VOL. IX DECEMBER, 1922 No. 12

THE BROWN BOVERI REVIEW

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

BADEN WORKS IN 1922, BROWN, BOVERI & CO.

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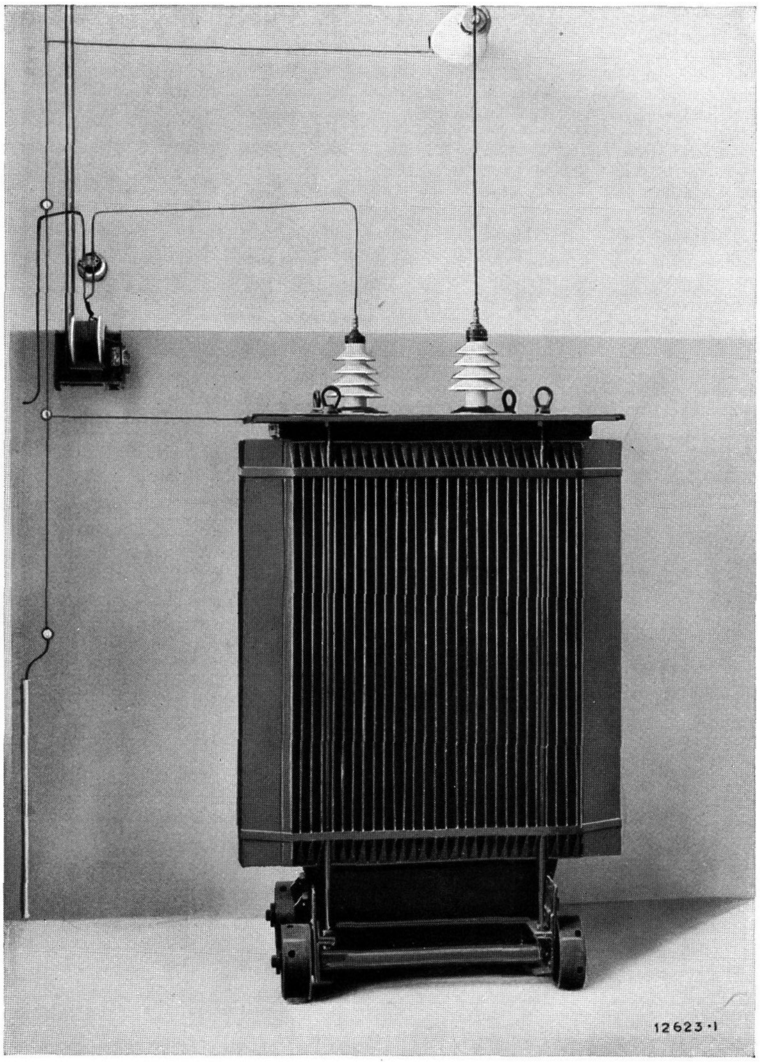

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THE BROWN BOVERI REVIEW

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

VOL. IX DECEMBER, 1922 No. 12

THE SYNCHRONISATION OF SYNCHRONOUS MOTORS ON LOAD.

Decimal index: 621.313.44.

Summary.

THE synchronisation of synchronous motors which have to start up asynchronously is examined, and attention is drawn to the dissimilar conditions which result from switching direct current on to the rotor when the latter occupies different positions with respect to the rotating field on the stator.

A description of the automatic device patented by Brown, Boveri & Co. for ensuring synchronisation under the most favourable conditions is also given, as well as an approximate method for estimating the minimum excitation necessary for pulling into step a synchronous motor of which the load and flywheel effect of the rotating masses are known, and the accuracy of this method is confirmed by tests.

INTRODUCTION.

THE advisability of improving the power factor of distribution systems has led to an ever-increasing field of application for synchronous motors within recent years. Synchronous condensers, which are simply synchronous motors running light, have been utilised for a long time, but the present tendency is to employ synchronous motors wherever possible instead of induction motors, and to take advantage of their very valuable property which consists of being able to carry a condensive load, if required, and thus improve the power factor of a system.

A result of this increased application has been the growing severity of the starting conditions of synchronous motors on load. Whereas the use of these machines was formerly restricted to cases where it is possible to start up on no load, e. g., motor-generator sets, synchronous condensers, etc., or to systems where the effect of a heavy current is immaterial if starting on load was allowed, synchronous motors are now able to accelerate when fully loaded just as satisfactorily as induction motors.

This improvement has been realised by motors having polyphase windings with starting resistances, thereby rendering the rotor similar to that of an ordinary induction motor when starting. The field winding, which is energised by direct current, may be either separate from or in one with the starting winding. The former arrangement enables the excitation pressure to be chosen independently of that at the slip-rings of the starting winding, but requires more copper than the other design. This explains the preference given to machines with windings combined, which resemble closely ordinary induction motors; the rotor, however, is excited by direct current once it has come up to speed. The possibility of constructing this kind of machine was first suggested by Danielson, and a great number of modifications are now built, which are generally known as synchronous induction motors.

The behaviour of a synchronous motor when starting always resembles that of an induction motor. By providing starting resistances, it is possible to start up on load without taking more than the normal full-load current. The rotor, however, never reaches synchronous speed as long as it runs as with an induction motor, since its torque under these circumstances would be zero if synchronism were attained. The transition from asynchronous to synchronous running takes place by exciting the rotor with direct current once the normal working speed under the former conditions has been reached.

Scarcely any investigations have yet been undertaken to ascertain what happens when this change is made. They would, nevertheless, be very valuable, as it is not always possible to bring a synchronous motor under load immediately into step when direct current is switched on so that it runs in a stable manner; very often synchronisation is accompanied by more or less violent fluctuations of the stator current. It remains to be seen how a loaded motor can be brought into step without hunting, and what excitation is required for this purpose, or, as the capacity of the exciter is limited, what is the maximum load which can be synchronised with a given excitation current without oscillations being set up.

These questions are discussed in the present article, and the method evolved by Brown, Boveri & Co. for automatic synchronisation is described.

SYNCHRONISATION.

Only the most essential features are examined in order to render these explanations as comprehensive as possible, and no account is taken of the particularities of different kinds of synchronous motors.

Consider a synchronous motor running in a steady manner under asynchronous conditions. The current induced in the rotor, together with the rotating field of the stator, produces a torque which balances exactly the load torque. Switching in the direct current excitation gives rise to no appreciable alteration of the rotating stator field, which is formed by alternating current taken from a system having an invariable pressure. The revolving field formed by the direct current in the rotor induces an electromotive force in the stator, which causes currents to flow whose effect is to hinder variations of this new field due to its rotation. These currents spread over the circuit external to the stator, and their frequency is somewhat lower than that of the system on account of the slip of the rotor. Their result is therefore to neutralise the revolving field produced by the direct current, so that only a small fraction remains effective, which depends on the stray losses and on the ohmic drop in the stator. The external system can be considered as forming a short circuit for the neutralising currents. The time taken by the latter to come into existence when the direct current is switched on is small when compared to the synchronisation process proper which follows on it. For this reason, these transient conditions will not be considered at present, and it will be assumed that the currents in the rotor are made up of an induced alternating current, whose frequency is given by the slip, and by a direct current of known value. The torque under these conditions is equal to the sum of two components, viz.:

1. An "asynchronous" torque due to the currents induced in the rotor and to the rotating field.
2. A "synchronous" torque due to the direct current in the rotor and to the rotating field.

The asynchronous torque may be taken as being independent of the position of the rotor in the rotating field, — as is the case with a symmetrical polyphase winding, — and only depending on the slip. The synchronous torque, on the other hand, alters with the relative position of the armature coils with respect to the rotating field, and oscillates periodically during each period of slip. If, for simplicity's sake, the rotating field of the stator be replaced by a stationary one, the rotor will turn in the opposite direction to that in which it really does with the same angular velocity as the slip ($s\omega$). These conditions are depicted in Fig. 1, where the armature winding is shown diagrammatically by a few coils.

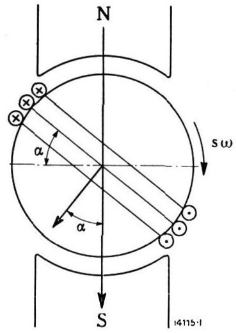

Fig. 1. — Simplified diagram of a synchronous motor.

As a first approximation, the synchronous torque can be taken as proportional to the sine of the angle α formed by the positive normal (directed from north to south) to the plane of the coils and the positive direction of the rotating field. It is consequently zero for $\alpha = 0$ and 180^0, and maximum for $\alpha = 90^0$ and 270^0. Assuming that the angles α are positive when they are described in the same sense as the slip, the value of the torque when α varies from 0 to 180^0 will be positive, since its direction is contrary to the slip, and consequently it causes the rotor to speed up. When α varies from 180 to 360^0, a braking torque exists, which has a negative sign. If S_{max} designates the maximum value of the synchronous torque, which is also known as the pull-out torque, the value of the synchronous torque for any position is given by

$$S = S_{max} \sin \alpha$$

After switching in the direct current, the rotor, which has been running with a constant slip, will be either pulled forwards or backwards, according to whether the synchronous torque is positive or negative when the excitation is applied. It follows that the slip, and with it the asynchronous torque, may be either augmented or diminished, so that the latter no longer balances the load torque. Imagine that the speed of the motor is increased, the slip and asynchronous torque fall off, and the synchronous torque takes over part of the load torque, with the result that the acceleration is less rapid. If synchronous speed has not been reached before the synchronous torque becomes insufficient to balance the load, the slip will increase, i. e., the speed will be reduced. This falling off of the speed becomes still more pronounced when the synchronous torque becomes negative, that is to say, a retarding torque. Forced oscillations of the speed are then set up; under these conditions the sum of the asynchronous torque (A) and the synchronous torque (S) balances the load torque (L) and the torque due to the inertia of the rotating masses (M), so that

$$A + S = M + L \qquad (1)$$

The asynchronous torque was able to carry the load with a slip s_o before the direct current was switched on. As this torque is, for the variations occurring, practically proportional to the slip

$$A = L \frac{s}{s_o} \qquad (2)$$

It has already been shown that

$$S = S_{max} \sin \alpha \qquad (3)$$

If I is the moment of inertia of all the rotating masses and ω the angular velocity of the rotating field produced by the alternating current, $(1-s)\,\omega$ is the angular velocity of a rotor with one pair of poles, $\Omega = (1 - s) \frac{\omega}{p}$ that with p pairs of poles, and the torque due to the inertia of the rotating masses is

$$M = I \frac{d\Omega}{dt} = -\frac{I}{p}\,\omega\,\frac{ds}{dt} \qquad (4)$$

On substituting these quantities, (1) becomes

$$L \frac{s}{s_o} + S_{max} \sin \alpha = -\frac{I}{p}\,\omega\,\frac{ds}{dt} + L \qquad (1a)$$

The angular velocity of slip $s\omega$ is by definition equal to the increase of the angle α per unit of time, so that

$$s\omega = \frac{d\alpha}{dt} \qquad (5$$

If this quantity is introduced in equation (1a), the law of oscillation is obtained

$$\frac{I}{p}\frac{d^2\alpha}{dt^2} + \frac{L}{s_o\omega}\frac{d\alpha}{dt} + S_{max} \sin \alpha = L \qquad (6)$$

Very often $\sin \alpha$ can be replaced by α and the differential equation rendered linear if the amplitude of the oscillations is small. This, however, is not possible with the conditions occurring, as the angle α can vary by 360^0 several times when the rotor slips. The resolution of this equation, therefore, does not lead to simple harmonic oscillations, but can only be carried out with the help of elliptic functions and Fourrier's series. On account of the complications thereby entailed, the analytical resolution will not be gone into, and only some special cases will be investigated by partial integration, which will enable an idea of the characteristic features of this law to be gathered.

The purpose of synchronisation is to bring the motor into step so that it runs continuously at synchronous speed. Hence, when this state has been attained, the slip and variations of slip become zero, and the first two terms of equation (6) disappear. The value of the angle α is therefore such that the synchronous torque exactly balances the load torque. On designating this particular value of α by α_o, the final state of equilibrium, as obtained from equation (6), is given by

$$S_{max} \sin \alpha_o = L \qquad (7)$$

The angle α_o is necessarily smaller than 90^0, as the pull-out torque of the motor is reached when $\alpha = 90^0$. The inverse value of $\sin \alpha$ gives therefore the ratio of the maximum torque which the synchronous motor can develop to the load torque, that is to say, the *overload capacity* u of the motor with respect to the given load. It follows that

$$u = \frac{1}{\sin \alpha_o} = \frac{S_{max}}{L} \qquad (8)$$

It is now proposed to find the smallest permissible value of u. In p. 244, attention has already been called to the fact that the way the motor is pulled into step depends on whether the rotor is speeded up or slowed down when direct current is switched in, or, in other words, on whether the formation of the armature field occurs when it will give rise to a positive or a negative synchronous torque. Because of this, the example given below has been worked out for both cases, so that what happens if direct current be switched in either at the instant the torque becomes negative ($\alpha = 180^0$) or positive ($\alpha + 0$) is gone into.

The following conditions have been assumed for the example considered: A twelve-pole motor, 400 kW, 50 cycles, having an initial slip $s_o = 0{\cdot}03$ at full load, is excited so as to obtain a pull-out torque equal to 1·5 times the full-load torque. The flywheel effect of all the rotating masses amounts to 7200 kgm^2, and is consequently four to five times as great as that of the rotor alone.

Fig. 2 shows the periodic variations of the slip if the direct current is switched in when $\alpha = 180^0$ and the synchronous torque begins to have a retarding effect. The abscissæ represent the time as a multiple

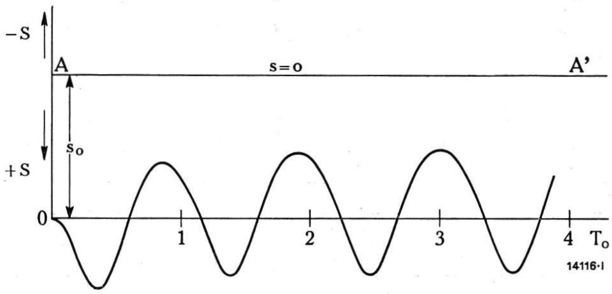

Fig. 2. — Periodic variations of slip if direct current is switched on when $\alpha = 180^0$.

of the period of initial slip, and the values of the slip are given by the ordinates measured from the line A A′, the positive direction being downwards so that the distance A O corresponds to the initial slip s_o, and the line A A′ to synchronous speed.

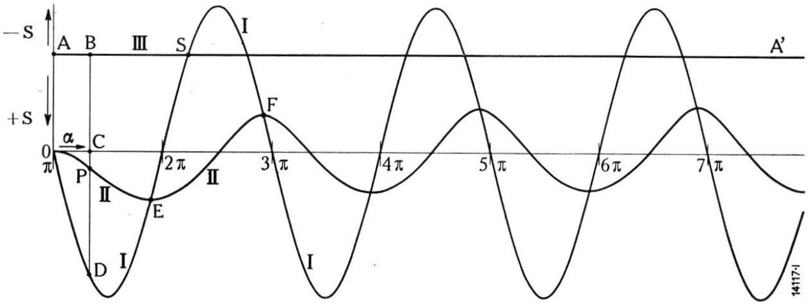

Fig. 3. — Accelerating and retarding torques when several pole spaces are slipped, the conditions being the same as in Fig. 2.

As soon as the field excitation is applied, a braking synchronous torque first of all comes into existence, which causes the slip to increase, as shown in the diagram, until it is equal to 1·5 times the initial slip. The torque then becomes greater and synchronous speed is approached. These torque reversals are repeated indefinitely, and the mean value of the slip is gradually decreased. However, as even the last oscillations shown in Fig. 2 differ so very little from one another, it will be readily conceived that what is practically a permanent condition is soon reached. The motor is never pulled into step, and forced oscillations about an average slip are set up, which is slightly smaller than the initial slip.

Since the asynchronous torque is proportional to the slip, the curve drawn in Fig. 2 also gives the variations of this torque, provided that the scale is suitably altered — the segment A O, for instance, to the new scale represents the load torque. Hence, the asynchronous torque will be greater or smaller than the load torque according to whether the slip is greater or smaller than the initial slip s_o. The ordinates, as measured from the time axis OT_o in the positive direction, will give the excess of the asynchronous torque over the load torque, and those in the opposite direction the corresponding deficiency. In the first case there will be acceleration, in the latter retardation. The resultant torque — which either causes the speed of the motor to be raised or lowered — is obtained by the addition of the synchronous torque. These variations are plotted out in Fig. 3 as functions of the angular displacement of the rotor due to the slip, i. e., of the angle α, as this mode of representation is the most simple because the synchronous torque is given here by an ordinary sine wave.

The sine curve I in Fig. 3 gives the variations of the synchronous torque, and begins with a negative half wave on account of the choice of the instant for applying excitation. In curve II, the variations of the asynchronous torque and the slip are shown, and are measured from the parallel III to the abscissa axis with the positive direction downwards. It follows that AO is equal to the initial slip when measured on the slip scale, or to the load torque L on the torque scale.

The intersection S of the straight line III and the sine curve I shows the final condition which is reached if synchronous speed can be attained — the synchronous torque being then equal to the load torque. In the present case, however, synchronous speed is never arrived at.

Curve II has an appearance which is quite different from that of Fig. 2: the ordinates remain unchanged, but the abscissæ are no longer the same, because the time required for a given angular displacement varies on account of the fluctuations of the speed of the rotor.

For an angular displacement $\alpha = OC$ (Fig. 3) the asynchronous torque is equal to BP, and the load torque to BC, so that the excess CP is available for acceleration. The synchronous torque CD is negative (braking), and the difference PD is equal to the resultant retarding torque. If this reasoning is repeated for different values of α, it will be inferred that the difference between the ordinates of curves I and II gives the resultant retarding or accelerating torques — a change of sign taking place at the intersections of the two curves. At such points (E, F, etc.) the load is exactly balanced, and curve II, which also shows the speed, has a horizontal tangent.

The forced oscillations of the rotor produced by repeated acceleration and retardation not only give

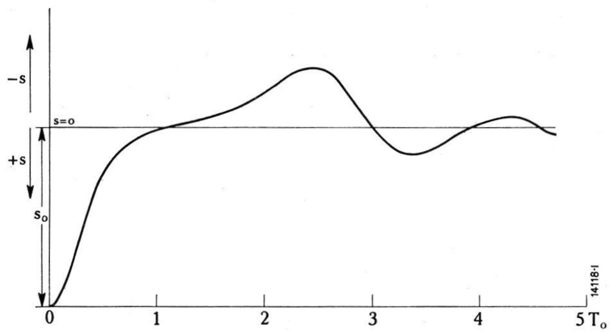

Fig. 4. — Periodic variations of slip if direct current is switched in when $\alpha = 0$, the excitation being the same as in Fig. 2.

rise to excessive stresses in the machines belonging to the set, but are also the cause of disturbing fluctuations of the current in the distribution system. These surges are produced by the working frequency of the line not being the same as that of the currents induced in the stator by the direct-current excitation, and their amplitude may exceed twice that of the normal full-load current.

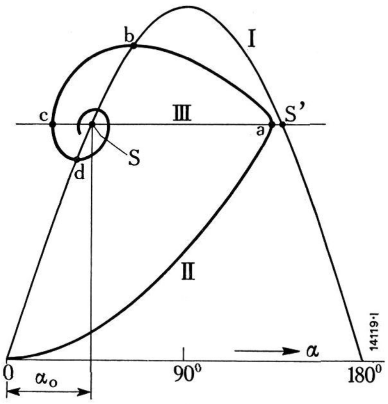

Fig. 5. — Accelerating torque, the conditions being the same as in Fig. 4.

If the excitation is switched in when the rotor occupies a position corresponding to the beginning of a positive half wave of the synchronous torque, i. e., $\alpha = 0$, the behaviour of the motor is quite different. On assuming the same load conditions as previously, the curves given in Figs. 4 and 5 are obtained. It will be noticed in Fig. 4 that synchronous speed is reached approximately at the end of one period of the initial slip, subsequently to which the speed still increases somewhat. After a few oscillations about synchronous speed, which very soon become imperceptible, the motor settles down to steady running. These variations are also given in Fig. 5 as functions of the angle α, that is, of the relative displacement of the rotor as regards the rotating field. Only the positive half of the sine wave I giving the synchronous torque need be considered in this case. The curve II gives either the slip or the asynchronous torque. The latter meets the straight line III, i. e. synchronous speed conditions, at the point (a) when the synchronous torque is still greater than the load torque, so that further acceleration is still possible. Since synchronous speed is exceeded, the relative displacements of the rotor with respect to the rotating field will be reversed, and the positions which have been gone through will be passed again in the opposite direction. In other words, the rotor will remain constantly under the same poles of the rotating field, and not slip from one pole to another, as in Fig. 3. The acceleration above synchronous speed stops at (b), which is determined by the intersection of I and II. During the subsequent retardation, synchronous speed is again passed, with the result that the sense of the relative displacements is altered afresh. Acceleration subsequently sets in at (d), and oscillations similar to the one just described are repeated, but gradually damped out until stable running conditions are finally reached at S with an angular displacement α_o.

As the motor always remains in step with the

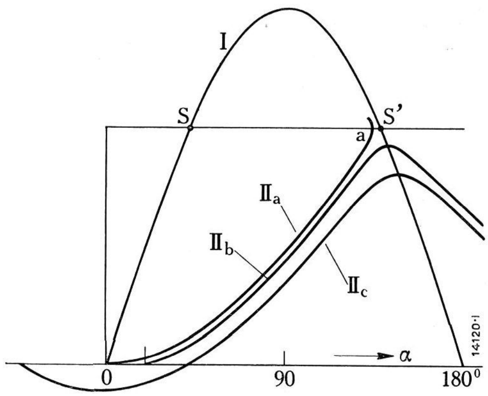

Fig. 6. — Acceleration for different switching positions.

same poles of the rotating field after excitation is applied, no fluctuations of current occur in the system, neither are abnormal stresses of the machines produced by the slight oscillations about synchronous speed, with the result that the motor is brought into step without jarring.

It is thus shown that although the excitation is absolutely inadequate in the first instance when $\alpha = 180^0$, it is amply sufficient to pull the motor into step when $\alpha = 0$. In the former case, a much stronger excitation is necessary if synchronism is to be attained. The second position is much the more favourable of the two, and it may be asked whether still more advantageous conditions could be chosen, that is to say, when is the excitation necessary to pull a given load into step a minimum? The answer to this question is given in Fig. 6, in which the first portion of curve II, Fig. 5, has been reproduced (curve II a), together with two other similar curves, II b and II c, which are obtained either by advancing or putting back the instant when excitation is applied. In both cases, synchronisation is not possible, and the rotor slips to the following pole of the rotating field.

In the example investigated, the conditions were intentionally chosen so that pulling into step without continuation of slipping for one or several pole spaces is almost exclusively impossible unless $\alpha = 0$ when excitation is switched in. This was for the purpose of demonstrating that this latter position is the most suitable for ensuring smooth synchronisation. These diagrams, therefore, not only enable it to be shown that the smallest excitation is required if switching in takes place when $\alpha = 0$, but also permit the value of the excitation necessary under these conditions to be determined with comparative accuracy.

Before entering into further details on this subject, it will be as well to examine how the most favourable instant for switching in can be found out in practice, and how it can be checked at the moment excitation is applied.

APPLYING EXCITATION AT THE MOST FAVOURABLE INSTANT

Reference to Fig. 7 will show how the most suitable moment for switching in direct current can be determined. As in Fig. 1, the rotating stator field is supposed stationary, and the rotor revolving in the opposite direction to that it really does with an angular velocity $s\omega$ equal to that of the slip. For simplicity's sake, a two-phase rotor has been chosen; I is the phase into which the direct current excitation is to be impressed, and moreover, it is shown in the desired position when $\alpha = 0$. Under these conditions, the slip current in phase I is zero, whereas that in phase II is a maximum, since when the slip frequency is small, the current is almost in phase with the slip electromotive force.

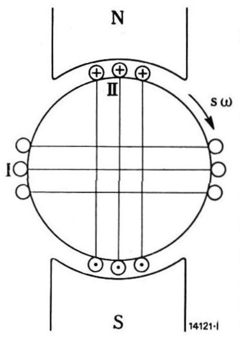

Fig. 7. — Simplified diagram of a synchronous motor.

The right instant for applying the excitation is shown by a polarised ammeter when the needle passes through zero in either direction. This operation, however, must be carried out somewhat earlier on account of the time taken to close the switch and for the current to be established. By means of a great number of tests carried out with both hand and automatic switching devices, it has been found that the excitation should be switched in approximately one-quarter of a period earlier, that is to say, when the slip current having the opposite sense to the succeeding direct current reaches its maximum value.

Switching in by hand at the right instant gives satisfactory results, provided that the slip is not greater than 3 to 4 %.

The Brown Boveri patent automatic synchronising device, as shown in Fig. 8, is operated by a relay having two coils, one of which is connected to the exciter and the other is energised by the slip current. The relay cannot be operated by one coil alone, but only by the combined effect of the two coils when the slip current has reached the required maximum value. The necessary manipulations are extremely simple, and consist of throwing the relay switch over to position (b) so as to close the exciter circuit on the pressure coil. Once synchronisation has been carried out, the current coil is disconnected and the pressure coil is short circuited by bringing the switch to position (a).

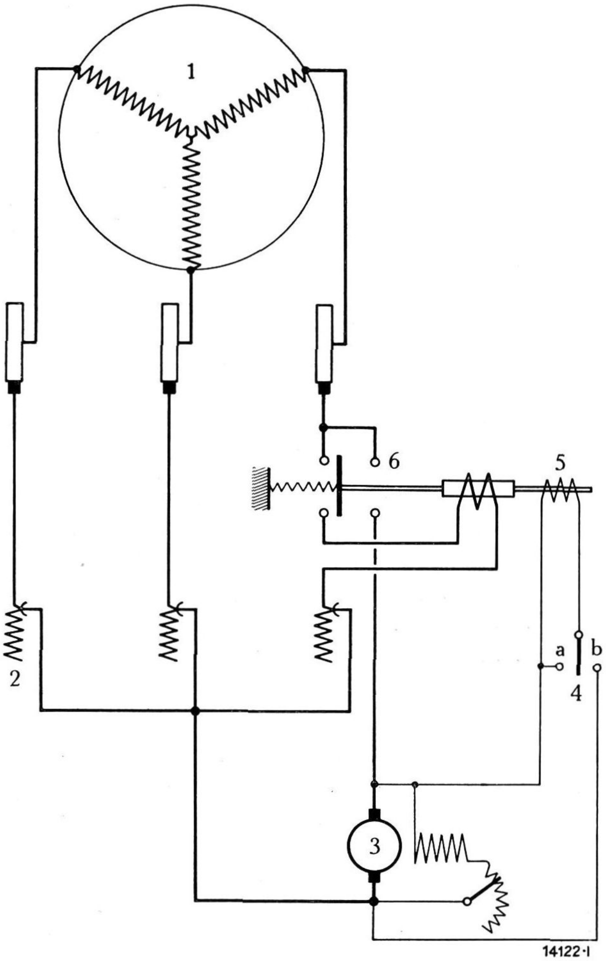

Fig. 8. — Brown Boveri automatic synchronising device.

Large motors having rotors similar to those of induction motors (synchronous induction motors) do not slip more than 1—2 % at full load. For this reason, motors of this description can be synchronised by hand without the slightest difficulty.

DETERMINATION OF THE EXCITATION REQUIRED.

In Figs. 5 and 6, the difference of the ordinates of the curves I and II, giving the synchronous and asynchronous torques respectively, shows the resultant torque available for acceleration. Consequently, the surface enclosed by these two curves between two ordinates α_1 and α_2, namely $\int_{\alpha_1}^{\alpha_2} M d\alpha$, corresponds to work expended. If switching in is carried out at the most suitable instant, as in Fig. 5, when the slip s is equal to s_o and α is zero to begin with, synchronism must be reached, i. e., $s = 0$, before α becomes greater than $(\pi - \alpha_o)$.

If curve II is known as far as its intersection with the straight line III, the area of the surface can be computed from $\alpha = 0$, $s = s_o$ to the value of α for which $s = 0$ — it depends on the value of S_{max} and L. Furthermore, the work expended in this interval can also be expressed in terms of the moment of inertia I and the initial slip s_o. A relation between these four quantities is thereby obtained. It has already been shown that:

$$M = -\frac{I}{p}\,\omega\,\frac{ds}{dt} \quad \text{and that} \qquad (4)$$

$$s\,\omega = \frac{d\alpha}{dt} \quad \text{hence} \qquad (5)$$

$$M\,d\alpha = -\frac{I}{p}\,\omega^2\,s\,ds$$

On integrating this expression from $s = s_o$ to $s = 0$, the value of the work

$$\frac{I}{p}\,\frac{(s_o\,\omega)^2}{2}$$

is obtained. This work is also given by the surface comprised between curves I and II from 0 to a, Fig. 5. When the overload capacity $u = \frac{S_{max}}{L}$ is sufficiently large — as when u is greater than 1·2 — the lower part of curve II can be replaced by a parabola passing through S′ without any considerable error being committed, thus enabling the enclosed area to be easily evaluated, since it becomes the difference of the areas bounded by a sine curve and by a parabola between $\alpha = 0$ and $\alpha = \pi - \alpha_o$, thus giving

$$S_{max}\,(1 + \cos\alpha_o) - \frac{L}{3}\,(\pi - \alpha_o).$$

As $S_{max} = u\,L$, $\sin\alpha_o = \frac{1}{u}$ and $\cos\alpha_o = \frac{\sqrt{u^2 - 1}}{u}$,

$$L\left[u + \sqrt{u^2 - 1} - \frac{1}{3}\left(\pi - \text{arc sin}\,\frac{1}{u}\right)\right] = L\,\varphi\,(u)$$

where φ (u) designates the function depending only on u between the brackets. Moreover, the following condition must be realised

$$L\,\varphi\,(u) \geqq \frac{I}{p}\,\frac{(s_o\,\omega)^2}{2} \qquad (9)$$

It has already been mentioned that this approximate solution is only valid when u is greater than 1·2; otherwise, a more exact method has to be resorted to, which will not be gone into here. The expression (9), however, holds good, provided that the exact values are given to φ (u), as has been done in Fig. 9, which shows φ (u) as a function of u. Expression (9) can be modified so as to render it more suitable for practical application: the moment of inertia is replaced by the flywheel effect GD^2 in kgm^2

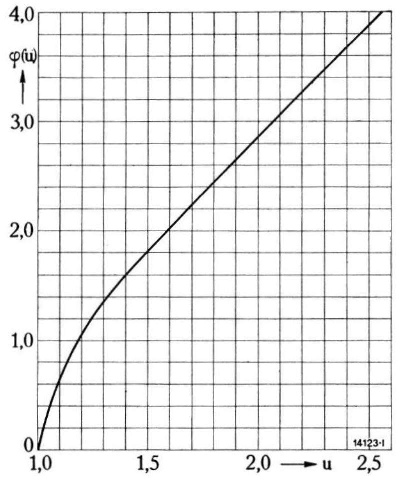

Fig. 9. — **Auxiliary curve for calculating the minimum excitation permissible.**

$$I = \frac{G\,D^2}{4\,g}$$

and the load torque L by the corresponding output P in kW

$$P = L\,\frac{\omega}{p}\,\frac{g}{1000}$$

thus enabling the following to be written: —

$$\varphi\,(u) \geqq \frac{G\,D^2}{8000\,P}\left(\frac{s_o\,\omega}{p}\right)^2\omega$$

Since $\omega = 100\,\pi\,\frac{f}{50}$ it follows that: —

$$\varphi\,(u) \geqq 0{\cdot}39\,\frac{G\,D^2}{P}\left(\frac{100\,s_o}{p}\right)^2\left(\frac{f}{50}\right)^3 \qquad (10)$$

This last expression allows the minimum values of u to be found, once GD^2, P and s_o are given. The values obtained in this way from equation (10) have been plotted out in Fig. 9, which consequently shows the smallest overload factor. It thus becomes possible to verify whether a motor can be pulled into step or not; for instance, if the excitation is known — to which corresponds an overload factor u — as well as the value of φ(u), the minimum value of u can be found from equation (10). This value of u must be smaller than or equal to the value

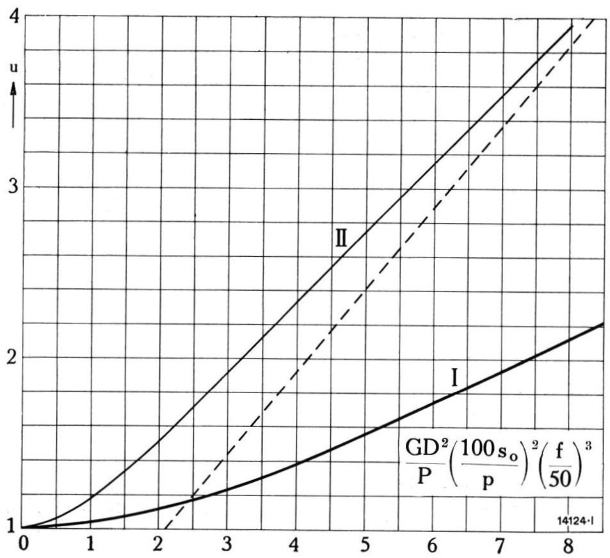

Fig. 10. — Auxiliary curves for calculating the excitation.

I. Minimum excitation for switching-in in the most favourable position (Equation 10).
II. Excitation for switching-in in any position (Carr).
--- Excitation for switching-in in any position (Bœhm).

of u given by the excitation if synchronism is to be reached.

In Fig. 10, the values of u itself have been plotted out as a function of $\frac{GD^2}{P}\left(\frac{100\,s_o}{p}\right)^2\left(\frac{f}{50}\right)^3$ thus obviating the necessity of employing the intermediate curve, Fig. 9.

If, for instance, the same conditions are assumed as for the example already treated (Figs. 2—6), that is, $GD^2 = 7200$ kgm², $P = 400$ kW, $s_o = 0{\cdot}03$, $p = 6$ pairs of poles, and $f = 50$ cycles, the following value is obtained:—

$$\frac{G\,D^2}{P}\left(\frac{100\,s_o}{p}\right)^2\left(\frac{f}{50}\right)^3 = \frac{7200}{400}\left(\frac{3}{6}\right)^2 1 = 4{\cdot}5$$

Curve I, Fig. 10, shows that the corresponding value of u is 1·47. In the foregoing example, u was supposed equal to 1·5. (Other cases are investigated in the next section.)

At this stage, a comparison of the published data for enabling the necessary excitation to be estimated will be of interest.

Carr[1] gives an approximate method for calculating the excitation when switching in takes place at the most unfavourable instant. In this case, the author replaces part of the sine curve by a straight line, and subsequently compensates the discrepancy. The following formula has been worked out on these hypotheses: —

[1] Journal of the Inst. of El. Eng., 1922, Vol. 60, p. 165.

$$u \text{ arc } \cos\frac{1}{u} = \frac{I}{p}\,\frac{(s_o\,\omega)^2}{1\cdot 2\,L}$$

The symbols used apply to the same quantities as formerly. On introducing therein the terms GD^2 and P, the values of u given in Fig. 10 are obtained. A glance at curves I and II, Fig. 10, will suffice to confirm the advisability of switching in at the most favourable instant. Since it is practically out of question when the conditions are severe to provide an excitation corresponding to an overload capacity of three to four, the suitability of the described method is especially marked in such cases.

O. Bœhm[1] has published the following formula, valid when switching in takes place at the most unfavourable instant: —

$$S_{max} \geqq \frac{\pi^2}{16}\,\frac{I}{p}\,(s_o\,\omega)^2$$

This formula is deficient, since no account is taken of the load torque. The latter sometimes can be larger than the right-hand side of the relation, with the result that the overload capacity becomes smaller than unity. The values of u obtained in this way are given by the dotted straight line, Fig. 10, and it will be noticed that $u < 1$ when the abscissæ are smaller than 2·1. On this account, the formula in question cannot be employed.

EXPERIMENTAL RESULTS.

(a) The oscillograms, Figs. 11a and b, show the stator and rotor currents and the slip during the synchronisation of an induction motor driving a set comprising three machines, each of 1000 kW, working together.

The rotor of the induction motor is provided with an ordinary three-phase winding with slip-rings, into which direct current is sent, as shown in Fig. 8. Switching in during these tests was carried out by hand. This operation caused the current to one of the slip-rings to be interrupted for about six periods of the line frequency (cf. the stator current), that is to say, for about one-eighth of a second. The rotor ran therefore with only a single magnetic axis for a short time, with the result that the slip increases somewhat, as can be seen in the slip curve.

The variations of slip were measured by the current flowing between a direct-current generator coupled to the set and a battery, and calibrated by means of a slip indicator.

Fig. 11a shows that when switching in takes place at the correct instant, the motor is pulled into

[1] Elektrotechnische Zeitschrift, 1922, p. 429.

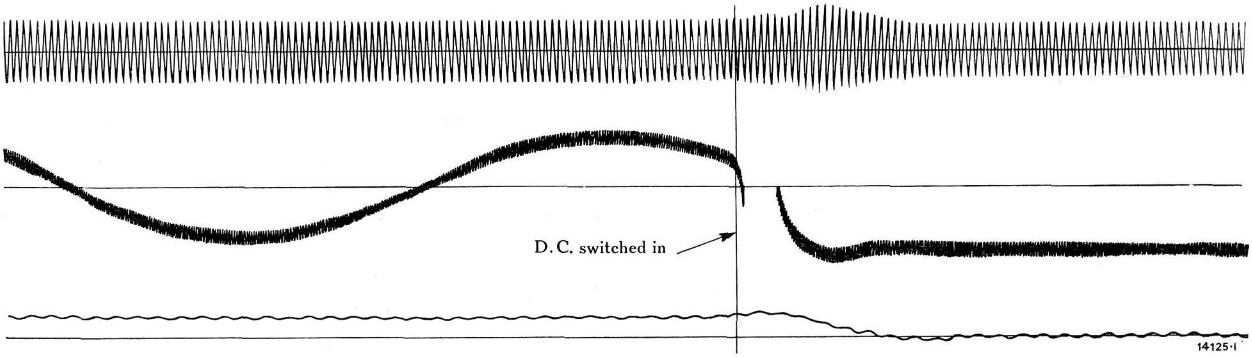

Fig. 11a. — Oscillogram showing the stator and rotor currents and the slip during synchronisation of a 1000-kW motor-generator set. Switching in takes place in the most favourable position.

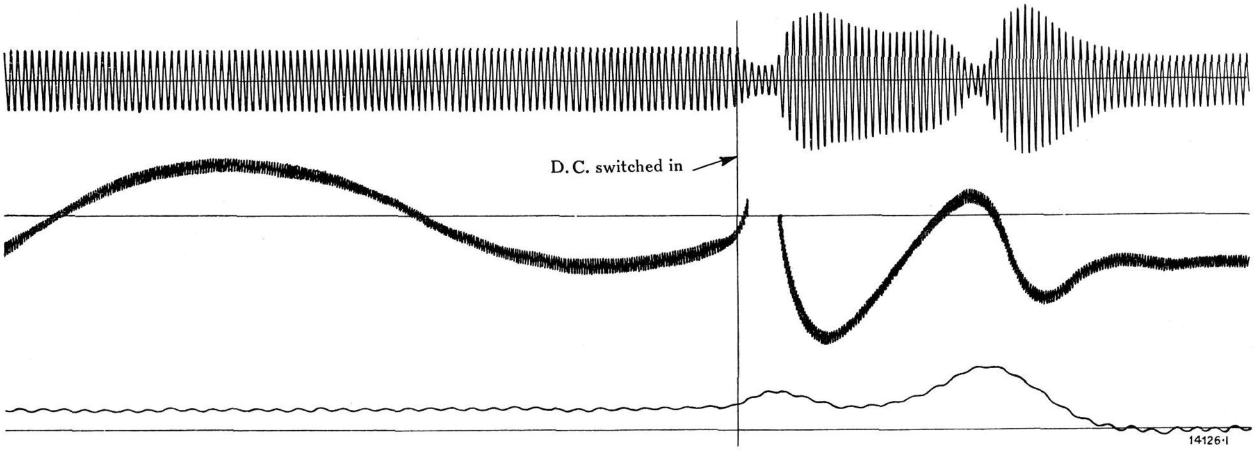

Fig. 11b. — Oscillogram showing the stator and rotor currents and slip during synchronisation of a 1000-kW motor-generator set. Switching in takes place in the most unfavourable position.

step without hunting. In Fig. 11b, on the other hand, when this operation is carried out under the most unfavourable conditions possible, severe oscillations and violent fluctuations of current are set up in the stator — the current almost attaining three times the normal full-load current. The excitation is, however, sufficient to pull the rotor into step as soon as the polarity becomes correct.

As it is practically impossible to determine the pull-out torque experimentally, the overload capacity with respect to a given load can be calculated from the rotor current during asynchronous and synchronous running conditions in the manner given below:

Since direct current takes the place of the alternating slip current, and the latter attains its maximum value when the rotor occupies the same position with regard to the rotating field as it does while the maximum synchronous torque is developed, that is, when $\alpha = 90^0$, the overload capacity is given by the ratio of the value of the direct current to the amplitude of the slip current, so that

$$u = \frac{I_d}{\sqrt{2}\, I_s}$$

This expression is naturally only valid for symmetrical polyphase rotors. With asymmetrical rotors — as, for instance, those of synchronous motors with salient poles which are provided with amortisseur and field windings so as to form a two-phase system, the phases of which do not have the same number of ampere turns under asynchronous running conditions — the torque pulsates, and the ampere turns of one phase afford no indication of the average torque, which should be obtained preferably from the average value of the ampere turns of the two phases.

In the present instance, $I_d = 720$ A and $I_s = 400$ A, so that

$$u = \frac{720}{\sqrt{2}\; 400} = 1 \cdot 27$$

The smallest overexcitation possible can be determined from Fig. 10 once the requisite quantities have been measured, and a comparison can then be

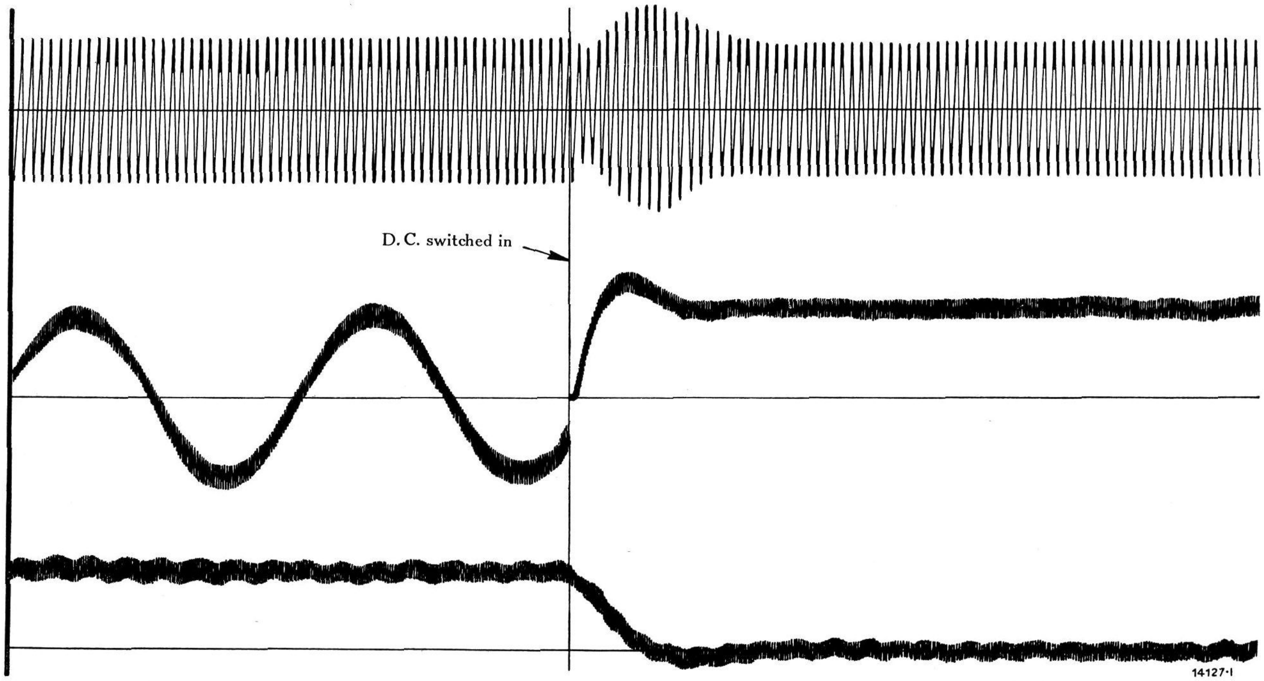

Fig. 12a. — **Oscillogram showing the stator and rotor currents and the slip during synchronisation of a 100-kW motor-generator set.**
Switching in takes place in the most favourable position.

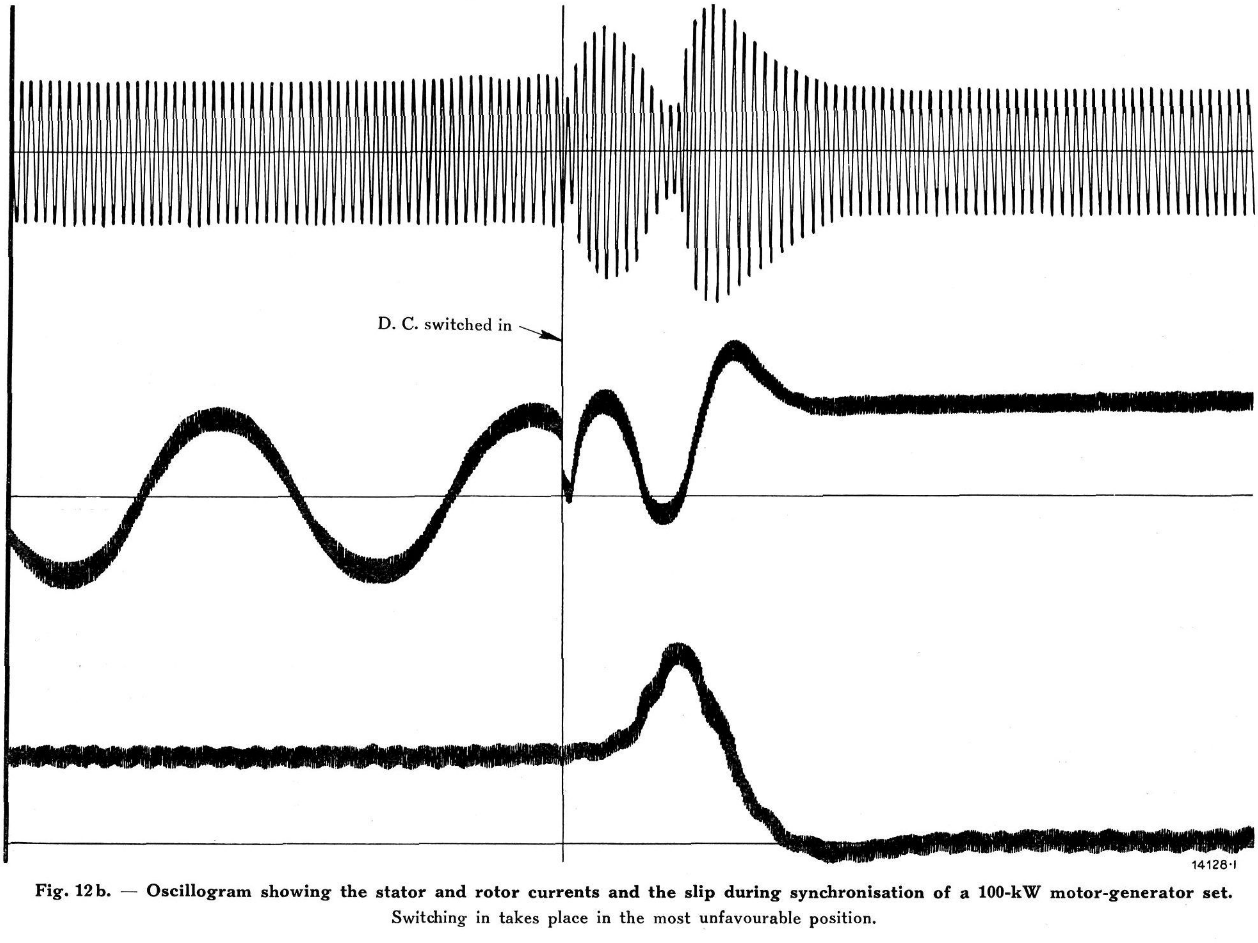

Fig. 12b. — **Oscillogram showing the stator and rotor currents and the slip during synchronisation of a 100-kW motor-generator set.**
Switching in takes place in the most unfavourable position.

made. The flywheel effect of the entire set amounted to 14 000 kgm^2, and the load was 800 kW. The initial slip was 1 %, but as it increased to 1·3 % during the interruption caused by switching in, this latter value will be considered in the following calculations. The number of pairs of poles p = 6, and the frequency was 50 cycles, which gave: —

$$\frac{G\,D^2}{P}\left(\frac{100\,s_o}{p}\right)^2\left(\frac{f}{50}\right)^3 = \frac{14\,000}{800}\left(\frac{1\cdot 3}{6}\right)^2 1 = 0\cdot 83$$

and the corresponding value of u = 1·04 is found by means of curve I, Fig. 10.

The excitation was therefore not only greater than strictly necessary, but also sufficient to pull the motor into step if switching in took place at the most unfavourable instant.

(b) The records shown in Figs. 12 a and b were taken on a small motor-generator set for 100 kW, comprising a three-phase motor and a direct-current machine. As before, the stator and rotor currents and the slip are given, and Figs. 12 a and b show the conditions when switching in was carried out at the most favourable and most unfavourable instants respectively.

In this case, use was made of an automatic switch operated by a relay which was closed by hand, and a polarised ammeter in the rotor circuit enabled the correct moment for switching in to be observed.

The load conditions were the following: — Flywheel effect of the set, GD^2 = 82 kgm^2; load, P = 80 kW; initial slip, s_o = 3·2 %; number of pairs of poles, p = 3; frequency, f = 50 cycles. The effective rotor current before switching in amounted to I_s = 175 A, and the direct current after switching in to I_d = 275 A, hence

$$u = \frac{275}{\sqrt{2}\;175} = 1\cdot 11$$

Moreover,

$$\frac{G\,D^2}{P}\left(\frac{100\,s_o}{p}\right)^2\left(\frac{f}{50}\right)^3 = \frac{82}{80}\left(\frac{3\cdot 2}{3}\right)^2 = 1\cdot 15$$

whence the corresponding minimum value of u from curve I, Fig. 10, is found to be u = 1·05.

As in the preceding instance, the excitation is greater than the minimum required, and furthermore, it is sufficient to pull the motor into step under the most unfavourable conditions after slipping one pole space.

Another series of tests was undertaken with this set: the load and slip were altered, — additional

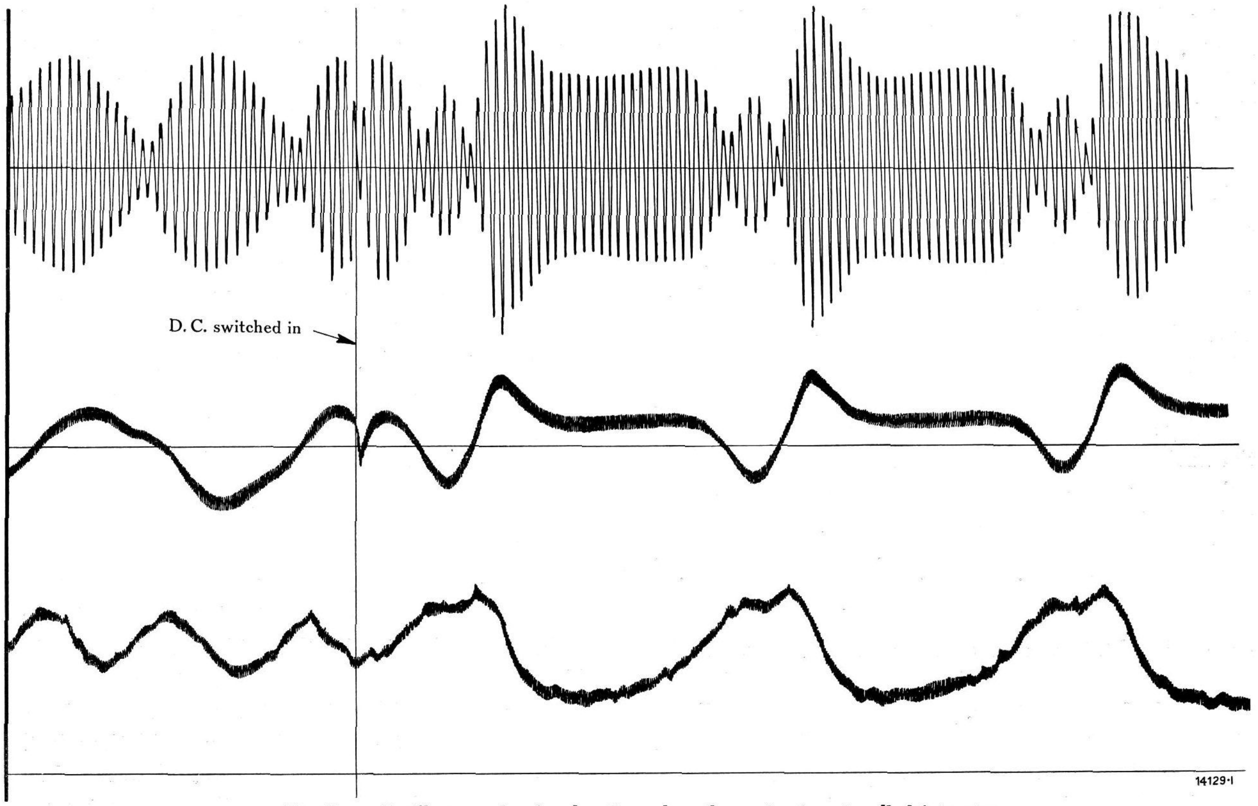

Fig. 13. — Oscillogram showing hunting when the motor is not pulled into step.

resistances being inserted in the rotor circuit, — and the figures thus obtained are tabulated below. Particulars of the load (P) and initial slip (s_o) are given in the table, together with the values of the rotor current before and after synchronising. The overload capacity is calculated therefrom, besides the smallest permissible value of the overexcitation u, which can be measured in curve I, Fig. 10.

P kW	s_o per cent.	I_s Amp.	I_d Amp.	u measured	u calculated
80	3·2	175	275	1·11	1·05
38	1·9	80	116	1·03	1·035
23	3·9	40	92	1·63	1·74
24	1·74	48	72	1·06	1·05
15·3	1·33	30	46	1·09	1·04

The agreement of the results obtained by tests and by calculation must be considered as satisfactory, as it was not only practically impossible to adjust the excitation so as to obtain exactly the minimum required and to switch in at precisely the most favourable instant, but also, account has to be taken of the hypotheses made to simplify the calculations.

Fig. 13 shows the typical charcteristics of the current and slip when synchronism is not reached on account of switching in having taken place under unfavourable conditions. The rotor on which these tests were made had an asymmetrical winding, which explains the fluctuations of the stator current and the pulsating slip while the motor is running asynchronously before direct current is switched in.

Dr. A. Fraenckel. (D. M.)

DISTURBANCES IN ELECTRICAL PLANTS DUE TO LIGHTNING.

STATISTICAL DATA, PRACTICAL CONCLUSIONS, THEORIES PROPOUNDED AND TYPICAL EXAMPLES.[1]

Decimal index 621. 317. 8 + 621. 319. 8.

B. OSCILLATIONS AT THE NEUTRAL POINT.[2]

THE formation of steep-fronted travelling waves during thunderstroms has already been gone into last month. They give rise to stresses between adjacent coils rather than between the winding and earth. The induced charges from which these surges orginate can, however, cause stresses between the winding and the earth by producing oscillations at the neutral point. This occurrence can be explained in the following manner:—

Should a travelling wave go through a circuit (Fig. 9) consisting of a choke coil 2 and a capacity 3, oscillations will be set up which produce at the capacity a potential having about twice the amplitude of the travelling wave. This case is met with in practice when a bound charge is liberated by a flash of lightning, and enters a transformer, as the latter forms a circuit similar to that just considered. With polyphase plants, e. g. three-phase ones, all the phases will naturally be affected by a thunder cloud.

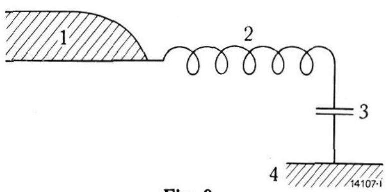

Fig. 9.
1. Travelling wave. 2. Choke coil. 3. Capacity. 4. Earth.

When a discharge occurs, travelling waves will be formed in the different phases, all of which will stress the transformer winding together, i. e. the same oscillations will be set up simultaneously in each of the different phases. Consequently, each phase may be examined independently, as shown in Fig. 10, where 1 represents the travelling charge about to enter the transformer, 2 and 3 the inductance and the capacity to earth of the transformer winding. Fig. 10 differs from Fig. 9 in that the capacity is evenly distributed, but the two figures present no essential difference. It follows that overpotentials, which are greater than those at the terminals, can be formed at the transformer neutral point. The truth of this theory has been borne out by experiments. Disturbances of this description have occurred in practice; however, they are rare and relatively unimportant.

C. BREAKDOWNS BETWEEN COILS PRODUCED BY ELECTROMAGNETIC OSCILLATIONS.

It has already been mentioned in the first part of this article that atmospheric disturbances lead to breakdowns of coils in the middle of the winding, which evidently cannot be ascribed to surges — as could those met with at the entrance of the winding — but are caused by electromagnetic oscillations in the transformer itself. If an arcing ground occurs in an overhead transmission line, vibrations are set up on

[1] Concluded from November, 1922.
[2] Cf. Dr. A. Roth, E. T. Z., 1920, p. 920.

both sides of the faulty point, whose frequency is inversely proportional to the length of the portion of the line at the side of the faulty point considered, and whose wave length is equal to four times this same length. For instance, the wave length of a line 1 km long is 4 km, and its natural frequency is $300\,000 \div 4 = 75\,000$ periods per second. When an oscillatory system, e. g. a transformer (Fig. 10), is connected to the end of the line, it will be excited by these oscillations, so that it begins to vibrate. The amplitude of these vibrations is a maximum when the natural frequency of the line and that of the oscillatory system are the same, that is, when there is resonance between the line and the system connected to it. Special tests carried out in this connection have shown that:

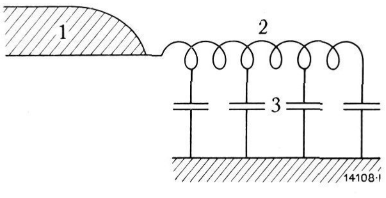

Abb. 10.
1. Travelling wave. 2. Transformer winding. 3. Capacity of 2 to earth.

1. In practice, arcing grounds can produce dangerous stresses in transformers connected to transmission lines.

2. The maximum stress can occur at different parts of the winding, and its position depends on the distance to the faulty point.

It follows that certain frequencies are dangerous for transformers, and, moreover, these frequencies can be met with in practice. As it is possible for arcing grounds to take place at any distance from the transformer, failures are just as liable to occur with large transformers in the middle of the winding as at the entrance.

IV. DIRECT LIGHTNING DISTURBANCES.

The disturbances so far examined are attributable to indirect discharges of thunder clouds, i. e., to flashes of lightning between the clouds and the ground, or between the clouds themselves. It is now proposed to examine the effects of a flash of lightning striking directly a transmission line. Although indirect lightning disturbances are by far the most common, direct strokes of lightning, though rare, nevertheless do occur. Their consequences are more violent, and they lead to interruptions of service almost without exception.

Suppose lightning strikes a transmission line similar to the one depicted in Fig. 4. A direct connection is then established between the line and the thunder cloud, with the result that a very rapid equalisation of potential is brought about. One flashover alone is ordinarily not sufficient to bleed off the excess pressure thereby produced in the line, hence, several insulators break down.

The sudden charging of the line, together with the arcing grounds, naturally gives rise to steep-fronted travelling waves.

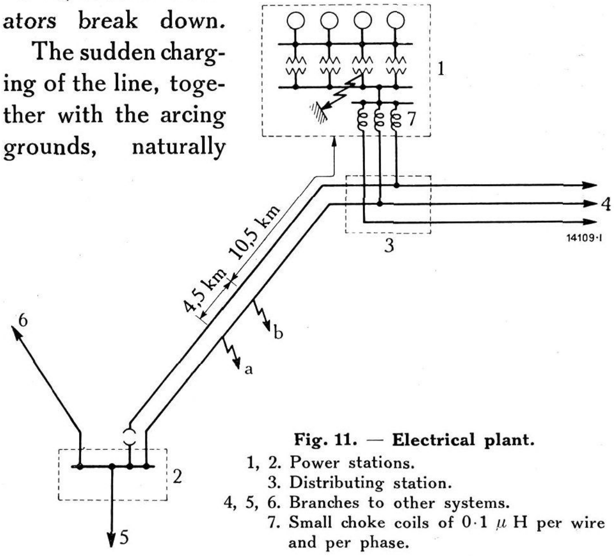

Fig. 11. — Electrical plant.
1, 2. Power stations.
3. Distributing station.
4, 5, 6. Branches to other systems.
7. Small choke coils of 0·1 μ H per wire and per phase.

Attention may be drawn to the fact that disturbances due to direct strokes of lightning remain confined to the immediate proximity of the discharge, and that a propagation of dangerous surges does not occur. The explanations of this anomaly are purely hypothetical.

V. THEORY AND PRACTICE.

In the first part of this article it has been shown that overpotentials to earth and surges are produced by atmospheric discharges, as are also electromagnetic oscillations. Interpretations of all these phenomena were given in parts II, III and IV.

These theories generally agree with what occurs in practice, although they still require completing. In order to illustrate the preceding explanations some typical examples taken from the many cases investigated by the author will be examined.

VI. TYPICAL EXAMPLES.

(a) Disturbance produced by an arcing ground.

The plant in question has a working pressure of 50 kV, and its layout is shown in Fig. 11. All the transmission lines are overhead. When a thundercloud above the line between power stations 1 and 2 discharged, the automatic releases of all the high-tension switches protecting the transformers were tripped in power station 1, as were also the section switches in power station 2 and at 4, thus cutting out the transmission line between 1 and 2.

At power station 1, smoke was observed to issue from a transformer, which also threw out a considerable quantity of oil. On examining this transformer, it was found that the "yellow" terminal had flashed over to earth. The breakdown pressure was subsequently determined, and found to be equal to 110 kV. Several double coils on the corresponding core limb had been greatly overheated between the middle of the winding and the neutral point.

The horn gap arresters on all three phases operated both at power stations 1 and 2. These arresters are set to discharge at about 70 kV, and are provided with a water series resistance of about 6000 ohms.

An inspection of the transmission line revealed two faulty points, namely: at (a), about 15 km away from power station 1, the insulators of the "red" and "yellow" phases were shattered, while an insulator of the "green" phase was badly burnt; and at (b), 10·5 km away from 1, an insulator of the "red" phase was shattered.

The cause of this disturbance must have been a flash of lightning 10 to 15 km away from power station 1 that liberated a bound charge on the transmission line which broke down the insulators at the points indicated. Travelling waves with steep ends were thus formed, but it is evidently not possible to say whether the breakdown in the transformer was due directly to the flash of lightning or to the induced charge. As already explained, the burning out of coils in the middle of the winding must be put down to stresses caused by oscillations set up inside the transformer.

The tripping of the section switches is naturally produced by the arcing grounds formed at (a) and (b). The destruction of the insulators at (a) and (b) is due either to a flashover or a short-circuiting arc.

It is noteworthy that neither the horn gap arresters with series resistances of 6000 ohms, nor the small choke coils of 0·1 millihenrys were capable of protecting the transformer.

(b) Disturbance due to a steep-fronted travelling wave formed by the screening effect of a building.

The general arrangement of this plant, which is a three-phase one, is shown in Fig. 12. The working pressure is 4 kV, and no cables are provided either between the busbars and generators or between the busbars and transmission line. A severe thunderstorm, accompanied by a hurricane, hail and heavy rain, broke out in the immediate neighbourhood of the power station.

A flash of lightning struck a tree (Fig. 12) about 250 m away from the power station, and about 50 m

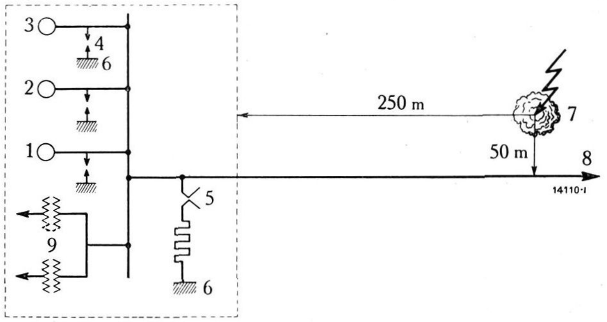

Fig. 12. — Electrical plant.

1, 2, 3. Generators.
4. Valves.
5. Horn gap arrester (one per phase) set to discharge at 7 kV, and provided with a water resistance of 600—700 ohms.
6. Earth.
7. Tree.
8. Overhead transmission line going to a local distribution system about 15 km long.

away from the transmission line. At the same instant, sparks were seen to issue from generator 1. An examination showed that the coil ends situated on the opposite side from the terminals were badly burnt in places. Signs of overheating were also discovered on the stator frame. The most severe damage was found to have occurred at the first bar of a phase. No other burn-outs or faulty places were detected in the plant.

This disturbance may be put down to a steep-fronted travelling wave, which was formed by the flash of lightning striking the tree, and by the screening effect of the power house. This wave entered the latter, and was apparently reflected at the terminals of the generators, where it piled up and caused an overpotential which produced a flashover either from the first bar to the stator or to a neighbouring bar. It was the arc thus formed that led to further damage.

Neither the valves nor the horn gap arresters operated during this disturbance.

Half an hour later a breakdown having exactly the same features as the preceding one occurred on generator 2. The first bar of a phase was pitted at the terminal end by an arc, as was also the iron stator frame, from which it may be inferred that a flashover between these two parts took place. Further, some bars were burnt in the centre of the stator core, and in part nearly melted through. All these bars were at the entrance of two phases. It is impossible to say whether this failure may be ascribed to a flashover from one bar to an adjacent one, or to the stator core. The place where the lightning fell was also unknown. Nevertheless, this disturbance can be explained in exactly the same way as the one examined above, thunderclouds being over the power house in both cases.

These two breakdowns show the danger of connecting the generators directly to the transmission lines (see also Part VIII).

(c) Disturbance caused by a direct stroke of lightning.

In this case the plant is single phase, and comprises an overhead transmission line fed by the power station 4 (Fig. 13). The working pressure is 5 kV,

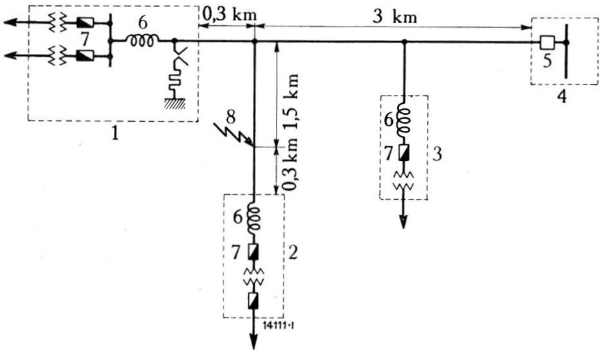

Fig. 13. — Electrical plant.

1. Substation.
2, 3. Pole-type transformers.
4. Power station.
5. Oil switch.
6. Small choke coils.
7. Fuses.
8. Lightning.

and the frequency 40 cycles. Substations 1, 2 and 3 are connected to the overhead transmission line, the transformers at 2 and 3 being mounted on poles. The insulators of the transmission line are tested up to 35 kV, so that their breakdown pressure must be greater than this figure.

Substation 1 is shown in detail in Fig. 14, and comprises two self-cooled step-down transformers 1 and 2, for 5000/2 × 125 V, 25 kVA each. Transformer 1 is immersed in oil, while transformer 2 is air cooled. A horn gap arrester 3, set to discharge at 13 kV, with a series resistance of 40 000 ohms, is inserted between each cable on the high-tension side and the earth. Small choke coils 4 with six to eight turns are connected in series with the high-tension line. The primary windings of the transformers are protected by fuses. The two transformers feed a distribution system having a pressure of 2 × 125 V with a neutral wire. This system forms a loop, with lines branching off, as shown in Fig. 14. Excess-pressure fuses are placed between the neutral wire and the earth, and fuses of 160 A are provided for the live wires. The total length of this low-tension distribution system is about 4 km.

Substation 2 (Fig. 13) has one pole-type transformer for 5000/2 × 125 V, 6 kVA. The primary

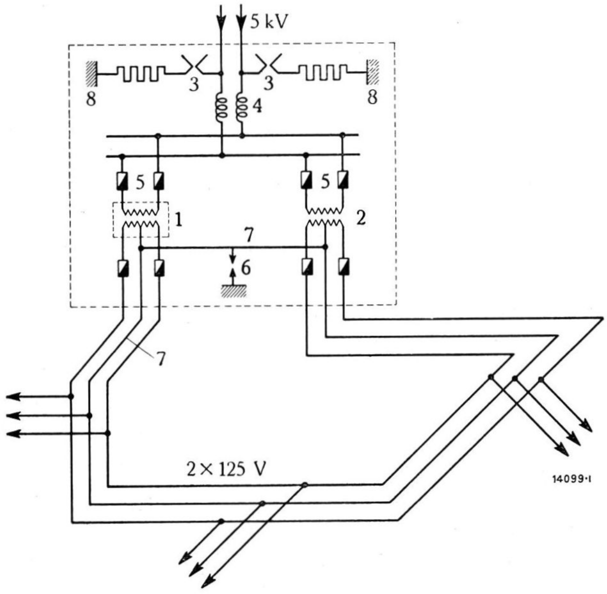

Fig. 14. — Substation with transformers.

1. Oil-immersed self-cooled transformer.
2. Self-cooled transformer.
3. Horn-gap arresters set to discharge at 13 kV, and provided with a water resistance of about 40 000 ohms.
4. Small choke coils.
5. Fuses.
6. Excess-pressure fuses.
7. Neutral-wire.
8. Earth.

side is protected by a small choke coil having twelve turns, and by fuses fitted directly in the transformer leads. The low-tension winding of the transformer is connected to a two-conductor distribution system of 2 × 125 V with a neutral wire. Fuses are provided for the live wires, and an excess-pressure fuse is placed between the neutral wire and the earth.

Substation 3 is similar to substation 2.

The weather was close and a loud peal of thunder was heard; at the same instant the light at 1, 2 and 3 (Fig. 13) failed. Shortly afterwards, the light came on again at 1 and 3. About 300 m away from substation 2, on the 5-kV transmission line, ten wooden poles were found to have been shattered, and had to be replaced. Splinters from these poles were thrown as far as 30 m away. Further, one wire had fused at several points near the insulators of the damaged poles. In order to clear this matter up, flashovers were produced at the insulators of a wire, thus causing an arcing ground to be formed. Not a single insulator was destroyed. As the breakdown pressure of the insulator exceeded 35 kV, the overpotentials occurring must have been necessarily greater than this value.

At substation 2 there was a flashover between a wire leading to a 5-kV terminal of the transformer and the transformer tank, the wire affected not being the same as that on which the breakdown in the transmission line took place. These two arcing grounds therefore made a short circuit.

At substation 1 (Fig. 14), the 5-kV terminals of transformer 2 flashed over to earth, and the entrance coils of the high-tension winding broke down. The high-tension fuses protecting this transformer were blown by the flashover which took place at the transformer terminals. The oil-immersed transformer 1 was intact, and continued to supply the distribution system, with the result that the low-tension winding of the air-cooled transformer 2 was fed by it through the loop after the fuses had blown. On account of the faulty points on the winding, transformer 2 overheated and began to smoke. It was not possible to ascertain whether the horn gap arrester had operated or not. The high and low-tension fuses protecting transformer 2, as well as the excess-pressure fuses at the neutral wire and several small fuses in the low-tension circuit were blown, and a number of lamps were also spoiled.

Power station 4 (Fig. 12) feeds a system about 30 km long, which includes the transmission line just described. The oil-switch of this line tripped, and was closed again three minutes later without anything abnormal occurring. The switch was doubtlessly opened by the double ground which was formed around substation 2. A horn gap arrester, set for 14 kV, also operated. Both before and after the disturbance nothing untoward took place.

From the theory already given, it may be deduced that this disturbance was caused by lightning going directly into the overhead transmission line, whose potential was suddenly raised to that of the clouds, which resulted in the insulators breaking down. The discharge was so violent that several wooden poles were shattered. It is, however, remarkable that the insulators of only one wire flashed over.

Overpotential to earth, produced by lightning, was probably responsible for the flashovers at the terminals of the transformers in substations 1 and 2, although it is possible that these may have been caused by travelling waves liberated by the lightning which were reflected at the transformer terminals. The breakdown at the entrance coils of the air-cooled transformer can be explained by steep-fronted travelling waves, but it is impossible to determine whether the steep front was formed directly by the flash of lightning, or by the discharges to earth at the transformer terminals. The immunity of the oil-immersed transformer is due to its better insulation as compared with the air-cooled transformer, and to the time necessary for an arc to be formed under oil, as has already been seen in Part I. The extinguishing and relighting of the lamps was accounted for by the tripping and reclosing of the switch in the power station.

No reason is forthcoming to explain the failure of fuses and lamps on the low-tension distribution system. Such occurrences, however, are often met with during thunderstorms. They must be attributed to overpotentials lasting a considerable time, and may possibly be static charges which have flowed through the transformer. This question must be left open for the time being.

The causes of disturbances of all kinds are consequently covered by the simple theory propounded last month.

Attention must be called to the fact that the small choke coils were, in this case also, incapable of protecting the transformer in substation 1.

VII. MAGNITUDE OF THE OVERPOTENTIALS AND SURGES PRODUCED BY LIGHTNING.

It has been seen that flashovers to earth are met with in electrical plants, and the breakdown pressure of the insulators enables an idea of the magnitude of the overpotential to earth due to atmospheric discharges to be gathered.

Experiments, which have for the greater part been carried out in American plants, show that disturbances attributable to lightning are never or only very seldom met with in extra-high-tension installations of 100 kV and over, whereas they are frequent in plants for lower tensions (50 kV and less).

As the breakdown pressure of the insulators for 50-kV plants is about 100 kV, it follows that overpotentials induced during thunderstorms certainly exceed this value. However, the intensity of these overpotentials is not known, as the pressure which insulation can stand up to when stresses are applied for only a short time is greater than when they last for longer periods; also, the influence of the time lag with flashovers in air has not been determined. In all probability, this last-named factor rarely affects breakdowns met with in practice, and the amplitude of surges producing discharges to earth is equal to the difference of potential between the conductor and earth when the flashover takes place. Consequently, this amplitude is greater than, or at least equal to, the breakdown pressure of the faulty point or insulator. As the dielectric strength of insulators for plants for lower working pressures is comparatively greater than those for high pressures (see adjoining table), the amplitude of surges causing breakdowns in different plants will also be in the same ratio.

Working pressure	Approximate breakdown pressure of the insulators when wet
6 kV	6 times the working pressure
10 kV	4·5 " " " "
20 kV	3 " " " "
30 kV	2·5 " " " "
50 kV	2 " " " "

The amplitude of surges produced by the screening effect of buildings, transformer tanks, etc. varies from zero to a maximum value. The latter is limited by the dielectric strength of the plant. The same remarks also hold good for discharge surges. The following rule, in connection with what has just been examined, is generally applicable:—

In plants where disturbances produced by atmospheric discharges occur, i. e., in plants whose working pressure is less than 100 kV, surges having an amplitude equal to or greater than the breakdown pressure of the insulators are met with.

The intensity of overpotentials produced by electromagnetic oscillations depends to a great extent on the design of the transformers, that is to say, on their size, working pressure, frequency, arrangement of the winding, as well as on local conditions, such as, the layout of the busbars, choke coils, connections, etc. As the influence of all these factors has not yet been cleared up, it is obviously out of the question to attempt to lay down any hard and fast rules on this matter.

VIII. PROTECTION AGAINST OVERPOTENTIALS DUE TO LIGHTNING.

From the foregoing, it appears that disturbances produced by lightning in extra-high-tension plants are exceedingly rare, and protection can be therefore entirely dispensed with. On the other hand, in plants for average and lower pressures, efficient protection is not available although very necessary.

The most satisfactory method of keeping down the number of disturbances would be to prevent the formation of overpotentials in the transmission line. One or several ground wires would enable this to be carried out; unfortunately, they are expensive, and for this reason only used for transmission lines with iron poles, as every pole can be then reliably grounded. The influence of thunder clouds on a transmission line is mitigated by the ground wire because the number of lines of force between the clouds and transmission line is thereby lowered. For instance, by protecting a single conductor with a ground wire, the intensity of the field, and consequently the overpotential, is brought down by about 30 %. If a sufficient number of ground wires is provided, the effects of thunder clouds can be entirely removed, but, on account of the heavy expense involved, such a solution can seldom be recommended. On this account, only one ground wire is generally used in practice, which allows the intensity of overpotentials to be somewhat reduced, and the working pressure above which disturbances are only exceptionally met with to be brought down in a corresponding measure. For lower working pressures, the intensity of overpotentials is also decreased, but not sufficiently to obviate all disturbances, although their number is naturally diminished, so that a ground wire does not fully protect such installations. In plants with wooden poles, a ground wire is more harmful than otherwise, as the insulation afforded by the poles is thereby done away with, and, moreover, in this case, the minimum pressure above which no disturbances occur is not affected in the slightest.

As no means of effectively avoiding overpotentials on overhead transmission lines exists in practice, it remains to be seen whether they can be prevented from reaching the more expensive parts of the plant, e. g., the transformers and machines. Two methods have been tried, namely:

(a) To prevent the overpotential from going beyond a certain point by choke coils, the effect of which should be to throttle the excess pressure. The cases which have come under the author's notice (Part VI) and special tests carried out for this purpose have shown that both with small and large transformers, the inductance of the choke coils used in practice, which varies approximately from 0·1 to 0·5 millihenrys, is much too small to afford any protection whatsoever; cases are even on record where they have led to an increase of the stresses.

(b) To clear off the overpotential before it can reach the apparatus requiring protection. Horn gap arresters are suitable for this purpose; they must, however, be provided with series resistances in order to prevent the dynamic current from flowing through the ionised gap, and thus forming a permanent arc. The greater the series resistance is, the smaller will

be the discharge capacity of the arrester. Theoretical considerations show that when this resistance becomes greater than the reactance of the transmission line to a surge, scarcely any protection is afforded by this class of arrester. As the resistance has to be increased when the working pressure is raised, the discharge capacity of the arrester falls off, so that only for working pressures lower than 15 kV is efficient protection ensured.

Electrolytic lightning arresters have been tried which do not require any series resistances, and have therefore a high discharge capacity. However, as a certain interval is always required (cf. Part. I) to puncture solid insulating material, doubts may be expressed as to whether such electrolytic arresters are really efficacious, because time enough for transformers and machines to be damaged may elapse before the arrester operates.

As it is not yet possible to exclude overpotentials due to atmospheric discharges, the insulation of machines and transformers should be strong enough to withstand such occurrences without being damaged. This condition implies that the dielectric strength of the winding of transformers and machines should be greater than that of the overhead transmission lines to which they are connected, and that coils, turns and wires should be able to bear not only any surges which may be impressed upon them, but also the stresses produced by electromagnetic oscillations. Account must naturally be taken of the much greater time required for a breakdown to take place under oil or through solid insulating material than across an air gap, since the stresses produced by atmospheric discharges last only a short time. As the amplitude of surges, the stresses due to electromagnetic oscillations, and other overpotentials to earth met with in plants for lower tensions are comparatively more dangerous than in extra-high-tension plants, the strength of the insulation for the latter can be proportionally less than for installations working with more moderate pressures. The additional dielectric strength of the insulation can be provided with transformers comparatively easily, and it is nowadays possible to go to a certain length in this respect with the improved insulating material available, notwithstanding constructional difficulties, in the case of generators.

Protection of generators.

Disturbances to generators in power stations can be guarded against by connecting them indirectly to the transmission line by inserting a transformer between the two. Nevertheless, this method of protection is dear, causes losses, and only excludes disturbances if the transformers are constructed in accordance with the aforementioned principles. All the same, should a defect occur, transformers can be repaired much more easily and cheaply than expensive generators.

In power stations which are connected to superpower transmission systems by transformers, it often happens that secondary local systems for dealing with only small outputs are connected directly to the generators. The latter, and consequently the continuous operation of the main transmission lines, are thereby jeopardised in the event of a lightning disturbance occurring on the local line. In such cases, a transformer between the generators and the local line is highly necessary, despite the extra outlay, as only a small transformer is then endangered, instead of several large generators. The intermediate transformer can be connected either directly to the generator busbars, or to the high-tension busbars. In the first case the transformation ratio is often equal to unity, whereas in the second case, the pressure must be lowered.

Acknowledgments and thanks must be tendered to the power-plant engineers who not only gave the author every facility for making investigations on systems where disturbances occurred, but also assisted him to undertake special tests for obtaining as complete information as possible about the disturbances.

S. Rump. (D. M.)

NOTES.

Electrification of the Sangritana Railway (Italy).

Decimal index 621. 331. 33 (45).

LIGHT railways of 950 mm gauge are relatively numerous in Italy. A number of these are already operated electrically, and it is proposed to convert some of the remainder. A recent example of this evolution is afforded by the Sangritana Railway of the Società per le Ferrovie Adriatico-Appenino, Milan, the electrification of which is now being proceeded with. The above-named company placed an order in October, 1921, with the Tecnomasio Italiano Brown Boveri, Milan, for the delivery of the complete electrical equipment of this railway, which is situated in the province of Abruzzi e Molise, in the southern part of Italy (see map, Fig. 1). Local traffic is chiefly dealt with, and the railway serves a sparsely-populated, mountainous district. Great care had therefore to be taken in order to keep the outlay involved by electrification as low as possible, in order not to impair the financial soundness of the concern. Direct current at an average pressure of 2400 V (2600 V at substations) was found to meet these requirements best, as large three-phase central stations are situated in close proximity to the railway from which electrical energy can be procured very cheaply. A notable advance is thereby made

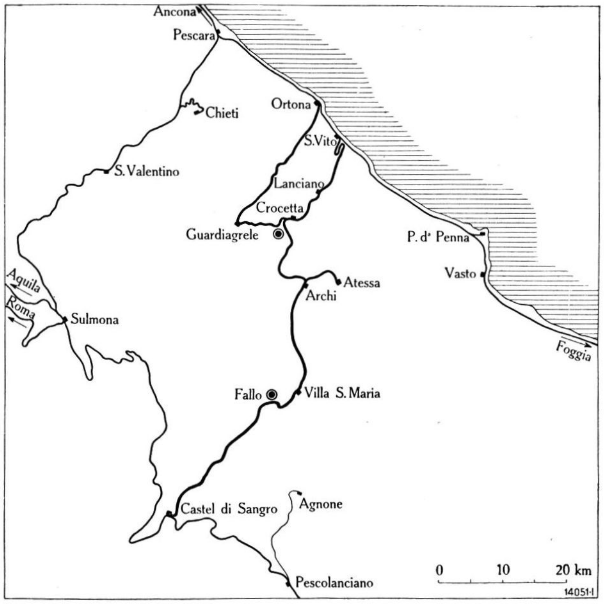

Fig. 1. — Map showing the Sangritana Railway, which is to be electrified.

— Sangritana Railway.
— Italian State Railways.
— Pescolanciano-Agnone local railway.
◉ Substations.

in the adoption of high-tension direct current in Italy, as the total length of this railway amounts to 150 km of track. On account of the mountainous nature of the country traversed, heavy gradients up to 3 % and curves as sharp as 100 m radius are met with.

The contract obtained by the Tecnomasio Italiano Brown Boveri includes the equipment of two substations, part of the overhead system, and 18 complete locomotives.

The railway is to be fed by two substations; one of these is at Crocetta and the other at Fallo. The first is equipped with three converting sets, each comprising a three-phase step-down transformer for 30000/3300 V, 42 cycles, and a synchronous motor-generator for a D. C. output of 600 kW at 2600 V. The second substation has only two such sets.

The overhead contact wires have as a rule catenary suspension, one grooved copper contact wire of 63 sq. mm section being provided per track. A supplementary copper wire of 80 sq. mm section is to be laid parallel to the contact wire between Crocetta and Ortona, the section being reduced to 60 sq. mm for the remaining portions of the railway. The poles are to be placed 50 m apart on straight sections, and the messenger cable of 40 sq. mm section will be of bronze.

Four two-axle and fourteen four-axle locomotives are to be supplied. The former are intended exclusively for passenger service, whereas the others are suitable for both passenger and freight traffic. The two-axle locomotives are able to deal with trains of a maximum total weight of 45 tons; with the four-axle locomotives, this weight is increased to 65 tons for passenger trains and 104 tons for freight trains. The maximum speed permitted is 45 km per hour.

Each of the two-axle locomotives is equipped with two motors permanently connected in series, whereas the four-axle locomotives are provided with four motors which are permanently connected in series by pairs. All these motors, which are of the self ventilated, geared type, are indentical, both mechanically and electrically.

The smaller locomotives have a one-hour rating of 167 H. P. at the tread of the wheels at about 22·5 km per hour with a tractive effort of 2000 kg; their continuous rating amounts to 129 H. P., at about 24·5 km per hour with a tractive effort of 1380 kg. The capacity of the four-axle locomotives is double that of the two-axle ones, i. e., 334 H. P. on a one-hour rating at about 22·5 km per hour and 4000 kg tractive effort, and 258 H. P. continuously at about 24·5 km per hour and 2760 kg tractive effort.

The weight of one of the two-axle locomotives is 17·5 metric tons, and that of a four-axle locomotive 28·5 metric tons.

Electric traction on the Sangritana Railway is to be inaugurated in the first half of 1923.

A. Brodbeck (D. M.).

Direct-current express locomotives for the Italian State Railways.

Decimal index 621. 334. 2 (45).

FIVE 1 C 1 locomotives, built by the Tecnomasio Italiano Brown Boveri, Milan, in conjunction with the Officine Mecchaniche già Miani e Silvestri locomotive works, Milan, were delivered in the latter part of 1912 to the Italian State Railways for working on the Milan-Varese line. These locomotives have given every satisfaction in service; during the war, in particular, they were called upon to handle very heavy traffic, and their performance has been warmly commended by the Italian railway officials. Recently, five more locomotives having the same general features have been ordered from the Tecnomasio Italiano Brown Boveri for working on this section.

With the new locomotives, the arrangement with two jackshafts and four connecting rods has been replaced by a drive which transmits the motor torque directly to the middle driving axle through a Scotch yoke (Fig. 1), similarly to the E Giovi, or the 1 C 1 Simplon locomotives. This alteration entailed placing the motors somewhat lower than with the former machines on this line.

The leading particulars of these new locomotives are the following:—

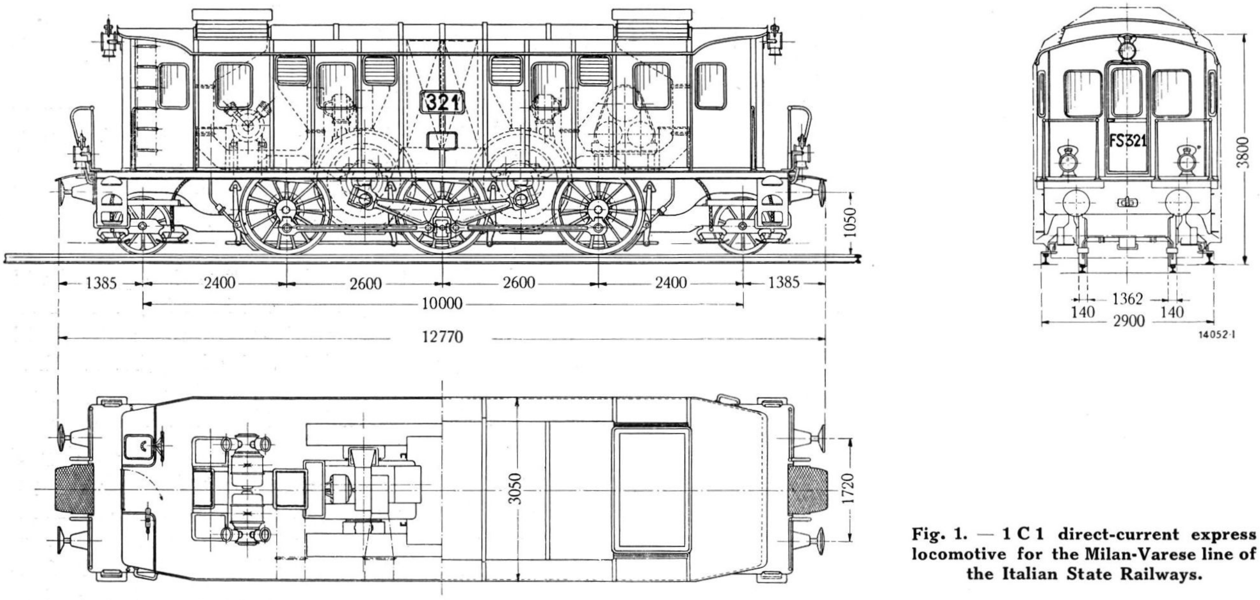

Fig. 1. — 1 C 1 direct-current express locomotive for the Milan-Varese line of the Italian State Railways.

General:	
Track gauge	1445 mm
Minimum radius of curves on open track	300 m
„ „ „ „ at points	115 m
Maximum gradient	1·2 %.
D. C. pressure at third rail	600—650 V.
Weights:	
Mechanical part	43 metric tons
Electrical equipment	26 „ „
Total weight of locomotive	69 „ „
Passenger trains hauled	200 „ „
Freight trains hauled	400 „ „
Speeds:	
Average speed of passenger trains on 1·2 % gradients	70 km per hour
Average speed of freight trains on 0·2 % gradients	45 „ „ „
Maximum permissible speed of express trains on 0·2 % gradients	95 „ „ „
Maximum permissible axle loads:	
On driving axles	16 metric tons
On guiding axles	13·5 „ „
Outputs:	
One-hour rating at the motor shaft	2 × 680 H.P. at 310 r.p.m. or 88 km per hour.
Continuous rating at the motor shaft	2 × 500 H. P.
Diameter of wheels:	
Driving wheels	1500 mm
Guiding wheels	960 mm

Apart from the alteration of the drive, which entailed a modification of the location of the motors, the latter, together with the remainder of the electrical equipment, are identical with those of the five earlier locomotives.

The new locomotives will be placed in service in the spring of 1923. *E. Schrœder. (D. M.)*

Official trials of the 1B-B1 locomotives for the Swiss Federal Railways between Lucerne and Chiasso.

Decimal index 621. 334. 2 (49. 4).

On September 23 and 24, 1922, the official trials of the 1B-B1 locomotives of the Swiss Federal Railways took place. The electrical equipment of these machines has been supplied by Brown, Boveri & Co., and their leading particulars are the following:— One-hour rating of motors 2400 H.P. at 58 km per hour; maximum speed 75 km per hour. A complete description of these machines is given in Brochure 731-734. The special train for these trials was made

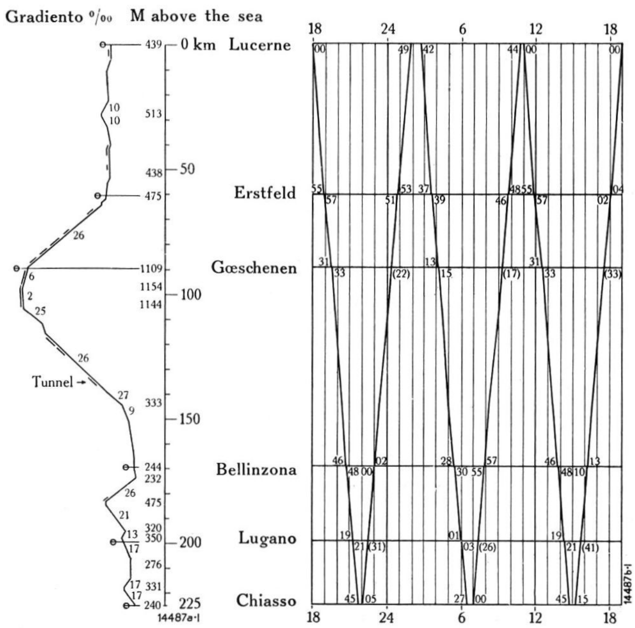

Fig. 1. — Time-table of the official trials of the 1 B - B 1 locomotive on September 23 and 24, 1922.

up of a dynamometer car and eight four-axle bogie carriages, and the total weight behind the locomotive amounted to 301·8 metric tons.

The specifications required that the 1B-B1 locomotives should be capable of performing three round trips between Lucerne and Chiasso in 24 hours, a quarter-of-an-hour layover being allowed at the terminals. The trial train was scheduled to run at the same speeds as ordinary express trains on the Gothard line, and its timetable is shown in Fig. 1. Special care was taken to prevent delays or stoppages which were not foreseen on the timetable.

The trial train left Lucerne on September 23, 1922 at 18 o'clock, whence it finally returned at 19 o'clock the following day, after having accomplished the required number of round trips between Lucerne and Chiasso. The layovers lasted just long enough to enable the temperature rise of the transformer to be measured, except for a somewhat longer stop, which was made at Lucerne from 1^{49} to 2^{42} so as not to interfere with the running of the regular trains.

Fig. 2. — 1B-B1 locomotive during trials with dynamometer car.

The 1B-B1 locomotive No. 12 328 chosen for these trials ran therefore 1350 km in 25 hours. The total time taken up by stops in stations was 3 hours 9 minutes, and, on deducting this time from the total time occupied by these trips, an average running speed of 62 km per hour is obtained. The total vertical rise amounts to approximately 6250 m (20 400 feet), the minor gradients having been neglected. The sustained speed up the principal 2·6 % (1 in 38) gradients ranged from 55 to 60 km per hour. During the last return journey, the train was stopped whilst ascending a 2·6 % gradient, and restarted again — a speed of 50 km per hour being attained in 2 ½ minutes, whereas the specification called for 4 minutes.

The dynamometer car, which was originally intended for measuring mechanical quantities only, has now been provided with electrical measuring instruments by the Swiss Federal Railways so as to permit complete records of the performance of electric locomotives to be made. The record strips of all the instruments are moved forwards by a common drive, which facilitates as far as possible the comparison and perception of the graphs obtained.

These comprehensive arrangements, and especially the provision of thermo couples, enabled the maximum temperatures of the electrical parts to be ascertained whilst travelling. The temperatures remained throughout the trips within the limits prescribed.

After completing these trials, the locomotive immediately resumed its normal working. These few details give an idea of the capabilities of electric locomotives. It would also be of interest to know to what extent a steam locomotive would be able to carry out this performance.

A. Luthi. (D. M.)

Completion of the electrification of a main-line railway.

Decimal index 621.331.42(44).

In the latter part of October, 1922, the trials of the 1500-volt, direct-current locomotives were begun on the newly-electrified Pau-Montréjeau line of the Midi Railway Company. Current is supplied to this section by seven substations, which are fed by three-phase current, 60 000 V, 50 cycles. Five of these are equipped with rectifiers and the remainder with rotary converters. As arrangements had been made to start the trials, which took place in the presence of the Public Work's Minister, M. le Trocquer, at the end of October, and, moreover, as the building operations were behindhand, the rectifiers and rotary converters, both of which were constructed by Brown, Boveri & Co., had to be erected and installed in the substations at Lourdes and Coarraze-Ney in a very short notice; in fact, the rectifiers had to be put in place in only a few days. The subsequent trials of the rotary converters and rectifiers were carried out without a hitch, the machines operating perfectly, both when alone and when in parallel with others. Their performance left an extremely favourable impression on all parties concerned. More ample details of this interesting equipment will be given in a subsequent issue.

W. Walti. (D. M.)

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

GENERAL INDEX TO VOL. IX, JANUARY — DECEMBER, 1922.

FRONTISPIECES AND SEPARATE ILLUSTRATIONS.