THE BROWN BOVERI REVIEW

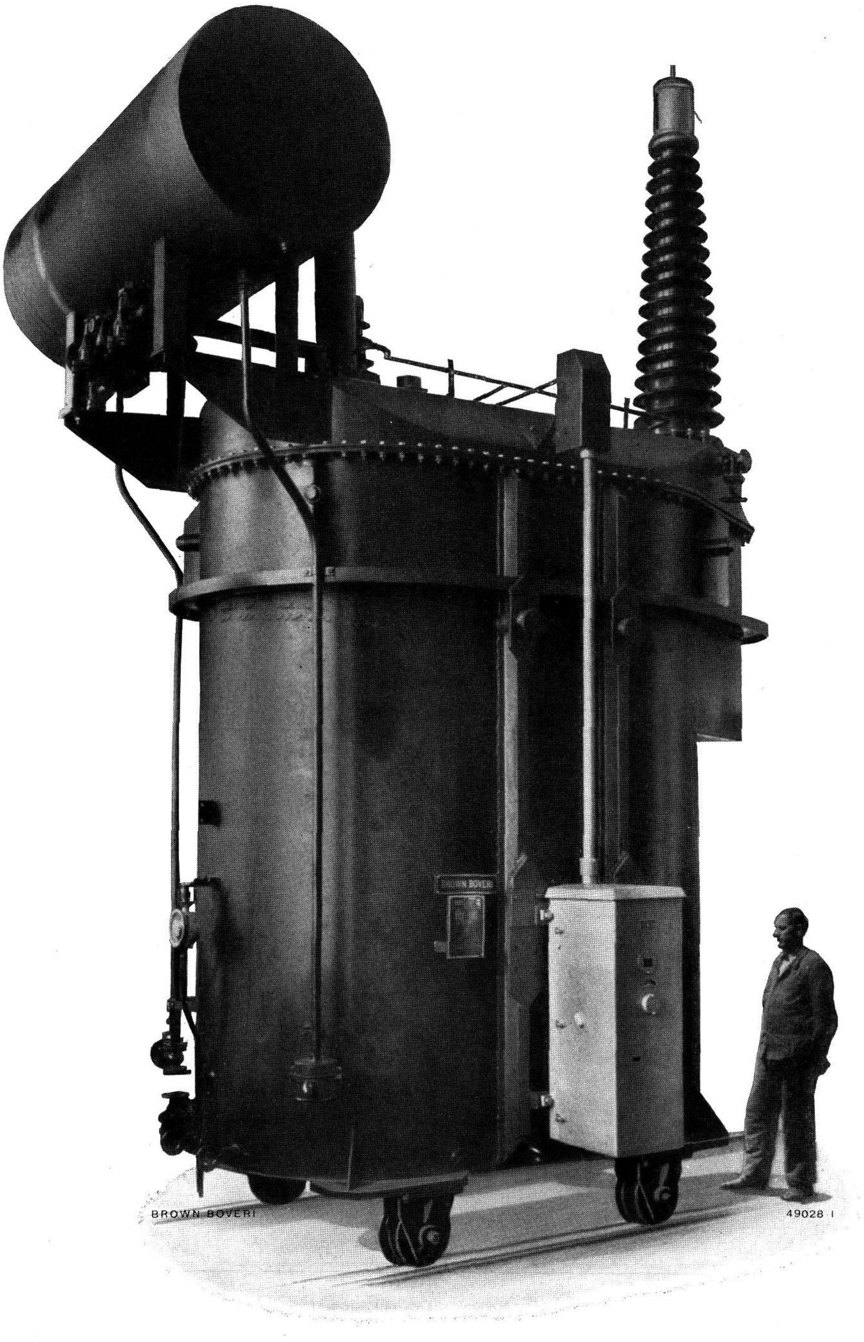
Authorized by Swiss Federal Council decision of 3rd Oct. 1939.

1891 BROWN BOVERI 1941

SPECIAL NUMBER: NETWORK PROTECTION.

VOL. XXVI JUNE, 1941 No. 6

Printed in Switzerland



AN OUTSTANDING ACHIEVEMENT IN THE BUILDING OF EXTINGUISHING COILS

DISSONANCE EXTINGUISHING COIL FOR A 220-kV OVERHEAD NETWORK
WITH AN OUTPUT OF 27,200 kVA.

THE BROWN BOVERI REVIEW

THE HOUSE JOURNAL OF BROWN, BOVERI & COMPANY, LIMITED, BADEN (SWITZERLAND)

VOL. XXVIII JUNE, 1941 No. 6

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NETWORK PROTECTION.

INTRODUCTION.

Decimal index 621.316.9

IT is surely superfluous to comment once again on the exceptionally rapid increase in electrical power consumption throughout the civilized world, in recent years. Electro-technology has penetrated deeply into every branch of our daily life, into the field of lighting, of industrial drives, transportation, heating, refrigeration, news distribution and chemistry, only to name its most important applications. As in other fields, increasing consumption of electrical power was accompanied by efforts to better the economical efficiency of production and, as in many other cases, this result was attained, at least partly, by a concentration of production on the most suitable sites. Thus, coal mines, coal conveying facilities, cooling water conditions were the deciding factors in choosing the site of steam power stations, while the site of hydraulic power stations was influenced by hydrographic considerations and facilities for putting up dams. Concentration of power production led, on the other hand, to long transmission lines. The conveyance of big blocks of electric power over long distances creates some very special problems and we cannot afford to treat them otherwise than generally in the space at our disposal. In the present number, we limit ourselves to the protection of transmission networks which, to-day, are practically exclusively of the three-phase type. Judging from the present-day rarity of breakdowns in power delivery, even to the remotest of power consumers, an outsider might be tempted to assume that the whole problem was an easy one to solve and that the difficulties encountered could be overcome by very simple measures. In so doing he would certainly do an unconscious injustice to those who have to grapple with the problems in question, namely the makers of electrical material and the engineers dealing with power generation and power distribution, whose efforts are bent on eliminating the last possibilities of trouble affecting the consumer. In this they start from the right principle that technology is not an aim in itself but is only a means to render service to other circles which it should be remembered give employment to a huge staff of engineers, draughtsmen, erectors, etc. by their consumption of electric power.

The aim of the present number of our Review is to give a section of the entire field of network protection. The first article is devoted to a general survey of the problem in its entirety, the following ones treating of specially interesting problems and giving some idea of the research work our firm has been doing recently in the sphere of network protection. Intentionally, we limit ourselves to tests which have been concluded and descriptions of apparatus, the development of which has been completed and tried out in practice. Only a little space is given over to developments not yet finished. Lack of space, also, makes it necessary to hold over for later publication articles dealing with future trends in the field of protection.

(MS 751) *Th. Boveri. (Mo.)*

RELATIONSHIP BETWEEN THE PROTECTIVE MEASURES APPLIED ON HIGH-VOLTAGE SYSTEMS AGAINST EARTH FAULTS, SHORT CIRCUITS AND OVER-VOLTAGES.

Decimal index 621.316.91

This article gives a survey of the protective measures applied on networks. The relationship is established between the fields of earth-fault protection, short-circuit protection and over-voltage protection.

I. INTRODUCTION.

THE protection of electric systems comprises all the measures taken to maintain unimpaired the transmission of power. These measures can be more or less arbitrarily subdivided into three groups, namely:— earth-fault protection, short-circuit protection, over-voltage protection. However, it is impossible to plan one of these protective measures without taking the other two into account. Progress made in one of these fields may result in the other two having to be considered in a different light. The object of the following article is to establish the most important relationships between the three main fields of protection and the advantages offered by certain methods of network protection in conjunction with the other fields; the other articles in the present number deal with various problems separately.

Network protection is not completely encompassed by the three groups just enumerated even when — apart from relays, extinguishing coils lightning arrestors etc. — high-voltage circuit breakers and the quick-acting reclosing devices of the latter etc. are considered as elements of the three fields of network protection. Fundamentally, the whole question of insulation rightly belongs to the sphere of network protection as well. This refers to the insulation of lines as well as that of stations and refers both to the absolute value of the insulating strength and to its grading or coordination for the different parts of the plant under consideration.

II. EARTH-FAULT PROTECTION.

Let us begin with protection against earth faults. The great majority of earth-faults are not represented by a solid connection between a phase and the earth but only by an arc, so that a rapid rupture of the latter generally suffices to allow the network to function at once normally, as before. In networks of relatively low voltages and limited extent single-pole earth-fault arcs usually rupture of themselves but, in the case of the higher voltage range and when the network is extensive, which means that the capacitive current to earth attains a considerable figure, it is imperative that special extinction measures be taken. On the other hand, intermittent earth faults, which are those which rupture and reignite of themselves, may give rise to very undesirable over-voltages. The rapid extinction of earth-fault arcs and the avoidance of over-voltages due to intermittent earth-faults can be attained by two quite different measures, namely either by using extinguishing coils or by a rigid earthing of the neutral point of the network.

When the latter measure is applied, every single-pole earth fault occurring leads to a short circuit, the clearing of which is the duty of the short-circuit protective devices. This signifies, however, that the defective section of line be cut out. This in its turn means an interruption in power delivery, if there is no second line parallel to the affected one and which is dimensioned to carry the whole load itself.

The utilization of extinguishing coils is undoubtedly the more elegant solution of the two, because, here, no short circuit is initiated by the earth fault and there is no interruption in power supply; no relay has to act and no circuit breaker be tripped. Nothing else happens than that the earth-fault current, the real cause of the trouble, disappears after a few half cycles, after which service on the network continues again normally. During the time the earth fault lasts, there is a displacement of voltage on the system, because the affected phase acquires the earth potential and the line voltage appears between both the other two phases and earth. This voltage displacement corrects itself very soon after the earth fault is cleared.

Another advantage of networks protected by extinguishing coils is that, even if the earth fault is of a lasting nature, the system can, in spite of it, continue to be operated, for a long time, if necessary. Thus, before cutting out the defective length of line, there is time to take all the necessary measures to allow of carrying on undisturbed power supply.

In networks with a rigidly earthed neutral point, every lasting earth fault means a longer interruption of power supply because the line affected has to be cut out immediately until the necessary repairs are made.

Finally, the network equipped with extinguishing coils has the advantage that it interferes less with neighbouring low-voltage lines than does one with directly earthed neutral point.

All the above reasons are in favour of the extinguishing coil and explain why it is so very extensively used in Europe. However, the network protected with extinction coils has the disadvantage that during the earth fault the insulation of the two unaffected phases must stand up to the line voltage while in a network with directly earthed neutral point, the latter limits the voltage of all three phases against earth to the value of the phase voltage — at least theoretically. This assumes, however, that the earthed transformer is so connected that as small a reactance as possible is opposed to the earth-fault current. Even then, the voltage of the neutral point will be the higher the bigger its earthing resistance in relation to that of the earth fault. Even when the neutral point is provided with an excellent earth, the resistance of which remains very low although the short-circuit current passing through it has dried the surrounding ground, it must be reckoned with that the potential of the neutral point will rise considerably, which causes the potential of the two phases which are unaffected to rise as well[1]. Only the insulation of transformers, the neutral point of which is directly connected to the tank, will not be more highly stressed during the earth fault.

Despite this drawback, the directly earthed neutral point has a considerable advantage, namely:— the voltage of networks with extinguishing coils rises to 173 % of the rated value when an earth fault occurs that is to say it becomes at least 40 % higher than the voltage of the network with directly earthed neutral point assuming that the latter is well earthed and has transformer connections of the right kind. It might, thus, be assumed that the great advantages which were enumerated in favour of the network with extinguishing coils have to be bought at the price of a bigger outlay for insulation. This, however, is very rarely so. The reason is that in the case of all network voltages which are not of the very highest range (that is to say up to about 100 kV) the atmospheric voltages and not the over-voltages at operating frequency are the ones to be reckoned with in dimensioning the insulation, and these atmospheric voltages bear no relation to the rated voltage of the system. Thus, a lowering of the insulation of the lines simply because lower over-voltages at operating frequency can be allowed for is inadmissible as the network would be subjected to far too frequent breakdowns due to the much more dangerous atmospheric over-voltages. As a matter of fact, it will be noted that American networks with directly earthed neutral point are not less strongly insulated than European networks with extinguishing coils of the same operating voltage[2]. It is only in very recent times that the progress made in over-voltage protective measures has allowed of effecting considerable savings on the insulation of networks with directly earthed neutral point. We will return to this point in the last chapter.

III. SHORT-CIRCUIT PROTECTION.

Over-current relays are only used, to-day, for protecting distribution plants of moderate voltage against short circuits. We would refer in this respect to Mr. J. Stoecklin's article on page 134. In the case of extensive high-voltage networks only distance-relay protection and differential-relay protection (protection of line sections) are used. We will not discuss the pros and cons of these two different types of protection here as Mr. J. Schneider treats the subject in his article in this number.

Both in differential-relay protection and in distance-relay protection efforts have been directed, for a long time past, towards cutting out short circuits as quickly as possible. The aim is to reduce as far as possible the electro-dynamic and the thermal effects of the short-circuit current on the machines, apparatus, cables, etc. affected, and, above all, to avoid damage to parts of the plant through the action of the short-circuit arc, so that if possible the part affected can take up its duties again, immediately, after the short-circuit has been cleared.

Apart from this, and from the point of view of the stability of the parallel operation of power stations and of groups of power stations, the rapidity of cutting out is a very important factor. Every possible means has been resorted to in order to improve stability and, as an example, we would only recall here the method of quick response excitation, which was so much discussed some years ago but of which one hears but little to-day. Although these remedies certainly had advantages, the only real method which gets at the root of the trouble and provides a genuine remedy is the creation of a high-speed selective protection system.

Theoretical investigations as well as many experiments in the test room and on networks showed convincingly that even a very violent short circuit was no danger to the stability of parallel operation if it was only of very short duration. The admissible duration of the short circuit varies according to operating conditions on the network, but not to such an extent as to make it impossible to establish values which were more or less valid. Thus, it is known that in most cases stability is maintained under the effects of a three-pole terminal short circuit (the worst case!) when it does not last more than 0·2 to 0·3 s. If, therefore, a protective system allows of reducing the duration to 0·1 s, stability should be kept up even under the worst conditions[1].

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[1] For the sake of safety a voltage rise of about 20 to 30 % must be reckoned with.

[2] The only exception is the insulation of the transformers.

[1] It is, of course, assumed that stability is perfect under normal conditions. If a system is so badly laid out that it falls out of step under simple load fluctuations, these conditions cannot be improved however perfect the short-circuit protection devices added.

The sole factor of importance is the total time from the beginning of the short circuit until its suppression in all phases. This time is composed of the inherent operating time of the relay and the total rupturing time of the breaker. There would be no object in shortening the operating time of the relay without influencing the time of the breaker, as well, because a shortening of the time of the relay to a tenth of its value, for example, let us say from 0·5 to 0·05 s, only allows of a much smaller diminution of the total short-circuit duration, as long as the rupturing time of the breaker amounts to some tenths of a second; on the other hand in many cases it is inadmissible that the operating time of the relays should be shorter than the rupturing time of the breakers. Thus, for example, the time stepping of distance relays must be somewhat bigger than the rupturing times of the breakers, because if this is not so, breakers which are in reserve on the network trip unnecessarily as their relays give the tripping impulse before the breaker nearest the fault has had time to complete the clearing of the short circuit.

This shows that the breaker is in an extremely important element in the scheme of short-circuit protection. A selective protection system with satisfactorily short-time stepping only became a practical possibility after the last development of the high-power breaker which allowed of attaining the short rupturing times of some hundredth parts of a second. Here the air-blast breaker is worthy of mention. It was originally designed in order to eliminate the danger of fires and explosions and it then showed itself able to provide these very short rupturing times up to the highest practical voltage range. After our comments on stability, it will be obvious that a selective protection system working to a breaker time of 0·05 s (inherent operating time + arc rupturing time) and a relay time of 0·05 s as well must be considered as very satisfactory. There is, however, a limitation to be imposed here. The section of line on which the short circuit has occurred is cut out after the trouble has been cleared and this means that all power generating and power consuming machinery connected to it are cut off from the remainder of the network. This can be tolerated when the affected line section is a feeder of little importance. Further, a momentary cutting out of a connecting line is not important if there is a sufficiently strong line in parallel to it (double line or ring connection). If, however, it happens to be an important connecting line, the cutting out of which means that whole networks or parts thereof are separated from one another or are left insufficiently coupled, the stability problem is not solved simply by a rapid clearing of the short circuit.

Here, the quick-acting reclosing method can be advantageously applied. By far the greater number of short circuits are of a transitory nature. In these cases, if the affected line section is switched in again after a short time, the network continues to function as though no trouble had occurred. If the short circuit is of lasting nature, the first rupture and subsequent reclosing must be followed by a second and definitive rupture. At first, in America, the reclosing method was applied with interruptions of some seconds. This, of course, except in some special cases, does not lead to the desired results, because the isolated networks have fallen out of step long before reclosing occurs and cannot simply be reconnected again by reclosing the breakers.

However, it is quite sufficient if the affected length of line is cut out only long enough to allow of the track of the short-circuit arc being deionized. According to operating voltage, this takes one to a few tenths of a second. If the line is switched in again after such a brief interruption, stability is maintained in most cases. The reason why this was not done long ago was the great difficulty in getting most of the breaker types available to reclose so soon after opening on a short circuit. A very happy solution of this problem has now been found in the air-blast high-speed circuit breaker [1].

It should also be stressed here that in the method of rapid reclosing, the very high-speed rupturing of the short circuit is of exceptional importance. In all cases it is the fundamental condition for the maintenance of stability and when rapid reclosing is used on a connecting line, it is all the more important because the total time of disturbance is made up of the short circuit itself and the time of complete interruption necessary to allow the track of the arc to deionize.

The method of rapid reclosing has certain repercussions on the relay system. We will not go into these here as Mr. Schneider's article treats the subject[2].

The development of the short-circuit protection system described with very short rupturing times and rapid reclosing, places the two methods of earth-fault protection in another light. In networks with directly earthed neutral point, every earth fault is a short circuit, but when rapid reclosing is used, a short circuit, if it is of a transitory nature, no longer means that the affected part of the network is cut out. The question therefore arises of whether there is any sense in using simultaneously extinction coils and rapid reclosing devices.

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[1] Immediately after rupturing a short circuit the same contacts of the air-blast high-speed circuit breaker can reclose the circuit. With other types of breaker, solutions have been put forward, in which one breaker is used to rupture the circuit and another to reclose it.

[2] See page 126 of this number.

Here it must first be stated that the extinction coils do not make the rapid reclosing method superfluous because the latter is able to cut out two-pole and three-pole short circuits of a transitory nature without interruption of service on the network; while the extinction coils only deal with single-pole earth faults. Although, in general, multi-pole short circuits and earth faults occur much less frequently than single-pole ones, it is worth the extra expense to make the former harmless in the case of important lines.

There, therefore, remains the question of whether, inversely, the utilization of rapid reclosing does not make extinguishing coils superfluous. We think that this question should be answered in the negative, because the extinguishing coil clears the great majority of transitory faults without initiating a short circuit with all its undesirable electro-dynamic and thermal accompaniments and also without any switching operations, that is to say independently of the good working of relays or other moving parts. It must be added that the clearing of a fault by the rapid-reclosing method does produce a momentary drop in the voltage with subsequent interruption of power flow while an earth fault on a network provided with extinction coils is only manifested by a passing displacement of the voltage which the consumer, connected up to all three phases, does not notice at all. Finally it should not be forgotten that a network with extinguishing coils can go on operating for some time despite the existence of an earth fault.

Thus, for all the reasons just enumerated, the installation of an extinguishing coil is perfectly justified on networks provided with rapid reclosing of the breakers. The additional outlay for the coils is justified by the benefit it brings. The question of whether a network with rigidly earthed neutral point is more economical than one with extinguishing coil, only comes up if the former offers the same security with weaker insulation than the latter. This, however, is a problem to be treated in conjunction with over-voltage protection.

IV. OVER-VOLTAGE PROTECTION.

The object of modern over-voltage protection of electrical plants is — to put it briefly — to prevent flash-overs and breakdowns due to over-voltages of non-atmospheric origin altogether and to localize unavoidable flash-overs due to atmospheric over-voltages to those parts where their occurrence will not disturb operations.

The first duty, prevention of punctures and flash-overs at operating frequency, during earth faults and switching over-voltages is accomplished by insulating all parts of the plant sufficiently. As the height of this type of over-voltage is in a certain relationship to the height of the operating voltage, a minimum level of insulation is determined in function of the operating voltage. As a rough and ready rule it can be assumed that the insulation against earth must be able to stand up to, at least, double the value of the highest operating-frequency voltage encountered between phase and earth, in order that the over-voltages mentioned should cause neither breakdowns nor flash-overs[1].

Contrary to all other kinds of over-voltages, atmospheric over-voltages are fundamentally independent of the operating voltage of the network. There are no practical means of eliminating entirely flash-overs due to atmospheric disturbances. All other conditions being equal, these flash-overs are the more infrequent the better the insulation of the network. For this reason, it is customary to insulate networks of low and medium voltages (as well as low-voltage systems) much better than would be necessary if only over-voltages dependent on the operating voltage had to be taken into account. It is only in the very high high-voltage range that over-voltages due to operating conditions alone are taken into account because in this range the insulation level is so high that flash-overs due to atmospheric over-voltages are very seldom encountered. In order to localize the flash-overs which despite all the measures taken cannot be entirely eliminated a suitable grading (coordination) of the insulating strength on the network is carried out. This, however, is a problem that must be handled separately for lines and stations.

Fortunately, there is a means available to counteract the *generation* of over-voltages on lines, namely by putting up earth wires. Experience shows that these are very efficacious. On the other hand, when direct lightning strokes on the earth wire or masts occur, some difficulties are encountered, in preventing the earth wire and masts, attaining such a high voltage that flash-overs to the phase conductors happen. Thus, it is essential that the resistance to earth of the masts be as low as possible, so that they can carry off the lightning discharge without reaching a high potential. Radiating ground wires and wires connecting the masts together, one mast to the next, have been tried in order to obtain a satisfactory grounding of masts.

In order to localize those flash-overs which cannot be prevented, it is possible to produce a coordination of the insulating strength by adding protector tubes in parallel to the line insulators themselves. These should prevent flash-overs taking place on the insulators.

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[1] The different kinds of over-voltages were described in detail in The Brown Boveri Review of Aug. 1939, page 179 (W. Wanger:— Over-voltage protection and coordination of insulation strength).

Proper adjustment of the flash-over voltage of these tubes causes over-voltages which occur to discharge solely through the interior of the tubes. The earth-fault current thus set up is interrupted automatically after one or a few half cycles by the flow of gas generated in the protector tube. Of course, it may be thought admissible to do away with an earthing wire when the line is equipped with protector tubes.

Practically the same result as that attained by using protector tubes is reached by the method of rapid reclosing of the circuit breakers. In this method a flash-over (as a result of an over-voltage) somewhere on the line is allowed to develop, but the arc to earth, which it produces, is immediately cut out, so that no interruption of power delivery on the network occurs. In this case, we have a device which is really a form of protection against short circuits taking over the function of a protection against over-voltages.

Further, it should be remarked that single-pole arcs to earth, initiated by atmospheric over-voltages, are put out by extinguishing coils, as well, without interruption of power delivery on the network. In this case, we have a device for protection against earth faults functioning simultaneously as a protection against over-voltages.

Now, as regards the protection of stations against over-voltages, the proper coordination of the insulation is the first measure which has to be taken. The basis for this is that the solid and fluid insulation of the apparatus, transformers and machines must not be allowed to puncture under any circumstance. Therefore, this insulation must be made the strongest of all. Further, it is generally recognized that a flash-over must never occur across the gap of open disconnecting switches. Also, it is advantageous that all air gaps difficult of access, such as those inside insulators, the gaps between phases and those across open circuit breakers must be provided with the highest level of insulation, so as to avoid flash-overs on these parts under all circumstances.

The open distances between the different phases to earth are provided with a lower insulating step because flash-overs on these points are less dangerous to plant and operators. As, however, it is desirable to avoid these flash-overs, if possible, another still lower insulating level is provided, which is best formed by lightning arrestors. The duty of the latter is to lead off to earth over voltages which would inevitably produce flash-overs, after which they have to rupture automatically and immediately the earth connection they have established during the discharge.

The higher the strength of the insulation of the material itself, the higher can be the flash-over voltage adjusted for on the arrestors and the less frequently they have to act. Up till relatively recently it was advantageous that arrestors should function rarely, because otherwise they were very apt to develop defects. In recent years, there have been great improvements made in arrestors and they are now so reliable in service that it is no longer necessary to put in strong insulation solely with the object of protecting the arrestors from damage. In other words, modern lightning arrestors allow of a lower level of insulation in electrical plants without trouble developing more frequently, because they lead off to earth over-voltages likely to be of danger to the material, without interrupting normal service.

It must be laid down here, however, that modern lightning arrestors are only intended to form a protection against atmospheric over-voltages and should not function under other kinds of over-voltages. Consequently, the insulation of the plant must be made so strong that it will stand up to all operating over-voltages, but need not take atmospheric voltages into account, the arrestors taking over the duty of rendering these harmless to the plant. For the lower range of high voltages, the standard rules in force to-day call for higher insulation than is necessary to deal with the over-voltages due to operating conditions, this in order to take atmospheric over-voltages into account. There are savings to be effected here, as regards insulation, if efficient lightning arrestors are used.

Further, and quite generally, economies can be made as regards insulation on condition that the over-voltages due to operating conditions be reduced, by some means or other. The recognition of this fact means an entire revision of the judgement we formed on the two systems of earth-fault protection. Rigid earthing of the neutral point does not only reduce the maximum operating frequency voltage possible between phases and earth to a considerable extent, but it leads to lower over-voltages due to switching than in systems with an extinguishing coil[1] and it limits the earth-fault over-voltages (transients) to low values.

In this respect, there is another point of view to be taken into account, namely the connection between flash-over, residual and extinction voltage of the lightning arrestor. The flash-over and residual voltage of the arrestor cannot be set arbitrarily at any low figure if the arrestor is to break the current to earth reliably, once the over-voltage is passed. The lower the highest possible operating frequency voltage is between phase and earth, the lower may the flash-over and residual voltage of the arrestor be set — with identical ex-

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[1] Over-voltages at switching out are chiefly reduced between phase and earth while between phases and across the breaker gaps there is also a reduction if not as big. The space at our disposal does not allow us to go more fully into this question.

tinction reliability — and the lower may be the insulation of the material against earth. Now, the stage of development reached to-day with the best arrestors is such that high-voltage material with an insulation corresponding to general standard rules (as, for example the REH), is just effectively protected by these arrestors if there is a possibility of the line voltage occurring between phases and the earth. In networks equipped with extinguishing coils these arrestors are, therefore, just sufficient for the insulation usual to-day; a considerable diminution of the insulation strength, on the contrary, would not be admissible, apart from networks of a lower high-voltage range.

Conditions on networks with directly earthed neutral point are quite different. On account of the considerably lower operating-frequency voltage which may appear between phase and earth, it is possible to use arrestors with much lower flash-over voltage and residual voltage without lowering their extinction reliability. Further, as already mentioned, as in networks with directly earthed neutral point the *over-voltages* due to operating conditions are lower than on networks with extinguishing coils, it is certainly admissible to use considerably weaker insulation between phase and earth. Practical use of an advantage latent in networks with directly earthed neutral point was only made possible by the development of modern lightning arrestors.

In station material the possibility of putting in insulation of lower strength is chiefly made use of in transformers. Especially in the case of very high voltages, great savings can be effected. It is precisely in this range — of about 200 kV and upwards — that the use of extinguishing coils offers a number of difficulties[1] unknown in lower voltage ranges. Thus a lot of arguments can be marshalled in favour of the direct earthing of the neutral point in the case of very high voltages.

It could be added that transformers which have to be freighted by rail — and none other come into consideration — cannot be built with their full insulation unless the output per unit is so low that the transformer cannot be considered from the economic point of view. However, in networks with extinguishing coils it is not absolutely necessary to insulate the transformers completely in accordance with what is still required by present-day standard rules. As the neutral point of the transformer winding is only raised to phase voltage when an earth fault occurs while the external terminals attain line voltage against earth, an insulation suffices which is so graded that the winding on the neutral point of the transformer has only got to withstand a test voltage equal to double the phase voltage and that only the external terminals have to carry a test voltage of double the line voltage. This is, of course, only admissible when care is taken that the over-voltages of short duration on the neutral point are at least $\sqrt{3}$ lower than on the terminals. To this end, an efficient lightning arrestor can be connected in parallel with the extinguishing coil or else a connection used which reduces considerably neutral point over-voltages at the moment of their creation[1]. The utilization of extinguishing coils at very high voltages is somewhat facilitated by these possibilities. However there still remain very considerable disadvantages as compared to direct earthing of the neutral point.

What was said, here, in connection with the choice of earth-fault protection, on the great importance of modern lightning arrestors for the insulation of plants, is only valid, so far, for stations. Reasons of economy make it impossible to apply this form of over-voltage protection to lines. The insulation of lines in networks with directly earthed neutral point was generally made stronger than in networks with extinguishing coils in spite of the lower over-voltage due to operating conditions (in this respect American and European practices should be compared). The reason was that, in the first case, each earth fault initiated by an over-voltage made it necessary to cut out the line. Therefore, efforts are made to prevent too frequent interruptions of service, by insulating the lines very strongly to make flash-overs of infrequent occurrence. By measures like the method of rapid reclosing of breakers this reason for putting in very strong insulation is removed and a lower level of insulation can be used on the lines of networks with directly earthed neutral point than is the case with networks with extinguishing coils because of the lower over-voltage due to operating conditions.

To summarize, the following comments can be made on the two methods of earth-fault protection:— the use of extinguishing coils seems to offer very considerable advantages. These seem somewhat less important, to-day, because new possibilities of short circuit and over-voltage protection have become available; however, in the case of high-voltages of the low and medium range, the advantages of the extinguishing coil are well worth consideration. In the very high voltage range the use of extinguishing coils offers some difficulties. Further, modern lightning arrestors and the method of rapid reclosing of breakers allow of applying weaker insulation to the lines of networks with directly earthed neutral point and this is of especial interest in the very high voltage range. For these reasons and in the present stage of technical developments it would appear that the direct earthing of the neutral point is more advantageous than the use of extinguishing coils, when the highest operating voltage range is under consideration.

(MS 752) *Dr. W. Wanger. (Mo.)*

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[1] The appreciation of the difficulties in question will form the subject of another article.

[1] See Mr. Meyer's article in this number.

PLANNING RELAY PROTECTION FOR HIGH-VOLTAGE TRANSMISSION NETWORKS.

Decimal index 621.316.925

The duties required of relay protection are summarized in this article:— selectivity, rapidity of action, suitability for rapid breaker reclosing. Then, rules are laid down to guide the choice of the type of relay:— usually quick-acting distance relays sometimes completed by remote control for transmitting tripping impulses, in special cases protection by comparison of the direction of power flow. Finally, some special network layouts which present difficulties for relay protection are touched on, and it is shown that when planning high-voltage systems it is necessary to take short-circuit protection into account, from the beginning.

I. DUTIES REQUIRED OF RELAY PROTECTION.

THE duty of the relay protection on high-voltage networks is to cut out all short circuits selectively. Are classed as short circuits:— flash-overs between two or between three phases, directly through an arc or, also, through the earth, further single-pole earth faults when the neutral point of the system is rigidly earthed. Are not included:— single-pole earth faults when the neutral point of the system is insulated or when it is earthed through an extinguishing coil. When a short circuit takes place, the affected section of the network should be cut out from all sides while all the other breakers should remain closed. There is no object, however, in cutting out a short circuit selectively while allowing the power stations on the network to begin hunting, owing to the short circuit lasting too long. Therefore, a short tripping time is as important for the relay as is selectivity.

Practical experience gained with extinguishing coils has made it a commonplace requirement, to-day, that all single-pole earth faults, the cause of which is not permanent, should be extinguished without interruption of power delivery. Further, the rapid reclosing feature of breakers also allows of eliminating short circuits, the cause of which is not permanent, without interruption of power delivery. This process makes a severer demand on relay protection, consisting in the realization of very short tripping times. Without the reclosing feature, very short tripping times are desirable but no sharp limitation can be set for the length of time a short circuit can be allowed to endure.

With rapid reclosing of the breakers, the line must be left dead for a few cycles and further, as will be shown, must be cut out simultaneously at both ends. The time which elapses from the initiation of the short circuit until both breakers are reclosed determines the stability of the network. In this case, the relay tripping times must not only be short but must also be equal. Let us examine Fig. 1. The times O A and O A′ of relays I and II on either side of the fault are short but, for some reason, are not equal. The period during which the section of line is dead is not, for instance, the tripping time B C or B′ C′ but corresponds only to length B′ C. By the fact of the tripping times O A and O A′ being unequal, it is necessary, in order to get a given dead time B′ C, to maintain the tripped time B C longer than would be the case did points B and B′ coincide. Therefore, for rapid reclosing the shortest possible and constant tripping times of relays are needed.

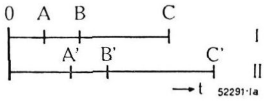

Fig 1. — Circuit-breaker and relay times for rapid reclosing on a line I—II.

I. Relay and breaker times I.
II. Relay and breaker times II.

t. Time.
0. Initiation of short circuit.
A, A′. The contact of the relay is closed.
B, B′. The breaker is opened.
C, C′. The breaker is reclosed.
B′—C. Dead pause.
B—C = B′—C′. Duration of breaker.

Of course, most short circuits occur on transmission lines. But those on bus-bars, in transformers and measurement transformers, that is occurring inside the stations, are not rare. Thus, relay protection should cover lines and stations, as well.

II. GENERAL RULES FOR CHOOSING THE RELAYS TO PROTECT HIGH-VOLTAGE PLANTS.

High-voltage networks connect several power stations or are composed of parallel and meshed lines. We would like to lay down the following rules for chosing the short-circuit relay protection best suited to plants like these.

In order to fulfil the requirement laid down in the preceding chapter relative to selectivity, there are fundamentally, two kinds of protections available:— the systems based on time stepping and those based on a comparison of various magnitudes. The first principle is exclusively represented by quick-acting distance relay protection, in the case of high-voltage networks. The systems which are based on a comparison of various magnitudes are, on the contrary, of various kinds. One can differentiate between cross differential protection, i. e. comparison between two parallel lines and longitudinal differential protection, i. e. comparison between the beginning and the end of one and the same lines, this by means of a measurement channel (pilot wire or high-frequency transmission superimposed on the operating high-voltage). The magnitudes used for purposes of comparison are, usually, the current, the polarity of the current or the direction of the flow of power.

The application of cross differential protection is limited to those lines which are rigidly connected in parallel at both ends and have no asymmetrical branch lines. This protection fails when one of the two lines of the double conductor is cut out. Despite its simplicity, it is little used in high-voltage plants because of this limitation.

The longitudinal differential protection can be used on all lengths of line and whatever the arrangement of the network. It allows of attaining as short tripping times as desired for short-circuits anywhere on the length of line protected in so far as these lines are sufficiently strongly supplied from both sides. In ring lines or on line sections which are only fed from one end and very weakly or not at all from the other, it is generally not possible to get simultaneous rapid tripping. Apart from the complications and expense inherent to the pilot line, longitudinal differential protection has the disadvantage that the stations are beyond the sphere of protection and must have their own special protective relays. The protective devices at both ends of a line section are attuned to one another which makes periodic checks more difficult.

Longitudinal differential protection fulfils perfectly the condition relative to selectivity and to short tripping times for short-circuit protection without reclosing of breakers and in most networks for the short-circuit protection with reclosing as well. The high-speed distance relay protection which is simpler and also includes station short circuits is, however, generally preferred to the various forms of longitudinal differential protection.

High-speed distance relay protection can be used on all lines, with a few exceptions to which we will return. The short circuits which take place on the greater part of the protected line are cut out within the fundamental time of the relay. As long as the latter does not exceed about 0·1 s, and is valid, for 85—90 $^{0}/_{0}$ of the length of line covered, stability is practically assured. Thus, high-speed distance relay protection fulfils all the requirements which may be made on short-circuit protection without reclosing of breakers, namely:— selectivity, short tripping time and inclusion of the stations in the protected zone.

As high-speed distance relay protection is bound up with time stepping, it would seem at first glance that its use cannot be reconciled with the rapid reclosing feature. The condition of simultaneous cutting out at both ends of the line may, however, be fulfilled by prolonging the length of line for which the relay trips on fundamental time, so that it goes beyond that section of the network belonging to the breaker. If the relays at both ends of a line act simultaneously, the short circuit will be cut out at both ends wherever it is, within the fundamental time. At the moment of reclosing the ordinary tripping characteristic of the quick-acting distance protection is automatically restored and, if the short circuit persists it will be cut out, according to its position, either with fundamental time lag or stepped time lag.

Fig. 2 shows a high-speed distance relay type L 3 W in its design for reclosing of breakers[1]. The length of line for tripping to fundamental time at the first pick up of the relay and at reclosing of the breakers can be set as desired and independently of each other.

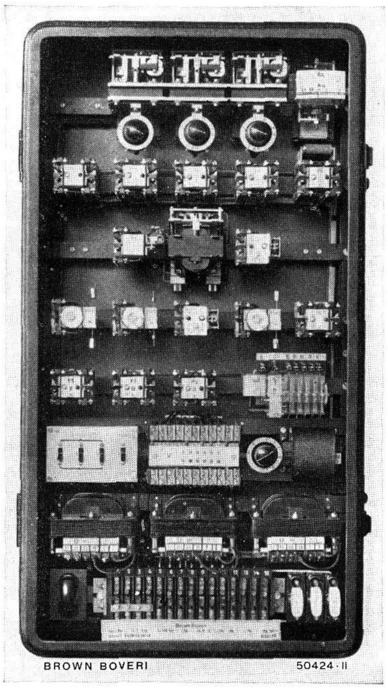

Fig. 2. — Three-pole rotating-field high-speed distance relay Type L3W, in design for rapid reclosing of breakers.
The breaker trippings are controlled without using high frequency or pilot wire transmission. This special arrangement requires only a few more devices that does the ordinary arrangement (see page 131, Fig. 1).

The first tripping impulse can be either on three poles or on one pole as is considered desirable. In the latter case, only the pole of the breaker corresponding to the phase the relay of which has acted trips under a single-pole earth fault.

In this process, it is possible that, at the first opening, the breaker of some section of line not affected by the short circuit also trips.

For example, in the case of a short circuit at D (Fig. 3), it may happen that, apart from breakers 4 and 6, breakers 1 and 5 trip. The importance of this tripping should not be exaggerated, because these breakers are immediately closed again and do not trip any more.

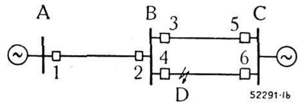

Fig. 3. — Network with reclosing of breakers.
□. Breakers with distance relays.

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[1] See article on "High-speed distance protection" in this number.

The connection between the power stations A and C which serves to maintain stability is interrupted during the duration of the cut out, however conditions are no less unfavourable than in the case of a short circuit between A and B. It must also be remembered that the distance BD, for which such trips are possible, is much reduced when point B is supplied from different sides.

What limits the utilization of this very simple process is rather the condition that both relays on a length of line should trip at once. For example, in the case illustrated in Fig. 4 this condition is not fulfilled. The double line AB is only supplied from one side. When a short circuit occurs in C, near A, by far the greater part of the short-circuit current flows from A through 1 to C. Relay 3 will only trip after 1 has tripped.

Fig. 5 shows a similar case. The double line AB is supplied from both sides. The neutral point of the system is earthed but only in station A. If an earth fault occurs at C, near A, it is true that a short-circuit current flows through breaker 4 but only a low earth-fault current. Distance relay 4 gets the necessary earth-fault current to make it pick up only after 2 has tripped.

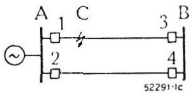

Fig. 4. — Network with reclosing feature.
□. Breakers with relays.

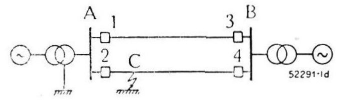

Fig. 5. — Network with earthed neutral point and reclosing feature.
□. Breakers with relays.

In positions in which high-speed distance relay protection of type L 3 W cannot be used, for the reasons laid down, simultaneous tripping is attained by imparting the tripping impulse of one relay to both breakers covering the length of line, by means of high frequency or a pilot line. However, this system calls for about the same expenditure on apparatus as does longitudinal differential protection based on direction of flow of power; it has, however, considerable advantages namely:— simultaneous tripping whatever the layout of the network, inclusion of the stations in the protected zone. If the impulse transmission fails, the protection remains entirely effective as an ordinary high-speed distance-relay protection. As a result of this, it is permissible to use an open circuit connection to couple the tripping devices instead of a closed circuit connection:— the former is simpler.

In medium-voltage networks fed at few points, the breakers on the supply lines alone can be designed with the reclosing feature, this for the sake of simplicity, and tripped by over-current relays the first time. The selective elimination of the short circuit of permanent character after reclosing has been carried out is then left to the selective protection of the different sections of the system without regard to reclosing. This system cannot be applied to high-voltage networks on account of their being supplied from various points.

To summarize, high-speed distance relay protection should usually be chosen for high-voltage networks. For rapid reclosing, this type of protection is so arranged that the distance-time characteristic is modified between the first and a possible second pick up. When this cannot be done, the high-speed distance relay protection is completed by the addition of a remote transmission of the tripping impulse.

III. INFLUENCE OF THE LAYOUT OF THE NETWORK ON THE RELAY PROTECTION.

In the last chapter, a normal network layout was assumed. By this we mean a network on which their are no branch lines connected to the sections of line considered and in which the latter have breakers at both ends, current and voltage transformers and relays. Further, the sections of line are assumed to be not very short, that is to say not under 0·1 to 0·2 km/kV operating voltage. Meshing and supplying from several points always increases the reliability of the distance relay protection, when short circuits occur on the line sections. Let us consider Fig. 6. Station C is supplied from the power stations A and B. There are distance relays placed at A, B and C. A short circuit occurs at D. Let us first assume that station B is not supplying power. The distance-time characteristic of relay A was so set that in the case of a short circuit in D, relay C must trip before relay A. If, now, station C is also being supplied from power station B, the short-circuit current and voltage drop in the line C—D will be increased, the current from A remaining constant. Relay A reacts to an increased short-circuit impedance while the relay C measures the distance C — D which remains unchanged. A meshing of the network increases the reliability of the relay stepping in the same way.

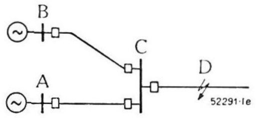

Fig. 6. — Line supplied from two points.
□. Breakers with distance relays.

Certain network arrangement, of which examples will be given, are difficult or impossible to protect by distance relays and require either a special type of protection or a more or less complete change in the layout of the network itself.

In town areas or between neighbouring power stations on rivers there are, often, very short lengths of overhead line or cable which it is impossible to protect by distance relays because the short-circuit impedance is too low.

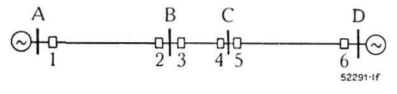

Fig. 7. — Network including a short section of line.
□. Breakers with relays.

Fig. 7 gives an example of this. The length B—C is so short that the fundamental time of a distance relay at 3 would extend beyond point C. It would be possible to raise the fundamental time of relay 3 by 0·5 s and so get the necessary stepping in conjunction with relay 5. This, however, would necessitate increasing the time lag of relay 1, for a short circuit near 2, by the same amount, which should be avoided. If it is possible to do so, the short length B—C should be protected by a longitudinal differential protection, for example, by ratio differential relays (Fig. 8). For bus-bar protection at B and C special differential relays are to be used.

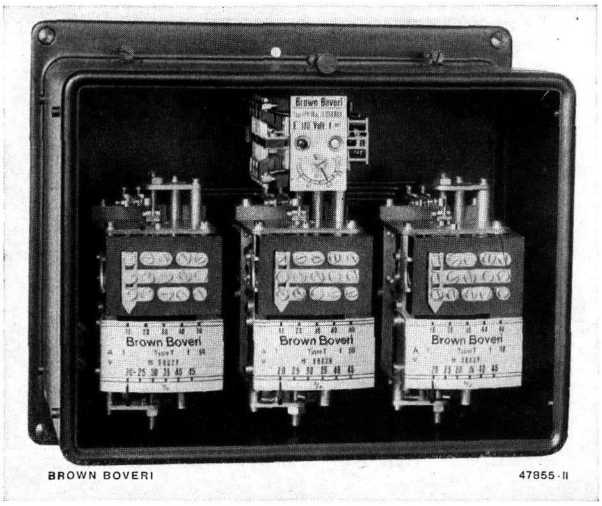

Fig. 8. — Ratio differential relay Type T.
Differential protection is primarily used for the protection of transformers but also for short lines which cannot be protected by distance relays; it is also used to protect whole bus-bar systems.

If, as is the case in Fig. 9, the short length of line is a double one and if there is no pilot wire between stations B and C, a cross differential protection can be used.

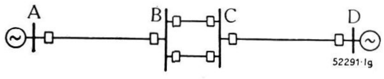

Fig. 9. — Network with a short section of double line.
□. Breakers with relays.

A layout which has often been a source of worries to engineers dealing with network schemes is represented in Fig. 10. A line is branched at C on line A—B and leads to D. For reasons of economy and in order to save operators at point C, no breaker should be placed there. If a short circuit occurs somewhere between C and D, the measurement of the impedance made at A and B is falsified on account of the supply from both sides of line CD. Conditions are exactly similar to those of Fig. 6 and relays A and B generally react to longer times than those which correspond really to the distance to the point of short circuit.

Whenever possible this is a connection diagram to be avoided. With proper reflection and if matters are taken in time it will often be found possible not to supply D from C but rather through a line carried from A or from B. If this cannot be justified economically and if it is also impossible to equip point C with three breakers, it will usually be found best to couple together the tripping impulses of the high-speed distance relays at A and B. This is especially so when point D is one where power is fed into the system and when high-speed distance relays are available. In this case every short circuit between stations A, B and D will be cleared reliably in the fundamental time.

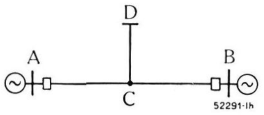

Fig. 10. — Line with a branch.
□. Breakers with relays.

We would add that the insertion of a single breaker at point C on the line to D does not form a complete protection of this system of lines. The reason is that although short circuits on the line CD can be taken care of by a distance relay placed at C, the fundamental time step of the distance relays in A and B must then only extend to the vicinity of C. For short circuits further off than C, that is between C and B, in the second part of the line, the relay A then always trips according to the time steppings set to.

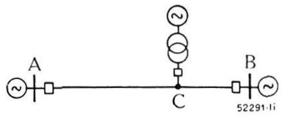

Fig. 11. — Line with branch containing a power station.
□. Breakers with relays.

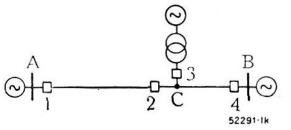

Fig. 12. — Line with branch containing a power station.
□. Breakers with relays.

If the short circuit is being supplied from the direction of D, as well, the fact that C is now supplied from several points increases the tripping times.

Fig. 11 shows a similar arrangement. The power station C is to be connected to the transmission line AB, which passes close to it, in order to allow of a relatively small exchange of power. According to the connections planned and shown in Fig. 11, no breaker should be placed at C on the line AB for reasons of economy. If the short-circuit power of the power station C is much smaller than that of A and B, it may be possible as regards relays A and B to disregard altogether the fact that C is supplied from several points. The difficulty consists in getting the breaker C to trip under short circuits on the line AB and not to trip under short circuits beyond the points A and B. By doing away with selectivity, the breaker C can be equipped with an instantaneous action overcurrent or minimum impedance relay. If, however, the short-circuit power of C is too big to be disregarded, the arrangement according to Fig. 11 is inadmissible. It is then necessary to put, at least, one breaker at C, according to Fig. 12. The line section AC is then protected by distance relays, without difficulty. In the case of short circuits on the line section CB, breakers 2 and 3 at point C must trip. A distance relay supplied with the total currents of the current transformers at 2 and 3 and which trips both breakers 2 and 3 fulfils this requirement.

There are various ways of combining connections for transformers so that the number of breakers is reduced. We give two of these connections, here, as examples.

In the plant shown in Fig. 13, each transformer has a breaker on the high-voltage and on the low-voltage side. The outgoing high-voltage line is directly connected to the station, without insertion of a breaker. Distance relay 5 provides the short-circuit protection of line AB; it is supplied by the sum of the secondary current-transformer currents of 1 and 2 and acts on breakers 1 and 2.

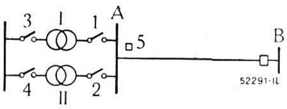

Fig. 13. — Connection permitting of economizing on the number of breakers for a transformer station with one outgoing line.

—o⁄o—. Breakers. ☐. Relays.

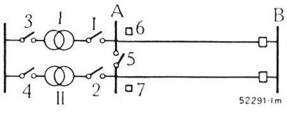

Fig. 14. — Connection permitting of economizing on the number of breakers for a transformer station with two outgoing lines.

—o⁄o—. Breakers. ☐. Relays.

Fig. 14 shows the same plant after a second line between A and B has been laid. The short-circuit protection of the lines AB is again taken care of by distance relays. For example, relay 6 is supplied with the sum of the currents in 1 and 5 and trips breakers 1 and 5 together. The disadvantage of this connection is, apart from difficulties of supervision, that when one line is cut out the transformer belonging thereto is also cut out.

It would be possible to show many other diagrams of connection, but the examples given should suffice to demonstrate the influence of different arrangements of lines on selective protection. We only desire to show that in planning a high-voltage network and, especially, when enlarging existing systems, when the designer is no longer entirely free to make the best possible layout, the short-circuit protection must be taken into account from the first. The short-circuit protection must never be lost sight of in establishing the diagram of connections of the plant as well as, in certain cases, when determining the layout of the lines and even when drawing up contract proposals on the subject of the linking up of high-voltage plants.

(MS 753) *J. Schneider. (Mo.)*

HIGH-SPEED DISTANCE-RELAY PROTECTION.

Decimal index 621.316.925

Very short tripping times and high selectivity are the characteristic features of the rotating-field distance relay. This new selective relay behaves as regards fault resistance at the short-circuit point to a considerable degree as a reactance relay without, however, having the inconveniencies of ordinary reactance relays which are susceptible to unstable network conditions or unfavourable phase deviations between current and voltage. The new combination of distance measurement and directional differentiation in the rotating-field relay is most advantageous in practical applications as well as allowing of great simplifications in design.

THE distance relay is the universal form of protection for meshed networks. As compared to all other devices, it has the decisive advantage of dealing not only with defects on the line section protected but of extending its protection to the next stations and line sections. Further, it is quite independent of pilot wires between the stations. For this reason, we devoted every effort to the development of this relay from the beginning. When the LB reactance relay was put on the market, more than 13 years ago, it aroused great interest because it made possible shorter tripping times which were independent of the resistance of the arc and which were constant down to values below the rated current. The size and importance of electric networks constantly increasing, called for still shorter relay tripping times in conjunction with the new high-speed circuit breakers which were being built. Thus, in the course of recent years, high-speed distance relays with a fundamental time of 0·1 and 0·05 s respectively were developed which were based on the wealth of experience gained with former types of relays, which experience allowed of taking into better account the processes of which the network was the seat during disturbances and permitted of improved stepping of the tripping times. The new protective devices cover comprehensively short circuits between phases, double earth faults on networks with insulated neutral point and earth faults on those with rigidly earthed neutral point. Thanks to the connection used, they are quite independent of the operating current or of capacitive charging currents on the lines and, thus, are suitable for networks operated up to the highest voltages. The time characteristic chosen, after careful study, was the stepped characteristic because it allows of the shortest tripping times for near or remote short circuits.[1]

When the tripping time is very short, the short-circuit arc has not sufficient time to travel, it therefore attains no resistance value which might have to be taken into account. Thus the distance measurement can be based on the *impedance principle* and not on the reactance principle and this eliminates the disadvantages of ordinary reactance relays built up till now which manifested themselves during hunting between power stations and when the deviation between current and voltage on sound phases was unfavourable. High-speed distance relay Type L 1 works on this principle. The favourable experiences gained in practice with this relay dependent on impedance have confirmed the exactitude of the above assumptions.

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[1] See The Brown Boveri Review, 1939, page 253.

If the reactance principle, which eliminates all additional resistances at the defective point, was abandoned, this was done exclusively because of its troublesome sensitivity to the phase displacement between current and voltage. Now, is there no way of retaining its advantages while eliminating its disadvantages?

The study of this problem finally led to the *rotating-field distance relay* Type L 3 (Fig. 1), the new distance measuring principle of which fulfils both requirements to a great extent and which also offers a whole series of other advantages.

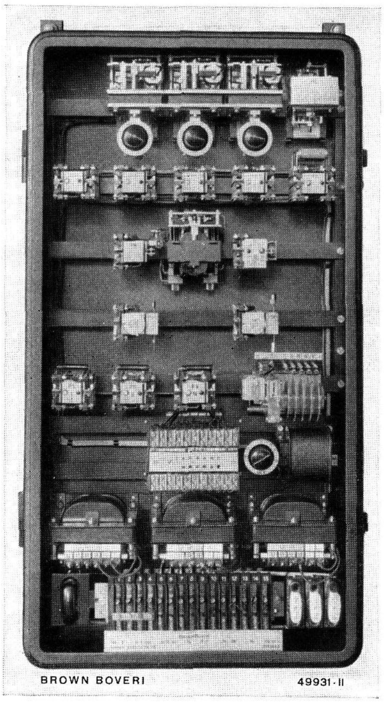

Fig. 1. — Rotating-field high-speed distance relay, Type L 3.

Complete equipment for a three-phase line. Highest-speed selective tripping under all kinds of short circuits, including double earth faults. Built-in blocking device against hunting.

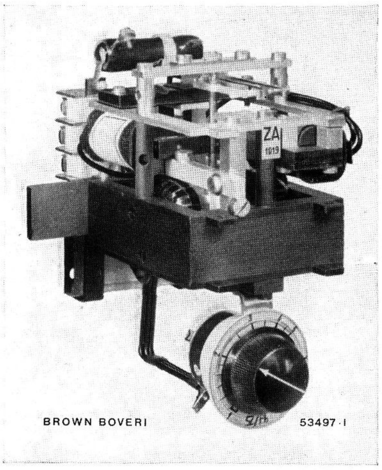

Fig. 2. — Impedance starting device ZA for high-speed distance-relay protection.

Acts on short circuits down to the lowest currents encountered, avoids unnecessary action of the protective equipment in the case of very remote short circuits.

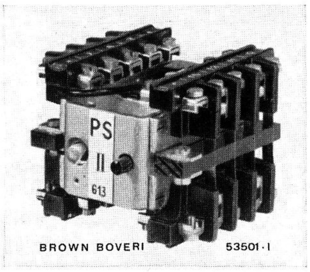

Fig. 3. — Small contactor P as a d.-c., auxiliary relay for high-speed distance-relay protection.

Remarkably compact design combined with accessibility to contacts and lead connections.

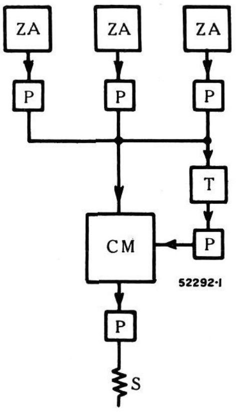

Fig. 4. — Working diagram of the high-speed distance relay protection, Type L 3.

One single element, the relay CM, serves simultaneously for measuring distances and differentiating between directions.

- ZA. Impedance starting devices.
- CM. Rotating-field relay.
- T. Step-regulating time relay.
- P. Direct-current auxiliary contactors.
- S. Line breaker.

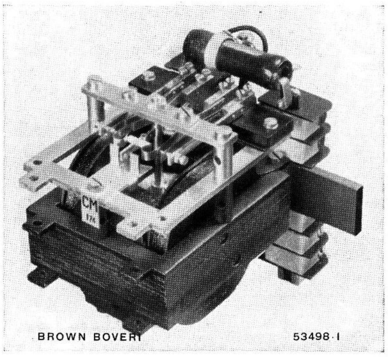

Fig. 5. — Rotating-field relay type CM, the distance measuring and direction differentiating device of the high-speed distance protection, Type L 3.

The main elements of the protection are the impedance starting devices, the distance measuring device and the step-regulating time relay.

The *impedance starting devices* ZA (Fig. 2), set the apparatus to work when a fault occurs in the area being protected, this by switching in the distance measuring device and the step-regulating time relay, through the agency of d.-c. auxiliary contactors (Fig. 3). The pick-up magnitude can be set by means of a knob which can be rotated to the desired figure and it is practically independent of the strength of the current and of the phase displacement. The principle of making the pick-up dependent on a drop in impedance allows of the apparatus acting on short-circuit currents the strength of which is even below the rated current value, contrary to devices acting only on over-currents; it facilitates the choice of the phase when switching in the distance-measuring device and limits the pick-up distance range of the relay on the network. Fig. 4 shows diagrammatically the way the different devices on one panel work together.

The distance-measuring device, which is the *rotating-field relay CM* (Fig. 5), is now excited and immediately determines if the short circuit has occurred on the nearest section of line, tripping according to circumstances, in the fundamental time. If the short circuit is more remote, the range of action of the relay is increased by the step-regulating time relay, Fig. 6, step by step, to the second, third sections of line etc., so that it trips after the second time step for a short circuit occuring on the second section of line and after the third time step for one occurring in the third section of line etc. Further, relay CM differentiates between direction of power flow and prevents tripping when power flow is inwards instead of outwards.

The CM relay is a simple Ferraris system with a contact for each revolution. Its working process is explained with the help of Fig. 7. Let AB be the length of line protected by relay CM, of which 85—90 %, that is AG, is tripped in the fundamental relay time. M is an auxiliary impedance on the secondary circuit of the current transformer and is equivalent in value to the impedance of the length AG. To measure the distance away of the short circuit, the difference U_D between the short-circuit voltage U and the voltage drop U_I of the short-circuit current in the impedance M is formed. Under normal conditions, the voltage U_D is simply a reproduction of the voltage at point G. When a fault occurs between A and G, U_I is bigger than U and U_D is negative. If the short circuit is on the right of point G, or on the left of A, the voltage U_D is positive, because U_I is either smaller than U or in the same direction. Thus the sign of U_D is an indication of the position of the short circuit and is measured by the rotating-field element. This is done by leading the voltage U_D to one winding of the Ferraris system, the other winding being supplied by a constant high voltage U_R of the diagram, as reference voltage, this voltage must form as big an angle with the first one as is possible, in order to create a big torque. Fig. 8 shows the voltage diagram on the relay terminals under a two-pole short circuit. The torque is proportional to the surface of the triangle formed by the voltages U_D and U_R. The relay trips for the negative shaded voltage region between A and G, Fig. 7, that is to say for a reversed torque of the voltage triangle. It blocks, on the contrary, under positive voltages on the left and right of the length AG, that is to say under normal rotating field. The relay differentiates between the protected line section and the whole of the remaining network simply by its sense of rotation and is thus both a *distance* and a *directional relay*. Thus, an ideal identification of the two functions distance measurement and directional differentiation which are, otherwise, independent of one another, is successfully attained by means of a simple Ferraris system and a contact to impart the tripping impulse.

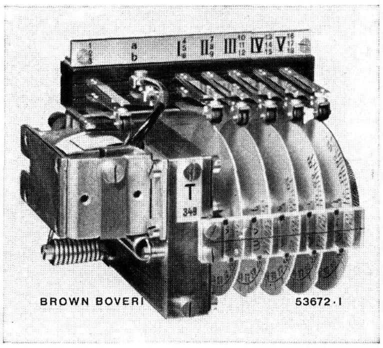

Fig. 6. — Step-regulating time relay Type T with 5 time steps *independent of each other.*

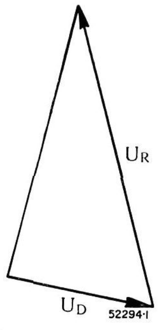

Fig. 8. — Voltage diagram on the relay terminals for a *two-pole short* circuit.

U_D. Voltage difference.

U_R. Reference voltage.

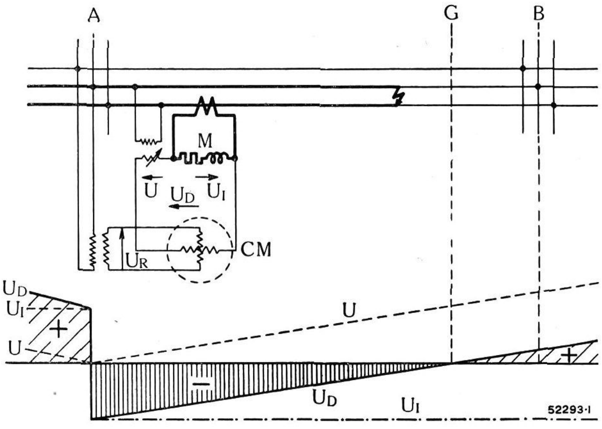

Fig. 7. — Fundamental diagram showing the operating process of the rotating-field distance relay.

AB. Line protected.
G. *Limit point for* fundamental time tripping.
CM. Rotating-field relay.
M. Substitute impedance.
U. Short-circuit voltage.
U_I. Voltage drop of short-circuit current in the impedance M.
U_D. Voltage difference U—U_I.
U_R. Reference voltage.

The direction of rotation of relay CM designates the site of the short circuit. Thus, the CM relay is similar to the instruments working on the zero-indicating measurement principle used in high-precision research.

As the voltage difference U_D always has a minimum magnitude (U_I) in the case of power flowing inwards that is to say for short circuits occurring on the left of A in Fig. 7, the *directional differentiation* in the case of metallic short circuits is assured. The only exception is a three-pole short circuit in proximity to the relay when the reference voltage U_R breaks down to the value of the arc voltage. This is the only case in which the sensitivity of the relay is severely tested. However tests carried out on networks as well as experience gathered in service show that even under these conditions the sensitivity is quite sufficient.

The reference voltage is chosen about in phase coincidence with the voltage drop across the *resistance of a possible arc*. Thus, the latter will not produce a torque and, similarly to what happens with a reactance relay, does not influence at all, or hardly at all, the measurement of the distance.

The combined distance and directional measurement in the rotating-field relay, already mentioned, also avoids all difficulties which may arise, especially on double lines, on the relays of the sound line, when the direction of power flow changes during the clearing of the short circuit on the defective line. In protective system having separate distance and directional parts, this type of trouble makes special demands on the proper collaboration of the different devices. The rotating-field relay, on the contrary, stays blocked against the stop pin and is not affected by the reversal in the direction of power flow.

The most important quality is the exact *distance measurement* independent of the current. The measurement principle of the rotating field relay, a method of zero-indicating measurement with a constant comparison impedance is, in itself, a method belonging to the technic of precision measurements. The substitute impedance M has a linear characteristic up to the highest short-circuit currents occuring in practice. Its phase angle can be adjusted to that of the line by means of a rheostat adjustable by rotation. A modification of the frequency of the network, as is possible when a fault occurs, does not influence the distance measurement because both the short-circuit voltage and the voltage across the substitute impedance are influenced in the same way.

When *2 and 3-pole short circuits* occur, the rotating-field relay CM is subjected to the line voltage as short-circuit voltage. The substitute impedance is supplied with the linked current, i. e. with the difference between two phase currents. When an *earth fault* occurs, an earth-fault relay RL acts and connects the impedance starting device, as well as the measurement device to the phase voltage to earth. The substitute impedance M is changed over, at the same time, from line current to phase current. A component of the total current, adjusted to the impedance of the line to earth, is added to the phase current. Usually only one phase is cut out when a *double earth fault* occurs and the remaining earth fault is dealt with by the extinction coil.

The connections and method of operation described result in exactly the same distances being measured whatever type of short circuit has to be dealt with. The normal *phase impedance* of the line is always measured independently of possible superimposed operating currents, capacitive charging currents or transients between power stations and independently of the distribution of the earth current in the network. As is known, this distribution can vary considerably in double earth faults according to the reciprocal position of the two earth faults and, when the neutral point is earthed, according to the position of the earthed transformers.

Hunting only occurs, to-day, in networks wanting in stability which are not uniformly equipped with modern high-speed relay protection or which fall out of step even under load fluctuations alone. As has just been said, the distance measurement of L 3 relay protection on the defective line section is not falsified, thereby. On sound lines, on the other hand, the relays are even less influenced than in the case of purely impedance protection, as has been shown by thorough investigation. Further a special blocking devise acting on the relays to prevent them tripping during hunting is provided, as a further guard.

Faults transmitted from defective to sound phases. — These are rare on account of the short tripping times possible to-day, but the design of the relay takes them into account, nevertheless. A flashover of the arc to the sound phases does not affect the proper operation of the protective equipment.

Short circuits appearing between two conductors of a *double line* form a special type of disturbance. In such cases, the earth-fault relay of the protective equipment acts and connects the relay to phase voltage. An impedance meter would often measure too high an impedance, in this case, and would consequently act after too long a time lag. The rotating field relay, on the contrary, trips properly with fundamental time as a result of the phase displacement arising between the short-circuit current and the reference voltage.

Two-pole short circuits behind in *⅄/△ connected transformers* make special demands on a distance relay protection. The rotating-field relay then always gives the same tripping times as when a three-pole short circuit occurs in the same place, or bigger tripping times, which is not the case for reactance relays unless special measures are taken. The time stepping with respect to the relays on the secondary side of the transformer is thus always to be relied on.

The recent utilization of the relays for circuit breakers with the *rapid reclosing feature* is of great importance. The Brown Boveri high-speed distance-relay protection is especially suitable here, not only on account of the very short tripping times which are reduced to 0·05 s in this case, but because of the rapid fall-back of the relay after a short circuit and its being immediately ready to resume service. A special connection was developed for this which allows of cutting out the defective line section at both ends with fundamental time.[1]

We give in the following paragraphs some details on the *construction* and *operating method* of the relay panel.

The protection panel of a branch line has *one* rotatting-field relay CM with substitute impedance M and adjusting voltage transformer V for all three phases. It is switched in by the impedance starting device in the phase affected by the short circuit. The low inherent power consumption of the apparatus as well as special intermediate current transformers facilitate this switching-over operation. Under ordinary service conditions the CM relay is not under voltage.

Each of the five impedance steps can be adjusted between 0·1 and 5 s independently of each other through the agency of the time mechanism T. The automatic passage from one step to the next only takes place at the end of the step time in question by reducing the voltage U of the distance measuring device by means of a finely graded adjusting transformer. The adjustment of the distance measuring device is made on the basis of the reactance of the line. The fundamental time, that is the first time step, is generally 0·1 and 0·05 s respectively but can be adjusted longer if necessary. The last time step or limit time corresponds to a trip with the impedance adjusted on the impedance starting device ZA and makes certain of the reserve tripping even in the case of power flowing in. With its 5 steps, the relay has

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[1] See Bulletin S. E. V., 1939, page 719.

great adjustment possibilities to meet the layout of the network. Apart from this, the pick-up impedance of the starting device can be adjusted over a wide range.

D.-C. auxiliary contactors are used as actuating devices excited by the main elements. The latter can thus be designed for very quick action and with low expenditure of power. The auxiliary contactors have signals which furnish data on the kind of trouble, on what step has acted and on the trip itself, after every short circuit. Under ordinary operating conditions the d.-c. energy consumption is zero. On the other hand, the connections are so made that no harmful temperature rise of the apparatus can take place even after a long pick-up duration of the starting devices, for example during checking.

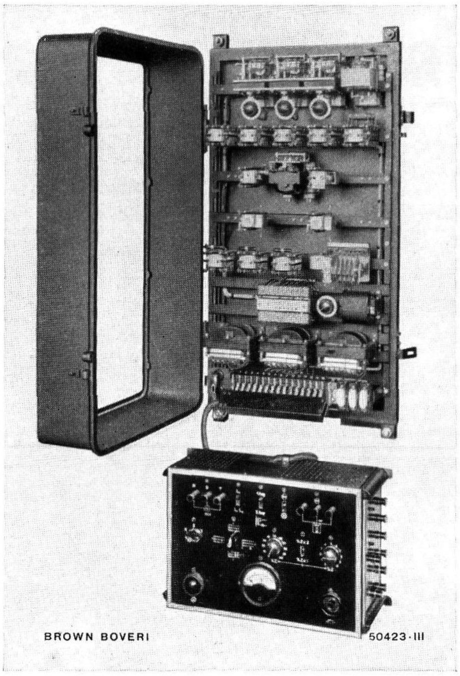

Fig. 9. — High-speed distance-relay protection panel with the testing apparatus connected up.

The relays should trip instantaneously when a fault occurs, but often have to remain idle for months at a time. The testing apparatus is to allow of periodic checking of the state of the relays; it allows of testing them exactly under the conditions met with in practical operation.

The panel is provided with terminals for connecting leads at the front or at the back. The different devices are mounted so as to be easily supervised; they can be swung out and are very accessible along with their connections, both back and front. There is another set of terminals to connect up a *testing apparatus,* Fig. 9, which makes a check of the relay possible when setting the relay to work and, later on, in service. This check is the more valuable as we have here apparatus which, under ordinary conditions, have relatively little occasion to work. By means of the compact apparatus lodged in a box to be carried by hand it is possible to reproduce all important short circuits.

These are the chief characteristics of the rotating-field relay for 5 A rated current:—

Tripping time.

Fundamental time	0·1 and 0·05	s.
Time steps (incl. limit time) adjustable from	0·1 to 5	s.
Pick-up impedance of impedance starting device . . .	1 to 7	Ω/Ph.
Pick-up reactance of distance measuring device minimum . (exceptionally 0·1 Ω/Ph)	0·2	Ω/Ph.

Power consumption.

Current circuit:—		
in normal service	3·5	VA/Ph.
under short circuit	3·5	,,
under earth fault	8	,,
Voltage circuit:—		
in normal service, max. . . .	9	,,
under short circuit max. . . .	25	,,
Direct-current:—		
in normal service	0	Watt
under short circuit	180	,,

The low inherent power consumption of the relay, so advantageous for the transformers is worthy of note.

The high-speed distance-relay protection is operating in many home and foreign plants. Only satisfactory experiences have resulted therefrom. Characteristic of this is a recent report from a high-voltage plant having 70 rotating field distance relays, which remarks on the high selectivity of the protection afforded and mentions specially that the falling out of step of machines, which used to be an inevitable consequence of trouble on the network, had not occurred in a single case since the L3 protection was put in.

(MS 754) *A. Matthey-Doret. (Mo.)*

INDICATING PRIMARY RELAYS AS PROTECTION AGAINST SHORT CIRCUITS AND OVERLOADS.

Decimal index 621.316.925.43

The further development of primary relays resulted in separate designs being brought out for protection against short circuits and protection against overloads. Further, the relays were so designed that they gave a direct indication of the magnitude measured. The built-on ammeter is a new complementary device for primary over-current relays. The operating process of the thermal relay as a protection against the overloading of transformers is examined and test results given.

APART from selective protection devices used for important networks of the high-voltage and very high-voltage range, the simpler primary relays used for power distribution and power consumption systems play an important part, if only on account of the number of these relays installed. Current strength and time lag are the two characteristic operating magnitudes of this class of relay. The service requirements regarding functioning of the apparatus are absolutely different according to whether protection against short circuits or protection against overloads is considered. The short-circuit protection takes no account of the rated strength of the operating currents, but calls for exact collaboration of the relays in the various stations, as regards time lag, in the line sections affected by the short-circuit current. On the other hand, the overload protection takes into account the rated operating currents of the part of the plant being protected and is intended for that part alone. In accordance with this sharp division between the respective requirements made on the relays, we have the well-known overcurrent time relays used for the protection against short circuits and special relays with characteristics which satisfy very closely the requirements of overload protection.

The question of whether primary or secondary relays should be used in simple substations for distribution and in power-consuming plants, has been answered by practical experience which very decidedly favours the use of primary relays. The economical and technical reasons for this are to be sought in the simple mounting of the primary relay directly on the circuit breaker, in the elimination of an auxiliary source of current and of a current transformer and the fact that modern primary relays are as precise in their action as are secondary relays.

When the primary time relay, which is the protective relay against short circuits, is used, the fact of there being no current transformer is often found an obstacle to carrying out measurements of the current on the line. This led to the building in of ammeters inserted directly on the conductor and placed above the relay, a solution which could not give satisfaction because the relatively low short-circuit strength of the ammeter as compared to that of the relay, which can withstand a current of 500 to 1000 times the rated current, meant inserting a weak point in the system and thus formed a danger point for the plant. Further, directly-indicating ammeters are not built for bigger operating currents than about 100 A; therefore, current transformers have to be included.

This measurement problem is as old as the primary relay itself. It found a surprisingly simple solution in the *built-on ammeter* (Fig. 1). The designation of the built-on ammeter in the letters patent as "parasite instrument" is a very apt one, because it has no winding of its own, being excited by the available magnetic field of the relay itself. Thus, it is not affected by the heating action of the short-circuit currents. The exceptionally stout measuring system allows the instrument to stand up, from the mechanical point of view, to all short-circuit stressing. The measurement error is less than 3 % of the end value of the scale. The range of the scale can be, according to requirements, 0 to 1·4 or 0 to 2 times the rated current of the relay and is indicated in factors of the rated current. Further, this instrument can be placed on relays type HB and HK without any alteration being made to the relay and for the entire range of current rating from 1 to 1200 A; there is an adjustment screw which allows of making an exact setting when necessary. The ammeter is placed, according to the position of the relay, so as to give easiest reading. The primary time relays HB and HK which, themselves, fulfil every protective requirement, now take over ammeter duty as well and this at very little extra expense.

The only representative of the primary overload protection relay, namely thermal relay type HT (Fig. 2), met with an exceptionally favourable reception in practice. In plants with widely fluctuating loads such as rolling mills, electric-furnace plants, etc. this apparatus, which is subjected to no wear, has become indispensable. We have already reported on its action, which is that of a thermal image of the cables and machines being protected.[1] This relay is equally advantageous

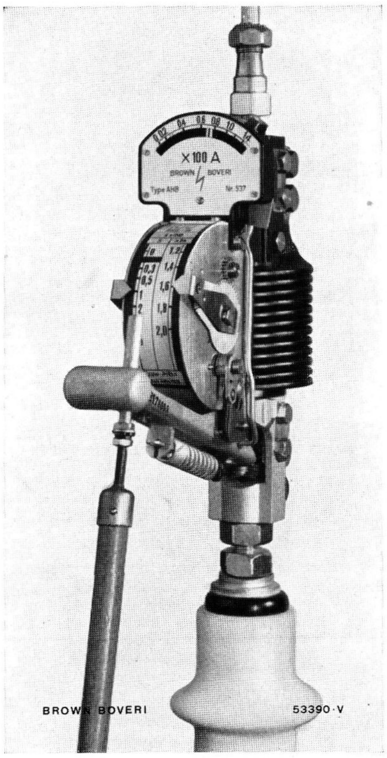

Fig. 1. — Primary time relay Type HB as protection against short circuits equipped with built-on ammeter.

This built-on ammeter has no windings and is absolutely short-circuit proof; it is an accessory device which solves the problem of a power current indicator.

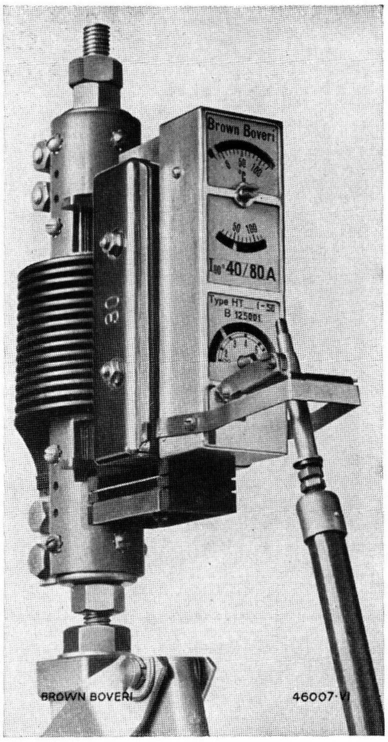

Fig. 2. — Primary thermal relay Type HT, the first primary relay to offer protection against injurious overloads.

The temperature rise attained by the object protected can be read off the relay directly.

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[1] The Brown Boveri Review, December 1937:— "The primary thermal relay type HT."

for the protection of transformers, as will be shown briefly in the following paragraphs.

The first duty of the overload protection is to provide reliable protection against dangerous over-heating liable to damage the machine while, at the same time, allowing the machine to be as fully utilized as possible, whatever the loading characteristics of service happen to be. In transformers, too high temperatures due to overloading shorten the life of the unit. An excessive temperature constantly maintained, damages the insulation slowly and ends in the break-down of the winding through a short circuit between turns. If, now, the life of a transformer operated at a temperature in oil of 80^{0} C is put down as 1, American investigations go to show that it is shortened by a half of the preceding value for every 8^{0} higher temperature. Now transformers are not only irregularly stressed, but are often operated in such a manner that excessive overloads are not noticed. An example of this are distribution transformers in town and country networks; on purely economical grounds, therefore, it is advisable to equip them with a reliable protection against overloading.

A measure for the overload protection is provided by the temperature rise of the transformer copper. It is the duty of the HT relay to follow the temperature-rise curve closely, to indicate the temperature and to trip the breaker when the limit value adjusted to has been exceeded. The adjustment of the relay to the operating current of the transformer is carried out by setting to the ratio $\frac{\text{Transformer rated current}}{\text{Relay rated current}}$. After this simple adjustment (by means of tapered keys), the HT relay indicates 70^{0} temperature rise, that is about the real temperature rise of the transformer winding, this when the transformer has reached a state of ultimate temperature equilibrium under the rated current. This value should be noted in order to allow of judging from the indications of the relay, when service control inspections are made, what the load conditions of the transformer are.

In order that the HT relay should follow correctly the temperature changes of the transformer winding, it must take account of the two essential temperature time constants, namely:— that of the copper as compared to the oil and that of the oil as compared to the surrounding temperature. The relatively short time constant of the winding, as compared to the temperature of the oil, is of decisive importance for the protective action, because in the case of a sudden heavy overload, that is in case of sudden danger, the temperature of the oil does not keep step with that of the copper. The time constant of the winding is taken into account perfectly by the HT relay[1] and this gives certitude that the HT relay will never act tardily in case of danger.

While a part of the time constant of the relay is a faithful image of that of the copper and thus allows the relay to act quickly when necessary, the part which is an image of the time constant of the oil is the measure of the utilization of the admissible overloading capacity. The time constant of the oil is relatively big, it is reproduced in relay HT by choosing heat carriers of a time constant of 45 min, but the time constant thus imparted to the relay is usually not as long as that of the oil. The shorter time constant of the relay is hardly noticeable when the load gradually increases over the danger limit. When the overload is applied quickly or instantaneously, the breaker is tripped somewhat earlier. The actual behaviour of the HT relay was investigated for this case which, as regards overloading capacity, appears unfavourable, by means of thorough tests carried out on a 200-kVA transformer. The temperature of the winding was determined by means of thermo-elements lodged in the highest coil. The curves of Fig. 3 give the tripping times of the thermal relay in function of the overload. The overloads were applied to the transformer after a 10-hour load which in one case amounted to 50 %, in the other to 80 % of the full-rated load.

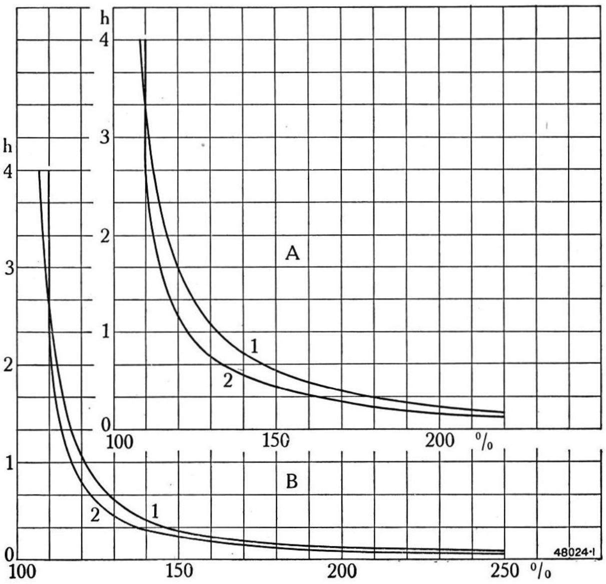

Fig. 3. — Coincidance of the times of the thermal relay with the admissible overloading times of a transformer 200 kVA, 10500/240 V.

Curve 1. Time to attain $\Delta t = 70^{0}$ C in the transformer copper in function of the overload.

Curve 2. Tripping time of the relay with a tripping temperature set to 80^{0} C.

A. Applied just after a 10-h load of 50 %.

B. Applied just after a 10-h load of 80 %.

The curves show that the tripping times of the relay, although shorter than those which the overloading capacity of the transformer would sanction, nevertheless allow of maintaining the overload over a range which is quite sufficient for practical needs. This is shown more clearly in the following table, in which some values taken from the curves are brought out.

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[1] See Bulletin S.E.V., 1938, No. 12: „Die thermische Abbildung elektrischer Maschinen als Grundlage eines Ueberlastschutzrelais."

To conclude, we give some indications for the utilization and setting of the relays, in service. Firstly, the adjustment of the tripping temperature. The HT relay indicates 70° under full-load ultimate constant temperature conditions, therefore, the tripping temperature should not be set lower than 75° C. The exceptional admissible overload of the transformer during 24 hours of 5% corresponds to a setting of about 80°. In general, the setting is made low, in cases in which the transformer is uniformly heavily loaded continuously or during long periods. In the case of load curves which are known in advance and which are characterized by periodic peaks, of short duration and up to peaks of a few hours, it is admissible to set to higher tripping temperatures. In standard HT relays, provided with temperature compensation, the lower surrounding temperature during the winter can be taken into account by increasing the tripping temperature, while remaining within the allowable limits of temperature rise of the transformer. It is, however, always necessary to remember that the room or cooling-water temperature of the transformer is not taken into account by compensated relays. The special design of the HT relay without compensation, takes the surrounding temperature automatically into account, this design, however, can only be used when the relay is always subjected to the same surrounding temperature as transformers with natural air cooling. The question of whether the breaker should trip immediately or if an alarm signal should be given when the HT relay trips, can only be decided when the consequences of a cut-out under overload to the operation of the plant are weighed. This question must be seriously considered when projecting the plant. The constant indication of the temperature rise, given by the HT relay, supplies the operator with information of load conditions at any time. To mark the highest temperature reached, the thermal relays have recently been equipped with a maximum-temperature indicator. As is known, the HT relay has, apart from its time-lag trip, an adjustable instantaneous over-current limit trip. Thus it can take over the duty of cutting out short circuits on condition that no time stepping is required on the system.

Preliminary load	Load consecutive to preliminary load	Relay HT	Transformer
		Tripping time for a temperature setting 80° C	Time to attain Δt = 70° C in copper of winding
%	%	min	min
10 hours continuous 50% load	120	70	100
	140	34	47
	160	22	30
	180	14	20
	200	9·5	13·5
10 hours continuous 80% load	120	48	64
	140	19	24
	160	11·5	14
	180	7·5	10
	200	5	7·5

The two protection relays against short circuits and overloads are the first primary relays to serve as measuring and indicating devices, apart from their excellent qualities of adaptation to the requirements of protection.

(MS 756) *J. Stoecklin. (Mo.)*

THE LATEST DEVELOPMENT OF THE AIR-BLAST HIGH-SPEED CIRCUIT BREAKER.

Decimal index 621.316.57.064.24

After referring to the fundamental advantages of the extinction of the electric arc by means of compressed air, the latest results of our research work are investigated. The operating experiences gained in the last years with the air-blast high-speed circuit breakers having been very satisfactory, it was decided to develop these circuit breakers further to meet with the ever increasing demands of high-tension technic. To this end, extensive research work had to be carried out, as a result of which dual arc extinction for medium voltages and potential-controlled multiple breaks for high service voltages have been found to meet with all the requirements. By the application of these principles of arc extinction, the severest demands of actual service with regard to the stresses due to the natural frequencies of oscillation have been coped with. The design of arcing chambers with potential controlled multiple breaks allows of an accurate pre-determination of the share of the total breaking capacity of the circuit breaker alotted to each break. Therefore, tests carried out with one arcing chamber and a correspondingly reduced breaking capacity permit an accurate control of the performance of the circuit breaker under full breaking conditions. Circuit breakers up to the highest breaking capacities and service voltages up to 500 kV can, therefore, be designed with a wide margin of safety. This design of circuit breakers is particularly suitable where automatic high-speed reclosing features are incorporated and additional parts required for this purpose can easily be fitted to the circuit breakers at a later date.

I. INTRODUCTION.

IN earlier publications[1] the fundamental advantages of the air-blast high-speed circuit breaker as compared to other designs have been dealt with in detail.

It has been specially emphasized that by the application of the air-blast high-speed circuit breaker, breaking times of 0·05 seconds and even less can be attained, a feature of great importance for the reduction of the duration of troubles. Tests carried out on the Sæntis mountain and the Jungfraujoch (Switzerland) have shown that the breaking time is absolutely independent of the ambient temperature as well as of the atmospheric conditions prevailing, so that the ex-

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[1] H. Thommen: "The further development of the air-blast high-speed circuit breaker up to the highest voltages encountered in service and for outdoor erection. Increased protection of systems by short rupturing times and rapid reclosings in cases of short-circuit trouble". Brown Boveri Review 1937, page 55.

H. Thommen: "Reduction in the number of network service break-downs by means of automatic quick-acting reclosing of circuit-breakers, or by using protector tubes". Brown Boveri Review 1940, page 84.

"Der Druckschalter und die Bedeutung seiner kurzen Einschaltzeit für den Netzschutz". Bulletin S. E. V. 1939, page 702.

tinction of the arc by means of compressed air represents the best solution also for outdoor plants. A further advantage of the air-blast high-speed circuit breakers lies in the fact that it can be easily adapted for high-speed reclosing. The metallic vapours arising between the open arcing contacts are almost instantaneously removed by the scavenging effect of the compressed air admitted into the arcing chamber, so that the reclosing takes place with completely cleaned arcing contacts. In addition to this, there is no danger of fire or explosions due to sudden pressure rises beyond control. Air-blast high-speed circuit breakers are now manufactured in large numbers, and the operating experiences gained with them have been very satisfactory. In a few cases troubles of minor importance occurred, but these troubles can be classified as growing pains and were not of a serious nature. It should be noted, however, that the application in practice of the principle of arc extinction came up to our highest expectations. Therefore, it was decided to advance the development of the air-blast high-speed circuit breaker to meet the ever increasing demands of technology. Particularly, there was a demand for circuit breakers for very high breaking currents in excess of 50,000 A r. m. s. and for service voltages up to 500 kV. The purpose of this article is to give a survey of the latest development in the field of the air-blast high-speed circuit breaker.

II. CIRCUIT BREAKERS FOR VERY HIGH BREAKING CURRENTS.

Apart from the breaking current and the r. m. s. value of the recovery voltage occurring at the terminals of the circuit breaker, the rupture of the arc is influenced by the rate of rise of the recovery voltage following immediately upon the extinction of the arc. In the past few years the problem of the oscillation of the recovery voltage has been a subject of researches carried out by Brown Boveri, so that fundamental data are now available.[1]

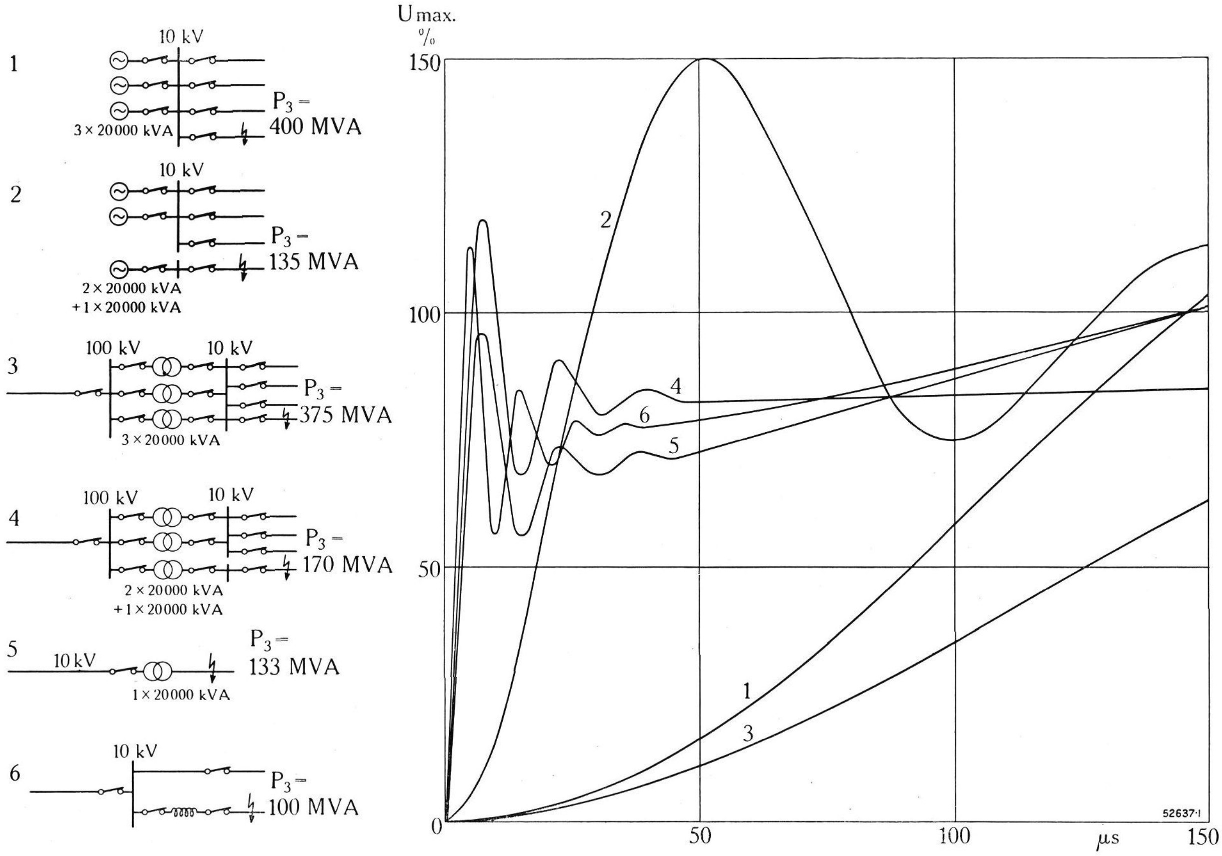

Fig. 1. — Oscillations of the recovery voltage across the terminals of a 10-kV circuit breaker near a fault under different service conditions.

1. Outgoing line from a power station.
2. Subdivision of the service in a power station, whereby only the outgoing line is fed.
3. Outgoing line of transformer station.
4. Subdivision of the service in a transformer station, whereby only one line is fed.
5. Circuit breaker in the feeder of a substation, short circuit on the secondary of a transformer.
6. Outgoing line of a substation, limitation of the short-circuit capacity by means of current-limiting reactors.

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[1] Dr. Wanger and J. K. Brown: "Calculation of the oscillations of the recovery voltage after the rupture of short circuits". Brown Boveri Review 1937, page 283. P. Fourmarier and J. K. Brown: "Determination of the behaviour of the recovery voltage after rupturing short circuits, by means of the high-frequency resonance method". Brown Boveri Review 1937, page 217. Dr. W. Wanger: "Die wiederkehrende Spannung bei Abschaltungen mit Hochspannungsschaltern". Bulletin S. E. V. 1939, page 325.

Fig. 1 shows the oscillation phenomena of the circuit breaker nearest a fault for different conditions of service. In this case a service voltage of 10 kV and an overswinging of the recovery voltage of 50 % has been assumed.

Cases 1 and 3 show the most frequent conditions of service of a substation or power station with several outgoing feeders. The rate of rise of the recovery voltage is much reduced by the influence of the capacities of the different feeders running in parallel.

Case 2 shows a condition whereby one generator feeds into a line. Similar conditions prevail when the energy of a power station is transmitted over a single line. In these cases the short-circuit capacity to be considered is generally moderate, as the stations considered are usually of moderate size, but the stresses due to the rate of rise of recovery voltage are considerably increased as shown by curve 2. A still steeper rise occurs if, as shown in case 4, the service in the substation is subdivided, so that a transformer feeds into one line only, or if, as shown in cases 5 and 6, a substation is serving a single outgoing line, or also where, to limit the short-circuit capacity, current-limiting reactors are provided. In this case, however, it must not be overlooked that, on the natural frequency of oscillation, an oscillation of lower frequency from the system is superimposed, so that the full amplitude of the recovery voltage is not obtained in its first rise.

A steep rise of the recovery voltage after the current passes through zero, allows only a short interval for the deionisation of the arcing path. To avoid oversized dimensions of the circuit breaker to take care of these relatively few cases with stressing due to extremely high natural frequencies of oscillations, the circuit breakers can be provided with a *dual arc extinction*.

A damping resistance in series with a spark gap is inserted in the circuit, which reduces the rate of rise of the recovery voltage across the open main arcing contacts from several thousand volts/μs to a few hundred volts/μs.

The striking of the arc across the spark gap is positively effected by the hot metallic vapours from the main arcing contacts. When breaking only the normal service current, this resistance is not inserted in the circuit, since the ionisation of the spark gap is not sufficient. After breaking the circuit of the main arc, the extinction of the residual arc is also effected by the flow of compressed air. No movable parts are required for the switching in and out of the resistance, and as it is only momentarily inserted in the circuit, only moderate thermal stresses are imposed on the same. Fig. 2 shows the oscillograph when breaking 50,000 A r. m. s. value in the circuit breaker with dual arc extinction. The current flowing through the resistance amounts to only 4 % of the total short-circuit current. Therefore, the small extension of the total arcing time due to the resistance step is practically negligible.

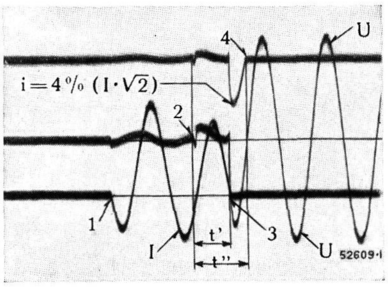

Fig. 2. — Oscillograph of an interruption by a 10-kV circuit breaker with dual arc extinction.

50,000 A are interrupted in 0·04 seconds.

1. Beginning of the short circuit.
2. Beginning of contact separation.
3. Extinction of the main arc.
4. Extinction of the auxiliary arc.

I. Short-circuit current.
U. Recovery voltage.
i. Residual current in the damping resistance.
t'. Current in the resistance step.
t''. Total duration of arc.

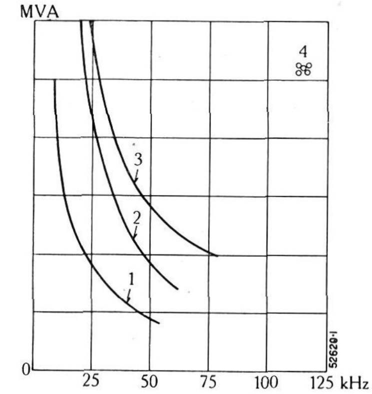

Fig. 3. — Limits of breaking capacity of 10-kV circuit breakers of different design in function of the natural frequency of oscillation.

By the application of dual arc extinction the breaking capacity is increased considerably.

1—3. Breaking capacity without dual arc extinction.
4. With dual arc extinction; positive breakings with the smallest circuit breaker (curve 1).

The advantages of a circuit breaker with dual arc extinction at very high natural frequencies of oscillation can be clearly seen from Fig. 3. The curves 1—3 indicate the limits of the breaking capacity in function of the prevailing natural frequencies of oscillation of circuit breakers of different sizes with single arc extinction. After the smallest of these circuit breakers has heen provided with dual arc extinction, the rupturings indicated by the dots 4 could be coped with without any trouble. The highest natural frequency of oscillation thereby attained amounted to 115,000 cycles, which in the case under consideration corresponds to a mean rate of rise of about 5000 volts/μs. Similar conditions can be reproduced in modern test plants only by means of special connections. These tests show that, contrary to statements in technical literature, it is possible to design air-blast high-speed circuit breakers with nozzle contacts to cope with the severest conditions such as occur in extreme cases at low service voltages. Fig. 4 shows a circuit breaker with dual arc extinction, designed for 20 kV service voltage and a breaking capacity of 1000 MVA. During the tests leading to the development of this design the breaking performance from the smallest to the highest breaking current has been investigated in detail, whereby the performance of the circuit breaker has been found to be satisfactory under all conditions. Even at very small inductive currents the damping resistance acted and was inserted in the circuit, limiting to an admissible value the voltage surges due to switching operations, which usually occur with oil- or air-blast circuit breakers of standard design.

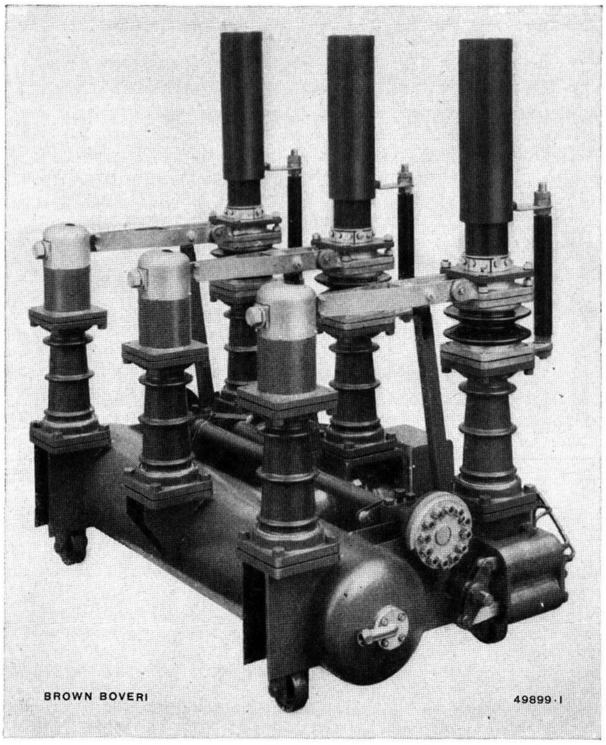

Fig. 4. — **1000-MVA air-blast high-speed circuit breaker with dual arc extinction, service voltage 20 kV.**

The dual arc extinction is very simple and requires only little space.

III. CIRCUIT BREAKERS FOR VERY HIGH SERVICE VOLTAGES.

At very high service voltages the natural frequency of oscillation amounts, even under the most unfavourable conditions, to only a few thousand cycles. This is due to the high inductivities under short-circuit conditions, as well as to the high capacities of the plant. The decreasing natural frequencies of oscillation with increasing service voltages for power plants and substations serving one feeder only are shown in Fig. 5. The curves 1 and 2 are based on calculations for a large number of different conditions of service. It should be noted that the natural frequencies of oscillation, particularly in extended systems, never occur simultaneously with the maximum short-circuit capacity, since the latter generally occurs only when several power stations or substations are working in parallel. In high voltage transmission systems the natural frequency of oscillation actually encountered under short-circuit conditions has been found to be less than 1000 cycles. Nevertheless, we are of the opinion that the circuit breakers designed for very high voltages have also got to perform satisfactorily over a wide range of capacity under the most severe conditions regarding rate of rise of recovery voltage.

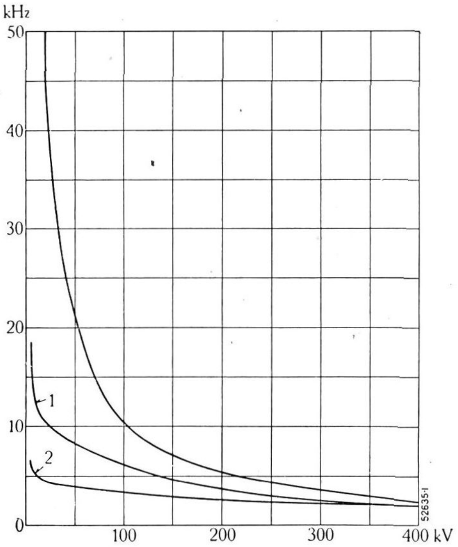

Fig. 5. — **Decrease of the natural frequency of oscillation in power stations with increasing service voltage.**

(Feeders are disregarded.)

Natural frequency of power stations.
1. With turbo generators.
2. With low-speed generators.

To meet these conditions, extensive investigations had been carried out, and it was found that the application of dual arc extinction is not feasible, as the natural frequency of oscillation, as mentioned above, never attains very high values. A further reduction of the rate of rise would call for very large and expensive damping resistances. The tests carried out have clearly shown that the application of *multiple breaks* presents the best means of coping with all conditions of service. It allows of re-establishing the dielectric strength across the path of the electric arc at several places at the same time, so that even at highest service voltages the arc is effectively extinguished.

Particular care has been taken to ensure the equal distribution of the voltage across the different breaks. It is to be remembered that in most cases of troubles in high-tension transmission systems a short-circuit combined with a fault to earth occurs. The conditions then prevailing with circuit breakers having two breaks in series are diagrammatically represented in Fig. 6. As long as the arc is maintained in the circuit breaker, the distribution of the voltage across the two breaks is determined by the characteristics of the electric arc.

With the rise of the recovery voltage the influence of the electric arc on the distribution of the voltage across the breaks is diminished. This is then governed only by the distribution of the charging currents in the mutual capacities C_1 and C_2 and in the capacity to earth C_3. The voltage across the one break increases rapidly with increasing value of the capacity to earth C_3. Curve 1 of Fig. 7 shows the distribution of the voltage across four breaks in series as determined by actual measurements. At an earth fault at one terminal of the circuit breaker the highest voltage across one break attains 71 % of the total, i. e. the distribution of the potential, with respect to the ideal condition, is displaced by 285 %. An improvement of this condition by adding small additional capacities C can be so effective that it causes a distribution of the potential according to curve 2, whereby the displacement amounts to only a few percents.

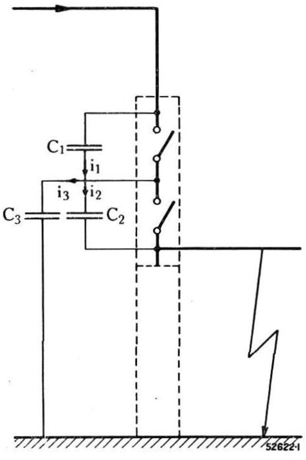

Fig. 6. — Diagrammatic representation of the capacitive currents of circuit breakers having two breaks.

One circuit breaker terminal earthed.

C_1, C_2. Mutual capacities.
C_3. Capacity to earth.
I_1, I_2, I_3. Capacitive currents.

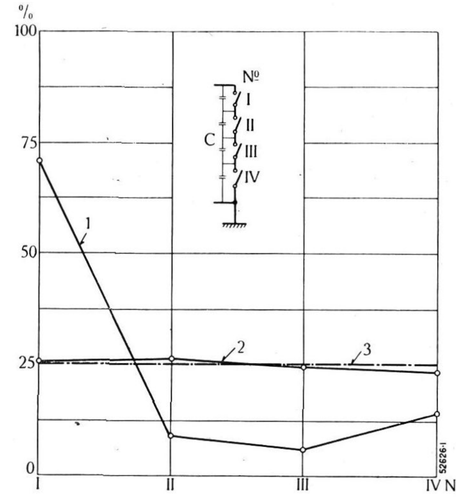

Fig. 7. — Distribution of the potential, measured across four breaks in series.

1. Without potential control.
2. With potential control.

By means of potential control, ideal distribution of the potential (3) is practically attained.

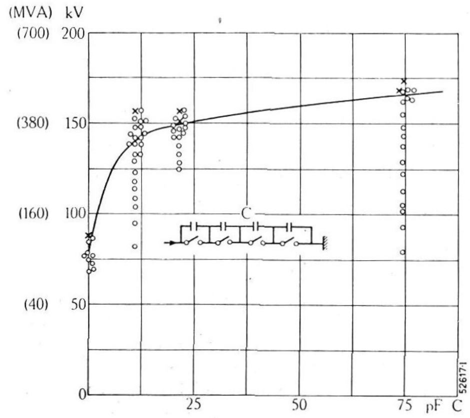

Fig. 8. — Interrupting voltage and capacity in function of the control capacity C with four breaks.

Potential control is a very effective means to increase the breaking capacity.

A large number of tests carried out has shown that an equal distribution of the voltage across the different breaks is of paramount importance. The influence of the additional capacities on the maximum attainable rupturing power with four breaks in series is represented in Fig. 8. It can be seen from this curve that the admissible rupturing capacity can be much increased with increasing values of the condenser capacity, that is to say without causing undue stresses on the individual breaks. To take full advantage of the multiple breaks it has been found necessary to control the voltage across the individual breaks by means of special condensers *(arcing chambers with multiple break and potential control)*. For this purpose only small capacities which are very reliable in service have to be arranged between the different breaks. Since all our air-blast breakers are provided with the disconnecting links, it should be noted that these condensers are subjected to full voltage only during the time the actual break takes place.

For circuit breakers intended for very high service voltages breaking capacities are generally specified which by far exceed the maximum output of the test plants available. For this reason, it has been impossible, up till now, to judge accurately what the performance of a circuit breaker will be under full-rated breaking capacity. The application of arcing chambers with multiple break and potential control allow definite conclusions to be drawn regarding the performance of the circuit breaker under full-load conditions by tests with reduced breaking capacity applied to one break only. This is particularly true if the distribution of the potential is maintained during the opening of the breaker, so that the stresses per break are in a pre-determined and definite relation to the total breaking capacity. This has been definitely established by potential measurements during openings by means of a cathode ray oscillograph. As shown in Fig. 9 it has been connected successively across three, two and one break; the results obtained are indicated in Figs. 9 and 10. The small deviation from the proportional rise of voltage across the break is due to the connections of the cathode ray oscillograph, which cause some shift in the distribution of the potential. Nevertheless, these results indicate positively that the distribution of the potential during the oscillations of the natural frequency of the recovery

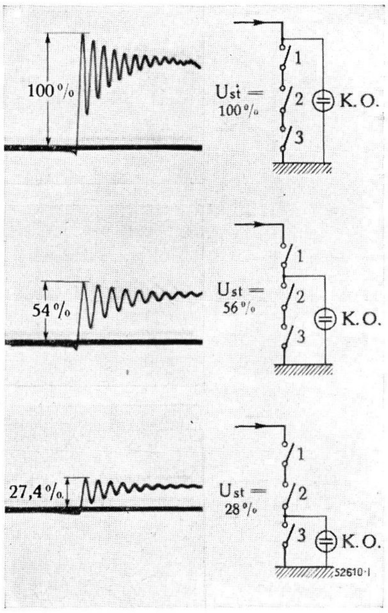

Fig. 9. — Oscillation of the recovery voltage across different breaks.

The oscillographs recorded show the even stresses over all the breaks, also during the opening of the circuit breaker.

K. O. Cathode ray oscillograph.
U_{st}. Distribution of the potential with static potential.

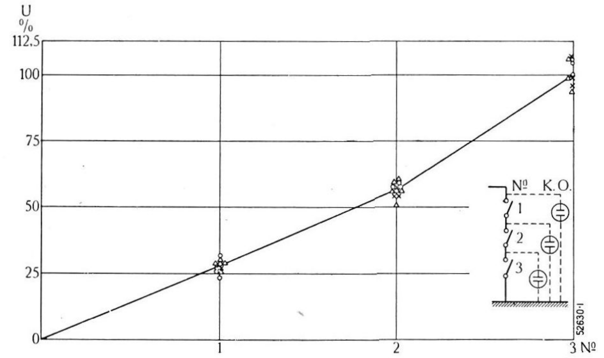

Fig. 10. — Distribution of the potential across 1, 2 and 3 breaks during opening under short-circuit conditions determined by the cathode ray oscillograph.

△. Point of measurement at natural frequency of 750 cycles.
×. Point of measurement at natural frequency of 3300 cycles.
○. Point of measurement at natural frequency of 5500 cycles.

The curve plotted corresponds to the static distribution of the potential with a cathode ray oscillograph (K. O.) connected.

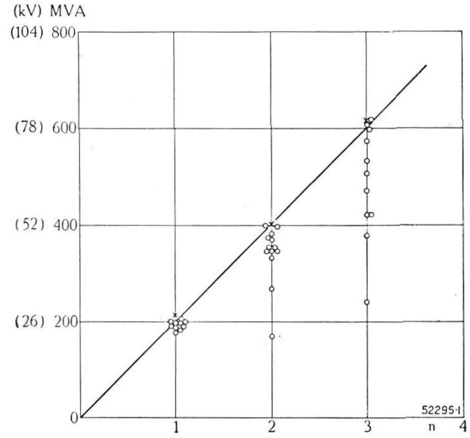

Fig. 11. — Increase in breaking capacity in function of the number of breaks with potential control.

The breaking capacity increases proportionately to the number of breaks.

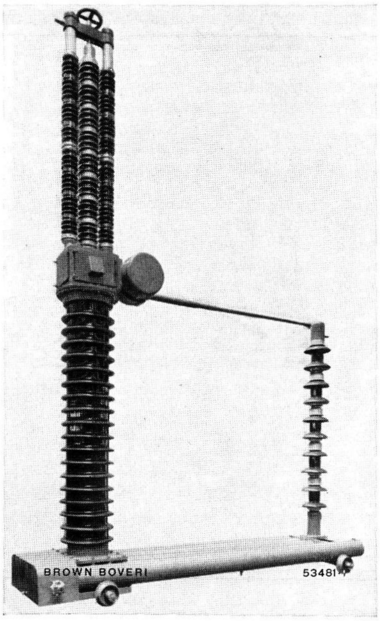

Fig. 12. — One pole of a 220-kV circuit breaker for high-speed reclosing with potential controlled multiple break.

Breaking capacity 2500 MVA.

For the service, it is very important that the revision of the contacts should be effected in a few minutes.

voltage immediately after the break is effected, corresponds to the stationary distribution of the potential. A further proof of the correctness of the contention that the potential control of the arcing chambers allows the testing of the guaranteed breaking capacity is shown in Fig. 11, which represents the proportional increase of the maximum admissible breaking capacity and interrupting voltage in function of the number of breaks applied. From the tests carried out it is definitely established that the performance of the circuit breaker having n breaks in series at a breaking capacity of P MVA can be accurately judged by tests carried out with one break only and a breaking capacity of $\frac{P}{n}$ MVA. This allows a reliable design of high voltage circuit breakers up to 500 kV inspite of the fact that at least at present no test plants for these conditions are available.

Fig. 12 shows one pole of a 220-kV circuit breaker having eight breaks. The control of the individual breaks is effected by compressed air which at the same time serves to extinguish the arc when the contacts are opened. Tests carried out have clearly shown that the opening of all the contacts occurs simultaneously. On account of the small contact travel of the arcing contacts, no disadvantages are to be expected in spite of the short breaking times. The high dielectric strength across the breaks immediately after the arc is extinguished, is absolutely necessary when long transmission lines are to be disconnected, as otherwise restriking of the arc and voltage surges would occur. The revision of the individual contact elements can be effected in a few minutes by simply loosening the spindle of a press clamp provided for this purpose.

For important transmission lines high-speed reclosing is very important. Depending on the conditions of service, the arcing contacts remain open during 0·25 to about one second. It is very desirable to have the circuit breakers equipped with high-speed reclosing devices, and therefore the latest design of circuit breakers has been laid out to allow the addition of the elements required at a later date.

(MS 755) *H. Thommen. (Wi.)*

A SURVEY OF THE PRESENT-DAY IMPORTANCE OF EXTINGUISHING COILS (ARC-SUPPRESSION COILS) AS A PROTECTION AGAINST EARTH FAULTS.

Decimal index 621.316.935

A survey is made of the actual position of extinguishing coils as regards design, construction and operation.

Coil load and duration of load depend on network conditions and, therefore, have never been standardized up till to-day. The output of coils built so far by us is between 3 and 27000 kVA.

Dissonance tuning serves to reduce the asymmetrical voltage on the neutral point when the system is sound. In some countries, attempts are made to keep the asymmetrical voltage small by increasing the watt component and to tune the coils to resonance. Tuning to resonance gives the most advantageous conditions for extinguishing the earth-fault arc.

The question of regulating the coils while under voltage and current has been attracting increasing attention of late. Regulation by tap switch, however, has disadvantages and, for this reason, the coils built by us with continuous regulation (no steps) over a wide range appear to be the desired solution. Further, the latter coils are especially suitable for automatic regulation.

25 YEARS have passed since extinguishing coils were introduced with the purpose of compensating the current flowing to earth when an earth fault occurs. Beginning with overhead networks of low and medium voltage, these coils — thanks to the excellent results recorded in practice — soon found an application on extensive networks of the higher voltage range. In recent years, they have been used as a protective measure on networks of the very highest voltages. In the case of cable systems, as well, the inductive earthing of the neutral point of the network has gradually become common practice.

The experience gained in the course of several years has allowed of laying down a number of guiding rules for the construction and operation of earthing coils and these characterize the present stage of development of earth-fault protection. In the following paragraphs the most important characteristics of extinguishing coils are enumerated and elucidated.

I. RATING OF THE EXTINGUISHING COIL.

This is determined by the magnitude of the earth-fault current which is to be compensated and also by the network voltage. As, however, the earth-fault current increases proportionally to the network voltage, the output of the coil is, finally, a quadratic function of the voltage. Thus, very big outputs were reached for high-voltage transmission systems, which had to be split up between several coils. The biggest coil rating is limited by the loading gauge of the railway, assuming conveyance to site of the coil fully mounted. Further, in many cases, the output of the transformers on site dictates the limit of the rating of the coil which can be placed there. Finally, in the case of very extensive high-voltage transmission systems, attention must be given to the problem of the value which the voltage against earth may reach; if the concentration of the extinguishing coils in one place is too great, it may cause big rises in voltage on the remotest points of the transmission system.

In the case of a 220-kV power transmission overhead line, we built coils of an output per unit of 27,240 kVA, while for 150 kV the biggest output per coil was 12,000 kVA. In cable systems, although the transmission distances are usually shorter, the coils are often of big output. Thus, for a 150-kV cable plant, 18,000 kVA coils were delivered. The curve of Fig. 1 illustrates the maximum output of extinguishing coils built by us in function of the line voltage. This curve is valid for overhead systems. Fig. 2 shows an extinguishing coil of an output of 23,300 kVA for a line voltage of 210 kV.

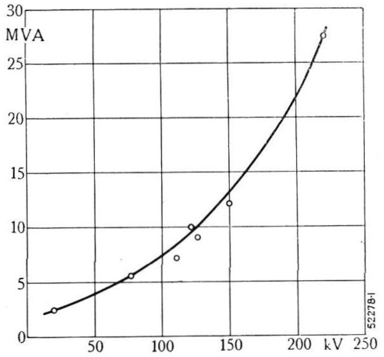

Fig. 1. — Maximum rating of extinguishing coils delivered by Brown Boveri in function of the line voltage of the network.

II. THE RATING OF THE EXTINGUISHING COIL.

This depends, generally, on the time required to carry out the necessary change-over operations on the system, when a permanent short circuit is the cause of the fault. Although the time in question may obviously vary very considerably, according to the organization of service and layout of the network, it has been found possible to arrive at a certain standard time during which the coil is assumed to be working. The great majority of coils are designed for a 2-hours' rating. The heat capacity of the extinguishing coil is certainly big enough to allow of a two-hours' rating without introducing any special cooling measures. A tank of the simplest design with plain sides is sufficient.

Apart from coils rated for two hours, there is a design for continuous rating. As a real continuous operation of the coil is certainly never intended, this design carries the designation: 24-hours' rating. The cooling surface is increased externally by the addition of radiators, but as compared to the coil for a two-hours' rating, no alteration is made to the active part.

III. THE TUNING OF THE EXTINGUISHING COIL.

Apart from adjustment to resonance conditions, that to dissonance conditions has also been found useful. The object of this latter adjustment is to limit the displacement of the voltage of the network against earth, which is created as soon as the capacity to earth of the three phases differs. It is true that the efficacity to extinguish the arc at the earth fault is reduced as a result of the extinguishing coil being no longer tuned for resonance; however, it still suffices when a certain range of dissonance is not exceeded (max. abt. 30 %). However, transposition of the conductors has become customary on lines of the higher voltage range, to compensate for capacitive asymmetry, so that it is advantageous to tune the coil for resonance conditions.

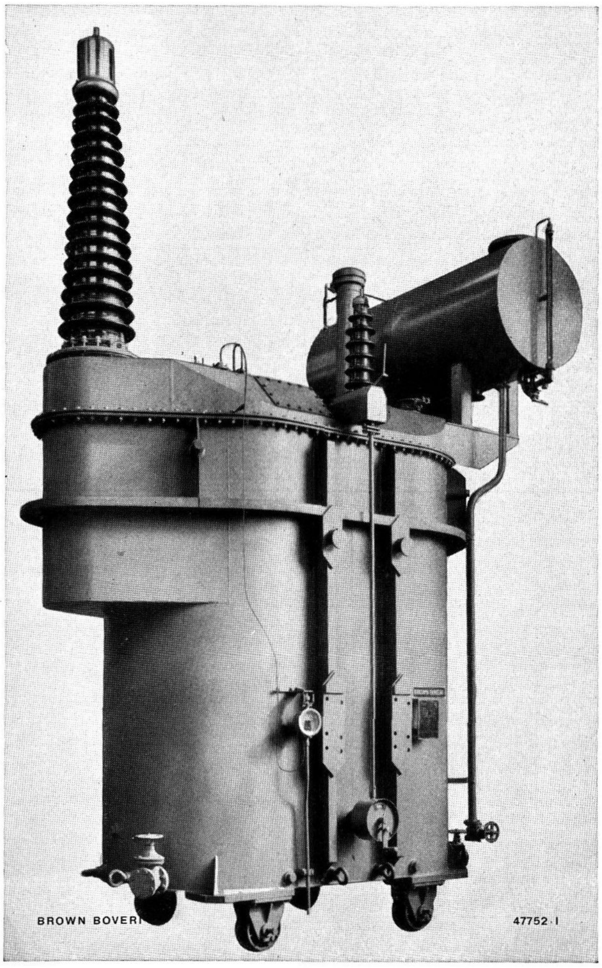

Fig. 2. — 23,300-kVA extinguishing coil for a 210-kV network. Design with tap-changing switch and with secondary winding for 4000 kW.

Instead of an adjustment of the extinguishing coil for dissonance conditions, the watt component of the earth-fault can be increased in order to limit the displacement of the neutral point. The following solution is one which gives satisfaction in every respect:— the extinguishing coil supplies a resistance through a secondary winding which is connected up under ordinary conditions but cut out immediately when an earth fault occurs. The coil is adjusted to resonance so that this connection combines the advantages of resonance and dissonance tuning in so far that in asymmetrical networks the extinguishing of the earth fault arc is not impaired by the limitation of the neutral-point displacement.

The above-mentioned increase in the watt component of the earth-fault current can be utilized to cut out permanent earth faults selectively by means of earth-fault relays in wattmetric connection. To this end, the resistance is only cut out momentarily and the earth-fault arc given an opportunity to go out. After the resistance has been connected again, the earth-fault relays, which operate with a short time lag, have as duty to determine which is the defective line section and to cut it out from the network. The connection for the automatic cutting out and reconnecting of the neutral-point resistance is shown in Fig. 3.

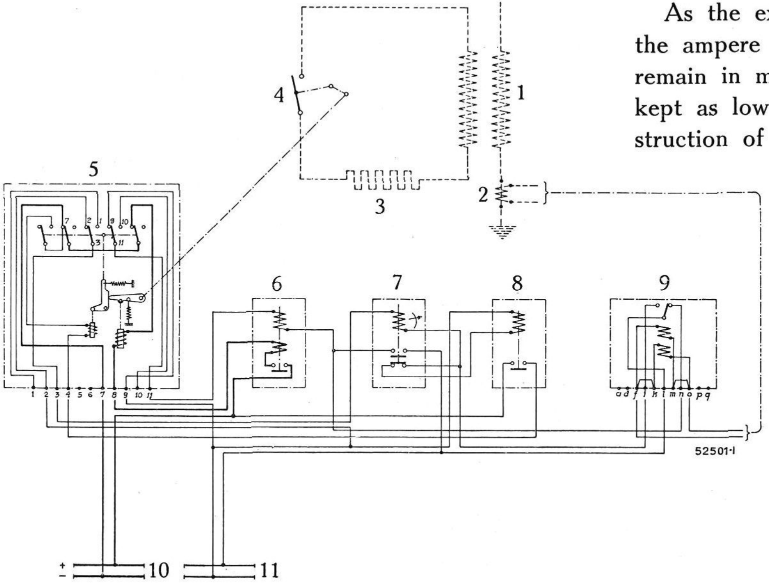

Fig. 3. — Connection for the automatic cutting out and reconnecting of the neutral-point resistance.

1. Extinguishing coil.
2. Current transformer.
3. Resistance.
4. Switch.
5. Drive.
6. Intermediate relay.
7. Time relay for reconnecting.
8. Cutting out relay.
9. Earth-fault relay.
10, 11. Auxiliary sources.

IV. THE REGULATION OF THE EXTINGUISHING COIL.

In order to adjust the current of the extinguishing coil to the variations of the network capacity to earth, which occur in service, the coil is provided with taps. Tap changing is usually carried out when the transformer is not under current or voltage, by means of a tap-changing switch. It is only recently that coils with taps, which could be changed under load, have been meeting with considerable attention. This became feasible after the development of the new on-load tap-changing switches used on regulating transformers, which are especially suitable for regulation in big voltage steps. The regulation of extinguishing coils differs from that of regulation transformers by having bigger steps and especially by covering a wider range of regulation. In Fig. 4 the regulation range which the tap-changing switch has got to encompass is plotted as a function of the current range. Thus, for example, the regulation range has to be 100 % of the voltage across the coil (phase voltage of the network) in order to attain a regulation of the coil current in the ratio of 1 to 4, which is quite normal. In a regulating transformer, on the other hand, with taps of 1·5 % and with 30 taps, this regulating range extends to 45% only.

As the excitation ampere turns on the winding and the ampere turns consumed by the air gap have to remain in mutual equilibrium, the number of taps is kept as low as possible in order to simplify the construction of the coil. But, even then, it is often difficult to adapt the numbers of turns to the desired current stepping. In this respect, Brown Boveri possesses a number of connections which have given good results in practice and have always worked perfectly.

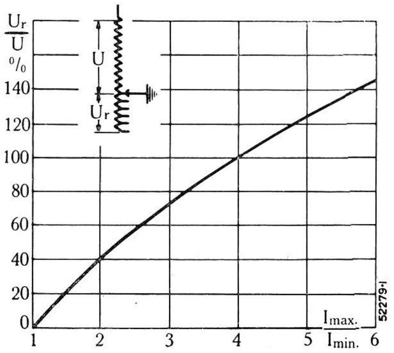

Fig. 4. — Regulating range of extinguishing coils as a function of the current range.

Fig. 5 is an example of an extinguishing coil with on-load regulation. This is a 12,000-kVA coil to protect a 150-kV line. The on-load tap-changing switch is seen in the foreground in the illustration, being worked through a spring (power storage) drive. The whole equipment it also suitable for manual control and also for push-button control.

If now, despite the satisfactory solution available of the problem of regulation under load, an entirely new design has been brought out, this has been done after due consideration of the following points.

The extinguishing coil with a fixed air gap and taps on the winding works with a variable induction. According to whether the iron core is more or less saturated, the current curve varies. The curve 1 (Fig. 6) is valid for operation with the full number of turns and with

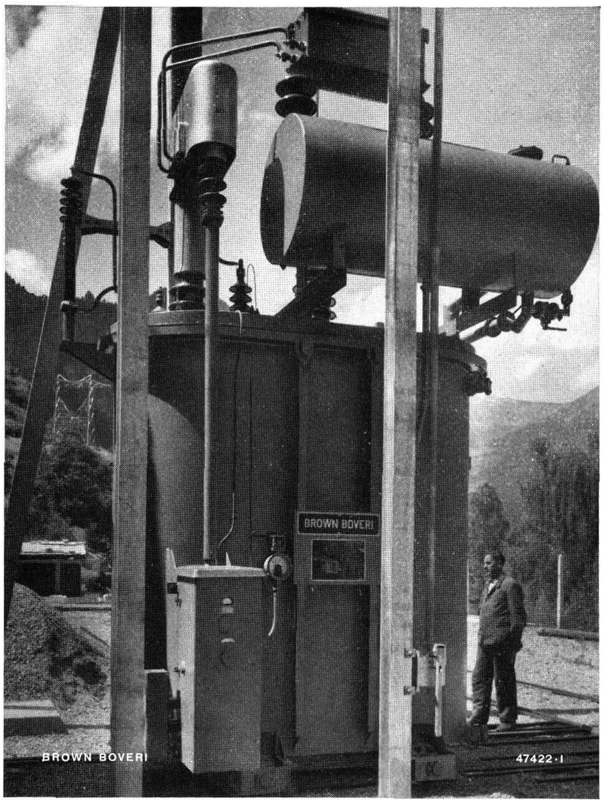

Fig. 5. — 12,000-kVA extinguishing coil for a 150-kV network.
The design with on-load tap-changing switch with spring drive allows of adjustment being made without preliminary cutting out of the coil from the network.

a minimum of induction; the curve 2 is valid for operation with the smallest number of turns and the highest induction and shows clearly the effect of saturation by a deviation from the straight line. Although the saturation is far less obvious than is the case in the magnetization curve of a transformer, because of the influence of the air gap in the extinguishing coil, the proportionality between voltage and current is nevertheless lost under voltage fluctuations. Thus, under a voltage of 110 % the coil current already reaches 120 %. This necessitates under certain circumstances a correction of the adjustment according to the network voltage, which can only be carried out easily on a coil with *on-load regulation* by tap-changing switch.

On the other hand, the measurement of the neutral-point voltage through a secondary winding, wound on to the core of the coil, is not so simple if a constant secondary voltage is called for with all the different taps. As the number of turns of the secondary winding is too small to allow of adding taps to it, it becomes necessary to add an intermediate transformation. For a simple measurement of voltage, the connection necessary for this is complicated (Fig. 7). This also applies to the coil with secondary winding to supply an ohmic resistance with the object of increasing the watt component of the earth-fault current. In this case, the secondary winding must be built with taps and, in both cases, it is recommendable to couple the tap-changing switches on the primary and secondary sides in order to prevent mistakes.

These complications are eliminated in the new design because it works to a constant number of turns and, therefore, with constant induction.

V. THE EXTINGUISHING COIL WITH CONTINUOUS (SMOOTH) REGULATION.

The extinguishing coil which can be regulated continuously is a recent development. It has a winding without taps, but has an air gap which can be regulated. Therefore, as said in the preceding chapter, there is no difficulty in placing a secondary winding for constant voltages on its core, either voltage measuring or power producing windings.

Further, the coil has the advantage of simple arrangement of the winding. Every tap forms a point of reflection for incoming voltage surges as there is here a conjunction of windings of various capacities. In this respect, a winding without any taps can really be considered as an ideal solution.

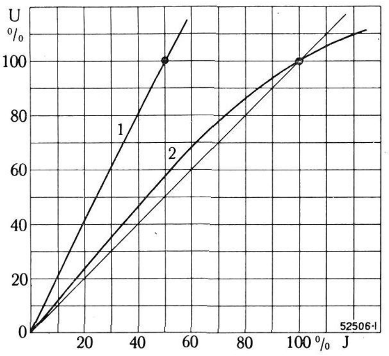

Fig. 6. — Current curves of an extinguishing coil for different numbers of turns connected.

1. With all the turns connected (J minimum).
2. With the minimum of turns connected (J maximum).

The curve 2 deviates from the straight line because the induction is greater (saturation).

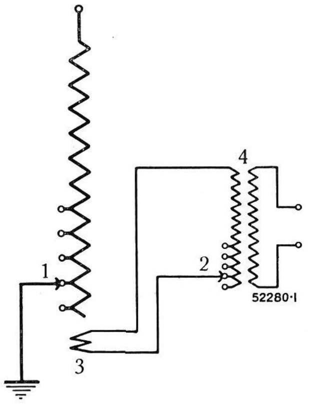

Fig. 7. — Connection for measuring the voltage across an extinguishing coil with taps.

1–2. Tap-changing switch.
3. Auxiliary winding on the core of the coil.
4. Auxiliary transformer with secondary winding for 110 V.

In order to avoid mistakes, the tap-changing switches should be mechanically coupled to each other.

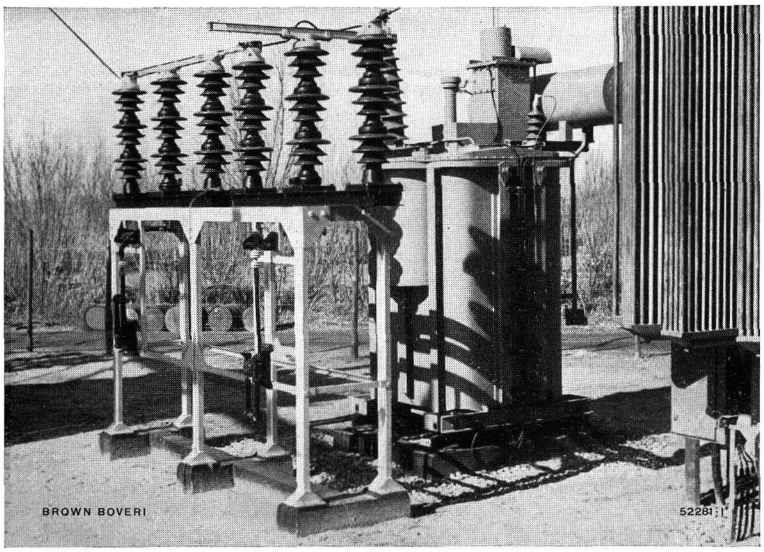

Fig. 8. — 5500-kVA extinguishing coil with continuous regulation to protect a 100-kV network.

This design allows of very precise adjustment during service without cutting out the extinguishing coil from the network.

The regulation of the air gap can, of course, be carried out under load as well, without preliminary cutting out from the system. Further, the adjustment can be made exactly in accordance with the earth current of the network because regulation is smooth and continuous (no steps). Even small deviations, such as are demanded by voltage fluctuations on the network, can be compensated.

The new coils are suitable for regulation over wide ranges. This opens up, for the future, the possibility of dividing up the regulation in one spot into one or several units, while placing coils without regulation at the other points of the network. This will simplify considerably the supervision of the earth-fault protection and when it will become possible to make a regulation of the kind entirely automatic, this problem which up till now — and especially by service men — has been estimated as the weak side of earth-fault protection will be considered as having reached a perfect solution.

Some of the coils with continuous regulation have been put into practical service. Fig. 8 shows one of them in a 100-kV plant.

(MS 757) *A. v. Gastel. (Mo.)*

THE AUTOMATIC REGULATION OF EARTH-FAULT EXTINGUISHING COILS.

Decimal index 621.316.935-52

On high-voltage networks with many branch lines, it is more advantageous to have a small number of extinguishing coils than to have numerous ones distributed on the branches of the network. One of these coils, however, must be built to allow of regulation over a wide range. Brown Boveri recently put on the market an automatic regulating device which has now been exhaustively tested. This device tunes the coil correctly and automatically according to the momentary capacity of the network to be protected.

THE extinguishing coil has proved to be an exceptionally effective device for the protection of high-voltage networks against the effects of transitory earth faults. Thus, for example, when a flash-over occurs on a line insulator, the coil reduces the arc current considerably and, after the passage of the earth-fault current, through zero, it retards the rise of the recovery voltage. In other words, the extinguishing coil renders the earth-fault arcs harmless by facilitating and accelerating its extinction.

However, this duty can only be fulfilled properly when the extinction coil is tuned, that is to say when its inductance is adjusted to the capacity of the network. The most efficacious action of the coil is then reached, in principle, when the current circuit formed of the inductance of the coil and the capacity to earth of the three conductors forming the line is in a state of resonance at the operating frequency of the network.

It has, however, been known for a long time[1] that the unavoidable inequality of these three capacities gives rise to a voltage between the neutral point of the network and the earth, namely the neutral point voltage or asymmetrical voltage. This voltage is the higher the greater the precision with which the extinguishing coil is tuned to resonance. For this reason a compromise is consented to and tuning of the coil is not carried out to absolute resonance but to a certain "dissonance".

The above general considerations will suffice to show the importance of the problem relative to extinguishing-coil tuning and the following paragraphs are chiefly devoted to the problem in question.

The simplest solution, the one which first suggests itself, is the equipment of every branch of the network with its own extinguishing coil, because each of the

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[1] Brown Boveri patents of the year 1918.

branches has an exactly defined capacity to earth. Therefore, if abstraction be made of small, transitory changes in capacity which can be safely disregarded, as for example those which are due to variations of temperature or are caused by the growth of trees in the vicinity of the lines, there is nothing to prevent placing an extinguishing coil on every branch and tuning it permanently to the conditions on that branch; it is then switched in or cut out along with the branch in question. The disadvantage of this solution, however, is the number of extinguishing coils to be distributed throughout the network, which becomes considerable as soon as we have to deal with numerous branch lines. To this must be added an equal number of transformers the neutral points of which have to be brought out. Therefore, both on economical and operating grounds, preference is generally given to centralized earth-fault compensation by means of a single extinguishing coil for the whole network or a small number of such coils. One of the latter must then, necessarily, be built so as to permit of regulation over a wide range, in order that all the operating conditions encountered on the network may be taken into account.

The construction of extinguishing coils which allow of regulation is, in itself, no easy problem to solve because operating voltages are always increasing and the electrical outputs to be dealt with getting bigger. A great number of extinguishing coils permitting of regulation when under no voltage, that is when cut out, by means of a tap-changing switch were put on the market, but we were the first firm to meet the requirement that it should be possible to regulate the extinguishing coil under voltage. The first coils of this type built were equipped with an on-load tap-changing switch such as is in general use on transformers for voltage regulation. A far more pleasing solution is that applied to-day consisting in varying the air gap of the coil by displacing the iron core, by means of a threaded spindle driven by a motor. This solution really does allow of continuous (smooth) regulation over a wide range.

Despite the high degree of perfection which has been attained in the design of these coils, there is still one technical weakness to be overcome, namely to know by what measures the extinguishing coil is to be regulated so that a suitable tuning between the inductance of the coil and the momentary capacity of the system is reached in every case occurring in service. We will show, here, how our firm has solved the problem. It is not only possible, to-day, to place at the disposal of the operating engineer, at every moment, the data he needs to tune the coil, but means have been evolved to equip the latter for full automatic regulation. The regulating devices necessary for this only operate as long as the network is perfectly insulated but they are interlocked as soon as an earth fault develops on one of the phases; the coil being constantly tuned to the momentary capacity of the network, it is unnecessary to continue regulation when it is actually in operation.

A network with sound insulation is shown in Fig. 1. The three distributed line capacities to earth are assumed as concentrated capacities C_1, C_2, C_3. All the parts defined in thin lines on Fig. 1 belong to the automatic regulating device the working process of which can be explained in the following manner:—

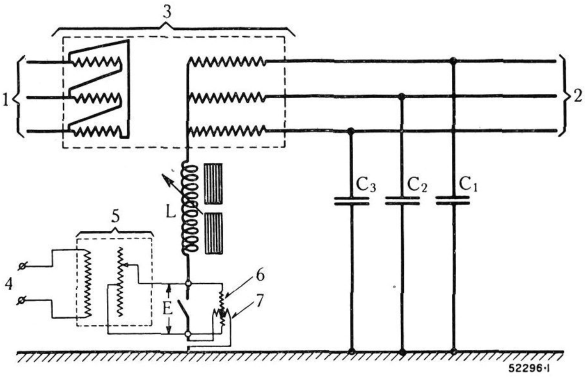

Fig. 1. — Fundamental diagram of connections for the automatic control of an extinguishing coil on a sound network.

1. Primary network.
2. Secondary network.
3. Transformer.
4. Auxiliary network.
5. Modulation transformer.
6. Voltage coil of the regulator.
7. Current coil of the regulator.

L. Inductance of the extinguishing coil.

C_1, C_2, C_3. Capacities against earth of the three conductors forming the line.

A voltage E is applied between extinguishing coil and earth which is supplied from an auxiliary network 4 the frequency of which is, in principle, in phase coincidence with that of the network to be protected. This voltage is supplied through a single-phase auxiliary transformer the ratio of which can be adjusted and which is termed the modulation transformer. The regulating device proper is designed as a Ferraris rotating system with two windings. The voltage winding 6 is connected directly to the voltage E and the current of the extinction coil passes through the current winding 7 through the intermediary of a current transformer not visible in the illustration. This regulator as is usual in Ferraris devices measures the wattless output delivered from the auxiliary network 4, that is to say the product $E.\ I.\ \sin \varphi$ (φ being the phase angle between voltage E and current I). The regulating device has two contacts which put the motor which adjusts the extinguishing coil under voltage.

The voltage E supplies a circuit which is formed of the inductance of the coil L and the capacity $C_1 + C_2 + C_3$ in series with it. The current I which flows in this circuit is in phase with voltage E if the circuit is in a state of resonance ($E \times I \times \sin \varphi = 0$). The current lags on voltage E if the network is under-compensated and leads on it when it is over-compensated. This will make it clear why the regulating device always tunes the network to a state of resonance.

Further, there is no difficulty in tuning the network to a state of "dissonance". In order to attain this object, an additional voltage is imparted to the regulator so that it maintains the product $EI \cdot \sin\varphi$ at a constant value which differs from zero. Another solution consists in introducing an additional phase displacement between E and I δ which is chosen arbitrarily so that the regulator now regulates to a zero value of the product $E \times I \times \sin(\varphi + \delta)$ and not to the zero value of $E \times I \times \sin\varphi$.

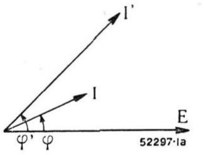

Fig. 2. — Vectorial diagram of the voltages and currents.

E. Measurement voltage.
I. Measurement current.
I'. Asymmetrical current.
φ. Phase angle between I and E.
φ'. Phase angle between I' and E.

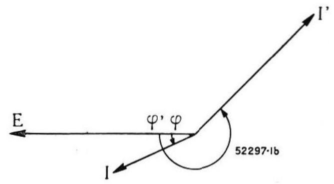

Fig. 2a. — Vectorial diagram of the voltages and currents after a half modulation cycle.

E. Measurement voltage.
I. Measurement current.
I'. Asymmetrical current.
φ. Phase angle between I and E.
φ'. Phase angle between I' and E.

From the above explanations, it will be clear that it suffices that the auxiliary network should have a frequency which is not absolutely the same as that of the network to be protected.

There still remains an important point to be discussed, namely how to overcome the difficulties caused to the regulation by the asymmetry voltage E' of the network, mentioned at the beginning of the article. This voltage produces a current I' in the circuit formed of the coil inductance L and the sum of the capacities $C_1 + C_2 + C_3$ and this current is added to the current I already mentioned. Thus, the current winding of the regulating device is not only subjected to current I alone but carries the resultant current of I and of I'. Thus, the torque exercised on the regulator corresponds not only to $E I \times \sin\varphi$ but to the sum of $E I \times \sin\varphi + EI' \sin\varphi'$, where φ' is the angle formed by the current I' and the voltage E (Fig. 2). Therefore, the working process of the regulator is completely falsified if the following preventative measures are not adopted. By means of the single-phase transformer with variable transformation ratio (5 in Fig. 1), the voltage E can be "modulated", that is to say its magnitude can be constantly varied while maintaining its phase position unchanged [1]. This modulation is carried out by making the voltage E, during equal lengths of time, positive and negative and by making the frequency of modulation small as compared to that of the network (4 cycles, for example, for a 50-cycle network). This alters the vectorial diagram of Fig. 2 and, after half a cycle of modulation, it takes the form shown in Fig. 2a in which E and I are in opposite directions as compared to Fig. 2, I' not having been modified. It will be seen that the product $EI \sin\varphi$ has the same sign in Fig. 2 and 2a while the product $EI' \sin\varphi'$ which is positive in Fig. 2 becomes negative in Fig. 2a; it fluctuates with the frequency of modulation around zero as medium position. If the inertia of the regulating device suffices, it will not react to the torques produced by $EI' \sin\varphi'$ but only to those of $EI \sin\varphi$. Thus, the proper working process of the regulating device is made independent of the magnitude of the asymmetry voltage of the network, at all times.

The apparatus for automatic regulation is characterized by great simplicity. It is nearly at earth potential and can be switched in and out without interrupting the circuit of the extinguishing coil. Further, when the network is protected by several extinguishing coils with automatic regulation, it is easy to arrange that the regulators never act against each other but work in collaboration for the entire network in such a manner that the greatest compensating effect possible is attained for the whole network.

To conclude, we would refer to tests carried out with an extinguishing coil equipped for automatic regulation, of 12,000 kVA and placed on a network of 150 kV rated voltage. This coil was delivered about three years ago and equipped with an on-load tap switch giving about 4 $^0/_0$ per tap. With a total extent of network of 160 km, a part of the network 8 km long could be connected up or cut out arbitrarily during the tests which corresponded to changing the total length of the network by 5 $^0/_0$.

At each switching operation, the regulating device responded correctly and displaced the tap switch of the extinguishing coil by one step. It is interesting to note that the auxiliary voltage inserted between earth and extinguishing coil only amounted to 62 V that is to only 7/10,000 of the rated voltage of the coil which is 86,600 V.

(MS 758) *Dr. P. Waldvogel. (Mo.)*

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[1] A simple kind of modulation transformer is formed, for example, by a single-phase induction regulation, the rotor of which is constantly and slowly revolved.

METHODS OF REDUCING THE STRESS IN THE INSULATION OF TRANSFORMER NEUTRAL POINTS AND OF EXTINGUISHING COILS CONNECTED THERETO.

Decimal index 621.316.91 : 621.314.2

Simultaneous high voltage surges in two or more line conductors cause oscillations to be set up in transformers during which the potential of the neutral point may rise to twice the voltage of the connected system, so that the insulation of both the transformer and of the extinguishing coil connected thereto is highly stressed. In the following article means are described whereby these high stresses may be reduced considerably.

I. INTRODUCTION.

The stress in the insulation at the neutral point of the transformer and of the apparatus connected thereto, due to the power frequency voltage, is only $\frac{1}{\sqrt{3}}$ times that in apparatus connected to the line conductors. During momentary surges, the stress at the neutral point may, however, attain values considerably higher than in the line conductors, especially when it is caused by multi-phase surges in the transmission lines. With a view to rational utilization of material, it is evidently of interest to search for means to reduce these most unfavourable over-voltage stresses which are due to natural oscillations inside the transformer windings.

The importance of this problem increases, of course, with the voltage of the system, and the connections described are accordingly particularly interesting where power is transmitted at extra high voltages over very great distances. The use of such measures enables then not only the design of the extinction coils to be considerably simplified and cheapened, but also the transformers to be executed with graded insulation, such as is otherwise permissible only in a system with an earthed neutral; this without sacrificing any advantages of the protection provided by the extinction coil.

II. CAUSE AND NATURE OF NEUTRAL POINT OSCILLATIONS.

Let us consider a transformer star-connected on the high voltage side and provided with an extinguishing coil connected to the neutral point. On the simultaneous occurrence of steep fronted surges in all three phase windings[1] voltages are set up in the windings the initial distribution of which is determined by the capacities between coils and between earth and the winding, exhibiting in all three phases a similar falling-off from the input terminal to the neutral point, according to a hyperbolic law. On the other hand, if the tail of the wave is of long duration, the entire winding attains a so-called steady condition of approximately constant potential, because the impedance of the extinguishing coil is considerably greater than the zero sequence impedance of the three parallel connected windings of the transformer. Transient oscillations are then set up, the amplitude of which at the star point is given by the difference between the initial and final distributions.

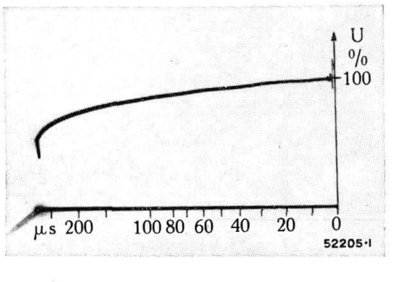

Fig. 1. — Behaviour of the voltage at the terminals of a three-phase transformer with insulated neutral, when subjected to a three-phase surge.

This cathode-ray oscillograph gives the voltage scale for judging the Figs. 2, 3, 6 and 8.

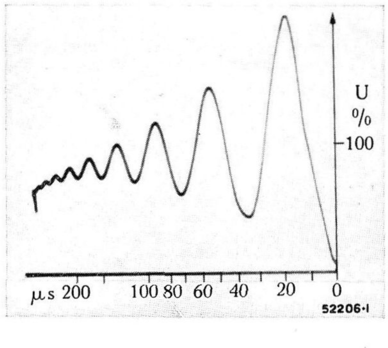

Fig. 2. — Behaviour of the voltage at the neutral point of a transformer stressed as in Fig. 1; secondary winding short-circuited (leakage field oscillations).

The surges coming from the line cause natural oscillations to be set up in the transformer, resulting in voltage rises at the neutral point, which may attain twice the magnitude of the over-voltage at the transformer terminals which causes them.

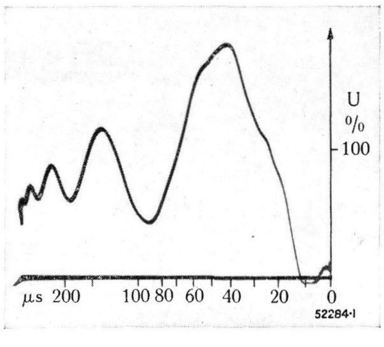

Fig. 3. — Behaviour of the voltage at the neutral point of a transformer stressed as in Fig. 1, secondary winding open circuited (main field oscillations).

Compared with the test Fig. 2, the self-induction participating in the phenomena is here greater and the period of oscillation longer.

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[1] Although the majority of over-voltages occur only in one phase, it is a fact that three-phase over-voltages, that is those which cause the greatest rise in voltage at the neutral point, are not infrequent.

The oscillations in the three windings, which for the fundamental oscillation are quarter wave oscillations, are then in phase and the voltage to earth attains at the neutral point (hence also at the extinguishing coil) twice the value of that at the line terminals of the transformer. The behaviour of these transient oscillations depends, however, also on the method of connection and the load conditions of the other windings of the transformer, because with short-circuited secondary winding the distribution of the magnetic flux is restricted mainly to the leakage path between the primary and secondary windings, whereas with the secondary winding open-circuited, the entire core section is available therefor. The frequency of the transient oscillations will therefore be greatest when the secondary winding is short-circuited, and least when the secondary winding is open-circuited, as is shown by the cathode-ray oscillograms Figs. 2 and 3. It should be noted that a delta-connected winding, due to the phase synchronism of the transients in all three phases may in this respect always be treated as a short-circuited secondary winding.

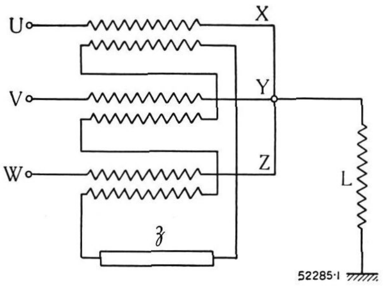

Fig. 4. — Connections for damping the neutral point oscillations.

UVW. Line terminals of the transformer.
XYZ. Star-point ends of the phase windings.
L. Extinguishing coil.
$\mathfrak{z}$. Impedance varying with the frequency.

The impedance $\mathfrak{z}$ is so arranged as to present a low value to the power frequency currents, in order not to have any effect thereon, whilst at the same time ensuring optimum damping of the high frequencies of transient currents.

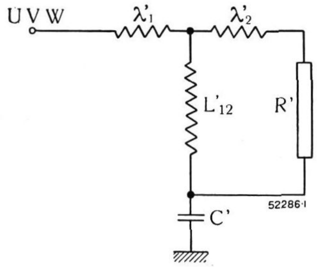

Fig. 5. — Equivalent circuit of the connection shown in Fig. 4.

UVW. Line terminals of the transformers.
λ'_1, λ'_2. Leakage reactances.
L_{12}. Mutual induction.
C'. Capacity.
R'. Damping resistance.

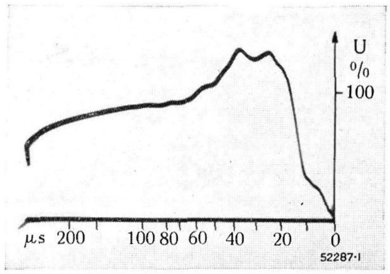

Fig. 6. — Behaviour of the voltage at the neutral point of a transformer as stressed in Fig. 1; optimum damping in connection Fig. 4.

Because of the damping, the voltage at the neutral point rises to only 134 % of the terminal voltage, instead of to 200 % as Fig. 2.

III. METHODS OF REDUCING THE NEUTRAL POINT STRESS.

In order to reduce the upward oscillation at the neutral point which causes the high stressing of the transformer and extinguishing coil insulation, it is possible to damp the oscillations by choosing an arrangement as shown diagrammatically in Fig. 4. The delta-connected winding, which is always provided on transformers for use with an extinguishing coil, is opened and an impedance $\mathfrak{z}$ is inserted, which is so connected as to present a sufficiently low value for the power frequency current, in order not to affect the behaviour of the transformer under normal operating conditions and to allow the unrestricted flow of the neutral system currents, and at the same time to provide the desired aperiodic damping in the case of the high frequencies of transient surges (of the order of several thousand Hz). Such an impedance can be designed in different ways, depending on the characteristic data of the installation. In the simplest case it consists of an inductance connected in parallel with a resistance. It may also, with a view to improving the symmetry, be divided into three parts, one being assigned to each phase.

In order to be able to form an idea of the behaviour and of the effectiveness of such a means during transient surges, it is possible to set up an equivalent diagram in accordance with Fig. 5, in which the system made up of distributed inductance and capacity, oscillating in quarter wave oscillations, is replaced by concentrated magnitudes λ'_1, λ'_2, L'_{12}, C'. These are given by the relations[1]

$$(1) \quad . \quad . \quad . \quad . \quad C' = \frac{2}{\pi} C = 0 \cdot 636\, C$$

$$(2) \quad . \quad . \quad (L'_{12}, \lambda'_1, \lambda'_2) = \frac{16}{\pi^3} (L_{12}, \lambda_1, \lambda_2) = 0 \cdot 516\, (L_{12}, \lambda_1, \lambda_2)$$

basing on the values of the self-induction and leakage per core, calculated on the assumption of a constant current flowing in all phases in the same sense from line terminal to neutral point; C being total earth capacity of one high voltage phase, and R' being equal to $\frac{ü^2}{3}$ times the damping resistance introduced into the delta-connection, where ü indicates the ratio of transformation per phase. (The extinguishing coil does

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[1] These conversion factors are given by the condition that the natural frequency of oscillation and the tuned circuit impedance of the equivalent circuit must be the same as those of the real system.

not need to be considered with this connection as its impedance per phase, which is in parallel with C′, and which therefore, as far as the transient phenomena is concerned, may be looked upon as being in parallel with $(L'_{12} + \lambda'_1)$, is in practice considerably greater than L'_{12}, and hence its effect is negligible.)

The smallest value of the neutral point voltage would be obtained if it were possible by a suitable choice of R′ to ensure that the voltage oscillation shall be aperiodic in character. For this purpose R′ would have to be sufficiently large, in order to damp the oscillatory circuit $(\lambda'_1 + \lambda'_2, C')$ in series (leakage field oscillations), and at the same time sufficiently small in order to damp in parallel the oscillatory circuit $(\lambda' + L'_{12}, C')$ (main field oscillations). These conditions are given by the following double inequality:

$$(3) \qquad 2\sqrt{\frac{\lambda'_1+\lambda'_2}{C'}} < R' < \frac{1}{2}\sqrt{\frac{L'_{12}+\lambda'_1}{C'}}$$

or expressed in terms of the generally better known periods of oscillation T_o and T_k, of the high voltage winding with secondary winding open and short-circuited respectively:

$$(4) \quad \ldots\ldots \quad \frac{T_k}{\pi C'} < R' < \frac{T_o}{4\pi C'}.$$

In order that the behaviour of the voltage at the star point may be aperiodic, it is necessary that

$$(5) \quad \ldots \quad \lambda'_1 + L'_{12} \geqq 16\,(\lambda'_1 + \lambda'_2) \text{ or}$$

$$(6) \quad \ldots\ldots \quad T_o \geqq 4\,T_k.$$

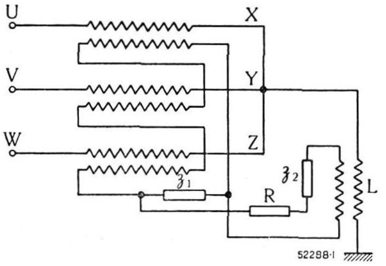

Fig. 7. — Compensating connection for reducing the oscillations at the neutral point.

UVW. Line terminals of the transformer.
XYZ. Star-point ends of the phase windings.
L. Extinguishing coil.
$\mathfrak{z}_1$, $\mathfrak{z}_2$. Impedances varying with the frequency.
R. Damping resistance.

The impedance $\mathfrak{z}_1$ which varies with the frequency, closes the delta-winding as far as power frequency currents are concerned; its value for the high frequencies of transients is large, so that the voltages occurring in it when fed to the extinguishing coil act in opposition to the voltage rise at the neutral point.

Measurements and calculations made by the author, as well as results given in other publications, indicate, however, that the ratio T_o/T_k is always smaller than 4, assuming only values within a range of 1·5 to 3; it is accordingly never possible to ensure with the given connection an aperiodic shape of the star-point voltage curve, and hence this method alone does not enable the maximum star-point voltage for waves of long duration to be reduced to the line voltage. The reduction of the star-point voltage attained with this connection is however quite appreciable, various tests having shown consistently that a reduction of the maximum star-point voltage from about 200 % to about 134 % of the voltage at the line terminals was obtained, as shown for instance by the oscillograms Figs. 2 and 6.

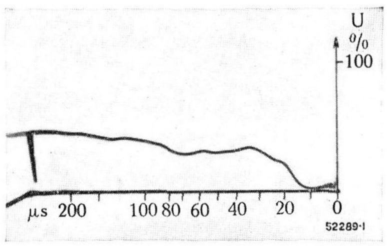

Fig. 8. — Behaviour of the voltage at the neutral point of a transformer when stressed as in Fig. 1, with compensating winding as per Fig. 7.

The voltage at the star point attains only a value less than $1/\sqrt{3}$ times the terminal voltage.

A considerably greater reduction of the maximum star point voltage may be obtained by means of connection shown in Fig. 7, in which the delta-connected winding of the transformer is again connected through an impedance $\mathfrak{z}_1$, which has a relatively small value for power frequency currents, but a high value for the high frequency currents of the transient oscillations, and which is so arranged that the voltage occurring therein is passed on to the extinguishing coil in such a manner that the resultant voltage between earth and neutral induced therein is opposed to the oscillatory voltage at the neutral point. As, however, the compensation is only effective for the main field oscillations, there must be provided in the connection between the delta-connected winding and the secondary winding of the extinguishing coil, as in the case of the first mentioned connection, a damping resistance R[1]; moreover owing to the conditions when operating with an earth fault, it is generally necessary in order to avoid that the extinguishing coil be loaded with a power frequency current passing through the damping resistance; to insert another impedance $\mathfrak{z}_2$ which may take the form of a condenser or of a tuned circuit. As here, thanks

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[1] A damping arrangement for the leakage field oscillations that would be included in the impedance $\mathfrak{z}_1$, as used in the first connection, would not be effective here, as it would be short-circuited by the opposition coupling.

to the compensation of the main field oscillations, the conditions are fundamentally different from those of the first connection; it is indeed possible to obtain a range of aperiodic damping for the star-point voltage, as well as an additional reduction of same, which can be shown by similar reasoning and calculations to those employed above, as well as proved by the oscillogram Fig. 8.

As can be seen from the above, it is quite possible by means of the method of connection described, to reduce also for surge voltages the ratio of the voltage stress at the star point to that in the supply lines, to the value $1 : \sqrt{3}$, corresponding to the ratio of the stressing due to power frequency current.

(MS 759) *Dr. H. Meyer. (Hv.)*

PROGRESS IN THE DOMAIN OF LIGHTNING ARRESTORS.

Decimal index 621.316.933

The reliability of modern lightning arrestors can be increased by carefully investigating the phenomena occurring during the discharge of very high currents and during their extinction.

I. INTRODUCTION.

DURING the early stages of the development of over-voltage protection, lightning arrestors were looked upon as extra features to be placed only at those points of a system which were particularly liable to danger from lightning disturbances, or where the insulation was weakest. Frequently, they were added only after flash-overs or failures had already taken place. To-day, the installation of lightning arrestors is governed by very different considerations. The arrestor is now regarded as an integral part of the plant with about the same justification as a disconnecting switch, over-current relay or similar apparatus. It is one of a number of measures of a comprehensive plan for over-voltage protection within the full meaning of the word, and the same concern would be felt over its omission as over a weak spot in the insulation. The main object of an arrestor in a modern distribution system, is to fix a minimum level for the grading of the insulation, and to prevent thereby all flash-overs and insulation break-downs due to atmospheric over-voltages. In addition thereto, this method of protection enables, when properly applied, the insulation of the plant to be limited to the amount just sufficient to stand up to the stresses caused by the voltage rises occurring during switching operations.[1]

The systematic use of lightning arrestors for network protection has become possible only by the latest improvements made to these devices. It would be perhaps more appropriate to ask what requirements must be fulfilled by a lightning arrestor in order that it may completely satisfy the needs of this new task. In the first place it must, of course, adequately serve its primary function, that of providing a discharge path for over-voltages; but another most important condition upon which great weight is laid by operating engineers, is ***absolute reliability*** in service. The lightning arrestor must operate satisfactorily, not only in the great majority of cases, but in ***every*** case. It is not easy for the designer to solve this problem, and it repeatedly happens that, after much labour and trouble has been expended in producing a very good design, as much labour and trouble again has to be spent in improving its performance by a few percent.

The reliability of a lightning arrestor depends on its behaviour during the discharge of very high currents and during the extinction process.

II. THE DISCHARGE OF VERY HIGH CURRENTS.

If it is desired to investigate the reliability of a machine, it is best to carry out the investigation under the most severe conditions which can occur in practice; indeed it is advisable to choose them even more severe in order to be quite sure of having a sufficient margin of safety. This method was followed also in the case of lightning arrestors, the component parts having been tested with the highest discharge currents attainable in modern test laboratories. The behaviour of the arrestor resistances when subjected to very high discharge currents has already been dealt with in a previous publication[1], and for this reason there is given in the present article only a cathode ray oscillogram of a test carried out on a resistance with a current of 70,000 A (Fig. 1). However, not only the resistance but all parts of the arrestor in series with the resistance are traversed by these high currents and they must be dimensioned accordingly.

In this connection it is interesting to consider the phenomena taking place in the extinction gaps during such a stressing. Figs. 2a—d show some of the marks of the short duration arc burning between the plate-type electrodes. The anode marks (Fig. 2 a) are characterized by the light colour of the slightly fused metal on the surface. They are caused by the intensive

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[1] See also page 120 of the present number.

[1] The Brown Boveri Review December 1940, page 243.

heating at the anode focus (impact of the electrons on the anode surface), which explains their circular appearance. The cathode marks (Fig. 2 b) differ from the anode ones by their irregular appearance. This seems to be associated with surface phenomena characteristic of the process of electron liberation. Fusion marks caused by the relatively small heating effect at the cathode focus are but seldom observed. Fig. 2c shows the effect of the current intensity. It will be seen that with a constant current density the diameter of the marks left by the arc increases approximately proportionally to the square root of the current.

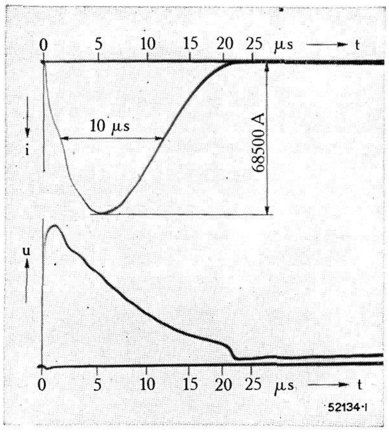

Fig. 1. — Discharge of a 68,500-A current through an arrestor resistance.

i. Arrestor current.
u. Voltage *across resistance.*

An arrestor with such a large capacity as this is capable of protecting the plant even against direct lightning strokes.

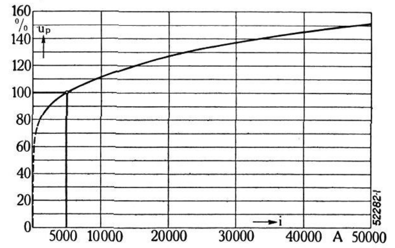

Fig. 3. — Behaviour of the residual voltage in a lightning arrestor.

The residual voltage u_p does not increase in a linear manner with the discharge current, but much more *slowly, owing* to the resistance varying with the voltage. An arrestor with a low residual voltage gives better protection to the plant.

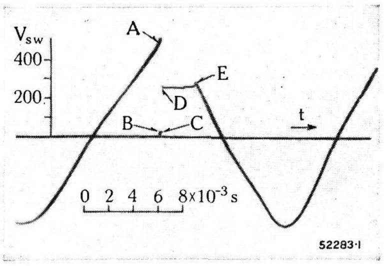

Fig. 4. — Extinction process in an arrestor, in which the interruption of the follow-up current takes place before the reversal of current through zero.

A. Ignition (breakdown).
B. Residual voltage.
C. End of the impulse wave.
D. Glow discharge.
E. Extinction of the follow-up current.

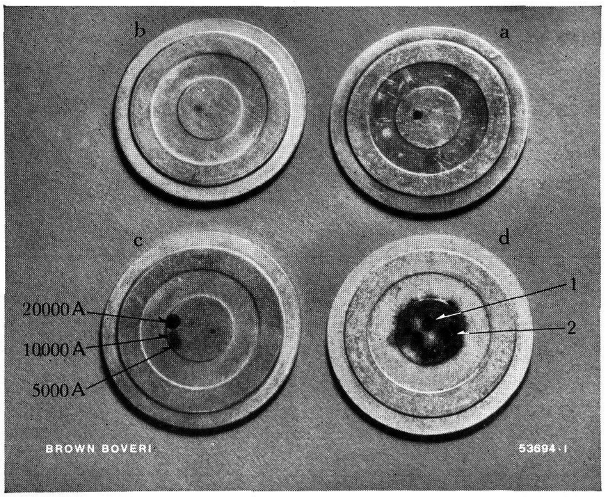

Fig. 2. — Arc marks on plate type electrodes.

a. Anode track of a discharge current of 5000 A and 30 μs duration of half amplitude.
b. Cathode track of a discharge current of 5000 A and 30 μs duration of half amplitude.
c. Arc marks of discharge currents of 5000, 10,000 and 20,000 A and durations of half amplitude of 20—30 μs.
d. Cathode tracks after testing with about 20 impulses of 10,000 A, 25 μs and subsequent extinction tests.

1. Impulse current. 2. Line current.

The important point about all these phenomena is the fact that the mechanical and electrical properties of the electrodes are not altered by the discharges. For instance, it is not possible to find any protuberances or hollows in the marks. This fact which at first sight, considering the high current intensities, seems astonishing, is explained not only by the careful choice of the electrode material, but also by the extraordinarily short duration of the arc. As the heat developed has not time in such a short interval to penetrate into the mass of the metal, all phenomena are restricted to a thin surface layer. When the discharge currents are large, not only the study of the physical phenomena, but also the electrical characteristics of the arrestor — especially the residual voltage — are of importance. The residual voltage u_p is given by the product ir of the discharge current i, and the momentary value of the resistance r. The greater the discharge current, the greater the residual voltage and the question *might* well be put as to whether real protection is still afforded by the arrestor, when the discharge currents are high. This doubt may, however, be set aside because of the fact that the arrestors have a variable resistance. The resistance r decreases with increasing discharge current i, so that the product ir increases much more slowly than i, as is shown by the curve Fig. 3. It can be seen here that when the capacity is increased from 5000 to 10,000 A, the residual voltage u_p increases by only 12 % and when the capacity is increased from 10,000 to 20,000 A by only 13 %.

III. THE EXTINCTION PROCESS.

The process of extinction is a complex one during which the arrestor is very highly stressed. It is, therefore, important to investigate the cause of this stress and to see whether by the use of suitable measures it is possible to reduce it. Experience shows that the process takes place in one of the two following ways:

In *extinction process of the first kind,* the network current persists after the arrestor has operated, until the next reversal through zero. Its duration in the most unfavourable case may accordingly attain a complete half-cycle. This current is undesirable, not so much because of its amplitude which is generally of the order of 10 amperes, but because of its relatively long duration of $^1/_{100}$ s compared with that of usual discharge phenomena. In the case of repeated consecutive discharges, this may cause the resistance to attain temperatures which may endanger the material. The marks left by the residual power current on the electrodes of the extinction plates, although much smaller than those left by the discharge currents, show definitely that fusing of the material has occurred. A slight thickening of the material takes place on the anode and a crater-shaped mark is formed in the cathode. Fig. 2 d is particularly interesting in this respect, as it enables the relatively large flat marks left by the discharge current to be compared with the small fusion tracks of the network current. The thickening of the electrode amounts in the case of power frequency discharge current of some 10 amperes to about $^1/_{100}$ mm.

In *extinction processes of the second kind,* the arc started by the igniting surge changes directly into a glow discharge, which breaks off automatically before the current has reached the zero transition point. A typical cathode-ray oscillogram of this kind of extinction process is reproduced in Fig. 4. It shows the way in which the voltage varies over a single gap during the extinction process. The ignition (breakdown), occurs in A and is followed by the surge current, the voltage having fallen at B to about 15 volts, this being the normal arc voltage. As soon as the over-voltage has been discharged, the arc is broken at C and the voltage rises to about 280 volts, a value characteristic of the glow discharge, the final interruption taking place in E. Between D and E flows the power frequency current the magnitude of which is, however, limited in this kind of discharge to 0·3 to 0·5 A.

It is evident that in the second type of extinction process the conditions are far less severe on the material than in the first type, as in this case both the resistances and the extinction gaps have to handle practically only the surge current. Consequently, it is very advantageous from the point of view of both the reliability and the life of the arrestor for the extinction process to take place in the second manner. This can in fact be ensured by employing a suitable design, and our arrestors extinguish in the great majority of cases with practically no following power frequency current. Only in extreme cases, that is when a lightning stroke is accompanied by a short circuit to earth, and in addition thereto the voltage rises to 1·1—1·2 times the line voltage, is extinction according to the first type of process likely to occur.

(MS 760) *G. Degoumois. (Hv.)*

BRIEF BUT INTERESTING

Service results obtained with Brown Boveri distance relays.

Decimal index 621.316.925.45

THE Kungl. Vattenfallsstyrelsen (Royal water-fall administration) in Stockholm, which control the most important of the Swedish transmission networks, have placed more than 70 rotating-field distance relays of our type L3 in their 77-kV and 132-kV plants, from 1939 up till to-day. These are very extensive networks equipped with extinguishing coils and they link up numerous power stations. This administration has been kind enough to place at our disposal a summary of service results obtained in the year 1940, in which year the majority of the above relays were working. The number of faults was relatively high because, apart from a normal number of storms, many cases of trouble were due to balloons broken loose from balloon barrages and carried across the sea.

The cases of short circuit are classed as follows:—three-phase short circuits 50%, two-phase short circuits 45%, double earth faults 5%. About one third of the cases of trouble are to be imputed to the balloons mentioned above and were, therefore, of the metallic type; the others were, mostly, arc short-circuits.

In over 98% of the cases the behaviour of the distance protection apparatus was perfect. Trippings, in so far as could be ascertained, took place with the time lags adjusted to, which goes to show the exactitude of the distance measuring equipment under the various kinds of trouble dealt with. The important point is that, thanks to the short rupturing times of these relays, the high-speed distance protection maintained the stability of these extensive transmission networks under the effects of all the faults which occurred on them.

(MS 772) *J. Schneider. (Mo.)*

Published by BROWN, BOVERI & COMPANY, LIMITED, BADEN (Switzerland). Printed by Kreis & Co., Basle, Switzerland.
Obtainable through A. Francke A. G., Berne and Rouge & Cie., Lausanne (Switzerland).