	.0722	.0709	.0399	.0319	.0299	.0261
300	.0385	.0362	.0602	.0592	.0393	.0314	.0295	.0257
350	.0333	.0311	.0520	.0507	.0383	.0311	.0290	.0254
400	.0297	.0273	.0460	.0444	.0385	.0308	.0286	.0252
500	.0244	.0220	.0375	.0356	.0379	.0303	.0279	.0249
600	.0209	.0185	.0319	.0298	.0382	.0305	.0278	.0250
750	.0174	.0185	.0264	.0240	.0376	.0301	.0271	.0247
1000	.0140	.0115	.0211	.0182	.0370	.0296	.0260	.0243

Note: Increased resistance of conductors in magnetic raceway is due to the effect of hysteresis losses. The increased resistance of conductors in metal non-magnetic raceway is due to the effect of eddy current losses. The effect is essentially equal for steel and aluminum raceway. Resistance values are acceptable for 600 volt, 5KV and 15 KV insulated Conductors.

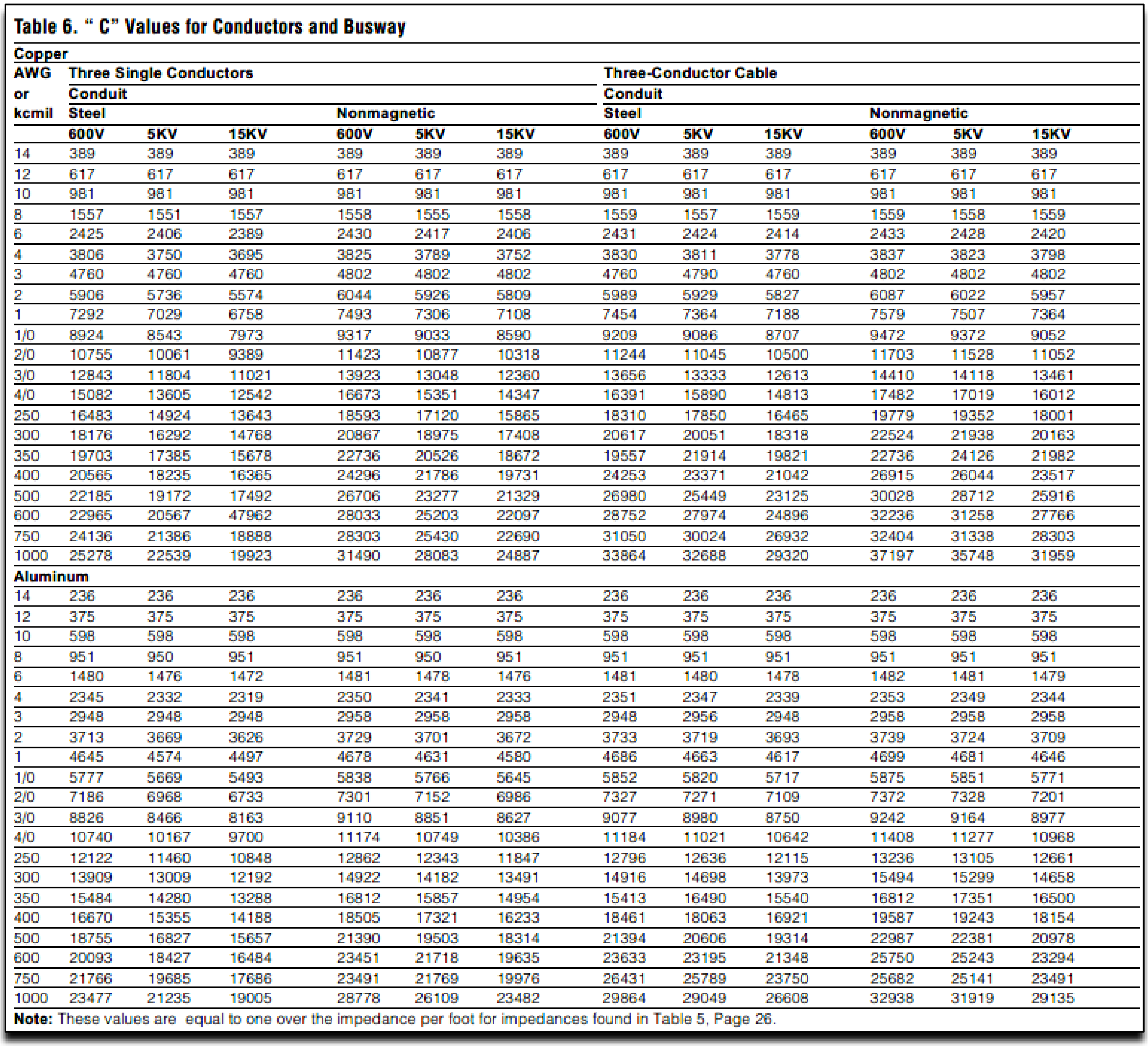

Table 6. " C" Values for Conductors and Busway

Copper												
AWG	**Three Single Conductors**						**Three-Conductor Cable**					
or	**Conduit**						**Conduit**					
kcmil	**Steel**			**Nonmagnetic**			**Steel**			**Nonmagnetic**		
	600V	**5KV**	**15KV**	**600V**	**5KV**	**15KV**	**600V**	**5KV**	**15KV**	**600V**	**5KV**	**15KV**
14	389	389	389	389	389	389	389	389	389	389	389	389
12	617	617	617	617	617	617	617	617	617	617	617	617
10	981	981	981	981	981	981	981	981	981	981	981	981
8	1557	1551	1557	1558	1555	1558	1559	1557	1559	1559	1558	1559
6	2425	2406	2389	2430	2417	2406	2431	2424	2414	2433	2428	2420
4	3806	3750	3695	3825	3789	3752	3830	3811	3778	3837	3823	3798
3	4760	4760	4760	4802	4802	4802	4760	4790	4760	4802	4802	4802
2	5906	5736	5574	6044	5926	5809	5989	5929	5827	6087	6022	5957
1	7292	7029	6758	7493	7306	7108	7454	7364	7188	7579	7507	7364
1/0	8924	8543	7973	9317	9033	8590	9209	9086	8707	9472	9372	9052
2/0	10755	10061	9389	11423	10877	10318	11244	11045	10500	11703	11528	11052
3/0	12843	11804	11021	13923	13048	12360	13656	13333	12613	14410	14118	13461
4/0	15082	13605	12542	16673	15351	14347	16391	15890	14813	17482	17019	16012
250	16483	14924	13643	18593	17120	15865	18310	17850	16465	19779	19352	18001
300	18176	16292	14768	20867	18975	17408	20617	20051	18318	22524	21938	20163
350	19703	17385	15678	22736	20526	18672	19557	21914	19821	22736	24126	21982
400	20565	18235	16365	24296	21786	19731	24253	23371	21042	26915	26044	23517
500	22185	19172	17492	26706	23277	21329	26980	25449	23125	30028	28712	25916
600	22965	20567	47962	28033	25203	22097	28752	27974	24896	32236	31258	27766
750	24136	21386	18888	28303	25430	22690	31050	30024	26932	32404	31338	28303
1000	25278	22539	19923	31490	28083	24887	33864	32688	29320	37197	35748	31959
Aluminum												
14	236	236	236	236	236	236	236	236	236	236	236	236
12	375	375	375	375	375	375	375	375	375	375	375	375
10	598	598	598	598	598	598	598	598	598	598	598	598
8	951	950	951	951	950	951	951	951	951	951	951	951
6	1480	1476	1472	1481	1478	1476	1481	1480	1478	1482	1481	1479
4	2345	2332	2319	2350	2341	2333	2351	2347	2339	2353	2349	2344
3	2948	2948	2948	2958	2958	2958	2948	2956	2948	2958	2958	2958
2	3713	3669	3626	3729	3701	3672	3733	3719	3693	3739	3724	3709
1	4645	4574	4497	4678	4631	4580	4686	4663	4617	4699	4681	4646
1/0	5777	5669	5493	5838	5766	5645	5852	5820	5717	5875	5851	5771
2/0	7186	6968	6733	7301	7152	6986	7327	7271	7109	7372	7328	7201
3/0	8826	8466	8163	9110	8851	8627	9077	8980	8750	9242	9164	8977
4/0	10740	10167	9700	11174	10749	10386	11184	11021	10642	11408	11277	10968
250	12122	11460	10848	12862	12343	11847	12796	12636	12115	13236	13105	12661
300	13909	13009	12192	14922	14182	13491	14916	14698	13973	15494	15299	14658
350	15484	14280	13288	16812	15857	14954	15413	16490	15540	16812	17351	16500
400	16670	15355	14188	18505	17321	16233	18461	18063	16921	19587	19243	18154
500	18755	16827	15657	21390	19503	18314	21394	20606	19314	22987	22381	20978
600	20093	18427	16484	23451	21718	19635	23633	23195	21348	25750	25243	23294
750	21766	19685	17686	23491	21769	19976	26431	25789	23750	25682	25141	23491
1000	23477	21235	19005	28778	26109	23482	29864	29049	26608	32938	31919	29135

Note: These values are equal to one over the impedance per foot for impedances found in Table 5, Page 26.

Table 8. Asymmetrical Factors

		Ratio to Symmetrical RMS Amperes		
Short Circuit Power Factor, Percent*	**Short Circuit X/R Ratio**	**Maximum 1 phase Instantaneous Peak Amperes Mp**	**Maximum 1 phase RMS Amperes at 1/2 Cycle M_m (Asym.Factor)***	**Average 3 phase RMS Amperes at 1/2 Cycle M_a***
0	∞	2.828	1.732	1.394
1	100.00	2.785	1.697	1.374
2	49.993	2.743	1.662	1.354
3	33.322	2.702	1.630	1.336
4	24.979	2.663	1.599	1.318
5	19.974	2.625	1.569	1.302
6	16.623	2.589	1.540	1.286
7	14.251	2.554	1.512	1.271
8	13.460	2.520	1.486	1.256
9	11.066	2.487	1.461	1.242
10	9.9301	2.455	1.437	1.229
11	9.0354	2.424	1.413	1.216
12	8.2733	2.394	1.391	1.204
13	7.6271	2.364	1.370	1.193
14	7.0721	2.336	1.350	1.182
15	6.5912	2.309	1.331	1.172
16	6.1695	2.282	1.312	1.162
17	5.7947	2.256	1.295	1.152
18	5.4649	2.231	1.278	1.144
19	5.16672	2.207	1.278	1.135
20	4.8990	2.183	1.247	1.127
21	4.6557	2.160	1.232	1.119
22	4.4341	2.138	1.219	1.112
23	4.2313	2.110	1.205	1.105
24	4.0450	2.095	1.193	1.099
25	3.8730	2.074	1.181	1.092
26	3.7138	2.054	1.170	1.087
27	3.5661	2.034	1.159	1.081
28	3.4286	2.015	1.149	1.076
29	3.3001	1.996	1.139	1.071
30	3.1798	1.978	1.130	1.064
31	3.0669	1.960	1.122	1.062
32	2.9608	1.943	1.113	1.057
33	2.8606	1.926	1.106	1.057
34	2.7660	1.910	1.098	1.050
35	2.6764	1.894	1.091	1.046
36	2.5916	1.878	1.085	1.043
37	2.5109	1.863	1.079	1.040
38	2.4341	1.848	1.073	1.037
39	2.3611	1.833	1.068	1.034
40	2.2913	1.819	1.062	1.031
41	2.2246	1.805	1.058	1.029
42	2.1608	1.791	1.053	1.027
43	2.0996	1.778	1.049	1.024
44	2.0409	1.765	1.045	1.023
45	1.9845	1.753	1.041	1.021
46	1.9303	1.740	1.038	1.019
47	1.8780	1.728	1.035	1.017
48	1.8277	1.716	1.032	1.016
49	1.7791	1.705	1.029	1.014
50	1.7321	1.694	1.026	1.013
55	1.5185	1.641	1.016	1.008
60	1.3333	1.594	1.009	1.004
65	1.1691	1.517	1.005	1.001
70	1.0202	1.517	1.002	1.001
75	0.8819	1.486	1.0008	1.0004
80	0.7500	1.460	1.0002	1.0001
85	0.6198	1.439	1.00004	1.00002
100	0.0000	1.414	1.00000	1.00000

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