VOL. X JULY, 1923 No. 7

THE BROWN BOVERI REVIEW

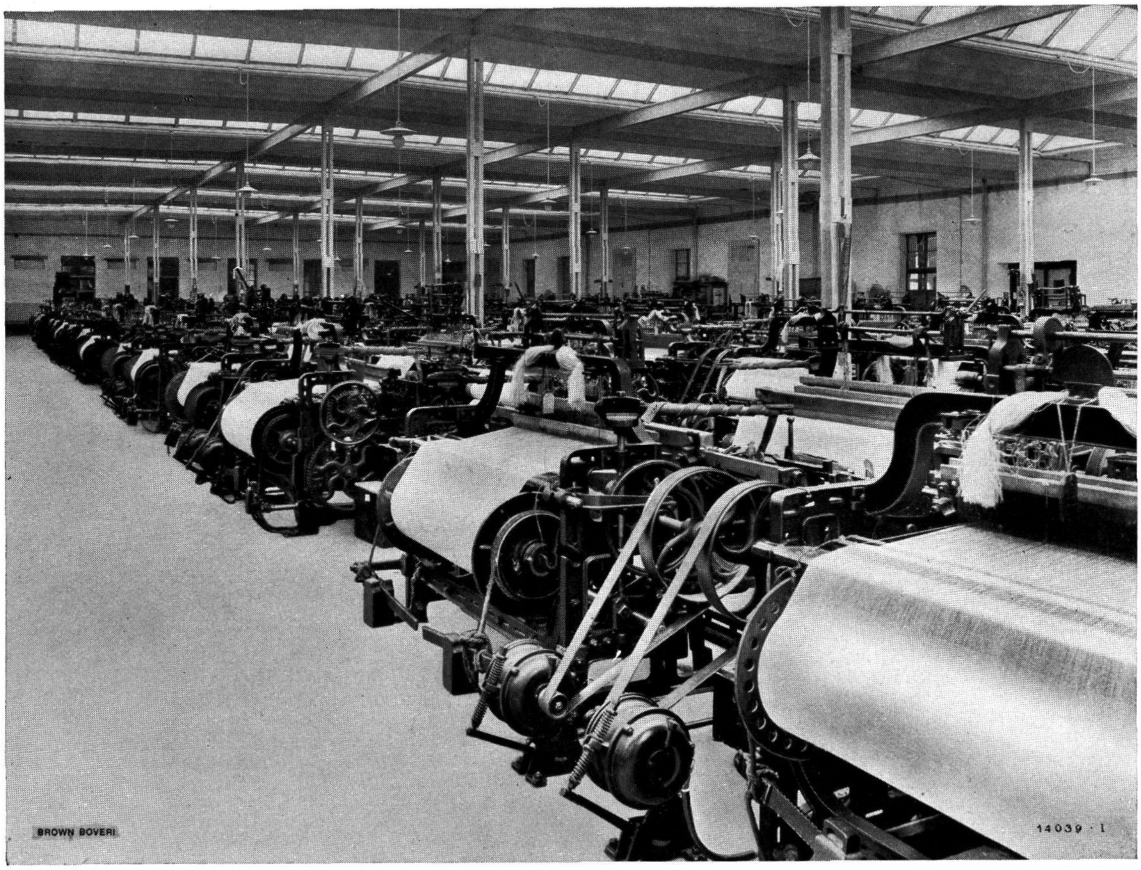
EDITED BY BROWN, BOVERI & CO., BADEN (SWITZERLAND)

TRAIN DRAWN BY BROWN BOVERI ELECTRIC LOCOMOTIVE LEAVING ZURICH MAIN STATION
on the recently electrified Zurich-Zug, section of the Swiss Federal Railways.

CONTENTS:

	Page
The Brown Boveri phase advancer	**119**
The new transformer testing installation in the Baden works of Brown, Boveri & Co.	**128**

ELECTRIC DRIVES FOR INDUSTRIAL PLANTS



WEBER & Co., AARBURG (SWITZERLAND).
Individual drive of 200 weaving machines by Brown Boveri weaving-machine motors.

TEXTILE, PAPER-MAKING, AND PRINTING WORKS
CHEMICAL, CHOCOLATE, AND SUGAR FACTORIES
CEMENT AND FLOUR MILLS - BREWERIES
MACHINE TOOLS - AGRICULTURE - SMALL INDUSTRIES

THE BROWN BOVERI REVIEW

THE HOUSE JOURNAL OF BROWN, BOVERI & CO., BADEN (SWITZERLAND)

VOL. X JULY, 1923 No. 7

The Brown Boveri Review is issued monthly. Single numbers: 1.20 francs (1 shilling). Yearly subscription: 12 francs (10 shillings).
Reproduction of articles or illustrations is permitted subject to full acknowledgment.

THE BROWN BOVERI PHASE ADVANCER.

Decimal index 621. 313. 006 + 621. 313. 64.

SUMMARY. 1. The meaning of power factor. 2. Disadvantages of a low power factor in alternating-current systems. 3. Methods of improving the power factor. 4. The Brown Boveri phase advancer. a) Principle. b) Construction. c) Drive. d) Connections. e) Influence of the phase advancer on a motor. f) How to determine which motors should be compensated. 5. Comparison of the different methods of correcting the power factor in an alternating-current system.

1. THE MEANING OF POWER FACTOR.

If a consumer connected to a direct-current system is supplied with a certain amount of power at a given pressure, the strength of the current can be at once determined. In an alternating-current supply system, on the other hand, only the smallest attainable value of the current is found from the power and tension; this minimum current is called the watt-current. The actual value of the current I flowing is generally greater, and it is customary to speak of it as being composed of two parts: the watt-current I_w, and the wattless current I_{wl}. The relation between the three currents is given by the equation:

$$I^2 = I_w^2 + I_{wl}^2.$$

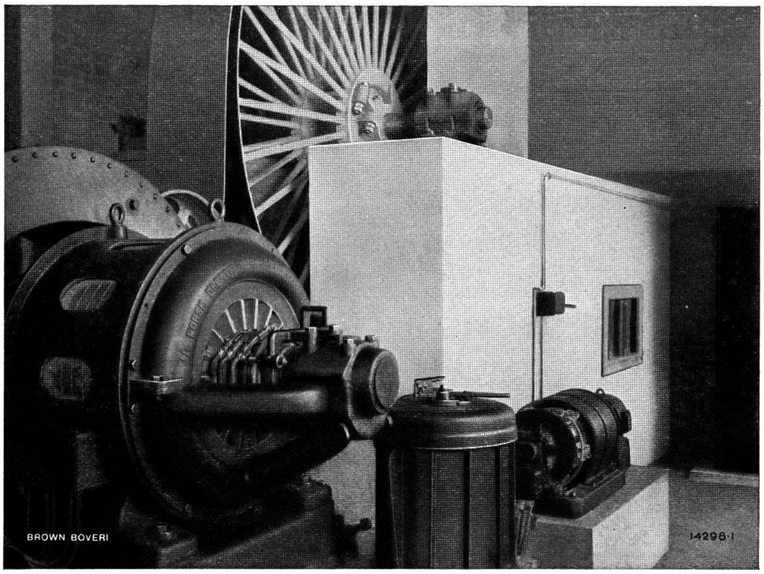


Fig. 1. — Three-phase induction motor, 185 kW, 600 r.p.m., 220 V, 50 cycles with a phase advancer for improving the power factor from 0·87 lagging to 0·98 leading, and relieving the system of 160 wattless kVA.

Like the total current, the wattless portion is an alternating one. It reaches its maximum value either a quarter of a period after or before the pressure has reached its highest value. In the first case, it is called lagging, and in the second, leading. At any moment, a leading current and a lagging current flowing in the same conductor have opposite directions, and the total wattless current is the difference of the two. The relation between the current I, the power P and the supply pressure E of a three-phase system is:

$$I = \frac{P}{\sqrt{3} \cdot E \cdot \cos \varphi}$$

The expression "cos φ" in this equation is that which receives the name power factor; its value is

$$\cos \varphi = \frac{P}{\sqrt{3} \cdot E \cdot I} = \frac{I_w}{I}$$

The product $\sqrt{3} \cdot I_{wl} \cdot E$ is often called the wattless power, and is measured in volt-amperes or kilovolt-amperes. The highest possible value of the power factor is unity. When this is attained, the wattless current is zero and only watt current flows in the conductor. In the majority of plants, the value of the power factor is considerably lower than unity, and varies usually from 0·6 to 0·85.

The fall in the value of the power factor is, for the most part, due to induction motors connected to the system. These machines draw a lagging wattless current (the magnetising current) from the mains for exciting their field. At no load, this current can be about 30 — 50 % of the normal full-load current, rising, however, only slightly as load is put on the motor. Since the watt current is roughly proportional to the load, it follows that the power factor rises with an increasing load — it

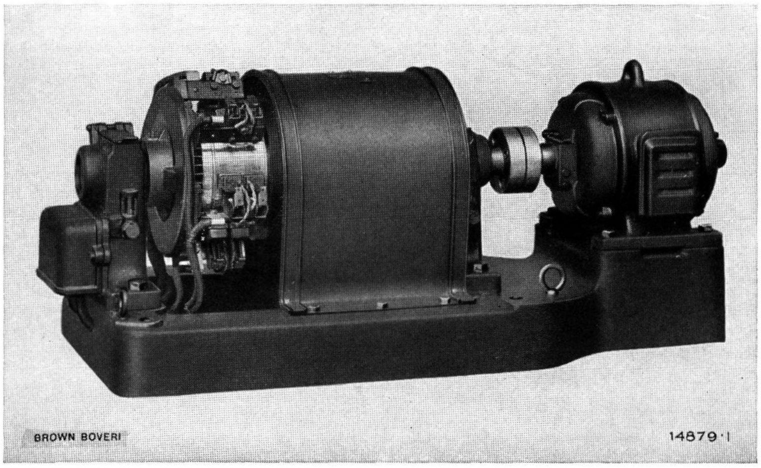


Fig. 2. — Brown Boveri phase advancer set (single type).

can, however, never reach unity. At no load, the power factor is very low, being only 0·10 to 0·15. The wattless current flowing in the mains is the sum of the wattless currents of the individual motors. The power factor of a plant is very unfavourably influenced by the use of slow-running motors, which take a large magnetising current, and by motors running on light load or no load.

2. DISADVANTAGES OF A LOW POWER FACTOR IN ALTERNATING-CURRENT SYSTEMS.

No power is transmitted by the wattless current, but it causes the same losses as a watt current. If the power factor has the value $\frac{a}{100}$, the total current is $\frac{100}{a}$ times, and the total heat losses $\left(\frac{100}{a}\right)^2$ times larger than would be the case if the same power were transmitted with unity power factor. The losses are increased in all portions of the installation, that is to say, in the generators, transformers and supply cables, and they can reach a considerable value, especially in the latter. Moreover, the kilowatt capacity of the generators and transformers is greatly reduced by the increased losses. The lagging wattless current also causes a large pressure drop in the whole system, which is greater than that due to a watt current of the same strength. On account of this, it is more difficult to keep the pressure constant, and for the same reason, the capacity of the plant may be reduced.

If an increased output is required from an installation which, with respect to losses or pressure drop, is already at the limit of its capacity, it is therefore possible to avoid the otherwise necessary extensions to the plant if the power factor is improved. Since additions to the generating plant are, in practically all cases, more expensive than the raising of the power factor according to one of the methods described later on, the latter is to be preferred. When a new generating plant is being designed, the capital cost can be kept down if it is planned on the basis of a higher power factor than that which would be reached without employing any special means for improving it.

Users of electrical energy who have their own generating plant can increase the power available and reduce the losses by power-factor compensation, while, at the same time, it is easier to keep the pressure constant. Although, on the other hand, consumers who take their energy from a supply company are not interested in the losses on the mains side of their meter, they must not overlook the losses in the cables leading from the latter to their machines, as such losses represent so much energy that must be paid for over and above the effective power used. The losses in question can be so high that the cost of current can be considerably reduced by correcting the power factor. The saving will naturally be still greater if the price per kilowatt-hour is made to depend on the power factor of the consumer's installation — a system of charging which is now being adopted more and more (see The Brown Boveri Review, 1922, No. 8).

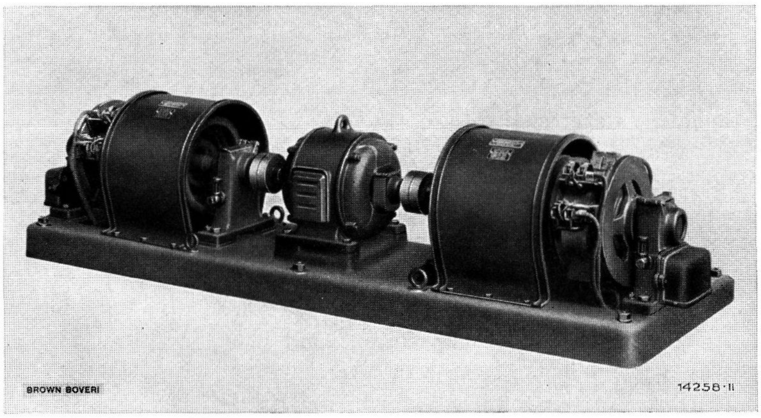


Fig. 3. — Brown Boveri phase advancer set (double type)
for bringing the power factor of a three-phase induction motor, 550 kW, 200 r. p. m., 530 V, 50 cycles, from 0·8 up to unity, and saving 450 wattless kVA.

3. METHODS OF IMPROVING THE POWER FACTOR.

As the poor power factor is caused in the majority of cases by the induction motors connected to the mains, the obvious solution is to raise the power factor of these machines, or to replace them by motors of a different type having a better inherent power factor. The improvement of the power factor of an induction motor is called phase compensation, and is attained by connecting a rotating phase displacer in the rotor circuit of the motor. By this means, it is possible to advance the power factor of the motor so far that it takes up leading current. It is for this purpose that the Brown Boveri phase advancer, of which a description is given hereafter, has been designed. The kinds of motor available with a good inherent power factor are the synchronous motor and the synchronous induction motor, both of which can work with unity power factor, or, if overexcited, with a leading power factor. Occasionally, the motor is not called upon to deliver any mechanical energy, but simply to run light and take up leading current, the value of this being so adjusted that it corresponds to the lagging current taken by the other motors connected to the system, so that in the latter only pure watt current flows. The synchronous motor operates here exactly like a condenser, which type of apparatus is occasionally used instead of this kind of motor. Finally, the power factor can by improved in a marked manner by choosing motors and transformers of a suitable size, and by avoiding long periods of light running. This branch of the subject will, however, not be further discussed here.

4. THE BROWN BOVERI PHASE ADVANCER.[1]

(a) Principle.

The power factor of an induction motor with a given magnetising current can be improved by transferring the latter partially or entirely from the stator to the rotor, so that the mains are correspondingly freed from the supply of this current. In order that the rotor current of an induction motor can have the necessary magnetising effect, it must be displaced so that it leads with respect to the current in the uncompensated motor. A pressure leading with regard to the current must therefore be introduced into the rotor circuit, and the duty of the phase advancer is to supply this pressure. This machine (Fig. 4) consists of a direct-current armature with a commutator having brushes placed 120 electrical degrees apart. Since the phase advancer must always be designed for a large current and a low pressure, its armature core is short and its commutator long. If the rotor current of the motor to be compensated, that is, a low-frequency polyphase current, is supplied to the commutator, the phase advancer when standing still will operate as a choke coil. Its effect, therefore, will be to give rise to a lagging pressure, whose magnitude depends on the frequency, i. e., on the speed with which the field produced by the polyphase current cuts the winding. The speed of rotation of this field in space depends on the periodicity of the exciting current, but not on whether the phase advancer is in motion or standing still, as any influence on the disposition of the current and of the field in the phase advancer (considered from a fixed point outside the latter) due to movement of this machine is nullified by the effect of the commutator and the stationary brushes. Consequently, if the winding rotates in the same direction as the field, the speed at which the two cut one another decreases, and the lagging pressure is reduced. The latter becomes zero when the speed of the winding is the same as that of the field. When, however, the phase advancer rotates quicker than the field, the relative movement between the latter and the winding will have the opposite sense, with the result that the induced pressure will be reversed in direction, and become leading, as required, so that the phase advancer operates like a condenser. As the speed of the field corresponds to the frequency of slip of the induction motor, which amounts to $^1/_2$—2 cycles per second, while a frequency of rotation of 30—50 cycles is usually chosen for the armature and commutator, the relative speed between the field and the

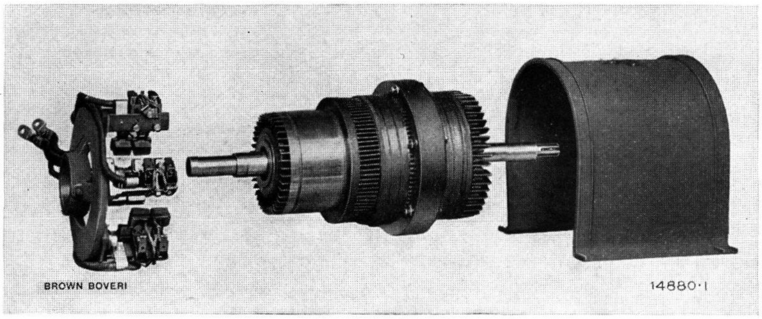


Fig. 4. — Brown Boveri phase advancer, dismantled.

[1] Cf. A. Scherbius: "Eine neue Maschine zur Kompensation der Phasenverschiebung von Ein- und Mehrphasen-Induktionsmotoren." Elektrotechnische Zeitschrift, 1921, No. 42.

winding is high, and therefore a considerable leading pressure can be attained with quite a small phase advancer.

(b) Construction.

A noticeable feature about the design of the phase advancer is the absence of a stator. In order, however, to provide a closed path for the flux, the armature core is so designed that it extends radially well beyond the winding, which is in entirely closed slots. A stator can be dispensed with, since the machine is only required to give a leading pressure without having to supply any energy either in electrical or mechanical form. A light enclosing cover of sheet iron takes the place of a stator, and serves to protect the rotating parts and define the path of the cooling air. The simplicity of the design makes for great reliability, which is one of the leading features of the phase advancer.

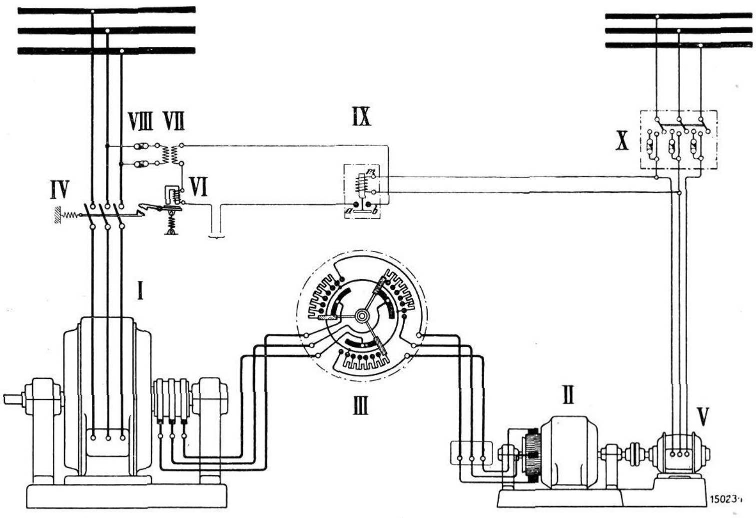


Fig. 5. — Diagram of connections of an induction motor with phase advancer.

I. Main motor.
II. Phase advancer.
III. Rotor starter with change-over device.
IV. Switch.
V. Auxiliary motor.
VI. No-volt release.
VII. Potential transformer.
VIII. Fuses for ditto.
IX. Contact relay.
X. Switchbox.

(c) Drive.

As the machine does not develop any torque, its armature must be rotated by outside means. For this purpose, the main motor itself can be utilised — in which case either direct coupling or a belt drive may be adopted — or a separate small auxiliary motor, which is generally of the squirrel-cage type. This latter kind of drive is as a rule preferable, since it permits of greater freedom as regards the place where the phase advancer can be situated. All chance of the drive of the latter failing must be eliminated by suitable attendance in the case of belt drive, and by some kind of electrical interlocking device, such as that described under *(d)*, with an auxiliary driving motor.

This latter machine has only to overcome the frictional losses of the phase advancer, which amount to about $^1/_3$ % of the output of the main motor. In order, however, to ensure sufficient starting torque, even with reduced pressure, it is usual to employ an auxiliary motor that has an output equal to $^1/_2$—$^3/_4$ % of that of the large motor.

(d) Connections.

A typical diagram of connections of a Brown Boveri phase advancer is shown in Fig. 5. Between the mains and the large motor is the usual switchgear, while the phase advancer is connected to three contacts on the rotor starter, so that the rotor of the main motor is switched over on to the phase advancer at the end of the starting operation. A separate change-over switch is used, however, when the rotor current is high or when the phase advancer is added to a motor which is already installed with its starter. In order to exclude the possibility of the main motor being started before the phase advancer is running, an electrical interlocking device is fitted. This also switches off the main motor should the current supply to the auxiliary motor be interrupted for any reason. Besides the arrangement shown in Fig. 5, there are various others which are used to suit particular requirements.

(e) Influence of the phase advancer on a motor.

Since the effect of the phase advancer is to cause part of the magnetising current of the main motor to be supplied by the rotor, it follows that less magnetising current is taken from the mains by the stator, with a consequent improvement in the power factor. If all the magnetising current flows in the rotor, then none comes into the stator, so that the motor works with unity power factor. Further, if the magnetising current in the rotor is raised above that necessary for exciting the field of the main motor, the latter balances the excess by drawing from the mains a current in the opposite direction, i. e., a leading current, which again causes the total stator current to be higher than with unity power factor. The current flowing in the rotor is lower when the motor is slightly compensated than when no phase advancer at all is used, but rises when the compensating effect is increased.

As long as the main motor is not over compensated, that is to say, the power factor is not made to lead, the heating losses in the stator diminish, due to the reduced current flowing in that part of the motor, whereas, above a certain amount of compensation, the heating losses in the rotor increase, but always in a smaller proportion than the reduction of the stator losses, so that the total heating losses of the motor as a whole are reduced. When the losses in the phase advancer are taken into account, the net efficiency of the motor is found to remain unchanged or to fall only by a negligible amount (up to about 1 %). If the power factor is made to lead considerably, the drop in efficiency would, of course, be somewhat greater.

The improvement of the power factor effected by a given phase advancer depends on the load of the main motor. At no load, the rotor current is zero, and the phase advancer causes no correction; on the other hand, even on light loads, quite appreciable improvement of the power factor is obtained. Generally it can be raised to about unity at any load from $^1/_3$, or in certain cases even from $^1/_4$, of the normal load right up to the overload capacity of the motor, thanks to a special design patented by Brown, Boveri & Co. Absolute no load scarcely occurs under actual running conditions, as a certain amount of current is necessary for overcoming frictional losses, etc.

It should be noted that at very light loads the power factor gives no definite measure of the amount of wattless current. Since the power factor represents the proportion between watt current and total current (see page 119), it is evident that its value depends just as much on the amount of watt current as of wattless current. Now, the watt current only varies within a comparatively limited range between full load and fractional loads, but when the motor runs light, its value depends on the losses alone, and these can vary considerably, which also influences the value of the power factor. When the motor is running on no load, the latter is, therefore, just as much a measure of the losses as of the wattless current. It would be more to the point in the case of no load or very light load to indicate, instead of the power factor, simply the amount of wattless current, or the wattless power, or the proportion the one or other of these bears to the value at full load.

In Fig. 6, the curves a and b show the power factor of a 300-kW motor as measured without and with a phase advancer respectively. The corresponding wattless power taken from the mains, which is proportional to the wattless current, is given by the curves a and b in Fig. 7. The difference between these latter curves is indicated by curve c; this represents the wattless power saved by using the phase advancer. In this case, the main motor is slightly over compensated at full load.

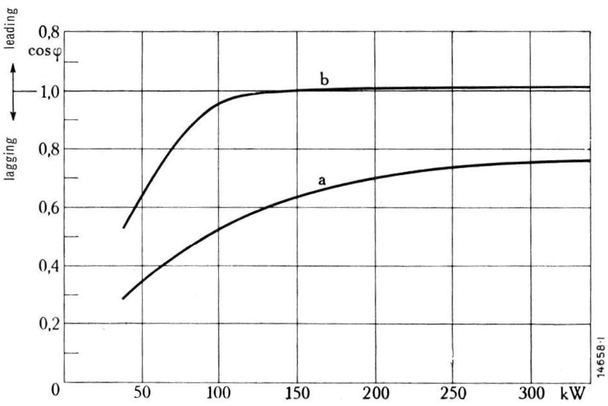


Fig. 6. — Power factor of an induction motor, 300 kW, 160 r. p. m., as a function of the output.

a. Without phase advancer. b. With phase advancer.

Since the slip of the induction motor is proportional to the losses in the rotor circuit, it will increase by about 25—75 % when the magnetising current flows in the rotor instead of in the stator. The speed of a motor will therefore fall about $^1/_4$—2 % when a phase advancer is employed. As seen above, however, the larger slip does not mean an increase in the total losses of the motor, as the stator losses are reduced at the same time.

The correction of the power factor possible with a given motor is limited in the first place by the maximum leading pressure allowable for the phase advancer, and secondly by the increase caused in the rotor current, since the losses must not exceed a certain amount on account of the permissible temperature rise. When the motor runs on partial loads, the rotor current is smaller, and so a much greater increase in it, and consequently in the amount of power-factor correction, is allowable than at full load. If full advantage is to be taken of this, the pressure of the phase advancer must be raised when the load on the main motor falls below normal. This is attained by running the phase advancer slowly at heavy loads and quickly at light ones, and in such cases, a shunt-wound direct-current motor best meets the requirements. Its speed has to be adjusted carefully, either by hand or automatically, so as to avoid overheating of the rotor winding which would take place if the phase advancer ran quickly while the main motor was well loaded.

The use of a phase advancer not only raises the power factor, but also the breakdown torque of the induction motor, so that its momentary overload capacity is increased. This is a further important advantage of the phase advancer, especially with slow-running motors. Not infrequently, such machines must be of a larger size than necessary from the point of view of heating, in order to obtain the requisite overload capacity and a good power factor without a phase advancer; whereas, when the latter is employed, a smaller type of main motor can be chosen. Hence, it can happen that a better power factor is attained with a smaller total first cost. Even when overload capacity is of quite secondary importance, the possibility of raising the normal output of the motor by installing a phase advancer — due to the fact that the rotor losses do not increase as much as those in the stator decrease — should be borne in mind.

The fitting of a phase advancer in no way affects the asynchronous characteristic of the induction motor, and the drop of speed between no load and full load takes place in the usual way. There is, therefore, no question of hunting or falling out of step.

Even with a motor run as an induction generator, the phase advancer improves the power factor and overload capacity, but in this case, it is either necessary to reverse the direction of rotation of the auxiliary machine, as compared with that in which it runs when the main machine operates as a motor, or else to change over two of the connections between the phase advancer and the slip-rings.

(f) How to determine which motors should be compensated.

A motor that is to be provided with a phase advancer must have brushes for continuous contact. If the machine has brush-lifting gear, the necessary alteration — which may occasionally include more liberally dimensioned slip-rings — can generally be effected without any great expense. When the plant contains only one motor, it will, as a rule, be found advisable to correct its power factor only to about 0·95 to 0·98 lagging, since a greater improvement would mean increased losses in the main motor and a larger size phase advancer, while the further reduction in the stator current would be small. In such plants, it is sometimes not worth while using a phase advancer if the motor has normally a power factor of, say, 0·9 or more.

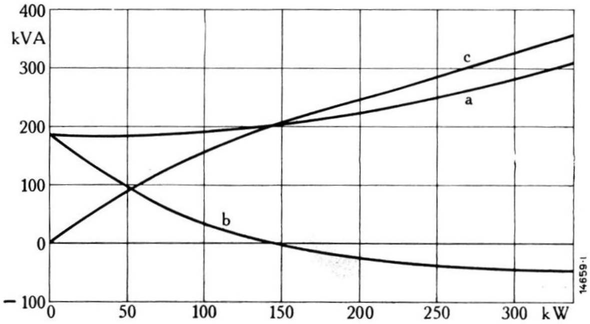


Fig. 7. — Wattless kVA taken by an induction motor, 300 kW, 160 r. p. m., as a function of the output.

a. Without phase advancer. b. With phase advancer.
c. Wattless energy of which the system is relieved with phase advancer.

The conditions are, however, quite different when numerous motors of various sizes are installed. In such cases, the overall power factor is usually rather poor, and if it is desired to improve the power factor of the plant by a certain amount, then a definite reduction of the aggregate wattless power taken by the motors must be aimed at. For this purpose, one or other of the motors can be compensated in a high degree, or else several motors compensated lightly. In individual cases, the question of which machine should be compensated may be settled by the fact that one of them is situated at a distance from the mains, the long cables causing relatively heavy losses when the power factor is low, or that one of the motors has insufficient overload capacity. If no machine has features which render it eminently suitable for having a phase advancer fitted to it, to obtain the desired reduction in wattless power, but all motors seem equally well adapted for this, the choice should be made on the basis of the following considerations: —

According to Fig. 7, the amount of wattless power in kVA of which the mains are relieved rises with increasing load on the motor compensated; consequently, a phase advancer should be fitted to those motors that work for the most part well loaded. Moreover, it is better to compensate the largest motors then a number of small ones, since a given saving in wattless power drawn from the mains can be effected more cheaply by providing one large phase advancer for a large motor than several small phase advancers for small motors. The amount of wattless power saved bears the same relation to the output of the phase advancer (which has a definite value for each type) that the periodicity of the mains does to the periodicity of slip of the main motor. It follows, therefore, that the smaller the slip is, the greater is the amount of wattless power of which the mains can be relieved with a given size of phase advancer. Large high-speed motors have the smallest slip, and also a good normal power factor. The initial cost of the phase-advancer set necessary for saving a certain amount of wattless power in a plant will thus be smallest when just those motors are compensated that would scarcely require any improvement when considered by themselves. The same saving in wattless power can be effected by improving the power factor of a high-speed motor of 1000 kW with 1 % slip from 0·9 lagging to 0·975 leading, as by advancing the normal power factor of 0·7 of a slow-running motor of the same power with $2^1/_2$ % slip up to 0·95 lagging; in the latter case, the phase advancer has to give about $2—2^1/_2$ times the output necessary with the high-speed motor. Further, as the power which the phase advancer must supply rises rapidly when the correction is carried to such an extent that the wattless power saved in kVA is more than about 75 % of the kW output of the main motor, it is not advisable to carry the compensation above this figure, Also from the point of view of running costs, the compensation should be kept within moderate limits, as the increase in the losses of the main motor and the phase advancer are small, or even zero, as long as there is not over-compensation, but rise rapidly if the power factor is advanced further.

Motors which, in conjunction with a slip resistance in the rotor circuit, utilise, at peak loads, the energy stored in rotating masses are frequently unsuitable for having a phase advancer of the above-mentioned statorless type fitted to them, as the possible compensation would then be small when much resistance is in the rotor circuit. Here the power factor can be corrected by employing a special regulating set like that used for the well-known Brown Boveri-Scherbius speed-regulating system, but usually of a simpler design, however. It can serve for merely improving the power factor or for causing at the same time the desired drop in the speed of the main motor with increasing load. Such an arrangement avoids the losses otherwise caused by the use of resistances for dissipating the slip energy. Moreover, it is possible to improve the power factor even at no load with such a set. For this reason, it may even enter into consideration instead of an ordinary phase advancer for compensating a motor which is used for a drive requiring no speed regulation.

The kind of drive for which the induction motor is used is not of any consequence, if only attention is paid to the points mentioned above. The phase advancer operates just as advantageously with constant load on the main motor as with heavy fluctuating loads. When peaks do occur, the increase in the overload capacity due to the phase advancer shows to its full advantage.

Compensation of the power factor of induction generators can also be of great importance in certain circumstances. Such machines supply watt current to the system, but as they draw from it at the same time wattless current which has to be furnished by alternators working in parallel with them, the current of the alternators is scarcely reduced at all — in some cases, it may be even increased when the induction generators are working. If, however, the latter are fitted with phase advancers, the alternators are relieved of supplying the wattless current, and it is only then that the benefit accruing from the employment of the induction generators to help the alternators is fully felt. In passing, it should be mentioned that even a compensated induction generator only operates satisfactorily when working on a system which is fed by an alternator at the same time.

5. COMPARISON OF THE DIFFERENT METHODS OF CORRECTING THE POWER FACTOR IN AN ALTERNATING-CURRENT SYSTEM.

The power factor may be adjusted either for the purpose of regulating the pressure, for reducing the heating losses, or for both these reasons together.

Since a lagging power factor results in a large pressure drop, and a leading power factor causes a rise of pressure in the mains, it is possible to adjust the pressure in a long supply line by taking from it either a lagging or a leading wattless current at certain points. A phase advancer does not come into consideration for this duty, and recourse is had to a synchronous motor whose exciting current is mostly varied by an automatic regulator in such a way that the pressure in the line is kept constant.

When it is not a question of influencing the line pressure at one place so that it remains steady, but of having as far as possible only motors connected to the system which cause roughly the same pressure drop at light load as they do at full load, — special provision for keeping the pressure constant not being so necessary in this case, — then the induction motor with a phase advancer is very suitable. This is due to that feature of the phase advancer which, from another point of view, is considered undesirable, i. e., that it raises the power factor when the motor is loaded but not when it is running light. As the lagging wattless current falls (Fig. 7) when load is put on a motor provided with a phase advancer, it follows that the pressure drop of the wattless current is reduced, while that of the watt current, of course, increases. The one effect balances the other to a large extent, and the variation of the pressure drop in the line is smaller than with a synchronous motor or a synchronous induction motor. The lagging wattless current of these two kinds of machine increases when load is put on, assuming that the excitation is not adjusted in the meantime, and so there is a larger pressure drop in the mains, which is augmented by the watt current rising simultaneously. The same holds good for a reduction in the leading wattless current as for an increase in the lagging current.

It should be noted that if condensers are connected to the mains at various places they will not influence in the slightest degree the increase in the pressure drop caused by load being put on the motor.

This change in the drop is of considerable importance as regards the overload the motor can carry. Since the overload capacity is approximately proportional to the square of the terminal pressure, a large fall in the latter will bring down the overload capacity to a great degree. The pressure tends to fall as soon as an overload comes on, and therefore the question of overload capacity is to a large extent one of avoiding an excessive drop in the pressure. The phase advancer influences the overload capacity favourably, and in a twofold manner: by reducing the extent of the drop in pressure when the load comes on, and by actually increasing the overload capacity of the motor with constant supply pressure — as already seen in section 4 e.

If the power factor is to be improved for the purpose of minimising the heating losses, then the phase advancer can be employed, as well as the other methods indicated in section 3. Like the condenser, it has the advantage of only increasing the losses in the plant by a negligible amount. Apart from the large floor space taken up by the condenser, and the fact that it can have an undesirable effect on the system under certain circumstances, the question of initial cost and depreciation plays the main part in settling the question of which kind of apparatus should be installed for correcting the power factor. So far, condensers have not been employed in Europe to any extent.

When comparing the phase advancer with the synchronous motor, it is necessary to make a distinction between the case where the latter runs merely for the purpose of raising the power factor, and where it is required to give a mechanical output at the same time. With the latter, the decision is more difficult. While the capital cost is here also an important factor, figures with regard to this must be treated with caution, as they depend too much on the assumptions made, and can scarcely give a fair idea of things. It is necessary to consider the cost of each complete set, that is, of the induction motor with phase advancer on the one hand, and of the synchronous motor on the other. The losses of each must also be taken into account when making the comparison. Although these do not differ materially when the machines are loaded, the losses when running light are much greater, at least with the synchronous induction motor, than with an induction motor with phase advancer, provided that the excitation of the synchronous machine is not made to vary according to the load. This latter type of motor then takes a considerable amount of leading wattless power from the line, whereas the phase advancer is ineffective when the main motor runs light. The increased losses with the synchronous induction motor are justified when it is desirable to take up leading current at no load, but they cannot be considered other than a disadvantage when no store is set upon this feature.

The adoption of a synchronous induction motor or an ordinary synchronous one with mechanical output cannot be considered in many places, e. g., where its characteristic features do not suit the drive in question. When heavy peak loads may occur, a motor with a synchronous characteristic is seldom desirable, and in such cases an induction motor with phase advancer is the appropriate solution, as such a machine still retains its asynchronous character, and is not only as suitable as an ordinary induction motor alone, but frequently still better, on account of its increased overload capacity.

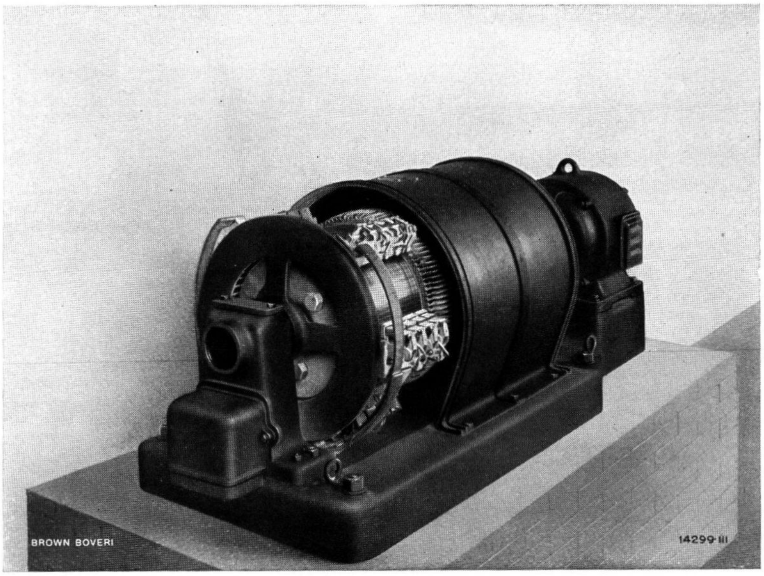


Fig. 8. — Brown Boveri phase advancer with its driving motor.

The only other practical alternative to a phase advancer is here a synchronous motor running light, and adjusted to take a leading current. As the comparison then lies between this machine and the phase advancer exclusive of the main motor, the balance as regards cost is in favour of the phase advancer. The light-running synchronous motor needs a watt input equal to at least 5 % of the amount of wattless power it saves, whereas the increase in the losses of the plant due to installing a phase advancer is only about 0—2½ % of the wattless power saved, corresponding to 0—1 % of the main motor output as mentioned above. The running costs of the phase advancer are therefore much smaller than those of a synchronous condenser. The initial cost of installing the latter type of plant will, of course, be kept down wherever possible by connecting only a few such machines of large capacity to suitable points of the supply system, instead of providing one for each induction motor that should have its power factor corrected. It is then, however, only possible to influence the losses in the mains between such points and the power station. With phase advancers, on the other hand, the losses in the connecting cables right up to the motor are reduced. Further, the advantage of better overload capacity, and, in certain circumstances, of the increased power the induction motor can furnish continuously must here also be put to the favour of the phase advancer, as the light-running synchronous motor has no effect of this kind on the induction motors in its neighbourhood.

When the operating conditions of a plant without any special devices for improving the power factor are looked into, it will be found, as a rule, that a considerable saving could be effected by power-factor correction. In many cases, this would be due to a reduction of the losses; in others, where the price per kilowatt-hour depends on the power factor, there would be the additional advantage of obtaining current on better terms; while in still other cases, extensions to the plant, which would otherwise be essential, can be postponed for years. Generally, it will be found that the best way to improve the power factor is to connect the phase advancers to individual induction motors. Besides the saving in the cost of current consumed, which can be stated directly in figures, there are advantages that cannot be expressed in this way: such as, smaller variation in the terminal pressure, higher overload capacity and even increased power of the motor. The results obtained with the phase advancer in numerous installations over a long period of years have proved that it is a most reliable machine, and the recognition of the advantages accruing from its use are leading to its more widespread adoption. *Dr. W. Seiz. (J. F. L.)*

THE NEW TRANSFORMER TESTING INSTALLATION IN THE BADEN WORKS OF BROWN, BOVERI & CO. [1]

Decimal index 621. 795: 621. 314. 3.

IV. TESTING BAY FOR STANDARD MEASUREMENTS WITH SPECIAL INSTRUMENT TABLES.

The development in transformer construction has resulted in increasing severity of the conditions to be fulfilled by the materials employed, and the transformer designer is limited, particularly as to the magnitude of the pressure that can be dealt with, by the dielectric strength of the insulating material at his disposal. Nevertheless, no transformer that is not perfectly able to stand the exacting demands met with in practice can leave the Brown Boveri works, as each one has first to pass a number of searching tests.

The following measurements and tests ensure the timely discovery of any defects:—

1. The measurement of the transformation ratio—for checking the number of windings.

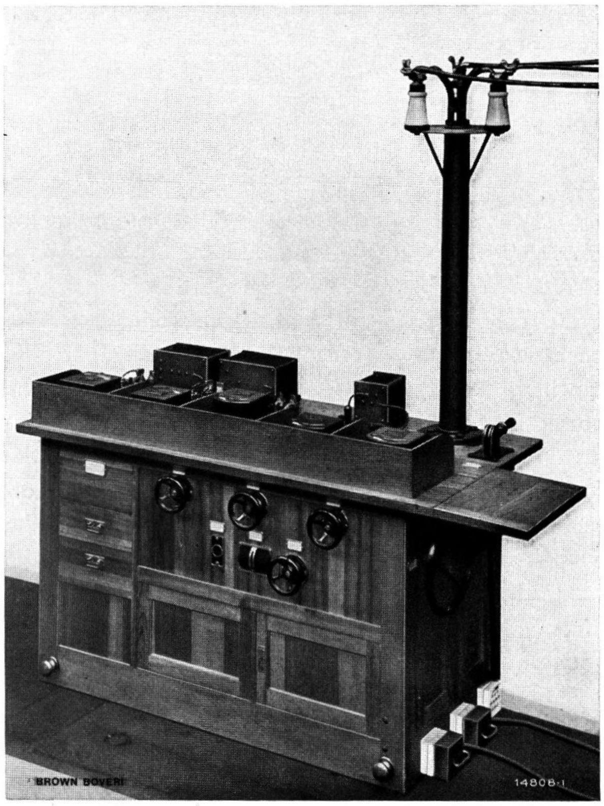


Fig. 7. — Instrument table for 400 A, 12'000 V.

2. The determination of the polarity—for checking the connections.

3. The measurement of the no-load losses—which is necessary for the determination of the efficiency.

4. The measurement of the copper losses with the transformer short-circuited—for checking the distribution of current in the primary and secondary windings. The extent of these losses must also be known for the determination of the efficiency and the pressure drop.

5. The measurement of the ohmic resistances.

6. The testing of the insulation resistance between the windings and the iron.

7. The testing of the insulation resistance between the windings themselves. For this purpose, the transformer is subjected to an increased pressure at a correspondingly high frequency.

8. The surge test, which was introduced two years ago and serves to test the strength of the insulation, particularly that of the end coils next to the terminals, with a pressure many times greater than normal.

For making the above tests, which must be undergone by all power transformers, the testing bay is divided into two sections which adjoin one another. In one of these, the large transformers, i. e., those having outputs of about 1000 kVA and upwards, are tested and, in the other, chiefly the smaller transformers, with outputs from 1 to about 1000 kVA.

Fig. 1 is the plan of the whole testing department, including the dark room and the room for surge tests, both of which are described more fully later.

From Figs. 1 and 3 it is seen that the erection shop and testing section for small transformers are adjoining, while the heavy transformers are tested in the section next to the large erection shop.

[1] Concluded from June, 1923.

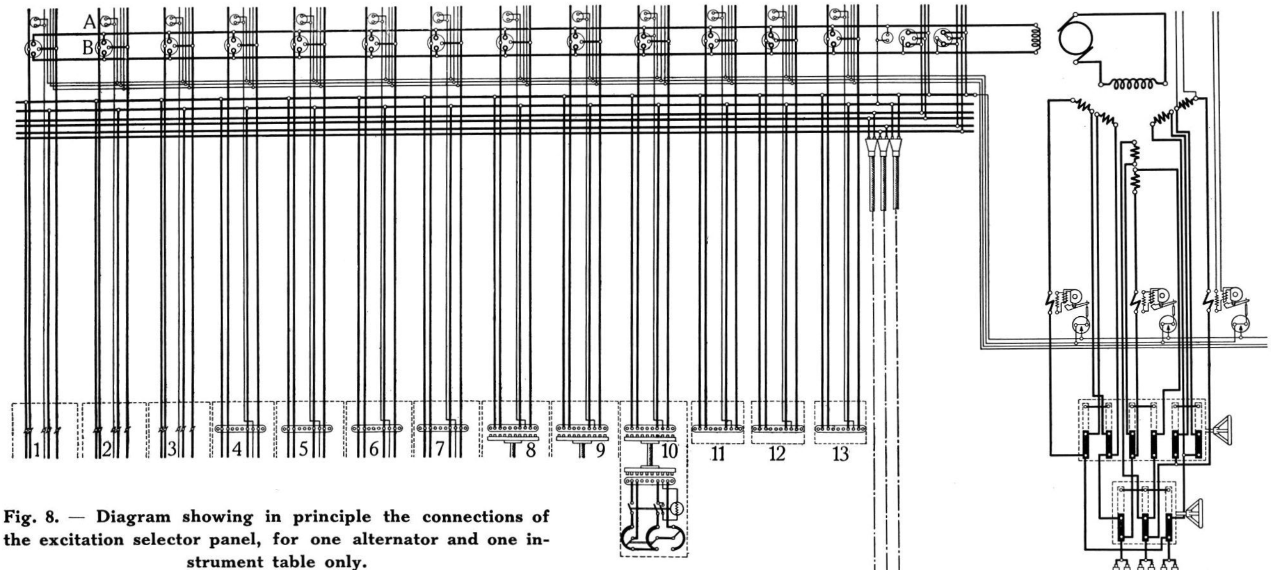
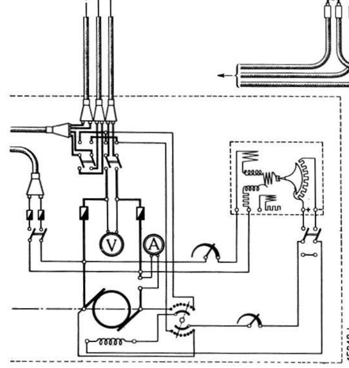


Fig. 8. — Diagram showing in principle the connections of the excitation selector panel, for one alternator and one instrument table only.

1—3. Leads from the selector boards in the machine room.
4—13. Junction points for instrument tables.
A. Sockets for plugs completing overload-release circuit.
B. Sockets for plugs completing field-rheostat circuit.



Before passing from the description of the distribution installation to the details of the actual testing plant, it should be mentioned that, for safety, all mains leading to the alternators and transformers are laid in channels, whether they are in the form of cables or bars — the latter being used for high tensions (3000—20'000 V).

The conductors pass from the selector boards to the junction points (Fig. 6), to which the specially constructed instrument tables are connected, short cables passing from the latter to the apparatus etc. under test. These tables are of two kinds, for pressures up to 3000 V and 12'000 V respectively. That shown in Fig. 7 is of the latter type, and constructed to take currents up to 400 A. The tables were designed with particular regard to the following points:—

1. As the rated pressure cannot usually be directly applied to transformers under test, it must be practicable to regulate the pressure of any of the alternators from each of the instrument tables, no matter to which of the junction points they may be connected.

2. The three-phase induction regulator in the machine room, which is used to supply current for making measurements, must also be controlable from the instrument tables.

3. It must be possible to include the current and pressure coils of the wattmeter, for making no-load and short-circuit measurements, directly in the measuring circuit, i. e., without the intermediate connection of current or potential transformers.

4. For checking the current on no-load and short-circuit tests, the use of a change-over switch should enable the current in the separate phases to be measured by a single ammeter, the pressure remaining constant.

5. From the instrument tables it must be possible to release, when necessary, the switches in the machine room that break the circuit of the 12'000-V cable from the machine-testing department.

To satisfy these conditions it was found necessary to fit a special excitation selector panel (Fig. 9) which enables the field of each alternator to be adjusted from any instrument table connected to any one of the ten junction points.

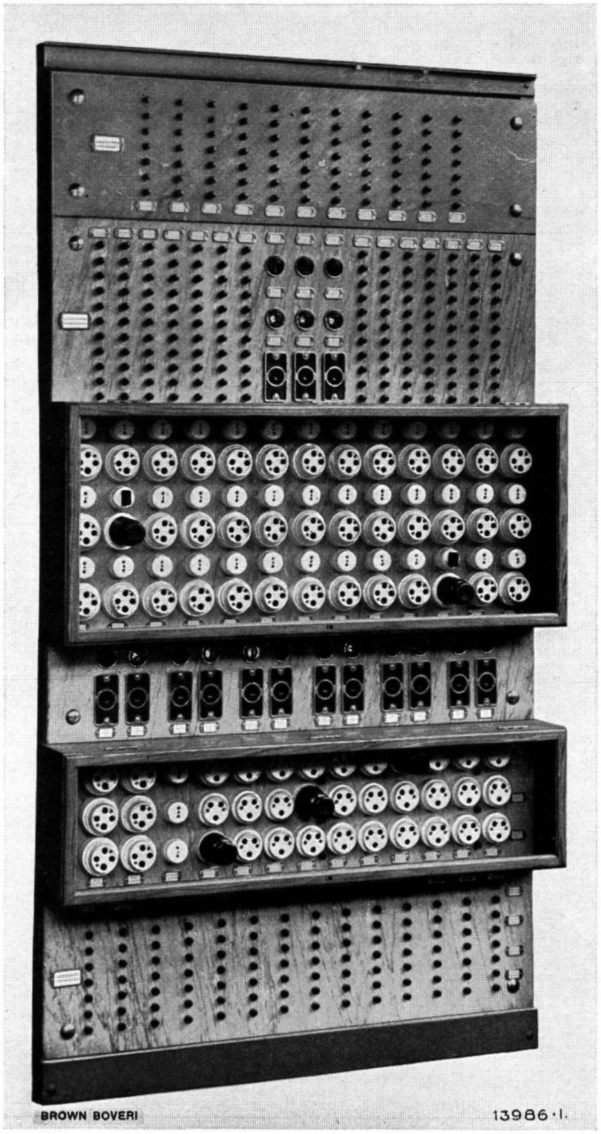


Fig. 9. — Excitation selector panel.

The range of connections provided by this selector is shown, for one alternator only, in Fig. 8. A direct-current generator, the pressure of which is kept constant by a quick-acting regulator, supplies the excitation selector panel. Each alternator has its own exciting machine the field of which is fed through the selector panel from the main exciter and controlled by the field rheostat on one of the instrument tables. To complete this rheostat circuit and that by which the automatic breaking of the field circuit is effected on overload, plugs are inserted in the rows of sockets (B) and (A) respectively. The sockets chosen correspond to the junction point occupied by the instrument table — for instance in Fig. 8, those corresponding to junction point 10.

The excitation selector panel not only deals with the alternator field current, but is also provided with push buttons for starting and stopping the driving motors of the alternators. These motors are all provided with automatic starters, the position of which is indicated by signal lamps mounted beside the push buttons. Similar buttons with signal lamps are also fitted for controlling the switches of the incoming 12'000-V three-phase cable. The panel is situated in the testing bay itself, and from the foregoing description it will be evident that, in addition to providing a means of controlling the alternator excitation, it is useful as an indication of the working conditions in the machine room.

Before closing this part of the description, mention must be made of the installation for the delivery and measurement of the constant flow of water that is particularly necessary for heating tests on large water-cooled transformers.

The 3000-litre cistern, seen in Fig. 3, is fed from the town water supply, and a four-inch distribution pipe carries the water to three junctions in the portion of the testing bay in which heavy transformers are dealt with. The water used during a test passes through a meter and, if desired, into a calibrated tank

Fig. 10. — Part of the cellar bellow the dark room.
1. Testing transformer for 500 kV. 2. Induction regulator for same. 3. Oil tank.

of 200 litres capacity. This can be connected in series with the meter, so that accurate checking of the quantity of cooling water is possible under all circumstances.

V. DARK ROOM.

The thorough testing of all materials employed in the construction of machines and apparatus generally, prior to their manufacture, is carried to a specially high degree in the case of transformers, tests on insulating materials being the most important. All these detail tests naturally do not replace the thorough testing of the finished apparatus, so that a modern dark room was included in the plans for the new transformer testing department. It was designed and equipped to allow of the following tests being made:—

1. Tests on the dielectric strength of all the materials employed in transformer construction.
2. Insulation tests on finished transformers up to the largest units.

The plan of the dark room as well as its situation is shown in Figs. 1 and 3; its floor space measures 7·5 m × 9 m. A track is laid through the centre of the room, upon which trucks can be run for the transport of large apparatus.

Figs. 13 and 15 convey an idea of the care given to maintaining an absolutely level floor — a precaution of the greatest importance for the observers carrying out insulation tests in the dark.

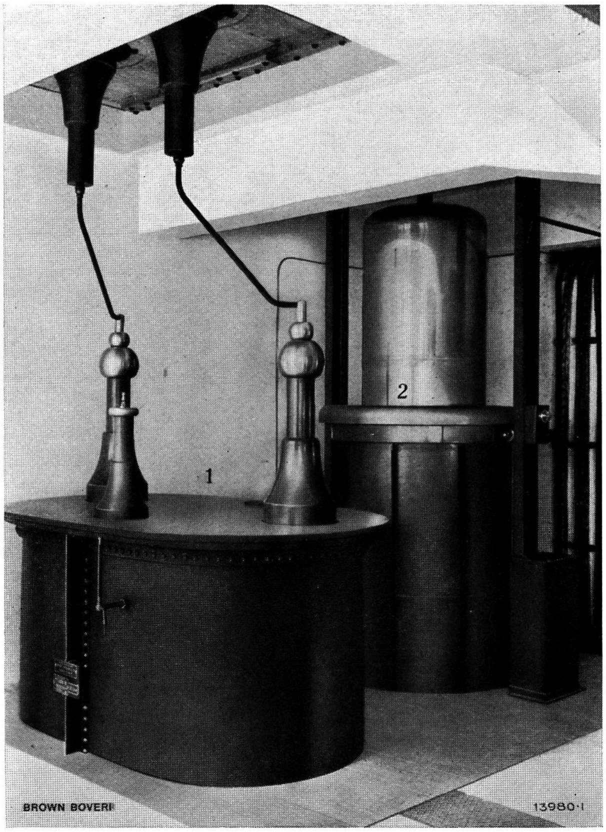


Fig. 11. — Part of the cellar below the dark room.
1. Testing transformer for 225 kV.
2. Air-gap condenser with variable capacity.

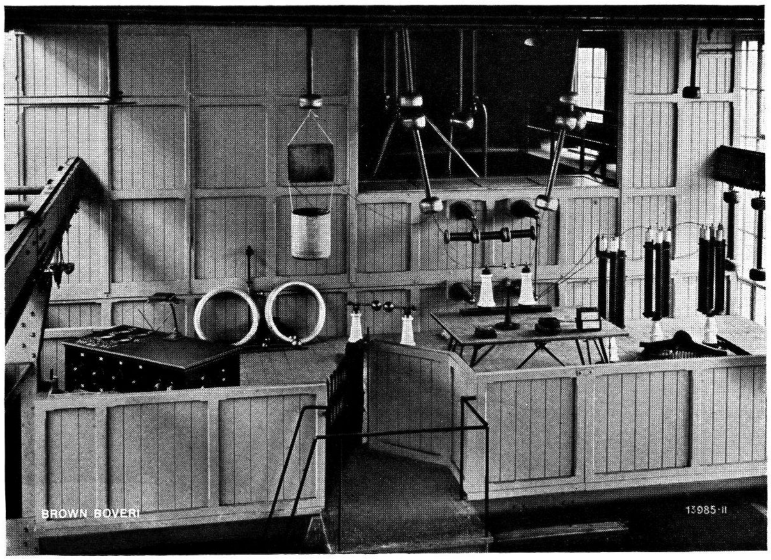


Fig. 12. — Pressure-surge test room, looking towards the dark room.

Besides a carefully constructed testing plant for pressures up to 500'000 V, a cylindrical oil tank of 10 m^3 capacity is installed in the dark room. For the testing of transformers, switches, and large insulators for outdoor use, artificial rain is provided by a system of sprinklers.

Immediately below the dark room is the cellar in which are housed the oil tank referred to and the testing transformer with its induction regulator (Fig. 10). This transformer has an output of 200 kVA with a ratio of 700/350'000 V when one high-tension terminal is earthed, and of 1000/500'000 V with both high-tension terminals insulated. It is erected so that its cover is on the same level as the floor of the dark room, above which only the insulators project. The spark gap, used for testing purposes, is directly connected to the high-tension winding and is normally fitted with spheres of 500 mm diameter, although others of 250, 125 or 62·5 mm can be employed if necessary.

The pressure at the testing transformer can be gradually increased from zero to the desired maximum by means of the induction regulator, to which an unregulated pressure is supplied, either from the step-down transformer in the machine room at 380 V, or from any of the alternators. It is also possible to work with any alternator connected directly to the low-tension side of the testing transformer. The induction regulator can be adjusted by remote control, or the pressure of the alternator can be regulated by altering its excitation—in both cases from the dark room. The observer's stand is to the right as seen from the entrance, so that he has the whole of the dark room before him. A gallery is also provided from which observations can be made in safety (Figs. 13 and 15).

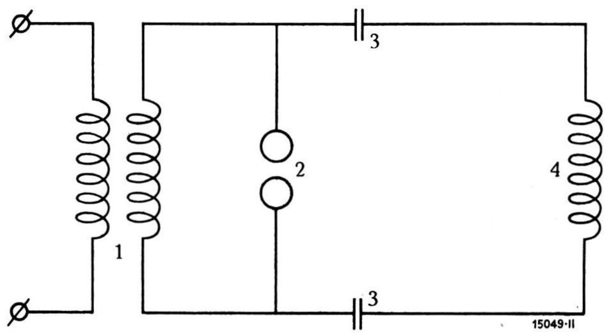


Fig. 14. — Diagram of an oscillatory circuit.

1. Testing transformer. 2. Sphere spark gap. 3. Condensers. 4. Object under test.

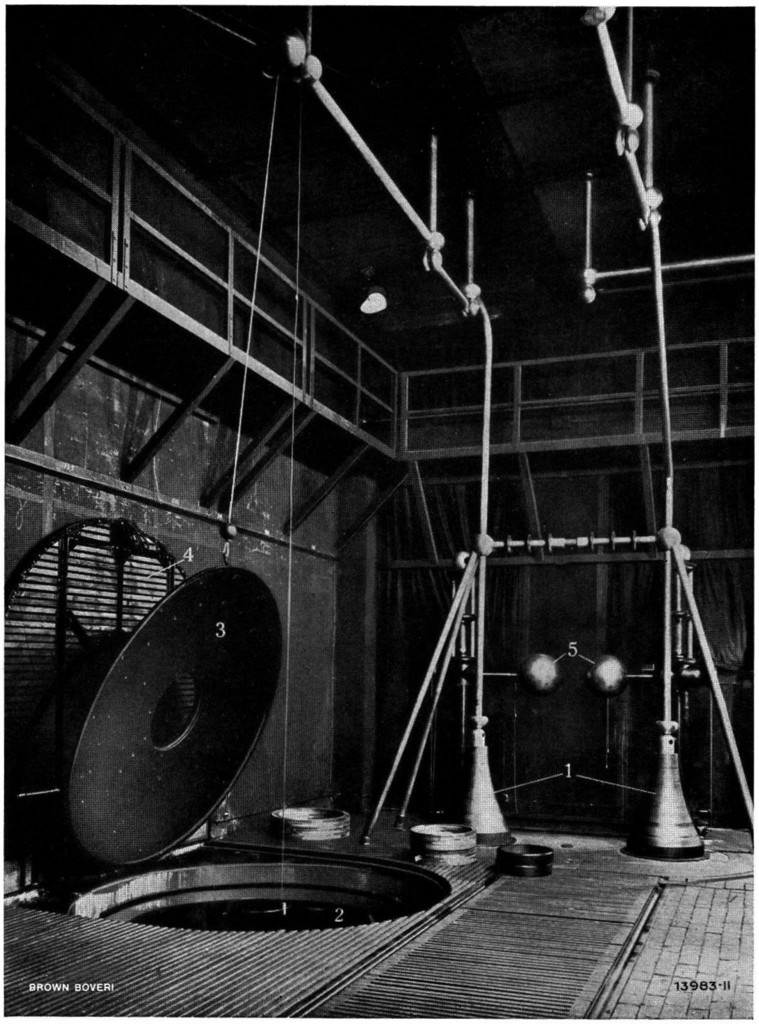


Fig. 13. — Interior of the dark room with oil tank open.

1. Terminals of 500-kV testing transformer.
2. Oil tank.
3. Sheet-steel cover.
4. Wooden grid.
5. Spark gap with spheres 500 mm in diameter.

In Fig. 11 is shown a second testing transformer having an output of 50 kVA, and a ratio of 500/150'000 V with one terminal earthed, and of 750/225'000 V with both terminals insulated. It is situated in the same cellar as the transformer already described. Both transformers can also be used for supplying either section of the testing bay for standard measurements, or the room for pressure-surge tests. Permanent conductors are laid for this purpose, the arrangement of which can be seen in Fig. 12.

Fig. 13 shows part of the dark room with the oil tank open for the testing of distance rings for high-tension transformers. An oil tank is necessary for all tests on materials for high-tension transformers, whether it is the determination of the breakdown pressure between two insulated conductors, the testing of the distance rings which separate the windings from the iron, or of the insulating tubes which separate the low and high-tension windings from each other. In all cases the object in question must be kept immersed in oil throughout the test if correct results are to be obtained. Moreover, an oil tank is indispensable where insulators for outdoor transformers and oil circuit breakers are to be tested.

The tank is a cylinder, 2·6 m in diameter and 2·4 m deep, with a movable wooden floor fitted inside it to carry the objects under test.

During the tests, the cover shown in Fig. 13 is closed. It is of double sheet steel, with an air space to prevent condensation of moisture on the lower surface when tests are made under rain conditions, the upper surface being cooled by the water from the sprinklers. A wooden grid is laid over this steel cover so that the floor remains quite level.

Fig. 16 shows a 7000-kVA transformer for 8000/50'000 V being taken into the dark room for making observations on brush-discharge effects.

VI. PRESSURE-SURGE TEST ROOM.

The progress in high-tension technology recorded during recent years is by no means purely the result of theory, but has depended to an equal extent upon exhaustive experimental and testing work. For some years, Brown, Boveri & Co. have employed a special research staff, working mainly on high-tension phenomena, and particularly on the investigation of means for preventing, or at least minimising, disturbances in high-tension plants.

This work can be divided into the following sections:—

1. Experiments connected with surges and overpotentials to earth.
2. Excess-current tests.
3. Tests on apparatus for protection against overpotentials (Horn lightning arresters, choke coils, extinction coils, etc.).
4. Measurement of losses in insulating materials using a special high-pressure wattmeter.

It is self-evident from this list that such work necessitates extensive apparatus and experimental equipment. The new transformer testing department includes a special room for experiments on pressure surges, containing apparatus with which it is possible to make insulation tests with high-frequency current.

It often happens that, due to switching operations, earthing, or winding defects, pressures arise which may seriously threaten the insulation of the machines and transformers. The testing of winding material under such working conditions is not possible with the normal insulation tests carried out in the dark room. The arrangement of connections shown in Fig. 14 is

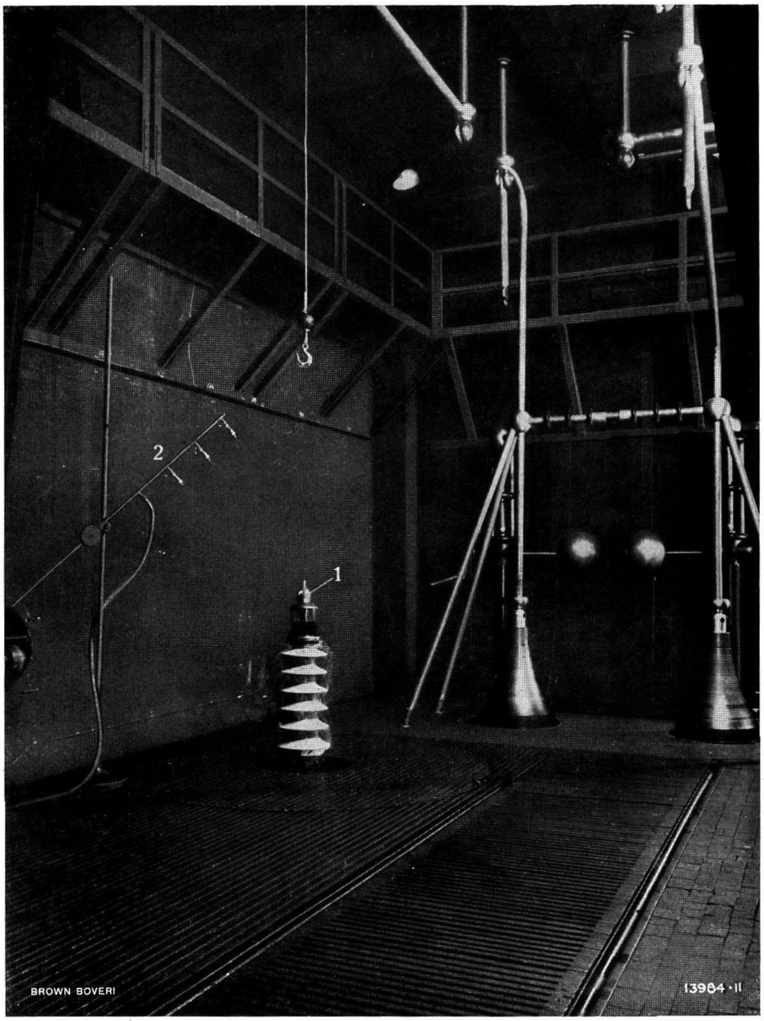


Fig. 15. — Interior of the dark room with a terminal bushing for outdoor use mounted in the oil tank.

1. Flashover test on an oil-filled bushing for 110 kV.
2. Sprinkler apparatus.

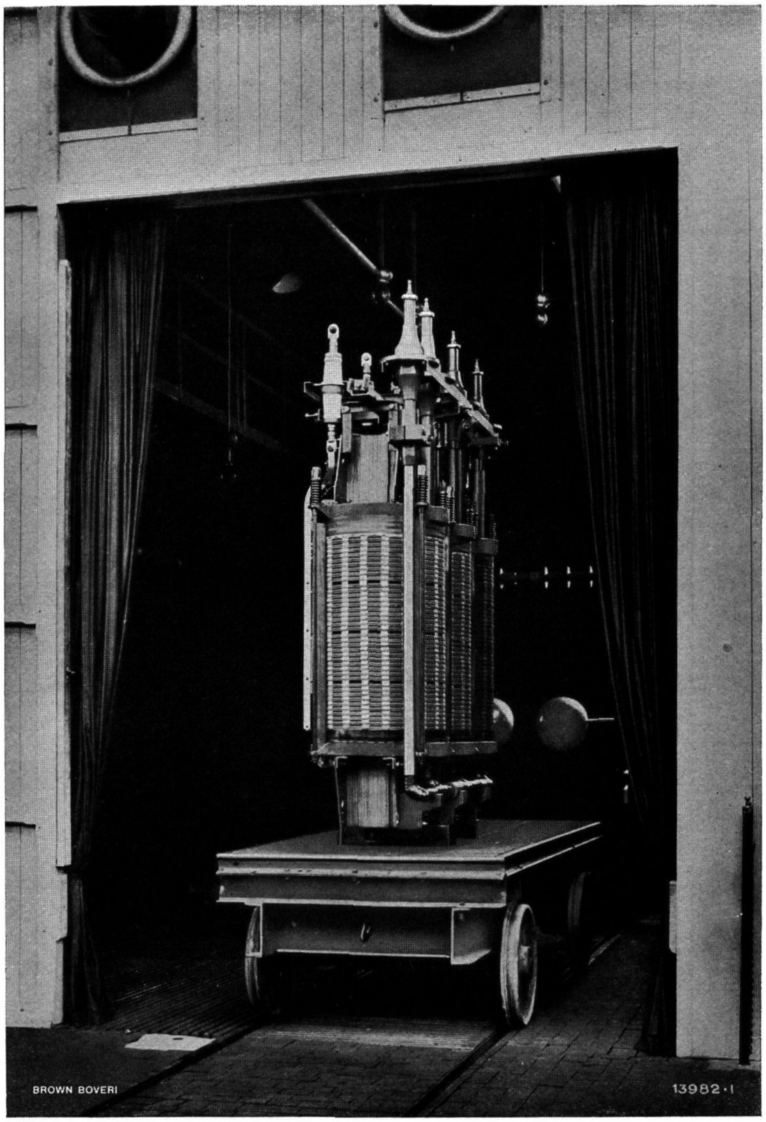


Fig. 16. — Entrance to the dark room.

frequently adopted for these tests, and is generally referred to as an oscillatory circuit.

It is not proposed here to deal with these investigations in any further detail, but the equipment of the pressure-surge test room will be outlined. This room is next to the dark room, as can be seen in Fig. 12. The leads from both the 500′000-V and

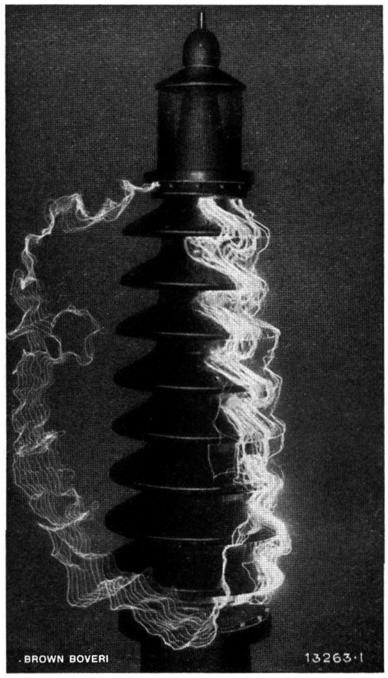


Fig. 17. — Flashover test on an oil-filled bushing as used for outdoor transformers and oil circuit breakers.

the 225′000-V testing transformers are so arranged that they can be connected to the test room as required by means of knife switches.

The pressure of the testing transformers can be regulated from two places by their induction regulators. Fig. 12 shows the switch desk and other arrangements for surge tests, which are mounted on a raised platform. The leads to the dark room can be seen in the background through the opening in the wall.

A second testing set, chiefly used for the measurement of losses by a high-tension wattmeter, is situated in the testing section for small transformers on the ground floor.

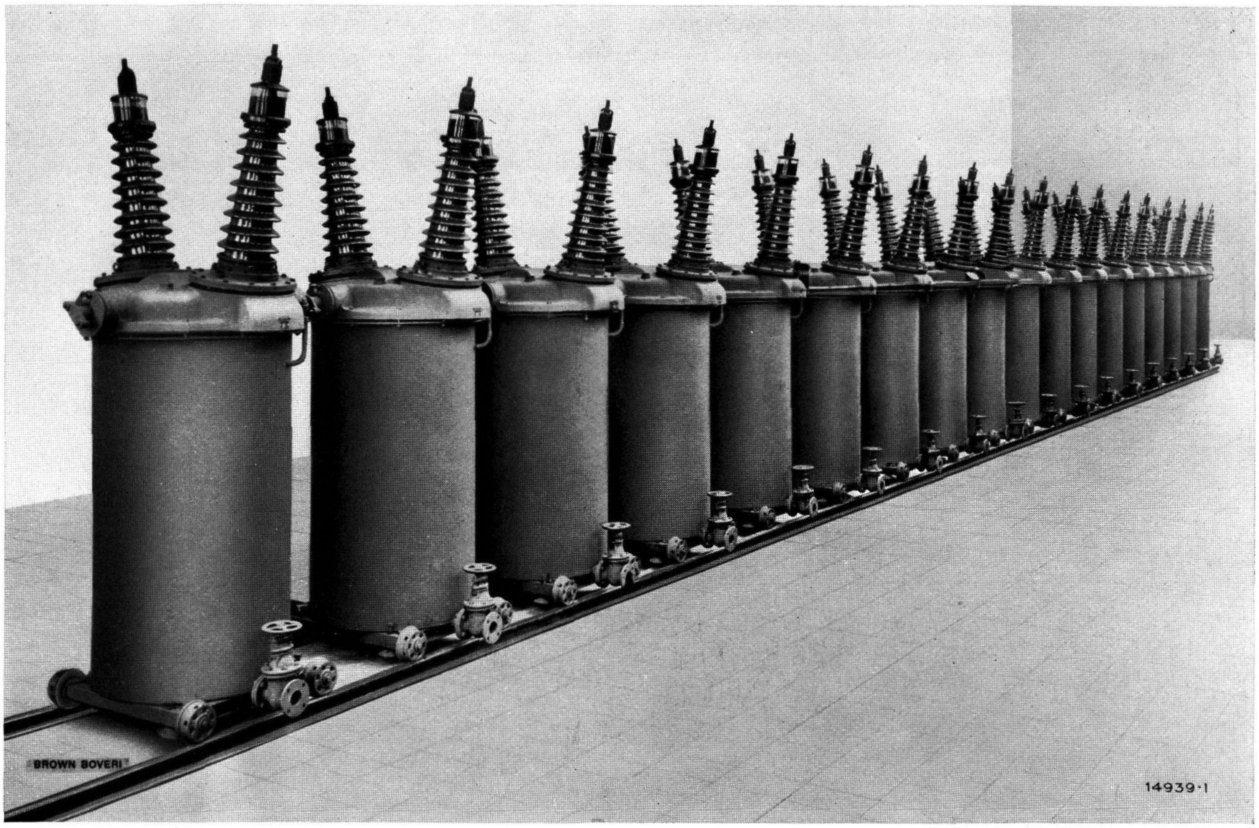
The pressure of any of the alternators can be regulated as desired from either of these testing sets.

Ed. Lienhard. (G.T.S.)

Published by BROWN, BOVERI & CO., BADEN (Switzerland). Printed by Kreis & Co., Basle.

BROWN BOVERI

HIGH-TENSION PLANT



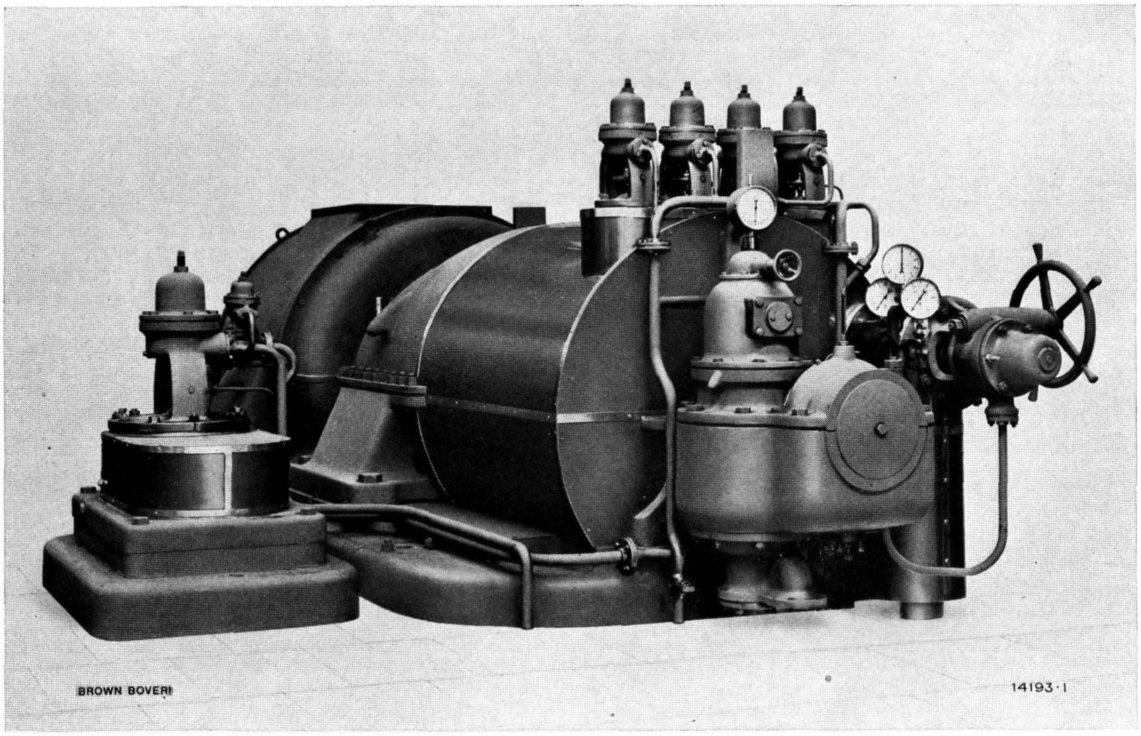
SINGLE-POLE OIL CIRCUIT BREAKERS OF OUTDOOR TYPE, 80 kV, 350 A, READY FOR DISPATCH.

OIL SWITCHES - REMOTE-CONTROL DEVICES
INSTRUMENT TRANSFORMERS - HIGH-TENSION FUSES
TRANSMISSION-LINE EQUIPMENT

BROWN, BOVERI & CO.

BADEN (SWITZERLAND)

WORKS: BADEN AND MUNCHENSTEIN (SWITZERLAND)



LES PETITS-FILS DE FRANÇOIS DE WENDEL, HOUILLÈRES DE PETITE-ROSSELLE (LORRAINE).
Mixed-pressure turbine of 3000 kW output at 3000 r. p. m. coupled to a three-phase alternator, 3750 kVA, 3000 V, 50 cycles

BROWN BOVERI STEAM TURBINES

HIGH-PRESSURE, BACK-PRESSURE, EXTRACTION, AND MIXED-PRESSURE TURBINES FOR ALL PURPOSES

LARGE AND SMALL TURBINES FOR ALL STEAM PRESSURES AND SUPERHEATS, BOTH FOR DIRECT AND FOR GEARED DRIVES