THE BROWN BOVERI REVIEW

Special High-voltage Engineering Number

Sidelights on our work

To commemorate the inauguration of our new high-voltage laboratory

VOL. XXX SEPTEMBER/OCTOBER, 1943 Nos. 9/10

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Frontispiece

Flash-over on 400 kV isolating switch at power frequency.

THE BROWN BOVERI REVIEW

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INTRODUCTION.

Decimal Index 621.3.027.3

BROWN BOVERI are in the fortunate position of being able to inaugurate a new high-voltage laboratory. Happily, the value of research results does not depend exclusively on the size and appearance of the laboratories, and in the present special high-voltage engineering number we hope to be able to show our readers that valuable research work was accomplished even under the more or less primitive conditions obtaining prior to the new buildings becoming available. When space conditions are restricted, however, the possibilities are also limited. It is true that even under such circumstances fundamental tests can invariably be carried out, but it is impossible to exceed a certain voltage, and if extrapolation is pushed too far results become unreliable.

This voltage restriction which has hampered our work for some time is now a thing of the past, inasmuch as the new laboratory is suitable not only for the highest voltages (220 and 287 kV) so far encountered in practice, but also for the values of 380 or 400 kV which have recently been mentioned in power transmission circles. In fact, there is an ample reserve in the event of service voltages of 500 kV or more being adopted in the relatively near future.

No less important than the higher voltage is the greater amount of space available for tests. Hitherto shifts had to be worked in the high-voltage laboratory, the test equipment being dismantled at the end of one shift to make room for the next set of workers and re-erected at the beginning of the following shift, in order to get the more urgent work done at all. Nevertheless, it was found impossible to carry out many interesting and important tests. In future a large number of extremely well-equipped test bays will be available and the much more rational working conditions will permit our large staff of research engineers to deal with the multifareous problems which hitherto had to be put back.

The whole of this special number could well be filled with details of the new laboratory and its equipment, but we have confined ourselves to its more salient features and devoted a relatively small number of pages to the laboratory proper. The remainder of the number comprises a selection of articles on topical subjects from the high-voltage engineering field. With one exception the investigations described were undertaken in our old laboratories before the new equipment was available. They are representative of the work accomplished, although it has been impossible to treat various special fields due to lack of space. The articles clearly show the extent to which electrical engineering depends on high-voltage investigations and also prove the importance of a modern high-voltage laboratory in a far more convincing manner than any lengthy treatises could do.

(MS 961) *Dr. W. Wanger. (E.G.W.)*

THE NEW BROWN BOVERI HIGH-VOLTAGE LABORATORY.

Decimal Index 621.317.2:621.3.027.3

The layout and salient features of the new Brown Boveri high-voltage laboratory are briefly described. A. C. voltages up to 1·6 million r. m. s. volts, impulse voltages up to 2·4 million peak volts, and d. c. voltages up to 1·2 million volts are available for testing purposes.

FIG. 1 depicts the new high-voltage laboratory at the main entrance to our Baden works. It comprises — as shown more clearly in Fig. 2 — a large high-voltage test room and a wing extending along the public throughfare in which the appertaining offices and a number of smaller laboratories are located.

Although fundamentally the new research laboratory is not intended for routine tests, certain special conditions may occasionally necessitate its being used for this purpose so that the situation of the high-voltage equipment assembly shops had to be taken into account when selecting the site.

Inasmuch as the testing of rotary machines, mutators, electric boilers and the like does not involve particularly high voltages, the cost of installing separate routine test equipment in the different assembly bays is not prohibitive, and the research laboratory can be dispensed with for this purpose. The testing transformers of the old high-voltage laboratory will in future be employed for the routine testing of transformers, while that in the assembly bay of the apparatus factory has been rewound to produce 750 kV to earth with the low-voltage winding supplied directly. As a result,

Fig. 1. — The Brown Boveri high-voltage laboratory.

In the foreground, the main high-voltage room with equipment for generating 1·6 million volts at power-frequencies and 2·4 million volts under impulse conditions. The lower part of the advanced section of the building contains the smaller laboratories and offices.

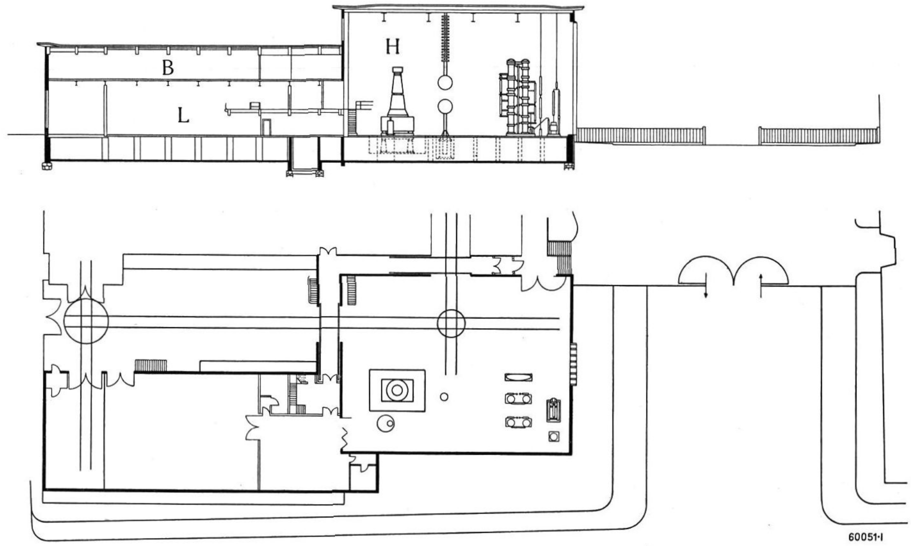

Fig. 2. — Plan and elevation of Brown Boveri high-voltage laboratory.

B. Offices. H. High-voltage room. L. Laboratories.

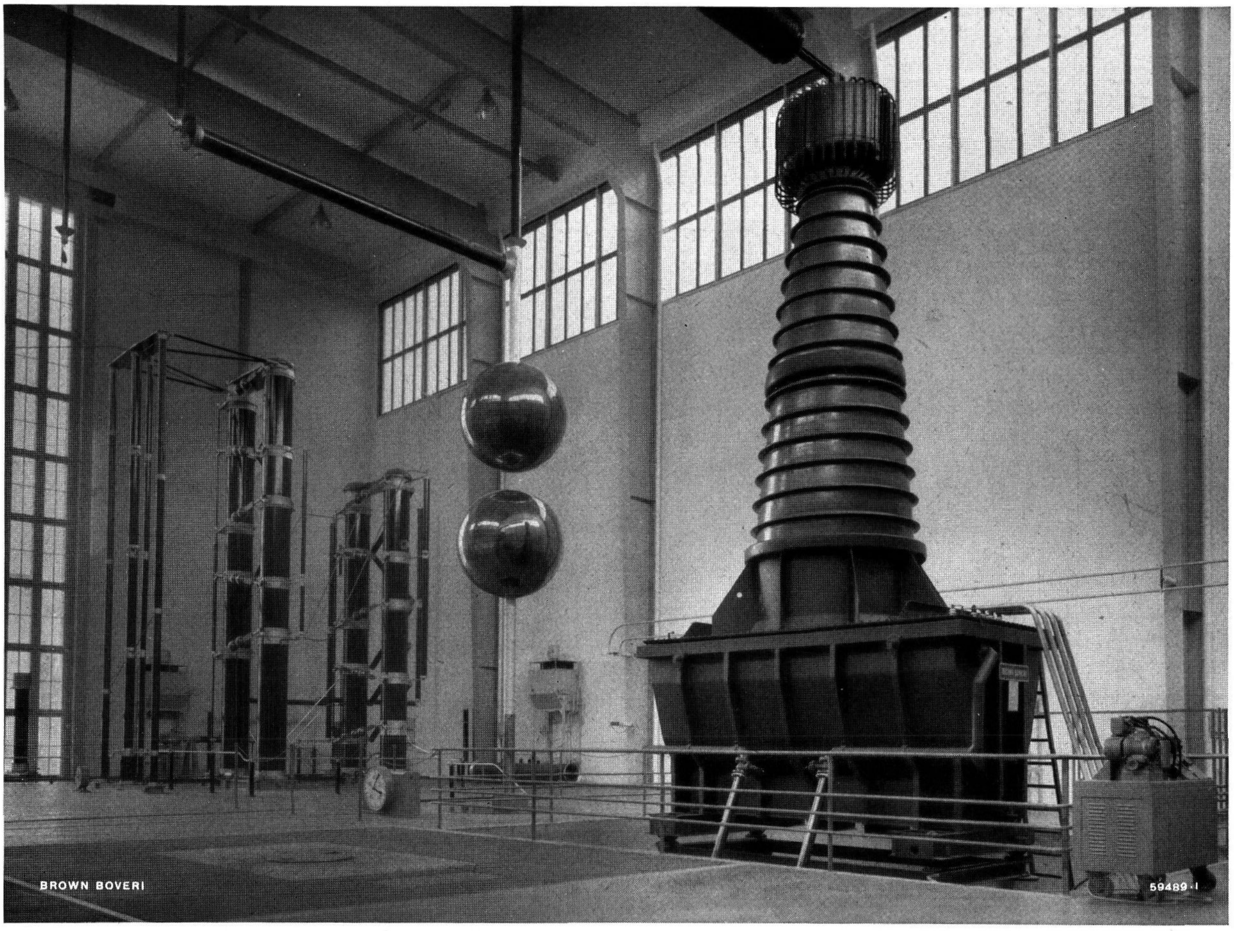

Fig. 3. — View of main high-voltage room with impulse generator, testing transformer, and sphere-gap.

The large spark-gap has spheres 175 cm in diameter.

ample means are available at both these points for the voltage testing of 220 kV equipment at power-frequencies.

For certain special tests and the routine testing of 400 kV equipment, however, the research laboratory has to be resorted to. This is the chief reason why the new building was erected adjacent to the transformer assembly shop and connected to it by a passage of approximately 6×6 m. Should the routine testing equipment prove inadequate in certain cases, transformers can be tested in the assembly and drying-out shop with a voltage supply taken from the new laboratory. Possible ultimate extensions to the transformer factory have also largely been taken into account, inasmuch as the assembly shop can only be lengthened at the end opposite the laboratory, which, therefore, will always be in the correct position with respect to the assembly shop. Moreover, there is still sufficient space for a further bay 16 metres wide between the existing factory buildings and the wing of the new building, and this could also be connected to the high-voltage laboratory at the desired end.

On the other hand, apparatus, such as circuit-breakers, required to be tested with the new equipment must be transported from the corresponding assembly shop. This, however, is far more practicable than where power transformers are concerned and should prove no great inconvenience, inasmuch as the excellent routine test equipment available will render such cases extremely seldom. The objects to be tested can be taken into the laboratory on railway trucks or lorries or can be left out in the open and a voltage supply led out through large normally-closed openings (the larger of which measures about 7×7 m) on two sides. In the same way a supply can be given to other bays over the roofs of the shops should such high voltages ever be required elsewhere.

The problem of the site having been satisfactorily solved, it was possible to consider the question of the voltage. In our opinion service voltages of 400 kV will not be long in coming. To be on the safe side, however, we have selected a voltage of 1600 kV to earth for the testing transformers to cover service voltages of 500 or 600 kV in the event of such high pressures being adopted in the relatively near future. The impulse generator is designed for a maximum voltage of 2400 kV and an energy of 25 kWs, the test transformers for a continuous current of 1 A.

Fig. 4. — Test bays, observation galleries, and high-voltage rectifier in main high-voltage room.

The size of the room can best be judged by comparison with the 400 kV isolating switch in the background or with the nearly 10 m long rectifier suspended, ready for service, from the ceiling.

The test voltage of 1600 kV is produced by two cascade-connected transformers, for we did not hold it advisable to generate more than 1200 kV to earth in one single transformer, which in itself is already a noteworthy achievement. For voltages up to 1200 kV one transformer operates solo, while the other can be simultaneously employed for independent tests with voltages up to 400 kV, the two transformers only being connected in cascade for voltages over 1200 kV.

The voltages adopted are considerably higher than has been the practice for laboratories constructed for similar conditions during the past few years. We considered this essential because such equipment has to meet future and not present requirements.

Furthermore, we could not entertain the idea of constructing a laboratory solely for power-frequency or impulse testing. The dimensions of the building were therefore selected so that independent tests could be simultaneously carried out with the two voltage systems, except at the very highest voltages. The resulting building, which has a useful superficial area of 24×31 m and a height from floor to ceiling of over 15 m is by far the largest high-voltage laboratory in Switzerland and has hardly a counterpart on the European Continent.

One half of the laboratory is designed for tests at power-frequencies and the other for impulse testing. The voltage sources — test transformers and impulse generator — are erected along the outside long wall (cf. Figs. 2 and 3). The space in front of them is reserved for the objects to be tested (Figs. 2—5) which can be readily observed from a gallery running at a height of 3·6 m along the whole of the wall abutting on to the transformer shop. The control desks are located on this gallery from where the engineer in charge of the tests has a view of the whole room. Small, mobile desks, however, permit of control from the ground floor of the laboratory if for any reason, e. g., in the case of tests in the dark, the observer desires to be nearer the object under test. There is a further gallery along one side wall and another above that on which the control desks are located. The upper gallery is at a height of 7·3 metres.

Provision is made for wet tests in both the power-frequency and impulse test areas. Bushings having their lower end immersed in a pool of oil can also be wet-tested. The conductivity of the water is adjusted to the desired value in the usual manner.

The laboratory is well illuminated by windows on all four sides which can be blacked out by remote-controlled roll-type shutters. It is possible to adjust the artificial lighting to any desired brilliancy by means of a sliding-coil voltage regulator.

By reason of the resulting complication of the high-voltage wiring and the prohibitive cost for a room of such dimensions, a crane has not been installed in the

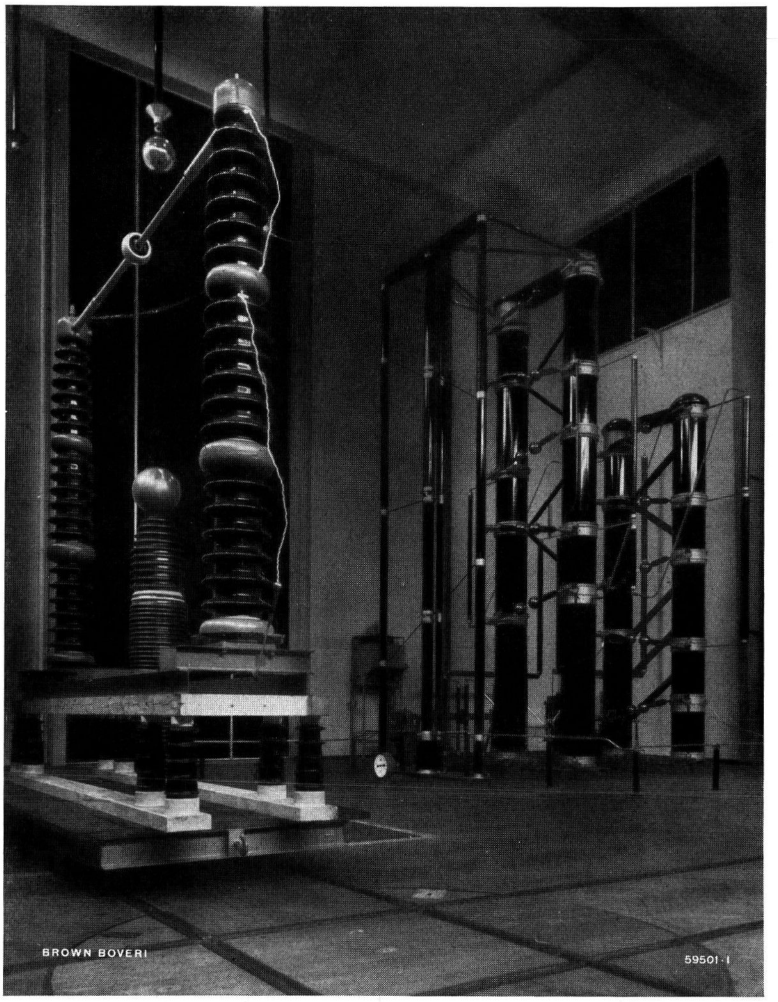

Fig. 5. — Impulse voltage flash-over on 400 kV isolating switch. In background, the impulse generator.

main laboratory. Large test objects are therefore run into the test area on open railway trucks where they remain for the tests. There are simply two electrically-operated mobile pulley-blocks with a lifting capacity of 1 ton each suspended from the ceiling for light work, e. g., the lowering of test objects into the oil basin. A larger, 5 t pulley block is situated in the passage communicating with the transformer shop. All work involving more powerful lifting appliances is carried out in the transformer shop which can be easily reached by two different routes. All rail-tracks are standard gauge and can carry loads of 60 t.

In view of the increased importance of high-voltage direct current for the transmission of big blocks of power, the necessary equipment for d. c. voltage tests could naturally not be left out of consideration. This problem was solved in an ideal manner by supplying a capacitor-controlled multi-needle rectifier from the testing transformer (Fig. 4). The only other accessory required is a condenser for connecting in parallel with the object under test. This plant supplies d. c. voltages up to 1200 kV.

Two cathode-ray oscillographs are installed in a room in the wing abutting directly on to the main high-voltage room on the ground floor. A large folding door permits of communication between the two rooms or enables them to be completely shut off from each other according as the oscillographs are required for tests in the main laboratory or for other purposes. The oscillograph room is electrostatically screened and connected to the high-voltage room by means of several fixed, loss-free instrument leads which are also screened. These leads serve not only to connect the cathode-ray oscillographs, but also permit measurements in connection with tests in the high-voltage room to be carried out in a screened room free from interference. The new four-element cathode-ray oscillograph complete with accessories is mounted on rubber-tyred wheels and can be run into the high-voltage test room or, for that matter, to any other part of our extensive factory premises when required.

In the wing of the building, apart from the oscillograph room, there is a further laboratory with a superficial area of nearly 500 m^2 in which tests with voltages up to 150 kV at power-frequencies and 300 kV under impulse conditions can be carried out (Fig. 6). The impulse generator is mobile and can therefore also be employed elsewhere. A further impulse generator is designed for very heavy currents at low voltages.

If particular importance was attached to the possibility of carrying out several independent tests simultane-

Fig. 6. — Laboratories in wing of building with various test bays for moderately high voltages.

ously in the main laboratory, the second test room surpasses the first in this respect, in that it permits an even greater number of further tests to be carried out at one and the same time with moderately high voltages. Such facilities are absolutely essential, for only in this manner can we hope to cope with the many problems awaiting our attention in the different high-voltage engineering fields.

The laboratory in the wing of the building already referred to is not only available for high-voltage investigations, but also for development tests of all kinds in connection with small and medium-size transformers, machines, etc. Any generator in the new laboratory and any machine in the routine test bays of the transformer and machine test shops can be switched over on to every test point. A very large number of machines is thus available. After the high-voltage and exciter line selectors have been appropriately manipulated the machine chosen can be remote-controlled (machine and its excitation switched on and off, excitation regulated) from the test point, the same control switches and regulating gear being employed for all machines.

The policy followed in the main high-voltage room of letting not only the oil tank, but also other components into the floor in order to make the best possible use of the height of the room was applied even more rigorously in the laboratories located in the wing, to gain as much space as possible for the tests. For instance, all machinery, line selectors, switch frameworks, switchgear, three testing transformers, an impulse generator, a compressed-air condenser, and other equipment are lodged in the basement.

Here, too, there is an electrically screened, highly sound-proof room which can also be blacked out. This serves for the optical, acoustical, and high-frequency investigation of infinitesimal glow discharge phenomena. The whole room can be adjusted to any desired degree of humidity, thus enabling the influence of air humidity on the flashover voltage of insulators to be investigated.

The basement also contains the necessary stores for test equipment as well as a number of other general-purpose rooms.

Roomy offices are provided for the research staff on the top floor of the annexe, where there is a well-equipped laboratory for the development of remote supervisory control gear. Apart from the work-benches at different parts of the building there is also a mechanical workshop reserved exclusively for the test departments.

Finally, it might be mentioned that in the yard between the wing of the new building and the transformer assembly shop tests or long-period investigations can be made out-of-doors.

This new addition to our works, of which the cubical content is over 26,000 m^3, was erected in the record time of eight months. Excavation work was begun at the beginning of August, 1942, while the laboratories were ready for service by the beginning of April, 1943. No stress need be laid on the fact that such an achievement was only possible through the strenuous and combined efforts of everyone concerned. If the work accomplished in the new laboratory is crowned with the same success, we shall indeed have grounds for satisfaction.

(MS 962) *Dr. W. Wanger. (E. G. W.)*

THE EQUIPMENT OF THE NEW LABORATORY.

Decimal Index 621.317.2 : 621.3.027.3

The high-voltage equipment was also briefly referred to in the preceding article on the architecture of the new Brown Boveri laboratory, so that the following description is confined to the more interesting items.

THE EXTRA-HIGH-VOLTAGE TEST ROOM.

THE *alternating-current plant* for a voltage of 1600 kV to earth comprises two transformers connected in cascade. Fig. 1 depicts the main 1200 kV transformer which is mounted on insulators and, on the score of voltage, power, and design, forms one of the most interesting items in the laboratories.

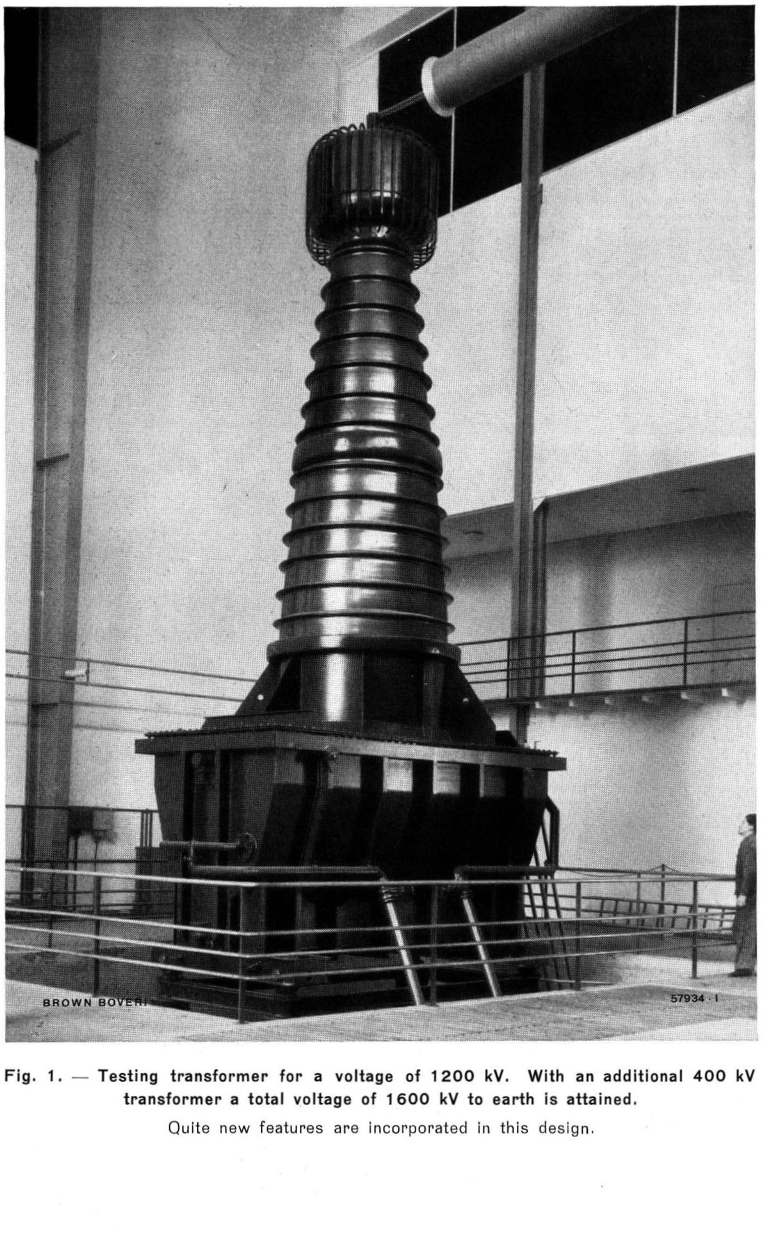

Fig. 1. — Testing transformer for a voltage of 1200 kV. With an additional 400 kV transformer a total voltage of 1600 kV to earth is attained.
Quite new features are incorporated in this design.

Its active part composed of a wound, single-limb, butt-jointed core is mounted horizontally in a tank adapted to its form. The high-voltage winding is divided into two halves, which are connected in parallel, the maximum potential both between the windings and to the tank occurring in the centre of the limb. This clear arrangement of the windings obviates large potential differences and enables the insulation problem to be solved in a simple and reliable manner. High-quality oil-impregnated paper is employed as insulation between the windings themselves as well as between the windings and the tank. Extra care was given to the insulation of the end turns of the high-voltage winding, due to the voltage surges they have to withstand every time the object under test flashes over or breaks down.

The high-voltage bushing, which is capacitively controlled both radially and axially, is protected against surface discharges at its lower end by special design features. The problem of oil expansion was also solved in an ingenious manner, an expansion vessel incorporating an air dehydrating device and which, to prevent brush discharges, is provided with a kind of cage, being mounted on top of the bushing.

In order to have a safe margin for any problems the future may bring the rating of the transformer was fixed at 1200 kVA. Since the tank is at a potential of 400 kV to earth in the cascade connection the piping to the water cooler had to be insulated.

As a result of systematic research and exhaustive preliminary investigations it was found possible to keep the overall weight of the 8·5 m high transformer down to 36·5 t, including 11·5 t of oil.

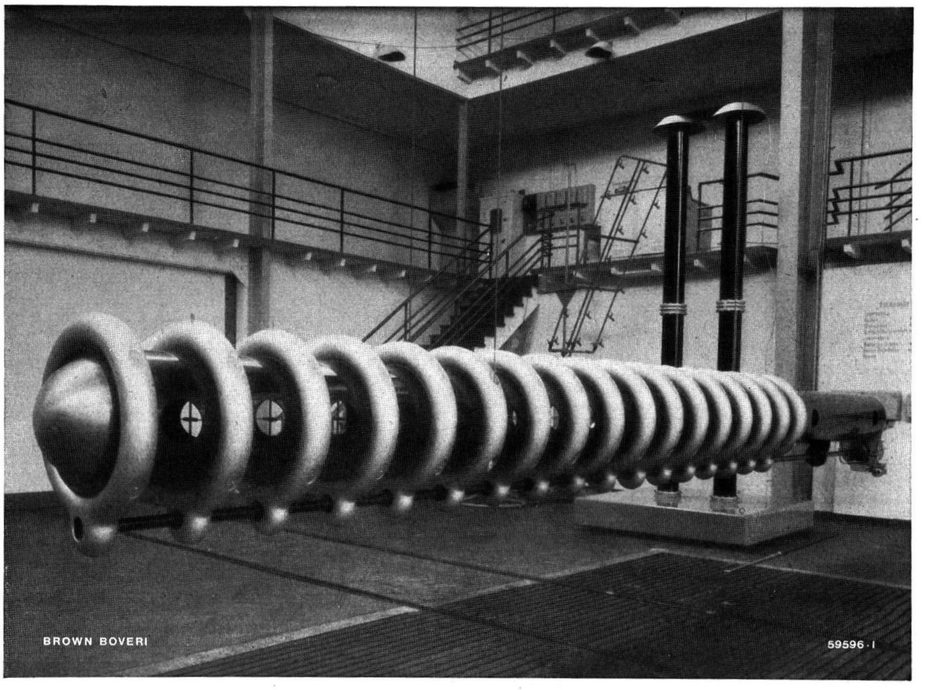

Fig. 2. — Multi-needle rectifier for a blocking voltage of 2,500,000 V.
The whole plant is of original design.

During high-voltage investigations the load on the test equipment is of an entirely capacitive character. If the supply voltage is not of sine wave-form the current curves will be distorted, and this may prove a disadvantage for certain special tests. Moreover, the high short-circuit current occurring when the object under test flashes over or breaks down — the impedance voltage of the transformer is only 6 % — may not always be desirable. Both problems can be simply solved by connecting a variable reactor to the low-voltage side of the transformer and accurately adjusting the inductance to offset the capacitance of the circuit, whereupon an excellent voltage curve is obtained and the supply has only to provide the active power. In this case and for the majority of investigations with moderately high voltages the 380 kVA regulating transformer presents advantages. For higher test powers and when the above-mentioned reactive-power compensation is undesirable machines up to 2000 kVA rating are available.

A new development also of interest is the *multi-needle rectifier* for a blocking voltage of 2500 kV, illustrated in Fig. 2. Together with the previously described testing transformer this serves to produce

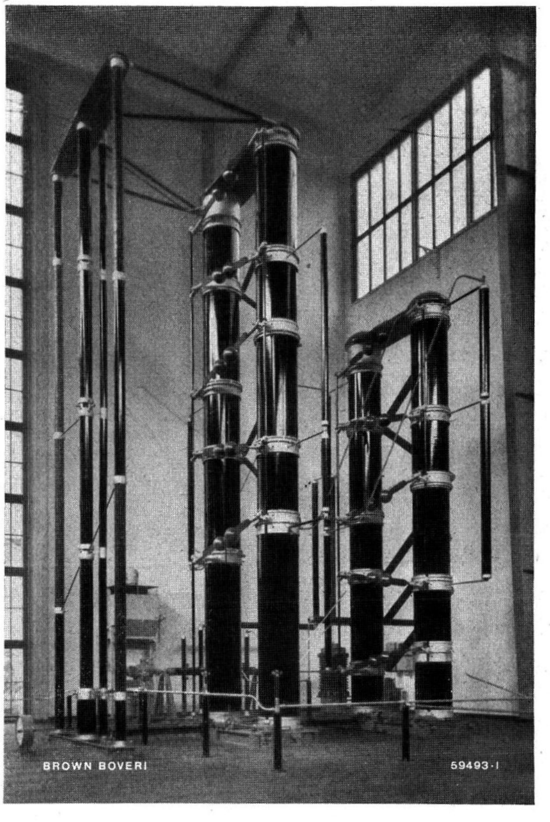

Fig. 3. — Impulse generator for a voltage of 2,400,000 V.
Regulation is effected entirely from the control desk.

a d. c. voltage of 1200 kV. The practically 10 m long rectifier is controlled by means of built-in condensers so that there is a virtually uniform voltage distribution over the seventeen series-connected needles, which are driven by a synchronous motor. The stator of the latter can be rotated by means of a motor regulated from the control desk. In this manner the position of the needles can always be adjusted to the phase displacement of the transformer voltage so as to obtain practically sparkless operation. A bank of condensers with a capacity of approximately 1000 pF is provided to smooth out the ripple in the d. c. voltage. The problem of the storage of the 10 metre long rectifier with its weight of 2 t was also solved in an ingenious manner by running it up to the ceiling with its own hoisting gear. This operation can be quickly effected, whereupon the whole test area is again free for tests up to the highest voltages with the a. c. plant.

As early as 1925 Brown Boveri installed an *impulse test plant* chiefly for research purposes in connection with atmospheric over-voltage phenomena. To meet probable future developments this was replaced in 1937 by a plant with a greater energy and capable of producing a higher voltage (1200 kV). In view of the research work which has been taken up in connection with power transmission at extra-high voltages a second similar plant, as shown in Fig. 3, has now been installed. With this ideal combination an impulse generator set affording enormous possibilities is available. By connecting the two plants in cascade or different stages in parallel practically the total energy of 25 kWs is always available for voltages between 600 and 2400 kV. The entire eight-stage plant is supplied from a double needle rectifier. To initiate the voltage surge, the condensers, which are charged in parallel, must be switched into series. Nine sphere gaps with progressively increasing clearances take care of this switching operation. Due to the needle rectifier being able to withstand heavy current surges with impunity the impulse testing plant with its special patented connection can be exploited to the full, even as regards the sequence of the impulses. Through simple change-over operations all of the more common wave-forms can be obtained (shortest wave-front time $0 \cdot 5\ \mu s$, longest time from crest to half-crest value $1000\ \mu s$). The load capacitor is in the form of a voltage divider to facilitate the recording of high-speed phenomena. For the measurement of the impulse and a. c. voltages a number of spark gaps with spheres up to $1 \cdot 75$ m in diameter are available.

THE INSTRUMENT ROOM WITH THE CATHODE-RAY OSCILLOGRAPHS.

It is hardly possible to conceive a modern high-voltage or high-frequency research laboratory without a cathode-ray oscillograph, inasmuch as this is the only apparatus capable of accurately recording high-speed phenomena, such as, for instance, electrical discharges or high-frequency equalizing processes set up by sudden changes of conditions in electrical circuits. Our new laboratory is equipped with two Trüb, Täuber & Co., Zurich, cold-cathode oscillographs (Fig. 4). One of these apparatus, an oscillograph with four beams and six recording systems, of which two for the direct measurement of a 50 kV voltage to earth, is in a class by itself. This instrument permits four different,

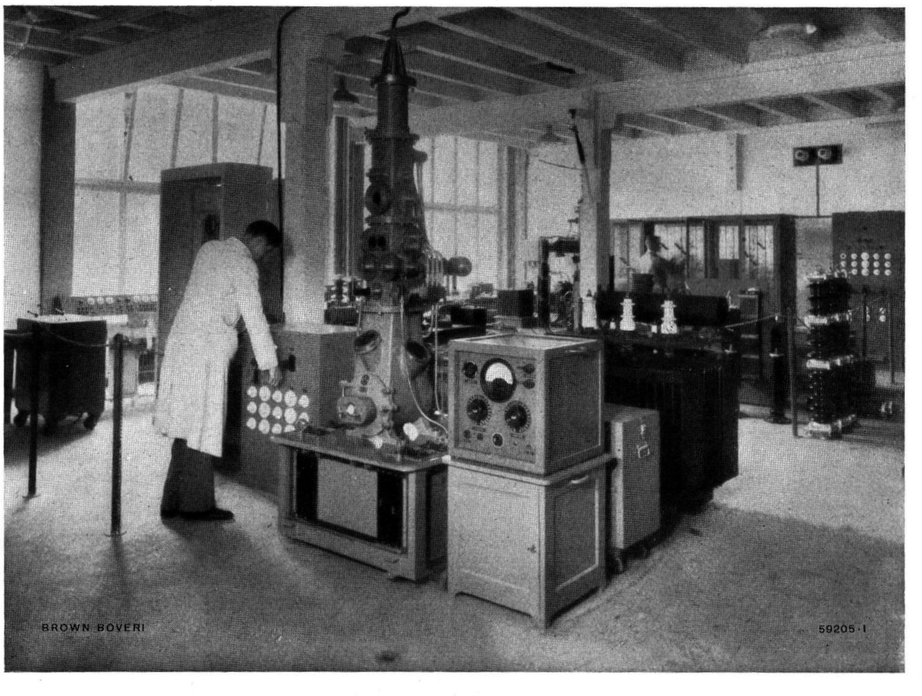

Fig. 4. — View of test room with cathode-ray oscillographs.
The new quadruple-beam, high-voltage oscillograph in the foreground is in a class by itself.

independent quantities to be simultaneously recorded.[1] The second instrument is of the single-beam type, but has also a recording system for 50 kV to earth. It will be chiefly employed for routine testing purposes.

The general layout of the oscillograph room with reference to the whole building is shown in Fig. 5. This arrangement was adopted due to the double purpose of the oscillograph laboratory, viz.—

1. For the convenient and rapid recording of the phenomena produced in the high-voltage laboratory.

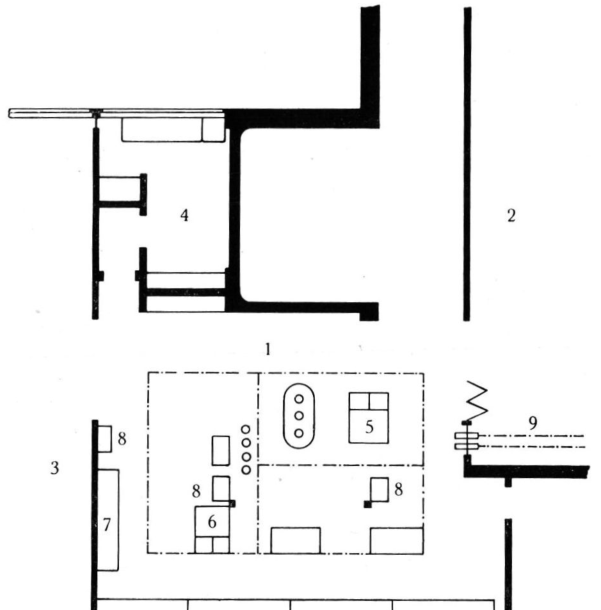

Fig. 5. — Plan of test room with cathode-ray oscillographs.

1. Oscillograph room proper.
2. Main high-voltage laboratory.
3. Medium-voltage laboratory.
4. Dark room.
5. Quadruple-beam oscillograph.
6. Single-beam oscillograph.
7. Line selector.
8. Switchboard and control desks.
9. Instrument leads.

2. For the independent carrying out of a whole series of special tests which require neither an extremely high voltage nor a particularly high power, i. e., investigations in connection with travelling waves (and in particular on the propagation of travelling waves in machine windings), switching and atmospheric over-voltages, lightning arrestors, electric discharges, and, finally, pure high-frequency investigations. To enable such varied tests to be carried out at all, a line selector and 100 lines had to be provided, through which the test set-up can be connected to all of the sources of supply in the other laboratories, if necessary. There are also a number of other sources of supply in the basement which are directly connected to the oscillograph room through 64 kV bushings. Among these is a high-current impulse plant with a total energy of 5 kWs which is capable of supplying currents up to 35,000 A for a short period. Apart from the oscillographs already referred to this laboratory has three fully equipped bays for special tests.

[1] See page 222 of the present number of this journal.

THE REMOTE SUPERVISORY CONTROL LABORATORY.

The applications of communication engineering to the power field have become so numerous in the course of the last few years that the company considered it advisable to create a laboratory of its own. This test room serves chiefly for the development of remote supervisory control, carrier-current telephony, and network control equipment, as well as for other applications of electronic engineering. At first sight it may seem strange that this communication engineering laboratory should be located in the same building as the high-voltage room. When, however, it is realized how closely this field is related to power engineering (we would only recall the transmission of speech over high-voltage lines and the remote regulating problems) and how many fundamental physical problems of the two fields resemble one another in principle (e. g., travelling wave phenomena in connection with the transmission of signals over wires) it will be readily understood why we desired also to make the equipment and research facilities of the other test rooms available to the remote supervisory control laboratory.

This new laboratory has a large Faraday cage with a superficial area of $4 \times 3 \cdot 5$ m and eight roomy and completely equipped test bays, each of which has sixteen selector lines connected to the large line selector in the oscillograph room.

THE WORKSHOP.

In connection with research work it is practically always necessary to be able to set up test equipment and manufacture so-called prototypes of apparatus and gear within a very short time. For this purpose a mechanical workshop exclusively at the disposal of the different test departments and not used for manufacturing purposes in the strict sense of the word, is provided. Due to this arrangement development work suffers the minimum of delay.

(MS 974) *Fr. Beldi and Ch. Degoumois. (E. G. W.)*

THE PRECISION-TYPE QUADRUPLE-BEAM HIGH-VOLTAGE OSCILLOGRAPH.

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A cathode-ray oscillograph with the following chief innovations is described: Four independent beams from a common cathode, four independent deflection assemblies for voltages up to 3000 V, two deflection assemblies for voltages up to 50,000 V, and completely screened 50,000 V lead to cathode.

THE Swiss Association of Electrical Engineers (SEV) and Brown, Boveri & Co., Ltd., were pioneers in the use of cold-cathode oscillographs in Switzerland. As early as 1926 the Baden firm ordered the first Dufour oscillograph in the design and technique of application of which there have been such outstanding advances in the interim. For the new high-voltage laboratory Trüb, Täuber & Co., Zurich, furnished an oscillograph on the same principle, which from the point of view of design and properties probably has no equal in the world (Fig. 1). The instrument in question is of the so-termed multi-beam type, that is, four separate beams are obtained from one single cathode. From their wide experience in the operation of cathode-ray oscillographs Brown Boveri recognized the importance of completely screening the entire discharge tube and the voltage supply lead, to which the multi-beam instrument lent itself particularly well. This was one of the main reasons for the multi-beam design being selected. Moreover, the clean-cut, straight-line beam arrangement of this type also has a marked influence on its precision.

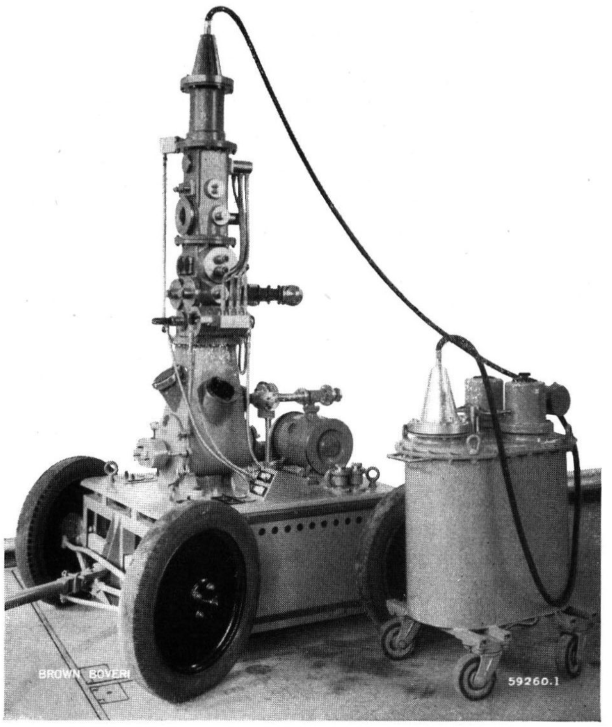

Fig. 1. — The precision-type quadruple-beam high-voltage oscillograph with accessory high-voltage supply equipment. Special features of this new instrument are, inter alia: Four independent beam systems, screened high-voltage d. c. lead to cathode, undercarriage for ease of displacement.

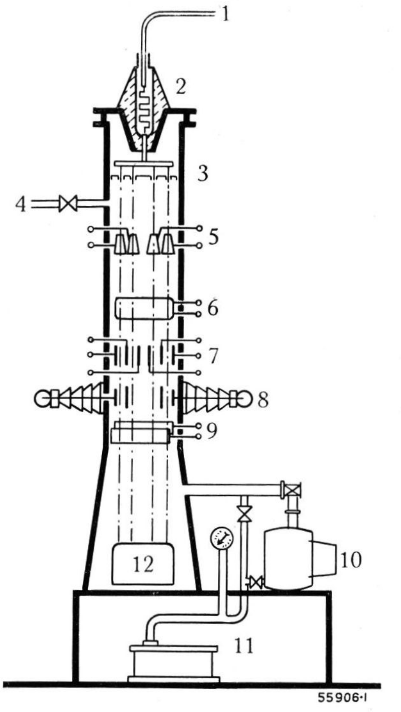

Fig. 2. — Diagram of oscillograph construction.

1. High-voltage lead to cathode.
2. Screened high-voltage lead-in assembly.
3. Discharge tube.
4. Air inlet valve.
5. Beam traps.
6. Focussing coil.
7. Low-voltage deflection plate assembly.
8. High-voltage deflection plate assembly.
9. Time deflection plate assembly.
10. Molecular pump.
11. Rotary vacuum pump.
12. Film box and fluorescent screen.

The construction of the new oscillograph is shown diagrammatically in Fig. 2. Compared to makes of which details are available the following new features have been incorporated: —

The body of the oscillograph is of cast iron which has proved to be highly vacuum-tight and, moreover, acts as an excellent screen against extraneous fields.

A further advantage of cast iron is that its remanence is lower than that of the steel employed hitherto which frequently became permanently magnetized in the vicinity of impulse discharges. The four beam-trap assemblies, which are of completely new design, can each be mechanically adjusted from the exterior to enable the intensity of the beams to be regulated.

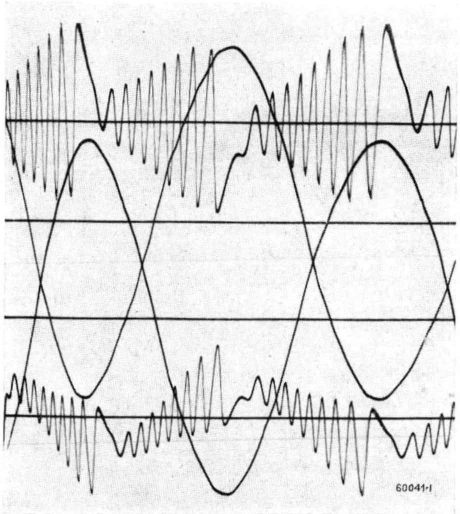

Fig. 3. — Typical oscillogram recorded with new cathode-ray oscillograph (original size 15×15 cm).

A common focussing coil permits all four beams to be simultaneously focussed without rotation. High-voltage deflection plates, as proposed by Brown Boveri and fitted by Trüb Täuber in an oscillograph supplied to the Baden firm as early as 1936, have been retained for the present instrument. In the new design of the two high-voltage deflection plates provided in addition to the usual low-voltage plates, the experience made earlier at Baden also proved very valuable [1].

The design of the parts for creating and maintaining a vacuum inside the oscillograph was also based on experience with preceding models. Rubber packing of round section is employed throughout and the degree of vacuum-tightness attained is so high that, notwithstanding the cubical content of approximately 60 litres, a single molecular pump suffices to give reliable service. As a result, water cooling, which is essential with diffusion pumps, is dispensed with. The high degree of precision of the instrument, as shown by the oscillograms in Fig. 3, is to a large extent due to its compact design and the material employed in its construction for the first time. A detachable under-carriage with standard motor-car wheels permits the apparatus to be readily transported from one place to another.

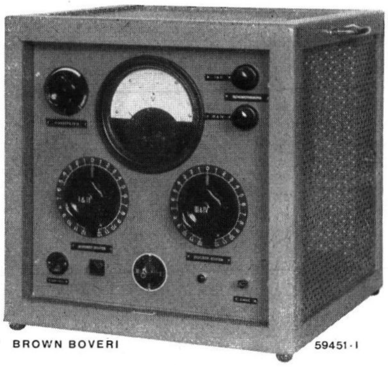

Fig. 4. — Rectifier for supplying zero-shifting and calibration voltages. The apparatus delivers two independently adjustable voltages for zero-shifting or calibration purposes.

An accessory of the oscillograph worthy of mention is a high-voltage rectifier plant for a d. c. voltage of 50 kV which, together with its special rectifier valves, is immersed in a mobile oil tank. The high-voltage is applied to the multi-beam cathode through a screened lead (Fig. 1).

A further rectifier supplies two voltages of any desired polarity, which can be independently regulated to shift the four zero lines. This apparatus can also be employed for calibration purposes (Fig. 4).

(MS 976) *G. Induni, Trüb, Täuber & Co., Zurich. (E. G. W.)*

[1] The Brown Boveri Review 1940, No. 12, p. 252.

THE INSULATION OF MACHINES AND TRANSFORMERS.

Decimal Index 621.3.048:621.313
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Transmission of large powers over considerable distances has led inevitably to the adoption of ever higher transmission voltages. The result is that the demands made on the insulation of transformers and electrical machines have become increasingly severe. In the following article some of the problems of high-voltage insulation and their solution are treated.

A considerable improvement in the insulation, and at the same time a substantial saving of material, was attained by the use of an oil-impregnated insulation between the high-tension and low-tension windings of transformers.

In the construction of electrical machines considerable advances have been made, in spite of the scarcity of mica due to the war, by using suitable synthetic products. Thorough investigations of the insulation in the slots and of the conductors within and external to the slots have been crowned by a noteworthy success. Amongst other achievements, successful voltage tests, according to standards specification and with the usual safety factors, have been carried out on a model of a 50 kV machine.

I. INTRODUCTION.

ACTIVITY in the electrical industry has experienced a tremendous increase in the last decades, due, no doubt, chiefly to the comparative ease with which electrical power can be transmitted and distributed at will to the various consumers. In this respect high voltages are not only employed to advantage for overhead transmission lines, but are also to be preferred, in the other parts of installations, to heavy currents. Switchgear and distribution plants can in this way be built more cheaply and with a reduced liability to damage as the result of short-circuits, while the problems associated with the internal distribution of the currents flowing within machines and transformers are considerably simplified.

High voltages imply high-quality insulation. It is, however, easier to generate high voltages than it is to insulate the windings of electrical machines and transformers for these voltages. This is one reason which induced the electrical industry to carry out extensive research work on insulating materials.

Insulating materials, as an integral part of electrical machines and transformers, have to satisfy the most widely varying demands. On the one hand they have to provide a high degree of electrical insulation between the conductors and the metal frame. On the other hand, all the heat generated in the conductor by the current must usually be led away through the insulation to the iron parts or to the cooling medium. There is thus a clash between diametrically opposed properties of the good insulating material, because poor electrical conductors are also poor heat conductors. Moreover, the stability at high temperatures of the insulating materials most commonly used is generally low, because they are weakened or even destroyed when subjected to temperatures of 120 to 150 °C.

Besides those problems attributable to heat, which arise in connection with all electrical machines chiefly on account of the copper and iron losses, a further complication, from the design and manufacturing point of view, is due to the purely electrical influences. These occur in the form of silent, electrical discharges in undisturbed service or in the case of sudden changes of state (switching operations or disturbances caused by atmospherical phenomena). Such changes of electrical state are not propagated from one point to another instantaneously, but with a certain finite velocity, resulting in potential differences in parts of the plant which can be a multiple of those existing at the service voltage. The steep-fronted voltage waves are particularly dangerous for the first turns and coils next to the terminal connections of machines and transformers. Excessive voltages can also occur, however, in the middle and at the end of phase windings due to the subsidiary effect of the inductance and capacity of the windings.

In undisturbed service the generation of heat in the insulation itself must receive attention in addition to the heating of the windings. Every insulating material, when subjected to an alternating field, absorbs a certain proportion of the electrical power, which is transformed into heat in the dielectric. By a simple transformation of the equation for the power in alternating current circuits, $P = E \cdot I \cdot \cos \varphi$ we can represent these losses by the following equation:

$$\underline{P = E^2 \cdot \omega \cdot C \cdot \tan \delta}$$

In this formula E is the voltage, ω is 2π times the frequency, C the capacity and $\tan \delta$ the factor of loss. The angle δ is the complement of the phase displacement angle φ. C can be represented by two factors, the dielectric constant ε and the constant C_o, which may be called the geometric capacity. The latter takes into account the shape of the insulator, when this is considered as a condenser. According to definition $C = C_o \cdot \varepsilon$ and thus

$$\underline{P = E^2 \cdot \omega \cdot C_o \cdot \varepsilon \cdot \tan \delta}$$

In other words, for given values of E and ω, and for a given shape of the insulator, ε and $\tan \delta$ are the material properties which determine the dielectric losses. The product $\varepsilon \cdot \tan \delta$ is called the coefficient of loss.

The dielectric losses of almost all insulating materials are dependent on the temperature. This dependence can be the cause of a puncture of the dielectric. Temperature and dielectric losses can rise due to mutual support until a weakening or even carbonization of the material takes place. The result is an electrical breakdown. It can be proved with the aid of the "heat puncture" theory,[1] and tests have also confirmed this fact, that the voltage which can be continuously held by a dielectric is independent of the thickness of insulation. A given insulating material only holds a definite voltage, of which the value is dependent simply on its thermal and electrical properties.

The theory of insulation breakdown due to the heating effect is only valid for a puncture of the insulation after a long period of stressing and at comparatively high temperature. In the case of short stressing times and especially for impulse stressing, the theory of ionization by impact, by which occurrences, not only in gaseous insulating materials, but also in liquid and solid materials can be explained, is of special interest. A detailed description would, however, exceed the limits imposed on this article.

II. TRANSFORMER INSULATION.

1. INSULATION BETWEEN WINDINGS.

The insulation between the windings connected to different parts of a network system, that is to say between the high and low-tension windings in the case of a two-winding transformer, was from the beginning the most important problem in the development of transformer design. It is interesting to note that modern insulating materials were also already represented in the years during which high-voltage transformers were being developed. The *thick insulating paper* used for the principal insulation was nevertheless soon laid aside. Its place was taken by *bakelized paper cylinders* which at first filled up the entire insulation space between the high and low tension windings. Difficulties with these cylinders, which were glued with a *synthetic resin,* led finally to an alteration in the arrangement of the insulation. *Oil* became the *principal insulating agent,* and the *cylindrical shells with thinner walls* were used *only as partitions* to subdivide the oil space. Detailed investigations led in the year 1927 to the adoption of the so-called "cylinder-cap" insulation. A considerable reduction of weight for the same output resulted from this construction, which proved itself over a number of years.

This insulation could not, however, be compared, as far as thickness of insulation was concerned, to the *oil-impregnated paper insulation* of extra-high-voltage cable. In principle, nothing seemed to stand in the way of adopting oil-impregnated paper insulation. Practical considerations, however, made it appear desirable to clear up certain questions by means of tests. In the case of the previously employed "cylinder-cap" arrangement, the heat generated in the dielectric was carried away by the oil itself. In contrast to this, the heat due to losses in this new type of insulation can no longer be directly led away. The flow of heat now takes place radially and the heat is for the most part transferred to the windings. Consequently, similar phenomena to those in solid dielectrics are to be expected. For these reasons we have undertaken a careful investigation of the electrical breakdown of oil-impregnated paper insulation due to heating effects. In this article we shall only refer to a single series of tests, since paper as a high-voltage insulating material is treated elsewhere[2]. Fig. 1 illustrates the remarkable

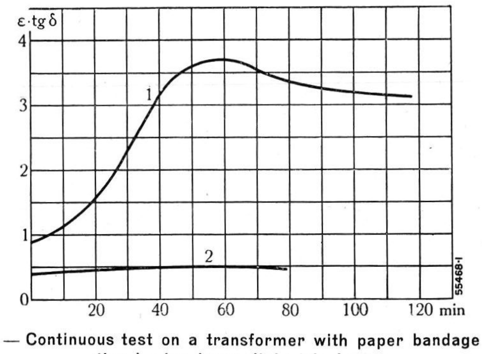


Fig. 1. — Continuous test on a transformer with paper bandage insulation having large dielectric losses.

The coefficient of loss is plotted in function of the time.
1. First test run at a constant a. c. voltage of 90 kV.
2. Second test run at the same voltage of 90 kV.
Oil temperature constant at 90° C.

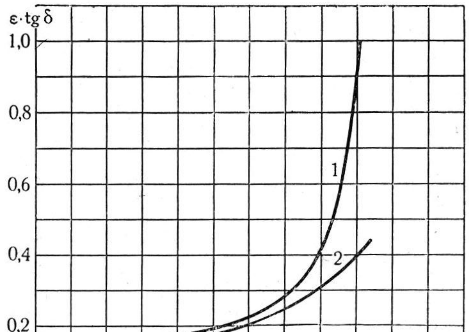


Fig. 2. — Variation of the coefficient of loss with the temperature of a transformer with paper bandage insulation having large dielectric losses.

1. Coefficient of loss measured before the test run of Fig. 1.
2. Coefficient of loss measured after the second test run of Fig. 1. An obvious improvement has taken place.

Test voltage constant at 35 kV.

[1] The Brown Boveri Review 1926, p. 115.

[2] See page 235 of the present number of this journal.

fact that paper bandage with high dielectric losses undergoes a spontaneous improvement. Shortly after being placed under voltage, the coefficient of loss increased due to the temperature rise and reached a maximum after one hour. The considerable increase in the coefficient of loss was accompanied by a rise of temperature within the dielectric. The course followed by the temperature results in a substantial reduction, as shown in Fig. 2, of the influence of the temperature on the coefficient of loss. A subsequent sustained test with the same stressing elapsed without appreciable temperature rise (see Fig. 1).

The *oil* in transformers plays an important double role as *cooling and insulating medium.* The corresponding investigations are therefore the subject of a detailed treatment in a special article[1].

Apart from oil, *compressed gas,* especially compressed air, has been used recently as an insulating medium. Investigations in the sphere of instrument transformer construction[2] have been crowned by success, for in addition to an improvement in the properties essential for metering purposes, an insulation, which is in practice non-inflammable, is obtained.

2. END SPACING.

The question of insulation at the ends of the windings is, in comparison to the problem of the breakdown of oil-impregnated insulation due to the heating effect, more difficult to solve. As a result of the great field strength in the inhomogeneous boundary region, and above all on account of the tangential direction of the field, surface discharges start to occur at low voltages. But in this case also, detailed research has produced an ingenious solution. End-insulation free of discharge effects has been obtained by adopting a special shape of the insulating body. The new development has allowed a considerable reduction in the thickness of insulation between high and low-voltage windings. This means nothing less than a reduction of the stray flux in the gap between the windings and consequently a reduction of the iron cross-section is possible. The total weight of a transformer for equally good or even better performance is thus smaller. In order to illustrate the points just described, reference may be made to Fig. 3, which shows a comparison between the weights of a transformer with "cylinder-cap" insulation and one built to the new design. Special attention is drawn to the extraordinarily large reduction, i. e., 35 %, in the weight of the transformer alone without oil. The reduction in the weight of oil amounts to 19 %.

[1] See page 240 of present number of this journal.
[2] See page 244 of present number of this journal.

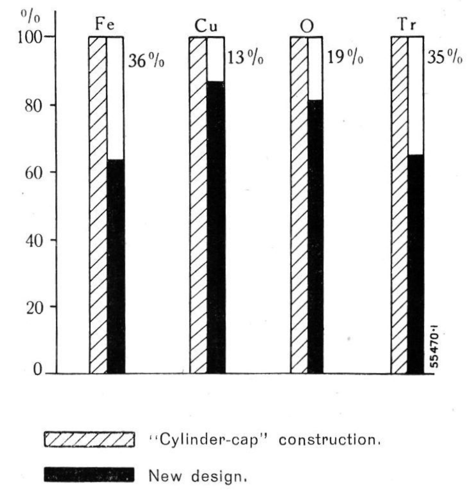


Fig. 3. — Reduction in weight and consequent saving of raw materials due to use of a modern type of insulation for a 20,000 kVA transformer for a service voltage of 150/20 kV in comparison with the old design with "cylinder-cap" insulation.

Fe. Iron. Cu. Copper. O. Oil. Tr. Transformer without oil.

The new type of insulation between windings possesses an excellent resistance to breakdown by puncture. This is best illustrated by a few figures. During tests on models of the old "cylinder-cap" design, radial punctures due to a. c. stressing could be observed. For example a breakdown of the old insulation occurred at 280 kV, the thickness of the insulation being 65 mm. On the other hand it was impossible to cause a breakdown on a model of the new type of insulation, which was likewise made to correspond to actual conditions, although the insulation was only 11 mm thick ($^1/_6$ of the former). Even in the case of stressing due to a voltage impulse of 530 kV, this model showed no radial breakdown; indeed no case of a radial puncture of the dielectric either for alternating current or impulse stressing could be recorded during the numerous investigations on models of the new type of insulation.

3. INSULATION BETWEEN TURNS.

The insulation between turns was also the subject of detailed investigations. Attention has already been drawn to the increased stressing of the turns and coils, chiefly at the outer end of the windings, due to steep-front voltage waves. Measurements were consequently extended to the investigation of the disruptive strength in the presence of voltage impulses.[3]

Some of the results of the extensive tests are summarized in Fig. 4. For stressing times below about 15 μs, and especially for small distances between electrodes, the breakdown strength of the oil increases rapidly. The breakdown strength in the case

[3] See page 275 of present number of this journal.

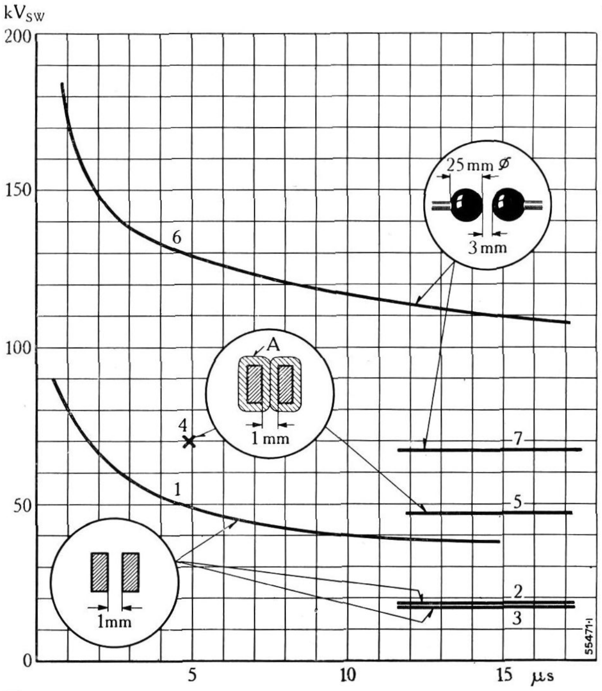


Fig. 4. — **Breakdown voltage (peak) of pure oil and paper insulation in transformer oil for various kinds of voltage stressing.**

1, 4, 6. Stressing by impulse voltage.
2. Stressing by d. c. voltage.
3, 5, 7. Stressing by a. c. voltage.
A. Paper insulation.

of a voltage impulse reaches two to five times that for alternating current. For paper-insulated wires, as shown in Fig. 5, the thickness of the oil layer between the wires has a smaller influence the thicker the paper insulation.

Detailed attention was also devoted to the reduction of breakdown strength for impulse voltage stressing due to ageing or alteration of the insulation. Paper-insulated wires in oil were subjected to voltage impulses of standard wave form (1·0/50 μs), the

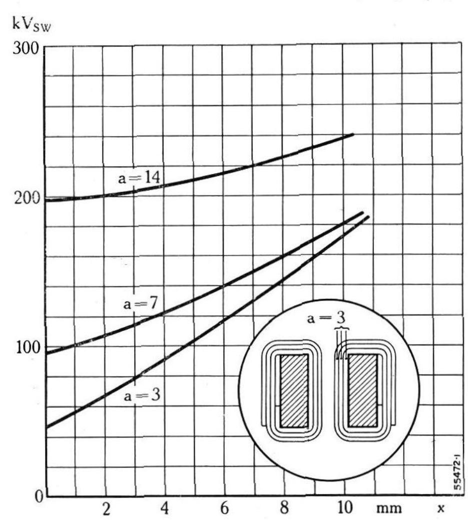


Fig. 5. — **Breakdown voltage (peak) in function of the spacing of wires, with a = 3, 7 and 14 layers of paper insulation, respectively, in transformer oil; stressing by impulse voltage.**

number of impulses for each point measured varying between 1 and 6000. The following values were observed, for example, in the case of insulation consisting of four layers of paper:—

Number of impulses per test value	1	10	100	1000	6000
Breakdown voltage kV . . .	57–60	57–59	57–61	54–57	52–61

The differences are, indeed, to be ascribed to straying of the breakdown values rather than to the influence of the voltage stressing. The conclusion to be drawn from the results is therefore that the preliminary stressing has no influence on the breakdown strength.

III. INSULATION OF MACHINES.

1. SLOT INSULATION CONTAINING MICA.

(a) *Dielectric Losses.*

The slot insulation is the most highly stressed insulation in electrical machines. It has therefore always been the subject of repeated and detailed investigations. The chief ingredient, and at the same time the part most resistant to heat, is mica, which is glued in thin sheets to a paper base by means of a suitable lacquer. Careful investigations have shown that the quality of the lacquer has the greatest influence on the magnitude of the dielectric losses, that in addition the paper quality plays a part, and that finally the percentage of the basic materials present must not be neglected. Shellac, which was originally used, has not proved a success at high temperatures. Fig. 6 shows the coefficient of loss

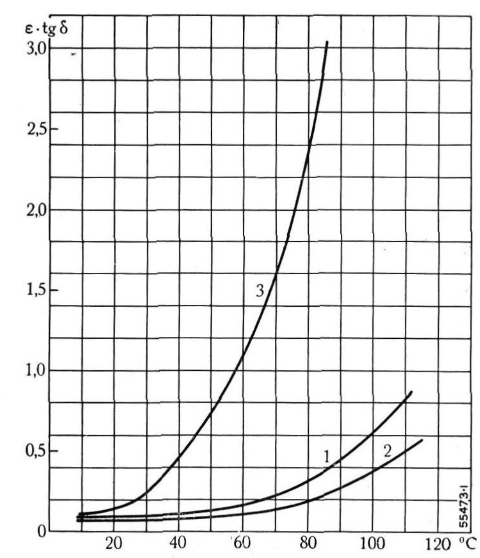


Fig. 6. — **Variation of the coefficient of loss in function of the temperature for various types of slot insulation.**

1. Previous construction.
2. Construction according to a new method of manufacture.
3. Shellac insulation.

for shellac insulation in function of the temperature in comparison to the well-tried insulation introduced by us some years ago, for which a lacquer of the compound type is used as adhesive. As mentioned in the first section, the dielectric losses, especially the coefficient of loss and its dependence on the temperature, are of decisive importance for continuous stressing of the insulation. It is therefore natural that systematic research work is repeatedly devoted to the reduction of these factors. Attempts were also made to achieve better results with the same components by varying the preliminary treatment and by employing appropriate manufacturing methods. As shown in Fig. 6, the extensive investigations were rewarded by a complete success. In this respect, it must be emphasized that the reduction of the losses has no practical influence on the efficiency of the machine. The dielectric losses of a 100,000 kVA alternator with a rated voltage of 13 kV only amount to 0·025% at the normal operating temperature. The losses are consequently only of significance in relation to the temperature equilibrium in the insulation in continuous operation; in this respect, however, they are of great importance.

(b) *Glow Discharge in Air Layers.*

In addition to the above-mentioned problems, which are more of a thermoelectric nature, discharge phenomena in thin layers of air were also studied. From an electrical point of view, air is weaker than the solid insulating materials, and if air pockets in series

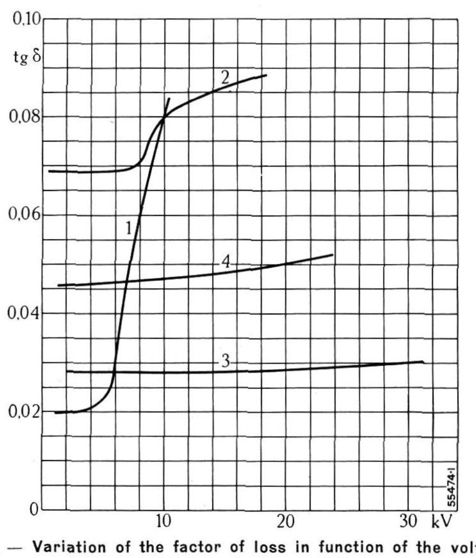


Fig. 7. — Variation of the factor of loss in function of the voltage for some types of slot insulation.

1. Insulation of an 8·5 kV machine after 26 years' service.
2. Insulation of a 15 kV machine after 24 years' service.
3. New type of insulation with 50 % mica.
4. New type of insulation, but without mica.

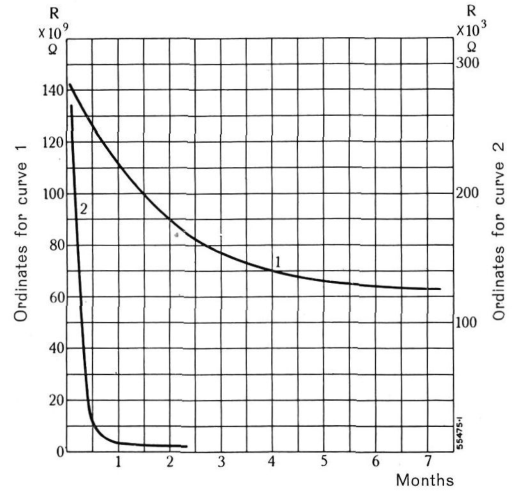


Fig. 8. — Influence of moisture on the insulation of machines.

D. C. resistance *R* in function of the time for storage in air with a relative humidity up to 97 %.

1. Slot insulation containing mica. 2. Lacquered presspahn.

with the latter are subjected to the action of an electric field, they have to withstand a much greater stress than the surrounding solid insulating material. The stressing can indeed be so great that the air layers break down and consequently become conductive.

This process is known as ionization by impact. Measurements on a model show that the field strength at which a glow discharge commences, depends on the thickness of the air layer. By the application of high pressures during the manufacture of insulation composed of layers, the air can be pressed out to such an extent that it is no longer a source of danger for the normal service stressing. The curve of the factor of loss, tan δ, in function of the voltage gives an indication of the quality of the dielectric. Dielectrics containing a considerable quantity of air have a characteristic as shown in curves 1 and 2 of Fig. 7, while curve 3 shows the behaviour of modern slot insulation containing mica. Generally speaking the effect of air pockets is over-estimated. Even insulation, which, judging by the voltage characteristic, contains a considerable number of air layers, has withstood the electrical stressing for decades without breakdown of the slot insulation occurring.

(c) *Influence of Moisture.*

High-voltage insulation is easily affected by moisture if special precautions are not taken (moisture-proofing, special lacquer). It is not always possible to attain such insensitivity from the outset by the application of such measures. The erection of alternators in moist surroundings and long idle periods are practical examples of cases in which damp weather can produce troublesome effects. In order to gain an insight into these conditions, conductors of a 10 kV alternator were built into an iron core corresponding to practical conditions, and were then exposed continuously to an atmosphere of high relative humidity (up to 97 %). The curve of d. c. resistance in function of the time, as shown in Fig. 8, is witness to the penetration of moisture into the insulation. Especially the slot lining of lacquered presspahn absorbed a large quantity of moisture in a short time. The measurement of the d. c. conductivity at high voltages also indicated that the insulation had become moist (see Fig. 9). What is surprising is the fact, proved by Table I, that the deciding dielectric factor, the coefficient of loss, was not influenced at all by the long storage in moist air. The absorption of moisture by this insulation is accordingly so small that it can only be detected by d. c. measurement.

TABLE I.

Influence of Moisture on Slot Insulation containing Mica.

Coefficient of loss at 50 cycles.

Condition of Insulation	$\varepsilon \cdot \tan \delta$
Initial condition at 20° C	0·18
Measurement at 100° C	1·07
After warming, measured at 25° C . .	0·18
After 6½ months' storage in moist air	0·17
Measurement at 100° C	1·05
After warming, measured at 25° C . .	0·16

A comparison with a typical hygroscopic insulation also confirms this conclusion, since bakelized paper insulation yields the characteristic curves of an insulation containing moisture (Fig. 10).

2. SLOT INSULATION WITHOUT MICA.

The long duration of the war is leading to a shortage of certain insulating materials. One of the most important of these in the electrical engineering industry, mica, has to be replaced by suitable materials wherever possible on account of the fact that it comes from overseas. The new substitutes have also been used for slot insulation, that is for an insulation of which the chief constituent was formerly mica. Fig. 11 shows curves of the coefficient of loss in function of the temperature for materials which were investigated and which come into consideration as slot insulation.

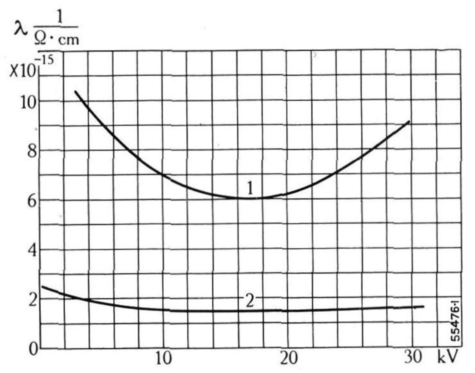


Fig. 9. — Influence of moisture on slot insulation containing mica.

D. C. conductivity in function of the voltage.

1. After 7 months' storage in moist air.
2. After heating up to 100° C at the end of 7 months' storage.

Measurements in the cold state.

Cellulose triacetate, which has been used, especially in other countries, as a substitute for mica, exhibits practically the same small losses as the slot insulation containing mica which was formerly employed. Investigations have shown, however, that this material yields acetic acid in the presence of heat, a disadvantage peculiar to all cellulose acetates. Better results were attained in this respect with a moulded insulation consisting of special paper impregnated with an asphalt lacquer. Although the coefficient of loss is rather larger than in the case of moulded "Triafol", the moulded impregnated paper insulation possesses a much better resistance to the effects of a continuous glow discharge (see Fig. 12). In this connection it may be mentioned that similar observations regarding "Triafol" were also made in other countries, and that attempts were made to overcome this weakness by employing gas under pressure in alternators.

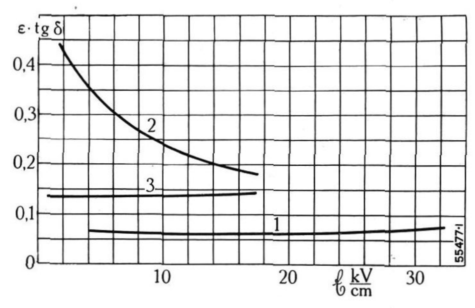


Fig. 10. — Influence of moisture on various insulating materials.

Dependence of the coefficient of loss on the field strength: a. c. tests.

1. Slot insulation containing mica after 7 months' storage in moist air (rel. humidity up to 97 %).
2. Bakelized paper insulation in moist state.
3. The same insulation after drying in hot air. The bakelized paper insulation was not protected from absorption of moisture by the usual lacquer coat.

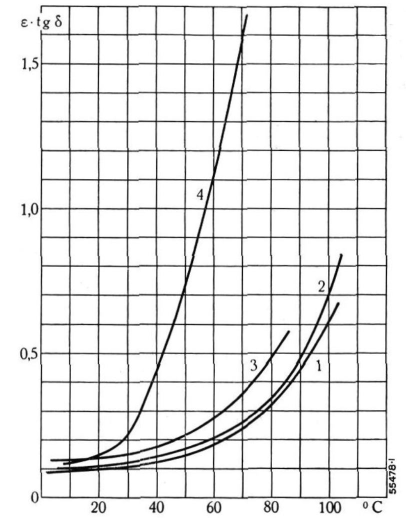


Fig. 11. — Dependence of the coefficient of loss of various types of slot insulation on the temperature.

1. New insulation containing mica.
2. Insulation of triacetate.
3. Insulation treated with a lacquer of an asphaltic nature but without mica.
4. Ordinary shellac insulation.

For electrical machines an insulation with the greatest possible elasticity is desirable, especially on account of the large mechanical stresses to which the windings are subjected during current impulses of a short-circuit nature. The finest cracks, invisible to the eye, can lead to a breakdown of the insulation under service conditions. By skilful arrangement of the tests, it is possible exactly to judge and select the materials accordingly. The particularly clear results of one pair of tests may serve to show that the above-mentioned insulation containing no mica is not only in no way inferior to that containing mica, but indeed, as far as flexibility is concerned, even superior. During the two tests, which were extended to the point where the insulation suffered a mechanical or electrical breakdown, the voltage was kept at 20,000 V. Measurements were made, as shown in Table II, for cold and warm insulation.

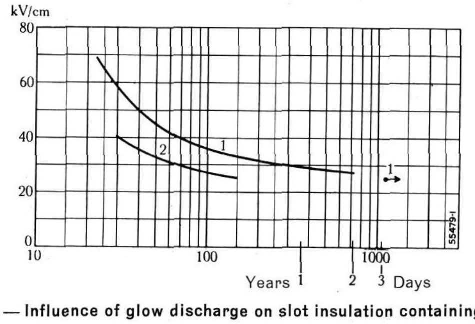


Fig. 12. — Influence of glow discharge on slot insulation containing mica.
Breakdown strength in function of time.
The test pieces were subjected to a continuous, excessive a. c. stressing until breakdown occurred.

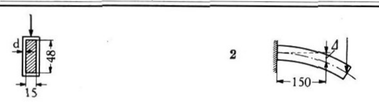
1. Special paper treated with lacquer of an asphaltic nature.
2. Triacetate insulation.

Only the results of the more unfavourable direction of stressing are given. The insulation can withstand much more when the force acts perpendicular to the flat side of the test piece.

TABLE II.

Bending Tests on Bars having Insulation with and without Mica.

Insulation	Thickness of insulation d[1] in mm	Test temperature °C	Maximum sag Δ [2] in mm
without mica	2·83	18	10·4
	2·95	18	12·0
	2·98	100	17·1
	3·03	100	24·0
with mica (50 %)	2·78	18	6·9
	2·84	18	5·6
	2·87	100	14·4
	2·88	100	20·7

1  2

The comparatively high electrical strength of the insulation without mica is also worthy of note. According to Table III it amounts to more than 80 % of the breakdown strength of the bars with mica insulation.

TABLE III.

Breakdown Field Strength in r. m. s. kV/cm for some Types of Slot Insulation.

Test bar and insulation	1 min. test voltage	Test voltage for rapid voltage increase
Special bar (homogeneous field) K-Fol (with mica)	—	380
Normal bar K-Fol	240	270
Normal bar Triafol	—	230
Normal bar C-paper	200	220
Oil cable (as comparison)	—	450

The cable industry reckons, indeed, with still higher breakdown strengths, but careful research work, of which the results may only receive mention here, shows that the difficulties in the case of electrical machines are attributable less to breakdown strength than to flash-over at the point where the windings leave the slot.

3. END OF SLOT.

Just as cable end boxes are used at the ends of cables to prevent flash-overs, so must every conductor be protected in a suitable manner at the point where it emerges from the slot. The difficulties are, it must be admitted, incomparably greater than in the case of cable, because the problem is rendered more

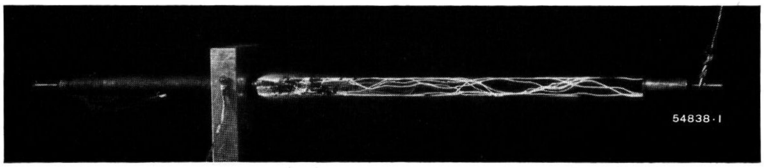


Fig. 13. — Flash-overs on a test conductor of a 50 kV machine.

The left hand end is provided with protection against glow discharge. No discharges occur even at 120 r. m. s. kV. The right-hand end with three times the insulating length, but without glow discharge protection, is subject to violent flash-overs.

difficult by the limited space available and the mechanical stressing of the insulation due to changes of length caused by temperature variations. Three examples may serve to show that our investigations have produced excellent results.

In connection with developmental work on insulation for a turbo-alternator for 36,000 V service voltage, a full-scale model of the stator windings was made. New measures were developed to suppress glow discharge at the exit from the slots. In the course of 40 successive one-minute voltage tests at 72,000 V no visible or measurable alterations could be observed. After storage for ten years in a room in which the model was exposed to heavy dust and the natural humidity of the room, the voltage test was repeated without a previous drying out and after simply removing the coarsest dust layer from the windings. For all that, the model again withstood the voltage test at 72,000 V. This test provided in addition a further confirmation of the observation recorded under 1c, that the decisive dielectrical factors are hardly affected by the action of moisture over lengthy periods.

Recently the investigations aiming at attaining higher alternator voltages were continued. In this direction also, as Fig. 13 shows, noteworthy advances were made. The left-hand end of the rod is provided with the improved protection against glow discharge and, in spite of its considerably shorter length of insulation in comparison to the right-hand end, it shows no discharges. The newly developed protection against glow discharge is also particularly effective in the case of impulse voltage stressing, a fact illustrated by Table IV.

Within the limits set for this special number it is impossible to treat exhaustively these problems of insulation for electrical machines. For the sake of completeness, reference may be made to the behaviour of complete machines in relation to voltage impulses and especially to the coordination of their insulation.[1]

[1] See page 286 of the present number of this journal.

TABLE IV.

Flash-over Voltage of Alternator Conductors with and without Protection against Glow Discharge for Impulse Voltage Stressing.

		Without discharge protection	With discharge protection
Impulse wave 1·0/50 μs	Positive polarity	60 kV peak	120 kV peak
	Negative polarity	68 kV peak	95 kV peak

4. WINDING SUPPORT.

Not only the slot ends, however, present interesting problems of breakdown voltage strength at the surface of the insulation. For the support of the windings external to the slots between iron and windings and between the windings themselves, attention must be paid to the mechanical strength of the supports as well as to their electrical insulation. It is one of the tasks of the designer to select the most suitable material from those entering into consideration, these

TABLE V.

Temperature Limit and Breakdown Strength of some Insulating Materials.

Material	Temperature limit in °C	Breakdown strength[1] in r. m. s. kV/cm
Luvikan	< 150	130
Bakelized paper	about 150	90
Impregnated hard wood .	> 150	50
Asbestit	> 150	13

[1] Material in layers, in the direction of the layers.

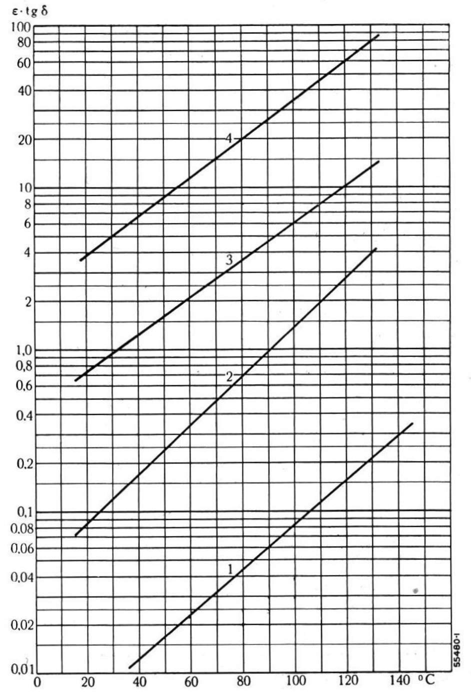


Fig. 14. — Coefficient of loss of various insulating materials in function of temperature.

1. Luvikan.
2. Bakelized paper.
3. Impregnated hard wood.
4. Asbestit.

often having widely divergent properties. That this problem is not always easy to solve may be seen by comparing the results shown in Fig. 14 with those of Table V.

Luvikan, for example, combines the smallest dielectrical losses with the lowest temperature limit. On the other hand Asbestit has the highest temperature limit and the lowest breakdown strength. There are many high-quality insulating materials, but if the application makes some special additional demands, in this case, for example, high mechanical strength at elevated temperatures, the number of suitable materials is reduced enormously. A generally applicable insulating material is unknown in the electrical industry.

5. TURNS INSULATION.

In one of the previous sections the behaviour of some types of slot insulation with regard to glow discharge was discussed. In recent years we have also investigated the turns insulation anew, and have at the same time studied the glow-discharge properties of the insulation. In the case of the slot insulation there were thin air inclusions in the layers of mica in which glow discharges, although not at all of a dangerous nature, could occur. For the insulation of the turns large air pockets, especially between the individual wires, cannot be avoided for reasons connected with manufacture. In the presence of the high voltages employed to-day, these air spaces can be overstressed to such an extent that ionization by impact takes place. Our investigations on the most widely varying materials, which cover a period of several years, have produced in part quite unexpected results. The investigations were carried out on models such as shown in Figs. 15 and 16 f, respectively, the models having been made to correspond to the conditions actually encountered in practice. The test pieces were surrounded by a bakelized paper tube representing the slot insulation. By means of suitable terminations at the ends of the tubes as well as by connecting the latter to pumps and heating appliances, it was possible to imitate the most widely varying service conditions. In normal service, defects due to glow discharge first make themselves felt after stressing for many years. In order to obtain results within a reasonable time it is necessary to increase the stressing to a point far above that occurring in normal service. The models were therefore subjected to a voltage of 9 kV, a value

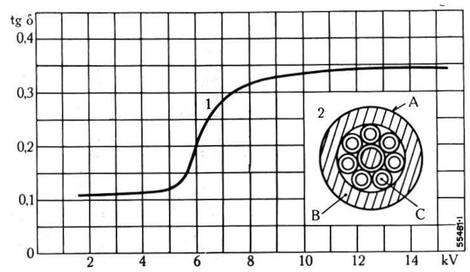


Fig. 15. — Test model for investigating the influence of glow discharge on wire insulation.

1. Dependence of the factor of loss on the voltage.
2. Section of test model (A = earthed metal covering. B = 3 mm thick bakelized paper tube. C = test wires under voltage.)

at which, according to Fig. 15, a considerable glow discharge takes place in the air layers. Since the primary object of the tests was to eliminate unsuitable materials, that is to say only the relative values were of interest, this extreme stressing could be chosen without hesitation.

In a series of tests with bar-type conductors, quite striking differences in the kind and extent of damage were observed, Fig. 16 shows clearly that the extensive destruction is influenced mainly by the metal conductor. On the copper conductor (illustration a) a considerable quantity of copper salt was formed, in this case copper nitrate $Cu\ (NO_3)_2$ and not verdigris which is a basic copper acetate. The formation of rust on the iron conductor (illustration b) was greatly furthered by the violent ionization. If the access of air is completely prevented, i. e., if there is no renewal of the air, the paper insulation and metal conductor remain intact.

Equally interesting results were obtained from another series of tests which were devoted especially to the study of the pretreatment of the material. The models were again continuously subjected to an a. c. voltage of 9 kV. Fig. 17 shows the test pieces after forty days under voltage, the insulation of paper and cotton being in every case the same as previously used. Of special interest is the test represented by illustration b, in which case a slight ventilation was maintained during the test. The spun covering was cut through due to bombardment by the ions, and all paper layers were punctured. In a quite unexpected manner, as shown in illustrations e and f, completely soaked insulation was practically unaffected. Neither the cotton covering (illustration e) nor the paper insulation and the conductor (illustration f) were destroyed. Such striking differences show what possibilities in the treatment of the material are open to the research engineer.

Fig. 16. — Influence of the conductor material on the glow discharge strength of wire insulation.

a. Copper conductor, model strongly ventilated during test.
b. Iron conductor, model strongly ventilated during test.
c. Iron conductor, non-ventilated during test.
d. Bakelized paper tube coated with lamp-black, model strongly ventilated during test. (a—d, conductors with unimpregnated covering of paper insulation.)
e. Covering of presspahn.
f. Test model.

Fig. 17. — Influence of pretreatment on the glow discharge strength of paper insulated wires.

Model	Pretreatment	Conditions of test
a	Dried at 110° C for 24 h	No ventilation
b	Dried at 110° C for 24 h	Weak ventilation
c	Stored for 6 days in surroundings of 100% humidity	No ventilation
d	Untreated	No ventilation but continuously 100% moist
e, f[1]	Immersed in water for 48 h	No ventilation

[1] e = complete insulation.
f = cotton covering removed after test "e".

As conclusion to this section, some test results may be mentioned which illustrate the success of the above-mentioned investigations. The tested material of cotton and paper consists mainly of cellulose, a highly polymerized natural product. Under the influence of the severe stressing by glow discharge, highly active reagents such as ozone and oxides of nitrogen are liberated in the air layer. The cellulose, which is normally comparatively stable from a chemical point of view, is destroyed by the action of these oxidizing agents when unprotected, an oxycellulose being formed. It may be seen from the diagrams in Table VI that the time for the first signs of destruction to become visible can be increased by about ten times by special treatment of the insulation and of the conductor.

TABLE VI.

Glow Discharge Tests on Wire Insulation for Various Kinds of Pretreatment.

Material and pretreatment	Time after which destruction due to strong glow discharge was observed
Cotton insulation	6 days
Usual insulation of paper and cotton without impregnation	11 days
As for 2 but suitably impregnated	7 weeks
Lacquered special paper. Conductor pretreated	4 months

It was naturally not only necessary to consider such phenomena in the stationary state, that is to say the stressing of the insulation due to glow discharge in continuous service, but also the breakdown strength. It was mentioned in the first part of this article that the turns insulation can also be subjected in service to severe stressing by voltage impulses. Importance was therefore attached to increasing the breakdown strength for short-time stressing, i. e., for voltage impulses. Table VII as last example serves to show that diametrically opposed properties are also possible in this case.

TABLE VII.

Resistance to Glow Discharge and Breakdown of Two Kinds of Wire Insulation.

Material	Breakdown strength (r. m. s. kV/cm) ⟼ Glow discharge strength (days) ■
Paper insulation impregnated with a mixture of paraffin and fatty acid.	550 13
Paper insulation treated with special lacquer.	310 61

6. EFFECT OF IMPROVED INSULATION ON ALTERNATOR CONSTRUCTION.

The quantity of insulating material employed is considerably greater than usually estimated. For an alternator with a rated voltage of 7 kV, for example, the slot insulation in which the copper is laid occupies more than 50 % of the slot volume. The interest in reducing this figure is due not only to the saving of expensive insulating material, but even more to the consequent *increase in output* attainable. A reduction of the thickness of insulation by 1 mm, in the case of a machine with the rated voltage cited above, results in an increase of the output of a given size of machine by about 20 %. In view of the fact that modern machines with a rated voltage of about 15 kV have an insulation thickness of about 4 mm, in contrast to a thickness of 7·5 mm for the first 13 kV machines, there is every justification for claiming that considerable progress has been made in the insulation of electrical machines.

(MS 975) *Fr. Beldi. (D. S.)*

PAPER AS HIGH-VOLTAGE INSULATING MATERIAL.

Decimal Index 621.315.614.6.027.3

In the first place the shape of the paper test specimens, which must be employed for the scientific investigation of their properties, is discussed. In the next part the author describes the physical process for the preparation of paper test pieces and complete transformers. The results of the tests on papers pretreated in this manner are favourable. Angles of loss of about 0·006 at 90° C were observed and from the dielectrical values measured critical voltages of 1200 kV at 20° C and 700 kV at 90° C calculated. The example of paper insulation in and permeated by compressed air is a further illustration of the favourable influence of a high-quality material for impregnating paper. The practical importance of the test results communicated is only revealed to its full extent when the influence of the insulation on the size and quality of high-voltage machines is taken into consideration.

THE investigation and determination of the properties of the paper alone and in conjunction with impregnating substances, such as mineral oil and gases under pressure, has become an equally important and many-sided work in view of its great importance as an insulating material in high-voltage engineering.

Testing begins with the critical

selection

of the paper to be used as insulating material. It is generally made from wood pulp prepared by careful and not excessive grinding, in such a manner that the fibres are not damaged. The so-called soda or sulphite papers, named according to the chemical preparation, come into consideration.

The shape,

in which the paper chosen is to be tested, is determined by the experimenter on the basis of his experience and intuitive skill. For investigating the specific properties of the material, for example, cylindrical or flat models — the advantage lying with a large number of small, easily manipulated ones — are to be preferred. Other influences can, on the other hand, be investigated best with specimens of great length or thickness, or even with complete models of the insulating arrangements of machines and especially of transformers. It is certainly difficult, and in many cases absolutely impossible without the adoption of special shapes, to cause a breakdown of a model consisting of a thick paper insulation in a homogeneous field, because the high voltages necessary to puncture the insulation produce a flash-over or surface discharges which destroy the insulation prematurely.

Since theory and test show to what a great extent the electrical properties of a given kind of paper and impregnating agent are dependent on the pretreatment, the insulating material is subjected to an additional, special physical

preparation.

By this is to be understood the physical process characterized by pressure, temperature, and time. The purpose of the process is to dry the material and to remove the gases. In the case of oil there is the additional possibility of increasing the surface by atomization.

The best process was not only found experimentally, but its effects were also analyzed mathematically. As is to be expected, for example, paper can only be warmed

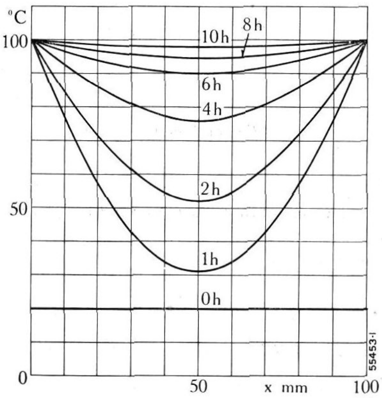


Fig. 1. — Temperature distribution in a paper board (100 mm thick) heated on both sides at 100°C after 1, 2, 4, 6, 8 and 10 hours.

Initial temperature 20°C. After 8 hours the temperature in the middle of the board has reached 95 % of the ambient temperature. Paper boards can, on account of their low thermal conductivity, be heated only very slowly during pretreatment since the penetration of the heat requires time.

up very slowly, because it belongs by virtue of its extremely low "temperature conductivity" to those heat insulators which present the greatest resistance to the *penetration of heat* when warmed externally. As an example, Fig. 1 shows the temperature distribution in a paper board 100 mm thick which is heated on both sides at a temperature of 100° C, the time being chosen as parameter for the individual curves.

The temperature distribution in function of time and position is determined by the following formula:—

$$\vartheta = 100 - \frac{320}{\pi}\left[\text{sine}\left(\frac{\pi}{s}x\right)e^{-0\cdot 37t} + \frac{1}{3}\,\text{sine}\left(\frac{3\pi}{s}x\right)e^{-3\cdot 33t} + \frac{1}{5}\,\text{sine}\left(\frac{5\pi}{s}x\right)e^{-9\cdot 25t} + \ldots\right] \quad (1)$$

where ϑ = Temperature in ^{0}C.
t = Time in hours.
s = Thickness of board = 100 mm.
x = Distance of a layer from the left-hand surface.

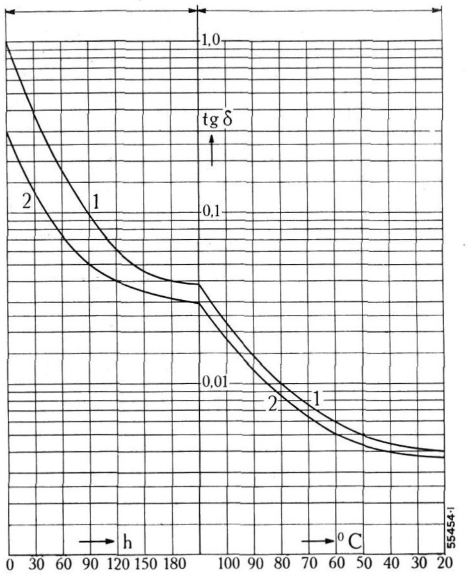


Fig. 2. — Angle of loss of two grades of insulating paper.

On the left in function of the drying-out time at 110 °C, on the right in function of the temperature during cooling. The shape of the curves on the left shows the considerable reduction of the angle of loss during drying, due consideration being given to the logarithmic scale of the ordinates. The further reduction shown by the right-hand curves is due to the temperature drop during cooling.
1. Porous paper. 2. Dense paper.

The favourable results obtained by means of *suitable preparation* are illustrated clearly in Fig. 2. The left half of this diagram shows the variation of the angle of loss during the drying out of a paper bandage in a hot-air oven at 110 ^{0}C for two different kinds of paper. The curves to the right of Fig. 2 show the further reduction of the angle of loss when the paper is cooled down to room temperature after completion of the drying process.

Fig. 3 shows the supervision of the *pretreatment process* under test conditions for an extra-high-voltage transformer. The air necessary for drying out is delivered by fans, and after being preheated, is passed into the transformer tank. Liquid-type manometers are provided for supervision of the air flow, while the measuring apparatus on the left of the photograph is for checking the electrical properties of the transformer by comparison with a condenser filled with gas under pressure.

Fig. 3. — Test equipment for drying-out and measuring the dielectric losses as check on the drying-out process.

On account of the fact that this high-voltage test transformer was of new design, the drying-out process in the factory was supervised by measurement.

Not only test devices were developed, however, but also *works installations* manufactured which allow even the largest transformers to be subjected to the best pretreatment process. Even transformers, which make full use of the prescribed profile for railway transport, can be mounted on the trolley with a loading length of over 6 m and pushed into the horizontal oven shown in Fig. 4. The oven is provided with all devices for supervising the drying-out, degassing, and impregnation processes.

With regard to

the electrical properties of paper

we do not intend to discuss further the raising of the breakdown voltage, an obvious aim to be striven after, but rather to deal with the special dielectric properties. These are characterized in the essentials by the dielectric angle of loss and its temperature coefficient, for which reason we shall briefly explain the physical meaning of these terms so far as this is necessary for understanding the following discussion.

The dielectric losses mostly produce only a small heating of the dielectric, but one which is nevertheless of importance in its effects. As the losses increase with the temperature, however, the heating is the greater by comparison, the higher the temperature. If the heat is not conducted away quickly enough, the temperature rises until the material carbonizes and breakdown results. The limiting voltage at which this phenomenon occurs may be called the *critical voltage.* For a given quality of insulating material it is a constant. It may be proved[1] exactly that, when the dielectric losses are a quadratic function of the voltage, every increase of the thickness of a layer is compensated by a reduction in the amount of heat led away, with the result that the breakdown voltage cannot be raised by increasing the thickness of material. It is on the other hand obvious that the critical voltage is dependent on the magni-

[1] For further details see K. Berger: "Breakdowns in Insulating Material". The Brown Boveri Review, May, 1926, p. 115.

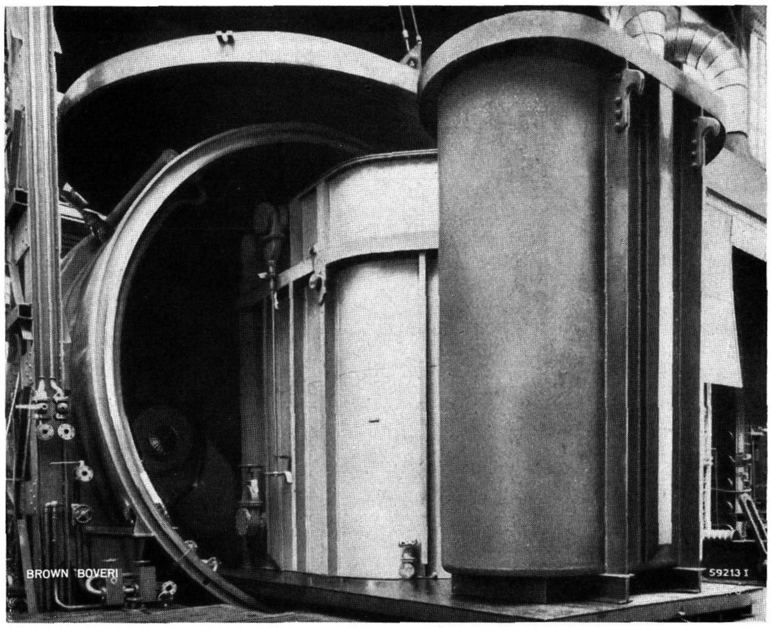


Fig. 4. — Oven for drying-out, evacuating, and impregnating transformers.

It is provided with a cover which can be operated hydraulically. Carefully applied packing ensures a vacuum-tight seal.

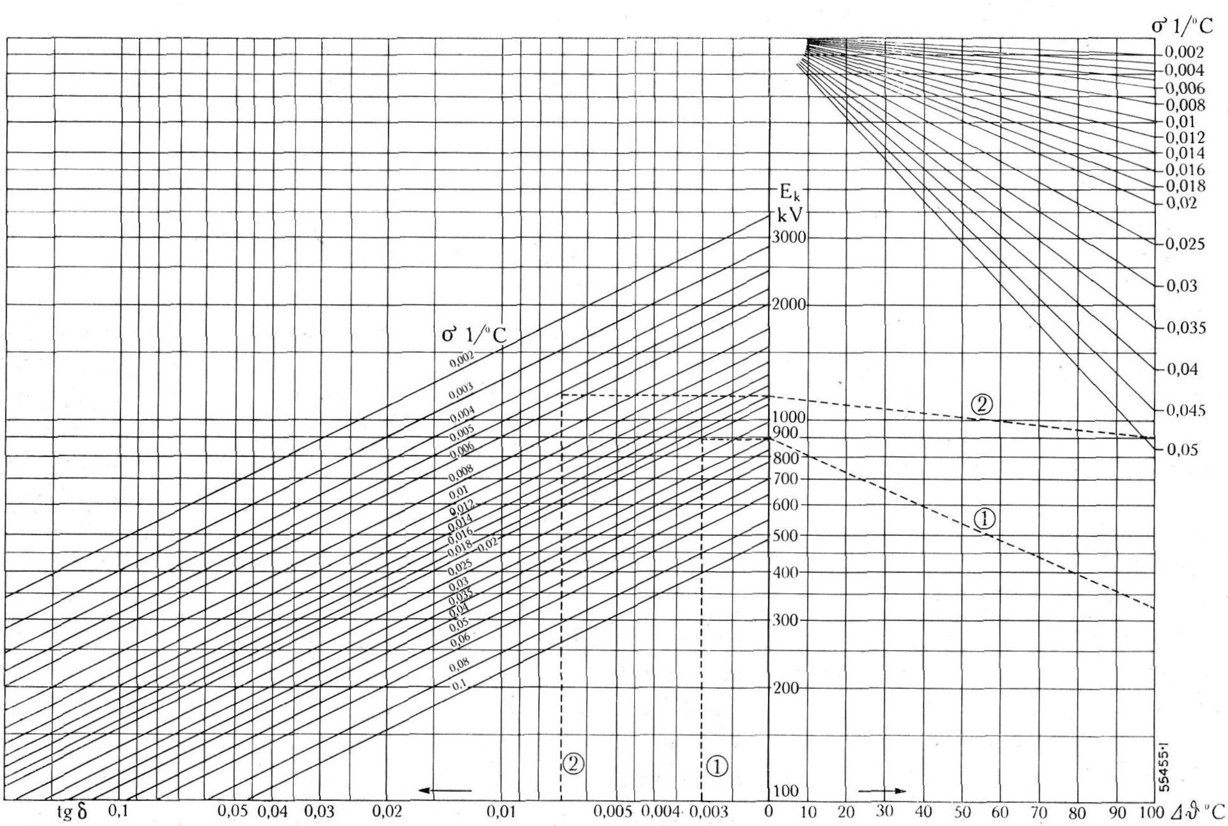


Fig. 5. — Nomogram for quick determination of the critical voltage of an insulating plate cooled on both sides for a wide range of the dielectric quantities concerned.

Left: critical voltage in function of the angle of loss (tan δ) with temperature coefficient (σ) as parameter.
Right: critical voltage in function of the temperature difference (Δ ϑ) with temperature coefficient (σ) giving slope of characteristic.

tude of the dielectric losses and consequently on the angle of loss tan δ at the initial temperature. The deciding factor is, however, the increase of the dielectric losses with the temperature[1]. Thus the most important magnitude for judging the material is the temperature coefficient.

The nomogram in Fig. 5 shows clearly the influence of the two factors tan δ and σ on the critical voltage. It represents the *critical voltage of a plate cooled on both sides.* In example 1 a critical voltage of about 900 kV is obtained for an angle of loss tan $\delta = 0{\cdot}003$ and a temperature coefficient $\delta = 0{\cdot}02$. The material of example 2, which on the basis of a superficial examination would be considered as of lower quality, with an angle of loss tan $\delta = 0{\cdot}007$ more than twice as large, but with a temperature coefficient $\sigma = 0{\cdot}005$, has, however, a critical voltage of 1170 kV. It is still more striking to compare the

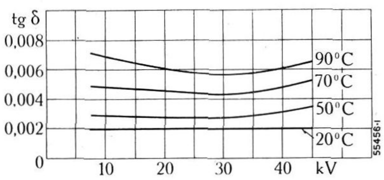


Fig. 6. — **Angle of loss, tan δ, of oil-impregnated paper test specimens in function of the voltage.**

The factors of loss are characterized by low absolute values and a small dependence on the temperature.

critical voltages of the two materials chosen as examples at a temperature higher than the initial temperature. In the right half of Fig. 5 radiating lines are drawn which show the dependence of the critical voltage on the temperature rise, parameters being various temperature coefficients. If the straight line corresponding to the desired temperature coefficient (0·02 in the first example) is drawn from the value of the critical voltage at the initial temperature (900 kV in the first example), this line represents the critical voltage in function of the temperature rise. As a result of the smaller temperature coefficient the straight-line characteristic of the second example is much flatter, i. e., this material behaves much better than that of example 1 at high temperatures, in spite of the initially larger angle of loss.

A particularly interesting problem of material research is to choose the component materials, paper and oil, and to carry out the impregnation in such a manner that the angle of loss and its temperature coefficient assume the most favourable values. Fig. 6

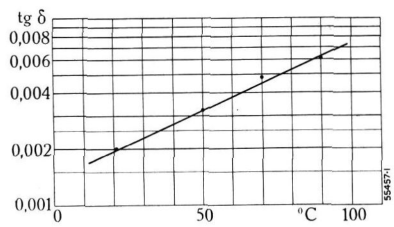


Fig. 7. — **Angle of loss of the material in Fig. 6 at 40 kV in function of the temperature.**

$$\tan \delta_{\Delta\vartheta} = 0{\cdot}002\ e^{0{\cdot}016 \cdot \Delta\vartheta}.$$

shows that this problem was actually solved and that a low angle of loss with a small dependence on temperature variations was attained.

Fig. 7 represents the angle of loss of the same material at 40 kV in function of the temperature. The curve shows that the dependence of the angle of loss on the temperature follows, with good approximation, an exponential law, since it is a straight line for the system of coordinates chosen. The index of the power of *e* is given by the slope of the straight line, and from this the temperature coefficient is found to be 0·016. From the angle of loss and the temperature coefficient thus found we obtain with the help of Fig. 5 a critical voltage of about 1200 kV at 20° C and 700 kV at 90° C. It must, however, be emphasized that the quality of a given design cannot be judged on the basis of the angle of loss and the temperature coefficient alone, because, in addition to these factors, methods of construction exercise a considerable influence on the properties of the completed design.

The *effect of the impregnating medium* has already been referred to on several occasions. The

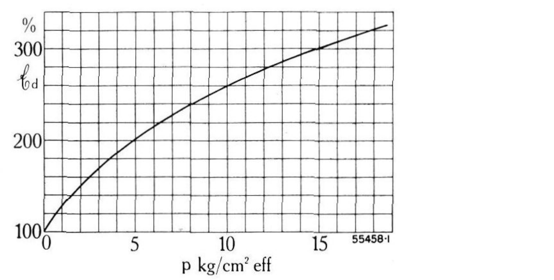


Fig. 8. — **Average values of the breakdown field strength of paper in compressed air in function of the pressure.**

Breakdown field strength as percentage of the value at atmospheric pressure. The rise of the curve is proof of the considerable increase of the breakdown strength with rising pressure.

[1] It is determined by the temperature coefficient σ, which appears together with the temperature rise as the exponent of the number *e* when determining the angle of loss in function of the temperature ($\tan \delta_{\Delta\vartheta} = \tan \delta_0 . e^{\sigma \Delta \vartheta}$).

phenomena, which are in themselves of a very complicated nature, may be explained in the light of the following simple example on the assumption that the chemical properties of the impregnating medium remain unchanged, and that only one physical quantity, the pressure, is subject to variation. We may therefore choose as impregnation for the paper a "material" which fulfils these conditions, e. g., air under different pressures.

Fig. 8 shows mean values of the breakdown strength of paper in compressed air in function of the gauge pressure. In order to illustrate the increase of the field strength at higher pressures, the breakdown strength at atmospheric pressure has been made equal

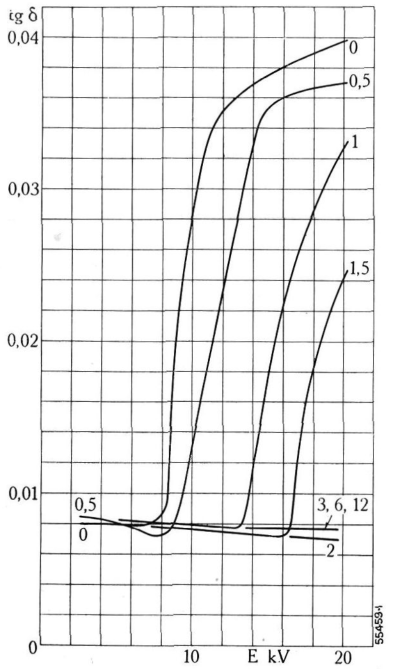


Fig. 9. — Angle of loss of insulation consisting of 5 mm of paper with an air-gap of 0·5 mm in function of the voltage, parameter being the air pressure in kg/cm² gauge.

The voltage at which glow discharge commences rises with the air pressure. Consequently the steep part of the curve is displaced towards the region of higher voltages, and finally disappears, within the range of voltages investigated, for pressures above 2 kg/cm² gauge.

to 100. At 15 kg/cm² gauge the breakdown strength of the paper, which even at atmospheric pressure is very high, has risen to three times the original value.

The influence of the pressure on the angle of loss is shown in a particularly instructive manner in Fig. 9. The insulation investigated consisted of a combination of paper with an open air-gap. It was purposely made in such a manner that glow discharge could take place. The curve, which illustrates the variation of the angle of loss in function of the voltage at atmospheric pressure, shows, after an initial stage in which the angle of loss remains practically constant, a rapid rise and a succeeding transition to a saturation stage. The rapid rise is caused by glow discharge in the air-gap. From the other curves may be seen how the voltage, at which glow discharge commences, rises simultaneously with the pressure, until at a pressure of a few kg/cm² the sudden voltage rise no longer occurs in the voltage range investigated.

We have now discussed the selection of insulation paper, its manufacture and suitable pretreatment and seen what excellent electrical properties can be imparted thereby to suitable qualities of paper. Research has won new laurels with these investigations and has once more paved the way for the most widely varying practical applications. To what extent the properties of paper influence the quality of electrical machines, not only in regard to their insulation, but also in connection with their whole behaviour, may be seen from the articles which deal with the influence of the insulation in the case of transformers.[1]

[1] Fr. Beldi, "The Insulation of Machines and Transformers", page 224 of the present number of this journal. — A. Meyerhans, "Large Transformers of Lightweight Construction", page 290 of the present number of this journal.

(MS 965) *H. Hartmann. (D. S.)*

THE DIELECTRIC LOSSES OF OILS AND OTHER INSULATING LIQUIDS.

Decimal Index 621.315.615:537.226.3

For the transformer insulation of to-day it is most important to use insulating oils having low dielectric losses. Oils, which attain inadmissibly high dielectric losses during service, can be restored to their initial state by suitable treatment. Substitutes generally display poor properties. They can, however, by expedient choice and subdivision of the solid insulation be turned into serviceable insulating liquids.

INSULATING liquids belong to the most important materials met with in electrical engineering, and it is natural that the demands made on them have become increasingly severe as the service and test voltages of the various products of the electrical industry have risen.

The oil in transformers, used as cooling and insulating medium, is indeed subjected to the most severe conditions. In order satisfactorily to fulfil these conditions, oils of high breakdown strength, of low viscosity and with a high resistance to oxidation are necessary. Mineral oils which do not satisfy these demands form oxidation products during ageing in service, which are deposited on the tank walls and also on the windings. Such phenomena may produce complete destruction of transformers due to interference with the cooling. Fig. 1 shows the state of a transformer after several years' service with unsuitable insulating oil.

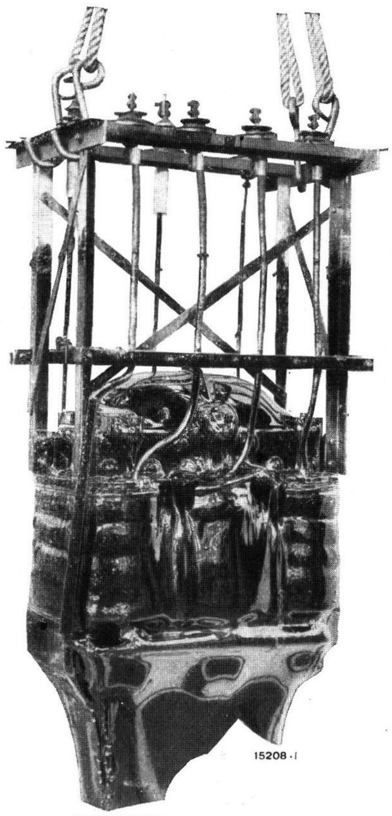


Fig. 1. — Three-phase transformer with thickened and hardened insulating oil of unsuitable quality.

In modern transformers the oil, as described in the article on insulation of machines and transformers [1], is also used for impregnating paper, of which great quantities are employed. We shall, however, confine ourselves here exclusively to the oil itself, since paper as a high-voltage insulating material is discussed in the preceding article [2].

The results of a test may serve to illustrate the effect of the oil on an impregnated paper bandage. A transformer model was impregnated with a good transformer oil after careful drying. To produce artificial ageing, the oil was heated over a period of 160 hours, the temperature reaching 115 °C. The dielectric losses between primary and secondary windings, and also those of the oil at certain intervals, were measured during the whole course of the test. The results of the investigations are collected in Fig. 2. The dielectric losses of the transformer remained constant for about the first 80 hours. Small irregularities are due to temperature variations, for the losses are to a high degree dependent on the temperature in the range of temperatures in question. The losses then began to rise after the heating period just mentioned had been exceeded. This observation is confirmed by the behaviour of the tan δ of the oil. The influence of the oil on the whole insulation and the alteration of the oil in regard to the dielectric losses when subjected to strong heating are thus proved.

On the basis of the knowledge thus gained, we decided to undertake comprehensive tests with the object of investigating the relationship between the chemistry of mineral oils and their dielectric losses. The first question to which we had to devote our attention was how the dielectric losses in mineral oils actually arise. On the one hand these are in part pure resistance losses caused by a certain conductivity of the dielectric. On the other hand there are what may be called the dielectric hysteresis losses, i.e., losses due to rotational movements of polarized molecules under the influence of alternating fields in the dielectric. The dielectric losses are therefore dependent firstly on the concentration of an electrolyte in the dielectric and secondly on the number of polarized molecules present. In perfectly refined transformer oils, such substances should not exist at all, or at least only in traces. The conditions are, however, quite different for oil which has already been in service. The oil is oxidised by the oxygen in the air at normal operating temperatures. The deciding factors for the kind of oxidation and the resulting

[1] See page 224 of the present number of this journal.
[2] See page 235 of the present number of this journal.

oxidation products are the origin and degree of refinement of the oil used. The initial oxidation products may be alcohols, aldehydes, peroxides and acids. As the reaction proceeds, products of higher molecular weight are produced by condensation and polymerization. With increasing oxidation and the

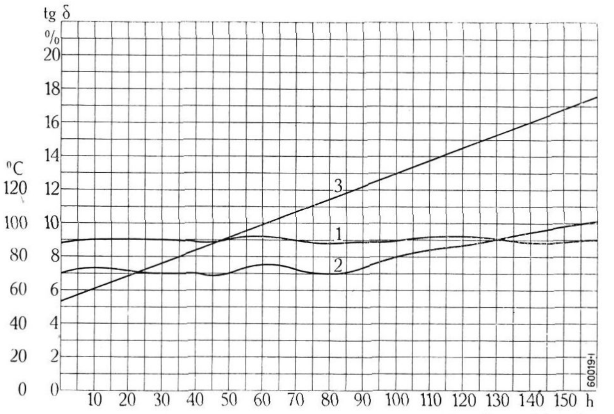


Fig. 2. — Behaviour of the factor of loss, tan δ, for the principal insulation of a transformer model as a function of the duration of heating during artificial ageing of the oil.

1. Temperature within the test model.
2. Factor of loss, tan δ, measured between primary and secondary windings.
3. Factor of loss, tan δ, of the oil used alone.

consequent formation of substances with a more complicated molecular structure, the solubility of the products in the oil decreases, for which reason solid substances due to ageing are deposited as sludge in the course of time. From this superficial description of the nature of the reactions which occur during the oxidation of mineral oils, we can nevertheless realize that, especially in the initial stages, substances are formed which contain polarized molecular groups and also pure electrolytes.

Fig. 3 shows the dielectric losses of two kinds of insulating oil as a function of the temperature. Measurements were made for both oils in the state in which they were delivered and after various kinds of treatment. Their characteristic properties and their behaviour during artificial ageing are summarized in Table I. A is a typical pre-war oil which satisfies the specifications of the Swiss Association of Electrical Engineers (S. E. V.) in all respects, B, on the other hand, is an oil imported into Switzerland from a Slovakian refinery after the beginning of the war. With the exception of its higher specific weight and the excessive formation of sludge during ageing, the latter oil likewise satisfies the specifications of the SEV. Both oils, when new, show practically the same behaviour of tan δ in function of the temperature. At all events the small differences are not of basic importance. Oil A was then artificially aged according to the method prescribed by the SEV, and the measurements were repeated in the presence of all ageing products, the behaviour of tan δ being as shown by curve A 1 of Fig. 3. It is clear that a very great deterioration of the dielectrical properties has taken place. The question is which of the ageing products are to be held responsible. In the first place it could be proved that the solid ageing products which are insoluble in oil have no influence on the dielectrical properties. The aged and filtered oil A 2 yields exactly the same characteristic for tan δ as the aged, unfiltered oil. If the same oil A 2 is stirred with 10 % of Fuller's earth at 80° C for an hour, during which time it is kept from contact with the oxygen in the air by passing through nitrogen, and after this treatment is then filtered, the oil regenerated in this manner has a characteristic for the factor of loss as shown by A 3 in Fig. 3. From the characteristic we may see that the oil has even better dielectrical properties than the new oil A. During the treatment of the artificially aged oil just described the acid concentration fell from 0·33 to 0·11.

Chemical and physical properties of the transformer oils used

Denomination	Specific weight at 20° C	Acid concentration	Viscosity in cst			Artificial ageing — SEV method					
			20° C	50° C	80° C	Acid concentration		Sludge %		Reduction of thread tensile strength in %	
						3 days	7 days	3 days	7 days	3 days	7 days
A	0·888	0·02	29·2	8·7	3·9	0·13	0·33	Traces	0·11	0	0
A 3	—	0·11	—	—	—	—	—	—	—	—	—
B	0·913	0·03	31·1	8·8	3·9	0·16	0·28	0·04	0·25	0	8
B 1	—	0·06	—	—	—	—	—	—	—	—	—
B 2	—	0·09	—	—	—	—	—	—	—	—	—
B 3	—	0·02	—	—	—	—	—	—	—	—	—

To clear up the question as to whether the acids still present in the oil A 3 have an unfavourable influence on its dielectrical properties, the acids were neutralized with the equivalent quantity of caustic soda solution and the oil afterwards washed three times with distilled water. Quite unexpectedly, measurements with the oil A 4 treated in this manner

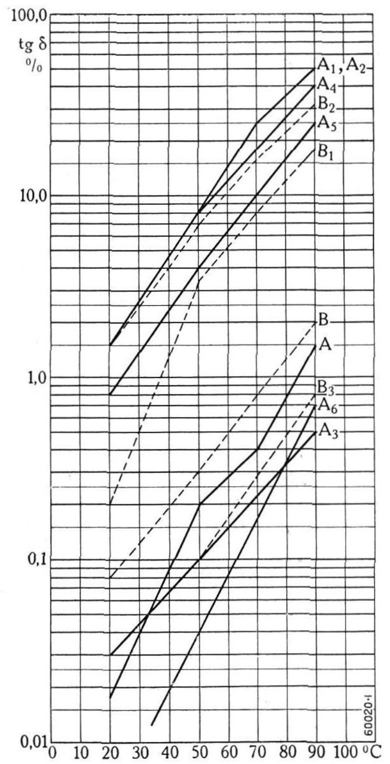


Fig. 3. — Factor of loss, tan δ, as a function of the temperature, of mineral oils in various stages of ageing and regeneration.

Laboratory tests.

A = New oil (pre-war quality).
A_1 = A artificially aged.
A_2 = A_1 filtered.
A_3 = A_2 treated with Fuller's earth.
A_4 = A_3 neutralized and washed.
A_5 = A_4 after further washing.
A_6 = A treated with Fuller's earth.

Tests in service.

B = New oil (usual present-day quality).
B_1 = B after 50 hours in a transformer at an average temperature of 95° C.
B_2 = B_1 used for drying out transformers.
B_3 = B_2 treated with Fuller's earth.

again indicated very high losses which practically corresponded in order of magnitude to those of the aged oil A 1. This phenomenon can only be explained by the fact that salts are formed during neutralization which can only be extracted from the oil with difficulty. This view is confirmed by the behaviour of tan δ for the oil A 5, the only difference between this oil and A 4 being that it was again washed three times with distilled water.

The dielectrical properties of the new oil A may also be improved by treatment with Fuller's earth. Similar observations to those which we were able to make for oil A after various kinds of treatment in the laboratory were likewise made for oil B in service tests. After being subjected to an increased temperature for a very short time, an obvious deterioration of its dielec-

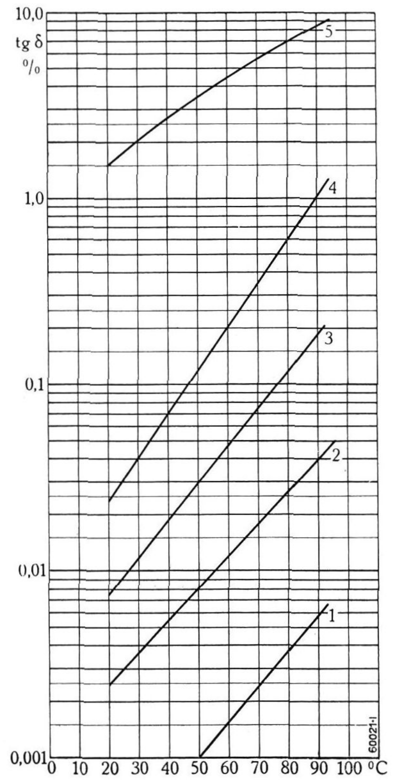


Fig. 4. — Factor of loss, tan δ, of various mineral oils and an oil substitute as a function of the temperature.

1. Mineral oil, good quality.
2. Mineral oil, medium quality.
3, 4. Mineral oil, poor quality.
5. Substitute with benzene base.

trical properties took place, but it was found possible to regenerate the oil by treatment with Fuller's earth. It may therefore be affirmed that Fuller's earth absorbs those substances in the oil which adversely affect the dielectrical properties.

We wish to draw special attention to the fact that this information is to be considered simply as the result of preliminary tests. It is the object of a more comprehensive series of tests to discover all the factors which decide the dielectrical behaviour of insulating oils. Some important conclusions can, however, already be drawn from these preliminary tests.

1. *The dielectrical properties of insulating oils are considerably affected by the stressing in service.*

2. *Oils, which already display inadmissibly high dielectric losses due to ageing, can be restored to their original values by means of treatment with Fuller's earth.*
3. *The dielectric losses of new oils can not serve as a basis for design, because they increase greatly in service due to alteration. It is therefore absolutely necessary to subject the oils to an ageing process and to remeasure the losses in this state. For more severe demands only those oils are suitable for which the difference between the losses in the new state and those after ageing is as small as possible.*

Since the beginning of the present war, the difficulties experienced in obtaining transformer oil in European countries have grown practically from day to day. As a result, various industrial concerns were compelled to use substitutes for filling transformers. Just as it is possible to replace other materials by artificial products of equal quality, so is it also possible to use suitable liquids with similar properties instead of insulating oil. The biggest difficulty is that the raw materials used in the production of such substitute insulating liquids of the necessary high quality are just as difficult to obtain as the oil itself. It was therefore necessary to make shift with liquids of poorer quality, which may, however, be used after suitable treatment and for a suitable design of the transformer insulation.

Although our firm has not found it necessary up to the present to adopt such substitute insulating materials, we have nevertheless examined them thoroughly, both alone and as impregnation for various other insulating materials. These substitutes consist of chlorine derivatives of benzene, naphthalene or diphenyl which are used either separately or mixed with one another. They are obtainable on the market under various names such as Chlophen, Pyranol, Afcolin, Dielectrol, etc.

So far as leakage, surface discharge and breakdown voltage are concerned, these substitutes behave in a similar manner to transformer oils of medium quality. From this point of view, the insulation of the windings must therefore be dimensioned in the same manner as for the usual designs. The great difference between these substitutes and transformer oil in regard to electrical properties lies in the magnitude of the dielectric losses. Fig. 4 shows the factor of loss, tan δ, of a benzene trichloride insulating liquid compared to those of mineral oils of various qualities as a function of the temperature. As may be seen from this diagram, the dielectric losses of this substitute are about 10^3 times greater than for mineral oils of medium quality. Such high losses place quite new demands on the construction of the insulation, which, as a result of thorough investigations, could be fulfilled. It would indeed require too much space to describe in this article all the tests made, but we wish to give a brief description of the results obtained with a potential transformer.

After being carefully dried out, the transformer was filled and impregnated with the substitute to be investigated. The factor of loss, tan δ, was ascertained after warming the transformer to 30, 50 and 70° C. Curve 1 of Fig. 5 shows the results of these measure-

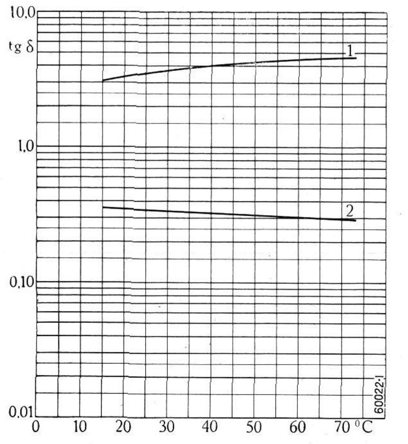


Fig. 5. — Factor of loss, tan δ, as a function of the temperature of a potential transformer filled with an oil substitute.

1. Factor of loss of the pure insulating liquid.
2. Factor of loss when the liquid is subdivided by barriers.

ments. The losses are too high and would be a source of danger to the transformer after a lengthy period of service. Considerably better results can be obtained, however, if the liquid insulation is subdivided by a number of barriers. Curve 2 of Fig. 5 represents the new values of the dielectric losses. In this way we have succeeded in making a serviceable transformer insulation out of this substitute in spite of the magnitude of its losses.

Finally, it may be mentioned that substitute liquids are generally subject to a greater deterioration due to ageing than transformer oils. They can, however, be regenerated by a similar process to that which we described for mineral oils.

Adequate cooling, low operating temperature, suitable distribution of the insulation, correct choice of the solid insulating materials and extreme cleanliness are the main points which must be observed in the design and manufacture of a transformer for operation with substitute insulating liquids.

(MS 970) *A. Putzi and J. Biert. (D. S.)*

THE USE OF COMPRESSED GASES FOR HIGH-VOLTAGE INSULATION.

Decimal Index 621.315.618.2.027.3

The well-known fact that the breakdown strength of air generally increases with the pressure has led to some interesting applications (air-blast circuit breakers, compressed-air instrument transformers, compressed-gas condensers). Other gases, e. g., nitrogen and carbon dioxide, behave in a similar manner. The dependence of the breakdown strength on the pressure, on the shape of the electrodes and their arrangement, as well as on the type of gas, formed the object of numerous tests of which the results are communicated in this article.

IN the natural desire to obtain economical and, from a technical point of view, high-quality constructions, designers of high-voltage apparatus and machines have always sought to make use of those insulating substances which require a minimum expenditure of material to fulfil the demands made by the high test voltages. Two fundamentally different insulating problems have to be solved to accomplish this end. In the first place the external distances necessary for insulation at the boundary surface between the solid insulation and the surrounding atmosphere must be maintained, and in the second place the insulating spacing in the interior of the high-voltage apparatus must be correctly dimensioned. While the choice of the external insulating distance is determined by the flashover strength of the air — already adequately investigated — and by the use of suitable electrode shapes, the dimensioning of the internal insulation remains, as always, the object of intensive research work.

Ceramic materials, fibrous substances, synthetic resin products, moulded objects, as examples of solid insulators, and mineral oils or non-inflammable hydrocarbons (e. g., Chlophen), as examples of insulating liquids, form, individually or in combinations, the principal ingredients of insulating materials used in high-voltage engineering. In recent times compressed gases have also gained in importance. In the high-voltage laboratory of Brown Boveri, the significance of compressed-gas insulation as a partial substitute for oil was already recognised more than a decade ago, and was made the subject of detailed investigations which, in the meantime, have proceeded much further than necessary to explain the purely physical facts, and have led to interesting, practical applications. It really does appear tempting to replace the inflammable oil, at least in switchgear, instrument transformers and standard condensers for high voltages, by a non-inflammable insulating material of equal or better quality. The present-day difficulties in obtaining high-quality insulating oils has furthered this tendency. It is only necessary to consider the advanced state of development of the modern high-speed air-blast circuit breaker. Our firm has also provided a decisive contribution in the sphere of the compressed-air potential

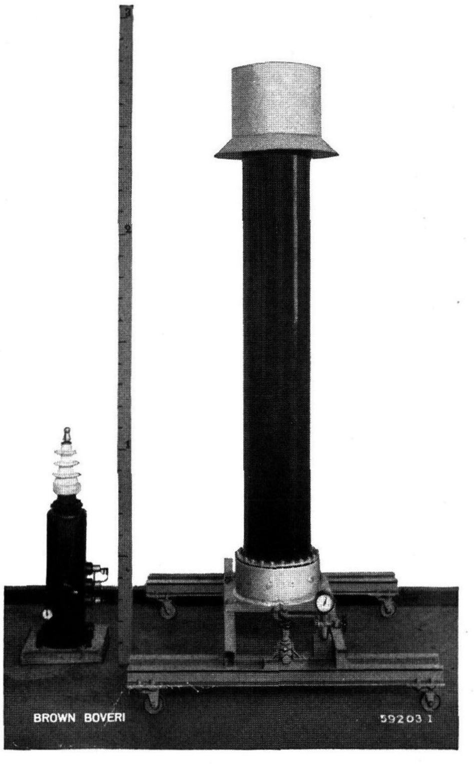


Fig. 1. — Compressed gas condensers for rated voltages of 400 and 60 kV, each with a capacity of 100 $\mu\mu$ F, rated pressure 12 to 14 kg/cm^2.
Due to the compressed gas filling, the condensers have especially small dimensions. The sharp-edged, sheet-metal cover of the 400 kV condenser acts as a protective electrode against external flash-over.
The straight-edge is 3 m in length.

transformer and also of the compressed-gas condenser, which is used to advantage for measuring purposes, especially in bridge circuits for measuring the dielectric losses of high-voltage apparatus. Fig. 1 shows two such measuring condensers for an operating pressure of 12 to 14 kg/cm^2. The larger of these, constructed in the usual manner with a bakelized paper insulator as pressure container, is suitable for measuring voltages up to 400 kV, the smaller one, with a steel housing and a special insulator, represents a design of our own for a maximum rated voltage of 60 kV. The scale, shown in the figure for purposes of comparison, proves that small dimensions can be obtained with compressed air as dielectric.

The Breakdown Strength of various Gases under Pressure.

According to the path which a possible breakdown arc would follow at a high test voltage, the insulation spacing between the constructional parts of a high-voltage apparatus, which behave as electrodes, may be divided into:

a. Pure gas paths.
b. Creepage and surface paths.

For pure gas paths, the arc passes through the compressed gas surrounding the electrodes without directly touching surfaces and walls of insulating material. For the creepage and surface paths, on the contrary, the arc passes completely or partly along an insulating surface, the type and structure of which exercises a considerable influence on the magnitude and on the dependence on the pressure of the flash-over voltage.

These two types of breakdown paths occur in countless insulating arrangements, often differing widely from one another, in high-voltage apparatus used in electricity supply systems. It is, however, sufficient to select some typical, geometrically simple electrode arrangements and to examine more closely their breakdown and flash-over strength for various pressures and for various gases (or, for the sake of comparison, also for various liquids). Conclusions for the correct dimensioning of constructions met with in practice can then be drawn from the measurements on such basic insulation arrangements.

Applications for the Case of the Homogeneous, Electrostatic Field.

For the two measuring condensers shown in Fig. 1, the compressed gas is between two concentric, cylindrical electrodes, and constitutes, therefore, a pure gas path with almost uniform field distribution in the whole sphere of the electrical field. Such a field may be termed practically *homogeneous*, and the increase of the breakdown voltage is approximately proportional to the product of the gas density and the spacing of the electrodes (Paschen's law). A homogeneous distribution of the field also exists between flat, parallel plates and even between spheres, at least as long as the spacing remains small in comparison to the diameter of the spheres and only that part of the field in the limited flash-over space, which determines the breakdown, is considered. Fig. 2 shows some curves of the breakdown voltage of compressed air in a homogeneous field plotted from our own measurements. The advantage of a greatly increased breakdown voltage obtained by compression immediately meets the eye.

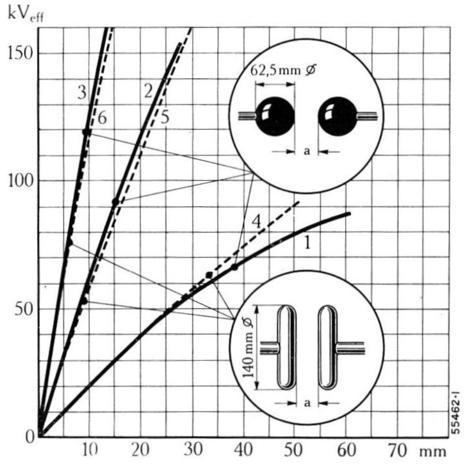


Fig. 2. — Breakdown voltage (r. m. s.) in compressed air between spheres and between plates in function of the distance (a) for pressures of 1, 3 and 6 kg/cm^2, and for a. c. voltage, 50 cycles.

1, 4. Pressure 1 kg/cm^2.
2, 5. Pressure 3 kg/cm^2.
3, 6. Pressure 6 kg/cm^2.

Application for the Case of the Non-homogeneous Electrostatic Field.

It is always the aim of the designer, in the case of high-voltage apparatus with compressed gas as an insulating medium, to obtain *as homogeneous a field as possible* in order to fully utilize the advantages illustrated by Fig. 2, and consequently to realize constructional forms which are economical in their space requirements. Unfortunately this aim can only be fully realized in few cases, e. g., for compressed-gas condensers. Generally, due to the necessity of considering other requirements, (e. g., in the case of transformers with compressed-gas filling as a result of the graduation of the windings and the limits to the iron core for the magnetic circuit, and again in the case of needle-type rectifiers rotating in compressed gas on account of the sharp edges of the electrodes) a more or less large deviation from the homogeneous field is unavoidable. Furthermore, a homogeneous field can, in any case, only be obtained in a pure gas path while, on the other hand, a distortion of the field is always associated with the boundary surface between the compressed gas and the solid insulation.

Fig. 3 shows the results of some *measurements of gas and leakage paths* between pointed and sharp edged electrodes. It may be seen from the curves that the almost proportional increase of the breakdown voltage with the pressure, as shown in Fig. 2, no longer exists over the whole pressure range for sharp-edged electrodes; indeed the increase of the voltage with rising pressure becomes smaller

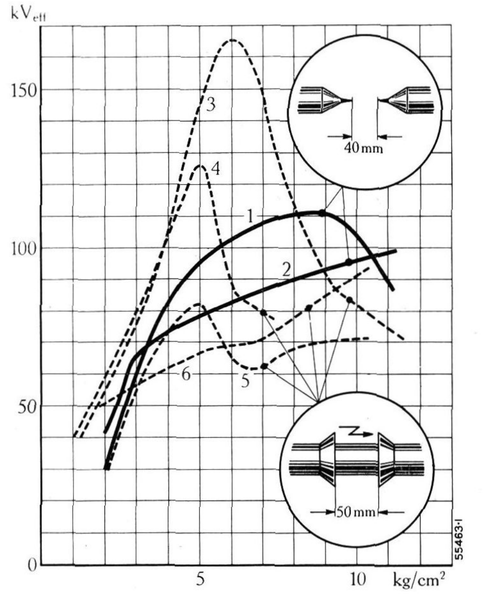


Fig. 3. — Breakdown voltage (r. m. s.) of a pure gas path in air (1, 3, 4), nitrogen (5) and carbon dioxide (2, 6) between needle points with a spacing of 40 mm and along a leakage path between sharp edges spaced 50 mm apart in function of the gas pressure; a. c. voltage, *50 cycles.*

3, 5, 6. Breakdown along porcelain tube.
4. Breakdown along bakelized paper tube.

Above 5 to 6 kg/cm² a strongly marked fall of the voltage for air and nitrogen, but not for carbon dioxide. The leakage path along the porcelain tube with dry surface yields higher flash-over values (3) than the hygroscopic bakelized paper tube (4).

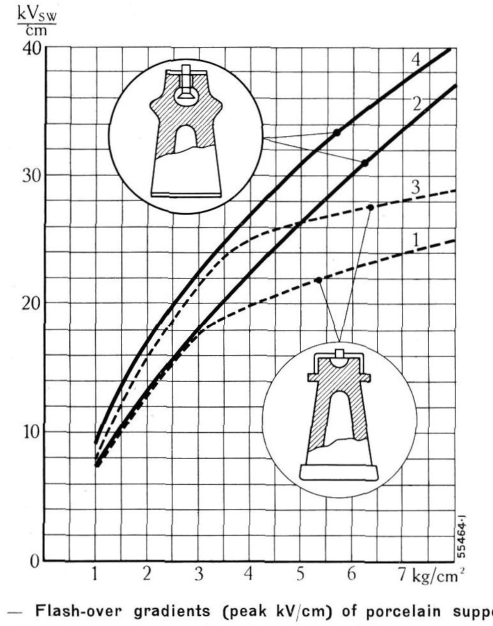


Fig. 4. — Flash-over gradients (peak kV/cm) of porcelain supporting insulators in compressed air in function of the pressure.

Older design of smooth supporting insulator, on right. New design with penetrating electrode, on left.

1, 2. Flash-over gradient for a. c. voltage (50 cycles).
3, 4. Gradient for 50 % flash-over impulse voltage, positive wave, 1/50 μs.

In the case of the older design with cap-shaped electrodes, no appreciable increase of the flash-over voltage can be observed above a pressure of about 4 kg/cm² (compare curves 1 and 2 in Fig. 3). For the new design, on the contrary, the flash-over voltage rises practically in proportion with the pressure.

and smaller. It is by no means seldom that a reversal of the desired effect, namely a reduction of the breakdown voltage[1], occurs, especially if there is a leakage path between the electrodes. It may be clearly seen from Fig. 3 that, for one and the same arrangement of electrodes, the various gases such as compressed air, nitrogen, and carbon dioxide behave differently in this respect, and that the material and state of dryness of the solid insulator exercise an influence. The considerable deviation of the behaviour of the non-homogeneous field from the results shown in Fig. 2 may be explained by the occurrence of glow discharges on the electrodes. These glow discharges always precede the breakdown and assume various forms according to the shape of the electrodes, the kind of gas and the pressure. Consequently they also result in different breakdown voltages.

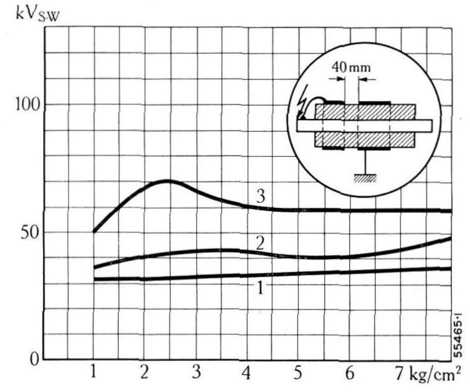


Fig. 5. — Flash-over voltage (peak) in compressed air along a steatite tube, with concentric metal conductor connected to one electrode, in function of the pressure.

1. A. C. voltage, 50 cycles.
2. 50 % flash-over impulse voltage, wave 1/50 μs, conductor connected to positive pole.
3. As for 2 but with conductor connected to negative pole.

The curves show the ineffectiveness of increasing the pressure in order to raise the flash-over voltage, in the case of surface discharges both for a. c. and impulse voltages.

As an example of an increase of the flash-over voltage with rising pressure in a non-homogeneous field, the flash-over voltages per cm striking distance ("flash-over gradients") of a smooth porcelain supporting insulator of old design and of a modern one, in which the electrode penetrates far into the body of the insulator, are compared with one another in Fig. 4 for a. c. at 50 cycles and for impulse voltages.

A special form of flash-over along a leakage path is the so-called *surface discharge,* which exactly follows the surface of the insulating material and which considerably reduces the breakdown strength

[1] This phenomenon is also mentioned in an article by G. Gänger, Archiv für Elektrotechnik 34 (1940), page 64.

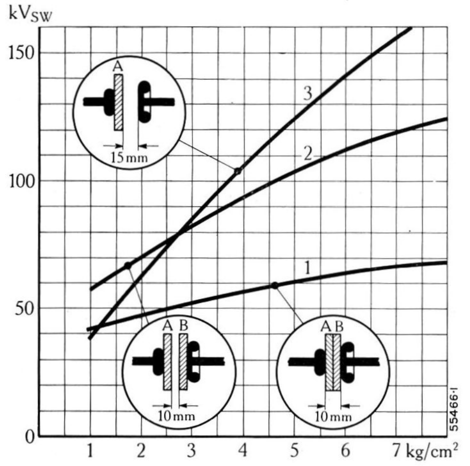


Fig. 6. — Flash-over voltage (peak) in compressed air along the surface of an insulating disc in function of the pressure.

When the discs are in direct contact (1), violent surface discharges along the disc (A), which cannot be eliminated by raising the pressure, precede the flash-over. An air-gap of 10 or 15 mm, on the contrary, absorbs with increasing pressure almost the whole voltage between the electrodes, so that only weak (2) or no surface discharges at all (3) occur before the flash-over.

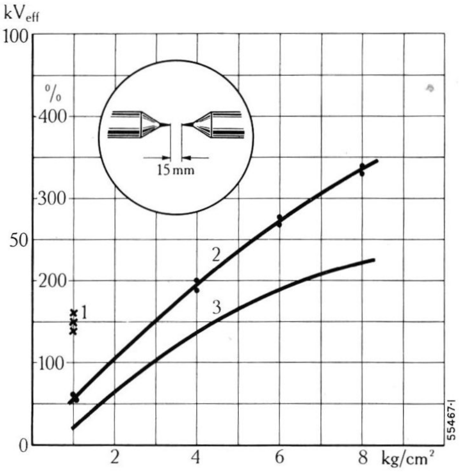


Fig. 7. — Comparison of the breakdown strengths of oil and compressed air.

Breakdown voltage (r. m. s.) at 50 cycles between needle points with a spacing of 15 mm.

1. Breakdown voltage of transformer oil.
2. Breakdown voltage of air in function of the pressure.
3. Ratio of breakdown voltages in air to those in oil in %.

From the curves may be seen that, above a pressure of 3 kg/cm² for the test set-up being considered, the breakdown strength of compressed air is greater than that of transformer oil.

of every design of insulation. Detailed investigations in our laboratories have shown that surface discharges cannot be eliminated merely by raising the gas pressure, a fact which Fig. 5 shows to be true both for a. c. and impulse voltages.

A similar behaviour was at first observed for another type of spark gap with circular insulating discs between the electrodes on which surface discharges could occur, i. e., a rise of the pressure only resulted in a small increase of the flash-over voltage (curve 1 of Fig. 6). If, however, an air-gap of 10 mm, for example, is left between the insulating discs (curve 2) or if this gap is increased to 15 mm by leaving out a disc (B), the behaviour of this arrangement approaches, according to curve 3, that of a pure gas path in a homogeneous field as shown in Fig. 2. The fraction of the total voltage drop which occurs over the disc (A) has, in this case, fallen to such an extent in comparison with curve 1 of Fig. 6 that no surface discharges occur at all when the voltage is increased until flash-over takes place.

All this knowledge has been applied in practice to potential transformers filled with compressed air [1], which are at present built for rated voltages up to 64 kV, and also for all high-speed air-blast circuit breakers which have often been described in the Review and for which the insulation of the arc extinction chamber is determined by the demand for high breakdown strength between the interrupting contacts during opening of the breaker.

Conclusions.

It was shown in the previous section that high breakdown strengths may be obtained by suitable arrangement of the insulation in compressed gases in homogeneous or almost uniform electric fields. The problem of applying very high pressures with breakdown strengths of several hundred kV/cm is therefore reduced to the question of the mechanical strength and sealing of the housing and insulator bushings. On the basis of these facts it would be possible in many cases for compressed gases to take the place of insulating oil. Fig. 7 shows a comparison of the breakdown strengths of both kinds of insulation for a particular application.

In the case of all insulation arrangements with a non-uniformly distributed field, special attention is to be paid to the shape of projecting electrode edges, the shielding of leads subject to glow discharge and to sharp-edged parts of the windings or housing. Arrangements which have a behaviour represented by the curves of Fig. 3 must be avoided or at least so designed that the test voltage lies in the range of rising voltages.

(MS 971) *M. Schultze. (D. S.)*

[1] H. Hartmann, The Brown Boveri Review 1941, page 84.

CERAMIC INSULATING MATERIALS AT HIGH TEMPERATURES

Decimal Index 621.315.612

At temperatures above 100° C the dielectric loss coefficient of porcelain attains such a high value that breakdown takes place and the material is destroyed. Other ceramic insulating materials, such as steatite and calite, behave much more favourably when subjected to the influence of heat.

CERAMIC insulators are products made from mixtures of ceramic materials which are worked at room temperature and then baked at high temperature. The best known of all these materials is porcelain, which has played a decisive part in the development of high voltage engineering. It occupies a special place in the construction of overhead lines, because it is able to withstand high mechanical stresses and is insensitive to the effects of the weather. It has also found widespread application in the manufacture of electrical machines and apparatus where the operating temperatures are normally below 100 ° C. On the other hand, it is not able to withstand simultaneously high temperatures and high electrical stresses.

The dielectric losses in the insulation of electrical machines and apparatus is, as far as the consumption of electrical energy is concerned, in the most cases so insignificant that for many years no attention was paid to this question.[1] Our investigations on porcelains at temperatures over 100 ° C show, however, an entirely new picture. Table I gives the electrical constants for quartz and for a few allied ceramic materials used in electrical engineering.

TABLE I.

Dielectric Constants of Ceramic Materials at Industrial Frequency and at Temperatures of 100 and 200 ° C.

Material	$\tan\delta$		ε		$\varepsilon \cdot \tan\delta$	
	100°	200	100°	200°	100°	200°
Porcelain I	0·29	2·9	8·0	50	2·32	145
Porcelain II	0·25	2·8	8·2	24	2·04	67
Ste tite .	0·08	1·4	6·5	12	0·52	17
Calite I .	0·010	0·160	5·5	6·5	0·055	1·05
Calite II .	0·005	0·013	6·8	6·9	0·034	0·09
Quartz . .	0·001	0·018	3·2	3·3	0·003	0·06

It is seen that in the case of porcelains I and II which differ only in the proportions of the basic materials, china clay, feldspar and quartz, the dielectric losses increase very rapidly when the temperature rises from 100 to 200 ° C. An insulator cube with a volume of 1 dm^3, for instance, which is subjected to a field stress of 1 kV/mm and has a loss coefficient of 67 (porcelain II at 200 ° C), causes a loss of 185 W at a frequency of 50 cycles, that is, it can almost be looked upon as a heating element. The magnesium silicate product known as steatite is much more favourable in this respect. Finally, the different qualities of calite (chemically a particularly pure magnesium silicate) attain, according to the degree of purity, almost the low values of quartz, which latter, due to its poor mechanical strength, can be employed only in exceptional cases.

In Fig. 1 the logarithm of the loss coefficient for calite has been plotted as a function of the test temperatures (abscissæ)[2]. The sharp bend near the bottom

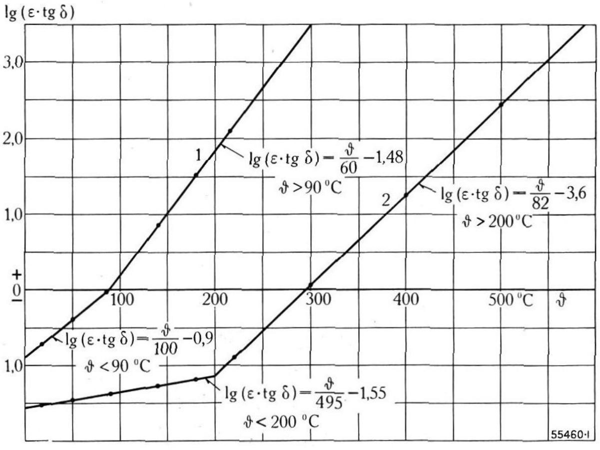


Fig. 1. — Loss coefficient for porcelain and calite at industrial frequency and temperatures up to 500 ° C.

1. Porcelain Measurements up to 300 ° C.
2. Calite Measurements up to 500 ° C.

of each curve is particularly noteworthy. A sudden change takes place at a temperature which depends upon the chemical consitution of the material. In the higher temperature ranges the loss coefficients of these two materials differ by no less than three orders of magnitude.

High dielectric losses such as are measured on porcelain at high temperatures, result in considerable heating of the material, which causes a further increase in the losses. If adequate arrangements are made for dissipating the heat this phenomenon may lead to thermal destruction of the insulator, and hence to

[1] See page 228 of the present number of this journal.

[2] The temperature variation of the loss coefficient appears to follow for both materials a law which may be explained by the equation

$$\log_e (\varepsilon \cdot \tan\delta) = \frac{\vartheta}{K} - A$$

In this equation ϑ is the test temperature in ° C, K and A are constants which vary according to the temperature range and the material.

breakdowns. The loss coefficients, which may vary with the temperature, have, therefore, in the higher temperature ranges, a high decisive influence on the breakdown strength of the material.

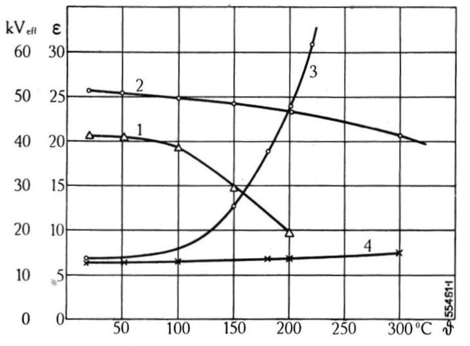


Fig. 2. — Arc-over voltage (r. m. s.) and dielectric constant of porcelain and calite bushings at industrial frequency and temperatures up to 300 ° C.

1. Arc-over voltage of the porcelain bushing.
2. Arc-over voltage of the calite bushing.
3. Dielectric constant ε of the porcelain bushing.
4. Dielectric constant ε of the calite bushing.

Apart from the puncturing voltage attention must also be paid in insulator engineering to the arc-over voltage. Measurements made on bushings of calite and porcelain, the results of which are plotted in Fig. 2, show a relation between the arc-over voltage and the dielectric constant ε. A large increase in ε results in a considerable increase in the arc-over voltage. A further analysis of the curve leads to the following law:

$$E_G \approx \frac{K}{\sqrt{\varepsilon}}$$

where E_G denotes the voltage at which the first discharges along the surface of the insulator — so-called creep sparks — begin to occur, which then, upon increasing the voltage slightly, lead to breakdown and K a constant which depends upon the geometrical dimensions of the insulator. The above relationship applies only as long as the creep voltage is smaller than the arc-over voltage through the air gap. In the case under consideration this was so because the bushings were very long in proportion to their diameter.

According to these experiments porcelain has at temperatures over 100° C dielectric losses which lead to puncturing and hence destruction of the material. Moreover, the arc-over voltage of porcelain decreases rapidly with increasing temperature. Calite, on the other hand, is much more favourable in these respects. It has stood up excellently to high temperatures in practice.

(MS 967) *Fr. Beldi. (Hv.)*

In our short-circuit testing installation: Arc produced at 400,000 V with a short-circuit power of 300,000 kVA.

The higher the voltages and powers of distribution systems the longer the arcs which occur in case of short circuit. This is a typical arc fed by our new 400 kV testing transformer. It was struck between two conductors 4 m apart and within a few seconds attained a total length of about 20 m, whereupon it was interrupted by an air-blast high-speed circuit-breaker. The illustration gives an idea of the effect such short circuits can have on high-voltage installations.

THE EFFECT OF THE WEATHER ON THE CORONA LOSS IN HIGH-VOLTAGE LINES.

Decimal Index 621.315.1.017.13
621.3.017.13:621.315.1
551.5:621.315.1.017.13

The influence of the weather on the corona loss in cables of large diameter was investigated. The investigations covered two different test lines. Bad weather caused the corona loss to increase a hundredfold when compared with the fine weather loss. A method which enables the results obtained on test lines to be applied to other lines is examined and found to be valid. Due to the mild weather during the test period no measurements could be made at extremely low temperatures. The tests will therefore be continued.

THE transmission of high powers over long distances requires for reasons of economy voltages of over 200 kV. In order to be able to calculate the most favourable diameter of conductor for such long distance transmission lines it is necessary to have an exact knowledge of the corona loss. As has been shown recently[1] the known formulæ for calculating these losses are not reliable enough, and also experimental investigations which have hitherto been made do not provide a complete explanation. Only very few investigations have for instance been made on the effect of the weather on the corona loss in lines of large diameter. For this reason detailed corona loss measurements were made in the high voltage laboratories of Brown Boveri on a cable of 20 mm diameter, on three different cables of 42 mm diameter and on two different cables of 50 mm, both on lines as well as on conductors enclosed in wire cages. With these it is easily possible to undertake comparative measurements on various kinds of cables and furthermore the investigation of the effect of various surface treatments is greatly facilitated. Comparisons between the measurements made on the lines and the caged conductors have shown, however, that the latter do not produce any useful results in the region where the losses are small and admissible in service.

Of the very numerous test results obtained, only those which show the effect of the weather on the corona loss can be recorded here, in view of the limited space available.

GENERAL OBSERVATIONS ON CORONA MEASUREMENTS MADE ON MODEL LINES.

On account of the high costs and the absence of an alternating current transformer with the necessary high voltage, it is generally only possible to operate a model line single phase. By means of a known method[2] it is possible, however, to apply the measurements obtained with simple test set-ups to actual overhead lines. The validity of this conversion rule was tested for two different lines.

As former investigations[3] have already shown, it is essential that special attention should be paid to the surface condition of the test cables. The so-called aged surface is of paramount importance as regards the corona loss in service lines. Ageing can be produced artificially according to a special method[3]. Before a measurement is made the cable must be subjected for a short time to a corona discharge at an increased voltage, so that dust and any adhering fibres are burnt or deposited, as is the case with a cable which has been under voltage for some time. The surface of the cable is also effected by weather conditions. When there is fog, dew, or rain, water particles adhere to the line, and during frost and snow ice crystals form on the conductors. Corona opposes surface deposits so that a condition of equilibrium is reached depending on these factors.

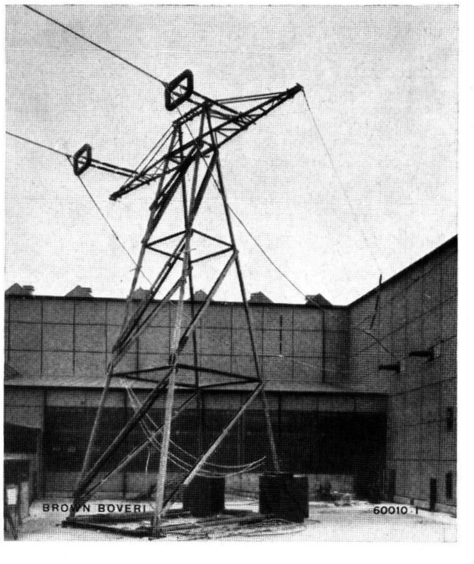


Fig. 1. — Tower for the two-wire test line with leading-in cable, the corona loss of which was determined with Schering bridges.

[1] K. Potthoff, Elektrizitätswirtschaft 30 (1931) p. 256 and ETZ 54 (1933) p. 169.

[2] K. Potthoff, ETZ 54 (1933) p. 169 and 57 (1936) p. 1054.

[3] Carroll & Cozzens, Electr. Engng. 52 (1933) p. 178.

TEST SET-UP.

(a) A two-wire line (Fig. 1) was suspended in two spans from the laboratory yard across the factory area and a plot of unused land. It had a single length of about 500 metres.

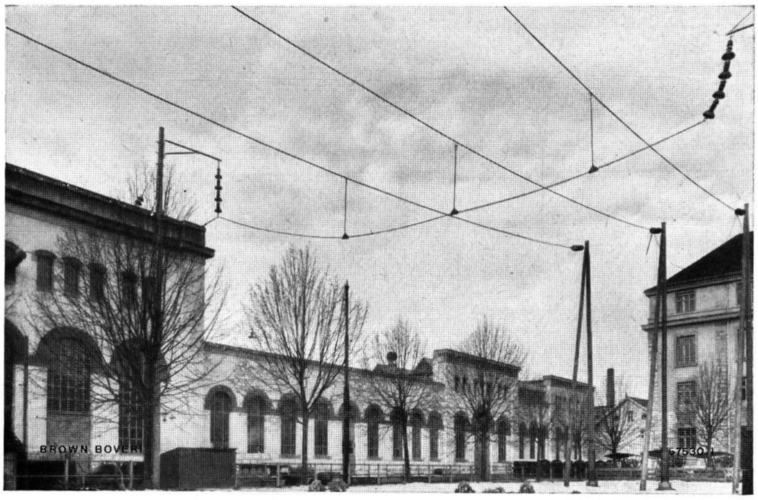


Fig. 2. — Part of the three-wire test line with leading-in cable. Corona loss determined with Schering bridges.

(b) A three-wire line (Fig. 2) was constructed with a single span of about 60 metres. This arrangement was selected to investigate the influence of different connections on corona conditions.

In both cases shielded cables were used for the current leads, so that the losses in the bushings and leads did not influence the measurements.

LINE DATA.

	Two-wire line	Three-wire line
Single length between end masts	490 m	55 m
Height of suspension points	19 m	11 m
Sag at 20° C . . .	6 m	1·5 m
Cable type	Hollow Al.-cable 50 mm diam. 12 wires	Stranded Cu-cable 20 mm diam. 23 wires of 2·3 mm diam. in the outside layer
Distance between wires	7·5 m	3·5 m

The copper cable was taken from a service line and had thus been subjected to a natural ageing process which had lasted eight years.

Before being built into the test line the hollow aluminium cable was artificially aged by cleaning and through being subjected to a corona discharge at an increased corona voltage, whilst during the test period which lasted 1 ½ years natural aging occurred.

MEASURING EQUIPMENT.

The losses were measured by means of loss-angle measuring bridges (Siemens & Halske and Trüb Täuber) which operate on the Schering principle. The diagrams of connections are reproduced in Figs. 3 and 4. Compressed gas condensers were used as standard condensers. Disturbances due to the capacitance of the leads were eliminated in one case by means of a double bridge, and in the other by a third equalizing circuit.

The losses can be calculated from the balanced measuring bridge as follows:—

$$N = \omega \cdot C \cdot \tan\delta \cdot U^2 \qquad \omega = 314 \cdot S^{-1}$$

With the two-wire line connected to the voltage as shown in the diagram of Fig. 3 the loss can only be determined correctly by a measurement on one conductor (the same corona conditions being assumed for both conductors) if the voltage vectors of both transformer limbs are in phase and of equal magnitude. When there is a phase difference this is equivalent

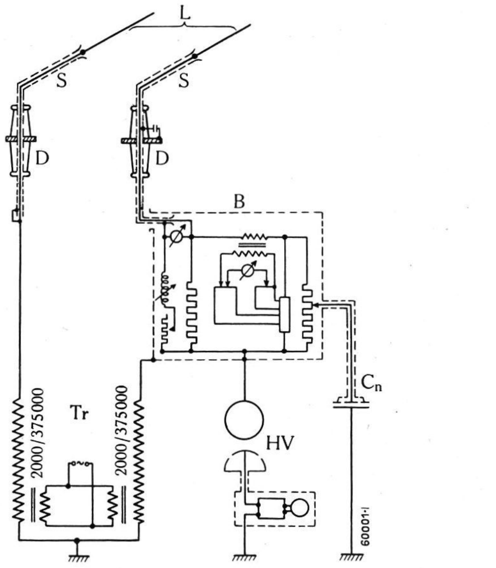


Fig. 3. — Diagram of connections for measuring the loss on a two-wire line (Fig. 1).

B. Measuring bridge.
D. Bushings.
Cn. Standard condenser.
HV. High-voltage voltmeter.
L. Test line.
S. Screened leading-in cables.
Tr. High-voltage transformer.

to a loss which appears on one conductor with a positive sign and on the other conductor with a negative sign. This loss due to dissymmetry can be eliminated by making two measurements with interchanged transformer connections and taking the mean. With the transformer used for the tests the loss

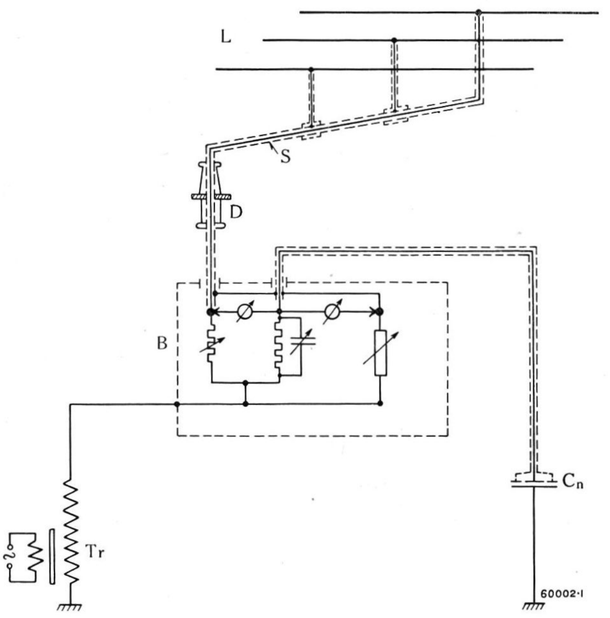


Fig. 4. — Diagram of connections for measuring the loss on a three-wire line (Fig. 2).

B. Measuring bridge.
D. Bushing.
Cn. Standard condenser.
L. Test line.
S. Screened leading-in cables.
Tr. High-voltage transformer.

due to dissymmetry, which was taken into account when working out the results of the measurements, amounted to 0·01 kW/km with a voltage of 200 kV to earth. To simplify the investigation the losses on only one conductor were determined.

Insulator losses during various kinds of weather were ascertained by special measurements and also deducted when working out the results.

OBSERVATIONS ON THE MEASURED RESULTS.

As already mentioned, corona has the opposite effect to surface deposits so that a state of equilibrium is reached which depends on the mutual effect of these factors. This action was observed in fog. From the curves shown in Fig. 5 it can be seen that equilibrium was reached after about 20 min.

Variations in corona loss due to small changes in the pressure and temperature of the air could not be ascertained by these measurements on account of the smallness of the variations and the effect of other influences.

In order to be able to compare corona losses for different conditions of weather, such as fog, rain and the like, it is necessary to convert to the same air density. All loss curves have been converted to a relative air density $\delta = 1$, as well as to 760 mm Hg and

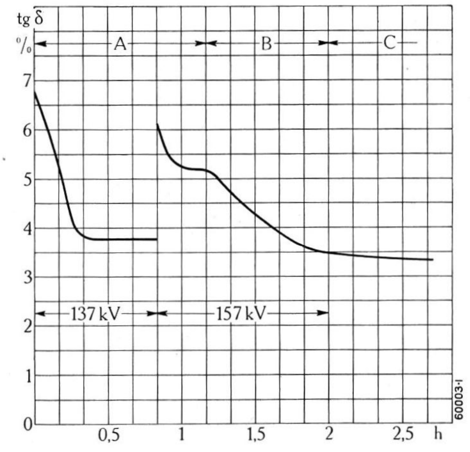


Fig. 5. — Effect of fog on corona loss measured on a 20 mm diam. copper cable. Angle of loss as a function of time with test voltages of 137 and 157 kV.

A. Dense fog. B. Fog lifting slowly. C. Fog cleared, cable still damp.

Ordinates: Angle of loss. Abscissæ: Duration of test.

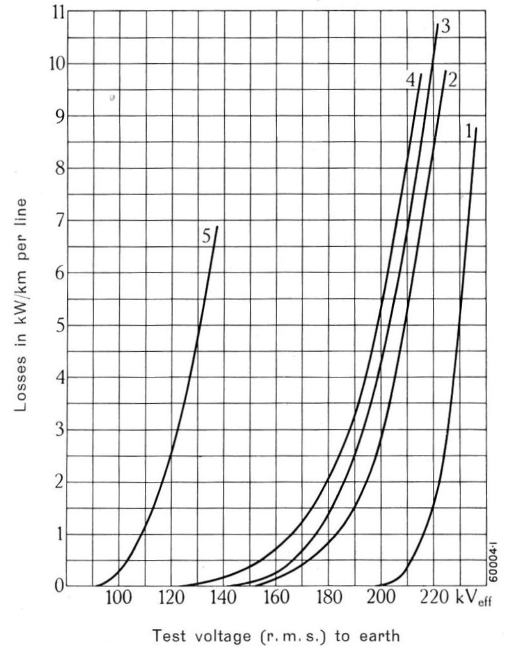


Fig. 6. — Effect of weather on corona loss measured on a 20 mm diam. copper cable. Losses as a function of the voltage for the following weather conditions:—

Curve	Air pressure mm Hg	Air temperature °C	Relative air humidity f %	Relative air density	Weather
1	732·0	20·5	74	0·965	Sunny to cloudy
2	729·7	5·0	85	1·01	Clear sky, no sun, dry
3	733·7	12·5	99	0·995	Slight fog
4	717·0	10·0	86	0·98	Light cloud, dew falling
5	728·4	— 4·0	98	1·045	Hoar frost, clear sky

With moderately bad weather, that is high humidity or light rain, the losses of the line are up to ten times, and with very bad weather, that is heavy rain, snow or frost, between ten and a hundred times greater than the fine weather losses.

20^0 C, by means of proportional conversion of the voltage with constant loss, according to the formula:

$$U_{\delta=1} = \frac{U_{\delta_x}}{\delta_x}$$

From the loss curves shown in Figs. 6 and 7 it can be seen that the effect of the weather is essentially to cause a parallel displacement of the curves. The total range of displacement covers 100 kV. When the weather deteriorates the corona voltage drops to nearly half its fine weather value. A comparison of the losses for a 50 mm cable at 240 kV (voltage at which noticeable losses occur with fine weather) shows that the loss is ten times greater when the weather becomes foggy and a hundred times greater when there is a heavy rain. The conditions are the same for the 20 mm cable. The curves for snow and frost lie between curve 3 (light rain) and curve 4 (heavy rain) in Fig. 7.

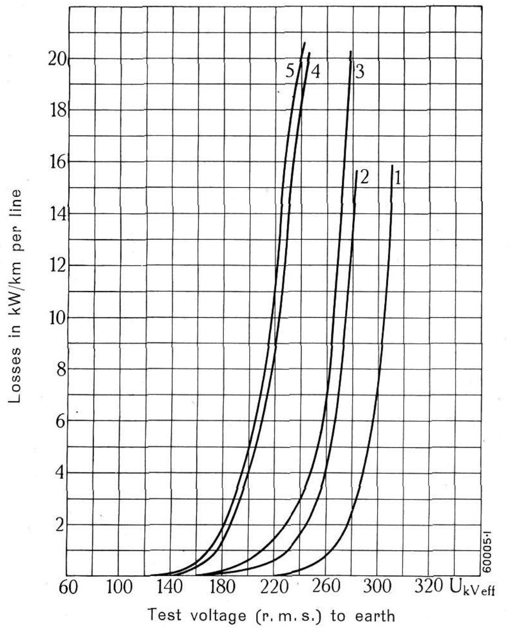


Fig. 7. — Effect of weather on corona loss measured on a 50 mm diam. hollow aluminium cable, after artificial ageing. Losses as a function of the voltage for the following weather conditions:—

Curve	Air pressure mm Hg	Air temperature °C	Relative air humidity f %	Relative air density	Weather
1	753	22·2	54	0·977	Sunny to cloudy
2	756	3·8	99	1·064	Cloudy, hazy
3	759	11·2	89	1·027	Light rain
4	758	11·0	100	1·027	Thick fog
5	759	11·2	88	1·027	Heavy rain

Three characteristic curves are shown in Fig. 8 for the 50 mm cable which aged naturally during 1 ½ years. A comparison with Fig. 7 shows that the effect of ageing was the same on both the fine weather and the bad weather losses.

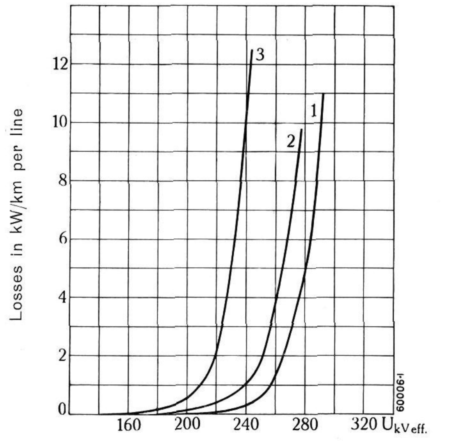


Fig. 8. — Effect of weather on the corona losses measured on a 50 mm diam. hollow aluminium cable, after natural ageing. The measured losses were only slightly higher than with artificial ageing. Losses as a function of the voltage for the following weather conditions:—

Curve	Air pressure mm Hg	Air temperature °C	Relative air humidity f %	Relative air density	Weather
1	762	8·0	53	1·036	Sunny
2	767	1·1	79	1·067	Cloudy
3	758	1·0	100	1·062	Average fog

POTTHOFF'S CONVERSION LAW.

According to a proposal made by Potthoff[1] a measured loss curve is converted to apply to another conductor arrangement by making the ratio of the field strengths at the surface of the conductor equal to the initial field strengths.

$$\frac{U_1 \cdot C_1}{r_1} : \frac{U_2 \cdot C_2}{r_2} = E_{o1} : E_{o2}$$

U_1, U_2 = conductor voltages.
C_1, C_2 = conductor capacitances.
r_1, r_2 = conductor radii.
E_{o1}, E_{o2} = initial field strengths.

If the line arrangements under investigation have the same conductor radius and the small dependence of the inital field strengths on the arrangement of the conductors is thus neglected, then the following relationship is established:—

$$U_2 = U_1 \frac{C_1}{C_2} \quad \ldots\ldots\ldots \quad (1)$$

U_1 and C_1 being the values for the measured arrangement.

[1] K. Potthoff, ETZ 54 (1933), p. 169 and 57 (1936), p. 1054.

If U_{2v} is the line voltage of an alternating current system, U_1 the measured voltage of the conductor to earth, C_1 the capacitance of the test line

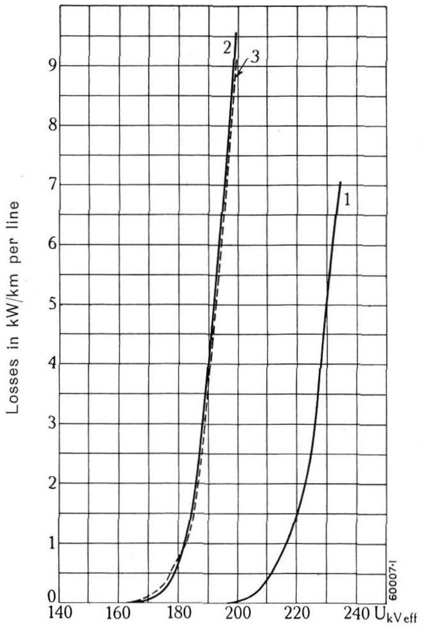


Fig. 9. — Effect of method of operation on the corona losses; measurements on a 20 mm diam. stranded copper cable. Losses as a function of the voltage for the following weather conditions:—

Curve	f %	δ	C pF	Method of Operation	Weather
1	74	0·965	355		Sunny to cloudy, dry
2	54	0·995	426		Sunny to cloudy, dry
3	Converted curve from symmetrical (curve 1) to unsymmetrical operation (curve 2)				

and C_2 the operating capacitance of the alternating current line per phase then the relationship is:

$$U_{2v} = \frac{C_1}{C_2} \cdot \sqrt{3} \cdot U_1 \quad \ldots\ldots \quad (2)$$

The usefulness of the conversion law was investigated on both test lines. The result is shown in Figs. 9 to 11. The loss of one conductor was measured with a symmetrical voltage on both conductors and also with the second conductor earthed. The desired loss curve can be determined from the measured values by calculating the associated voltage U_2 and U_{2v}, respectively, for a constantly maintained loss according to formulæ 1 and 2, respectively.

From Figs. 9 and 10 it can be seen that the calculated loss curve coincides with the measured one, thus proving the validity of this conversion law. In order to obtain proper agreement between calculation

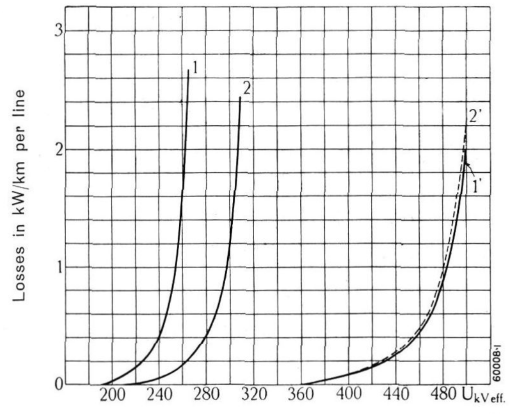


Fig. 10. — Corona loss on a single and three-phase line, hollow aluminium cable 50 mm diam. Losses as a function of the voltage. Curves 1′ and 2′ for the three-phase line are calculated from the measured values obtained for the single-phase line curves 1 and 2 and plotted as a function of the line voltage.

Curve	f %	δ	Weather	Single-phase line C pF/cm	Three-phase line C pF/cm	Method of operation
1	70	1·060	Sunny to cloudy	0·1017		
2	70	1·060	Sunny to cloudy	0·0868		
1′					0·0923	
2′					0·0923	

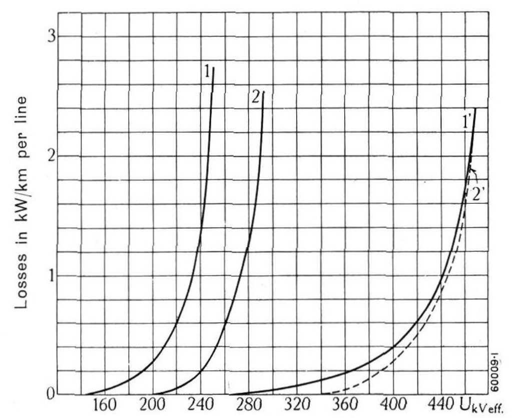


Fig. 11. — Corona loss on single and three-phase line, hollow aluminium cable 50 mm diam. Losses as a function of the voltage. Curves 1′ and 2′ for the three-phase line are calculated from the measured values obtained for the single-phase line curves 1 and 2 and plotted as a function of the *line voltage*.

Curve	f %	δ	Weather	Single-phase line C pF/cm	Three-phase line C pF/cm	Method of operation
1	98	1·064	Cloudy, slight fog	0·1017		
2	98	1·064	Cloudy, slight fog	0·0868		
1′					0·0923	
2′					0·0923	

and test it is important that both measurements should be made in quick succession during the same weather. In the case of the measurement made during fog, it was difficult to fulfil this condition and this accounts for the divergence of curve 2′ from the expected characteristic of curve 1′ (Fig. 11).

In order to be able to undertake this investigation it is essential that the surface condition of the conductors should be the same for both arrangements, the space filled by the discharge restricted to a small area around the conductor, and the changes in capacitance due to corona should not be very considerable.

The first condition is a matter of course. The second one is also fulfilled by adequate distances between conductors, because the charge carriers of a conductor only fall within the range of another conductor if the distances are small and favour discharges. The third condition is also fulfilled within the range of losses which can be borne economically.

(*MS 972*) *P. Geiser and Fr. Beldi. (Op.)*

ARC-OVER VOLTAGE OF MULTIPLE-PART INSULATORS WITH METALLIC INTERMEDIATE FLANGES.

Decimal Index 621.315.62.015.52
621.3.015.52 : 621.315.62

The physical behaviour of built-up insulators during arc-over is first briefly explained and thereafter experimental results are given for impulse and alternating-current high-voltage tests on built-up and single-piece insulators. The tests show that in order to determine the arc-over voltage of built-up insulators, it is best to reckon with the net breakdown distance, that is to say not to take into account the length of the intermediate fitting.

THE evolution of the electrical industry, which is due largely to the continuous expansion of the market for electrical energy, has resulted not only in the creation of further generating plants, but also of new transmission systems. These serve, in addition to the direct transmission of energy, more and more for the exchange of energy over long distances. The necessity of economical planning of such super-power transmissions, imposes a further increase of the transmission voltages hitherto used. Thus we may now look upon a service voltage of 400 $kV_{r.m.s.}$ for transmission over long distances as a matter for the immediate future, and for which high-voltage electrical switching apparatus will soon be required. The insulators for such devices, however, take on such large propositions that it is practically out of the question to make them in one piece. The total length of insulator must consist of two, three or even more pieces fastened together by metallic intermediate flanges, which ensure a proper mechanical joint.

It is proposed in the following to consider first the physical behaviour of such built-up insulating sets with metallic intermediate flanges as far as is necessary for properly understanding the test results given below. In conclusion, a very practical formula is deduced, which, sufficiently accurate for most practical purposes, enables a built-up insulator length to be converted into the equivalent length of a single-piece insulator having the same arc-over voltage.

In order that an arc-over shall occur on a single insulator, the condition for discharge must first be realized, that is to say the voltage must have attained the necessary value in relation to the time of application corresponding to the breakdown value. The occurrence of the total arc-over on a built-up insulator requires, on the other hand, that the discharge condition be fulfilled first for one section of the insulator, and that after the breakdown of this section the similar condition be fulfilled for a further section, and so on. In practice, this means that the breakdown of one part of the insulator leads to the immediate total arc-over voltage of the complete insulator.

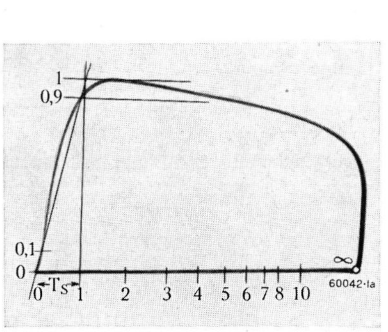
The total arc-over voltage of a built-up insulator, which in a general way can be looked upon as a system of capacities and resistances, depends, however, also on the nature of the stress. Thus, with an alternating-current voltage of 50 cycles, the voltage distribution at low values is capacitive. Above the initial voltage the ohmic resistance then begins with strong preliminary discharges to act in a stabilizing manner, and affects the arc-over in the immediate neighbourhood of the arc-over voltage at least by its influence on the peak value of the voltage wave. With impulse stresses, due to the high rate of variation of the field during the frontal period of the wave, the capacitive conductance is so considerable that the amount of leakage manifest as pre-discharge has no effect on the voltage distribution. It is therefore always possible, in the case of waves of a frontal duration of 1 μs and less to base on a purely capacitive distribution of the voltage.

It should also be noted that the characteristic forms of discharge during alternating high-voltage tests are very different from those of impulse tests. Thus, in the first case a strong preliminary ionization takes place at the electrodes, and with built-up insulators also at the intermediate electrodes, which means that this design is at a disadvantage compared with a single-piece design. In the case of surge tests, on the other hand, there is no appreciable preliminary discharge, and for this reason single-piece and multipiece insulators behave practically identically.

It can be seen from this brief description of the phenomena leading to the occurrence of a total flashover that it is not possible to give an exact relation for calculating the arc-over voltage of a built-up insulator span, and hence that reference has to be made to test results.

The following experimental results apply to a multiple-piece test object set up vertically on a metal plate and whose insulator parts consist of multiple-skirt porcelain elements with sharpened cylindrical fittings. Measurements with alternating-current voltages were effected with a good sine wave-form test voltage. The impulse voltage tests were carried out with the new impulse generator[1] which has now been in operation for more than six months. The standard wave of $^1/_{50}$ μs was employed for all tests, and from the oscillogram Fig. 1 it will be seen that the characteristics of the wave agree extremely closely with the nominal values and that the maximum harmonic amplitude in the neighbourhood of the peak is less than 1 %.

[1] See of pages 219/220 of the present number of this journal.



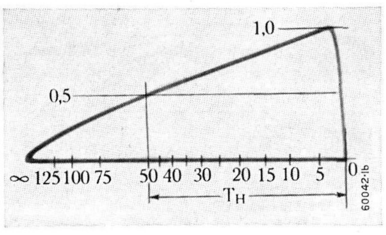


Fig. 1. — Oscillogram of the wave shape employed during the tests.

(a) Diagram with a high-speed time deviation for examining the wave front. T_s = duration of wave-front = 1 μs.

(b) Diagram with a slower time deviation to show the tail of the impulse wave. T_h = Time to half amplitude on tail = 50 μs.

The characteristics of the wave agree closely with the nominal values and the amplitude of the harmonic is very small.

Measurements were made of the arc-over voltage on the test object described above with varying arcing distances for one, as well as for two and three intermediate fittings, the lengths of which were also varied. In order to obtain a scale of comparison for the arc-over strength of a built-up insulator, it seems natural to compare its arcing distance with that of a single-piece insulator of the same breakdown voltage as the former. The single-piece insulator then represents the equivalent breakdown distance of the built-up arrangement.

It is readily understandable that the relation for the equivalent breakdown distance must include the individual partial arcing distances as well as the length of the intermediate fittings. This suggests two limiting values, the upper one being represented by the sum of all the partial arcing distances inclusive of the full lengths of the intermediate flanges, and the lower one only by the sum of the partial arcing distances exclusive of the lengths of the intermediate fittings. Written in mathematical form these two limiting values are:

$$S_{equivalent} = \Sigma_s + \Sigma_a \tag{1}$$

and

$$S_{equivalent} = \Sigma_s \tag{2}$$

where

$S_{equivalent}$ = Equivalent arc-over distance of the single-piece insulator.

Σ_s = Sum of the partial arcing distances of the built-up insulator span.

Σ_a = Sum of the lengths of the metal intermediate fittings.

The average of these two limiting values is:

$$S_{equivalent} = \Sigma_s + \Sigma\frac{a}{2} \tag{3}$$

The validity of this formula can be judged only on the basis of experiments. Our measurements are given in Figs. 2 to 5, Figs. 2 and 3 referring to impulse tests, and Figs. 4 and 5 to industrial frequency alternating-current tests. Figs. 2 and 3 and 4 and 5 are the same, the only difference being in the method of representation; Figs. 2 and 4 show the arc-over voltages as a function of equivalent arcing distance as given by formula (3), whereas in Figs. 3 and 5 they are given as a function of an arcing distance according to formula (2). The curves 1a of all the diagrams were

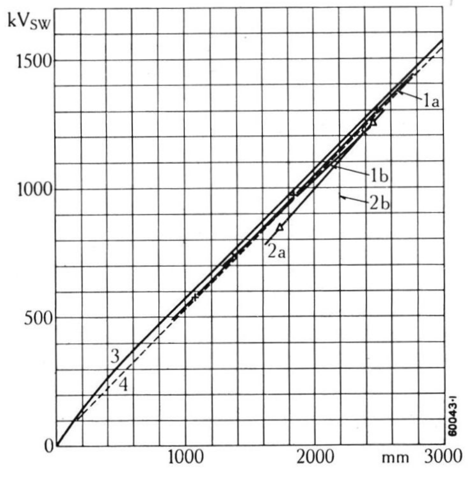


Fig. 2. — Positive 50 % impulse flash-over test voltages (peak) of simple insulators as a function of the arcing distance as well as of multiple-part insulators as a function of the equivalent arcing distance

$$S_E = \Sigma s + \Sigma \frac{a}{2}.$$

Curve 1a – 2b. Built-up insulators.
Curve 1a (test points +). 1 intermediate fitting, 120 mm long.
Curve 1b (test points ×). 2 intermediate fittings, 120 mm long.
Curve 2a (test points △). 1 intermediate fitting, 350 mm long.
Curve 2b (test points ○). 2 intermediate fittings, 350 mm long.
Curve 3. One-piece insulators.
Curve 4. Required arc-over voltage according to REH as a function of the corresponding minimum arcing distance.

A few points fall below the limit curve 4, which is inadmissible.

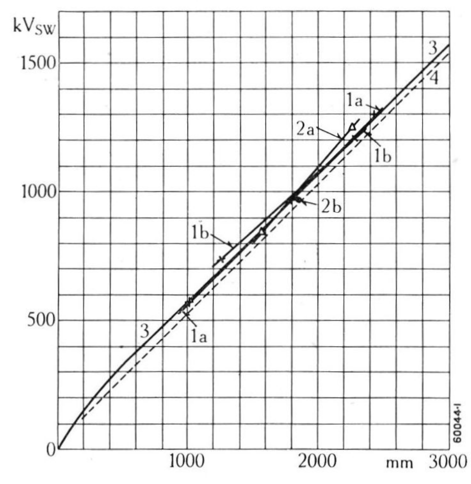


Fig. 3. — Positive 50 % impulse flash-over test voltages (peak) of simple insulators as a function of the arcing distance as well as of multiple-part insulators as a function of the equivalent arcing distance

$$S_E = \Sigma s .$$

Curve 1a—2b. Built-up insulators.
Curve 1a (test points +). 1 intermediate fitting, 120 mm long.
Curve 1b (test points ×). 2 intermediate fittings, 120 mm long.
Curve 2a (test points △). 1 intermediate fitting, 350 mm long.
Curve 2b (test points ○). 2 intermediate fittings, 350 mm long.
Curve 3. One-piece insulators.
Curve 4. Required arc-over voltage according to REH as a function of the corresponding minimum arcing distance.

All points lie above the limit curve 4.
The compliance with the regulations is ensured.

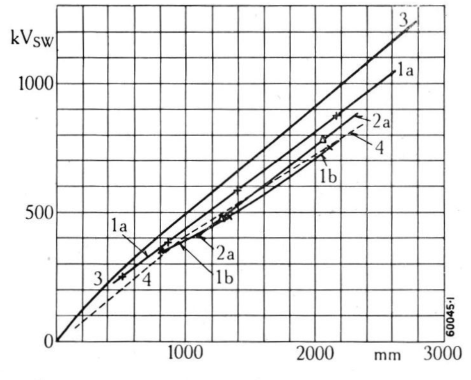


Fig. 4. — Arc-over alternating-current voltages (peak) at 50 cycles for one-piece insulators as a function of the arcing distance as well as of multiple-component insulators as a function of the equivalent arcing distance

$$S_E = \Sigma s + \Sigma \frac{a}{2}.$$

Curve 1a—2a. Built-up insulators.
Curve 1a (test points +). 1 intermediate fitting, 120 mm long.
Curve 1b (test points ×). 2 intermediate fittings, 120 mm long.
Curve 2a (test points △). 1 intermediate fitting, 350 mm long.
Curve 3. One-piece insulators.
Curve 4. Required arc-over voltage according to REH as a function of the corresponding minimum arcing distance.

Individual test points lie below the curve 4, which is contrary to the regulations.

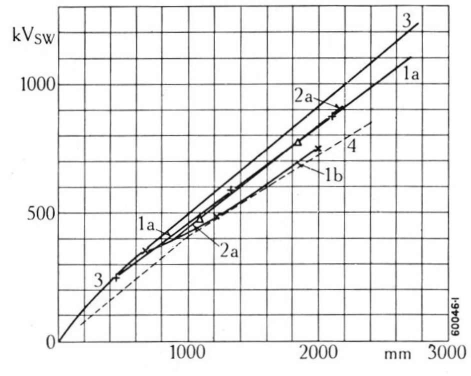


Fig. 5. — Arc-over alternating-current voltages (peak) at 50 cycles for one-piece insulators as a function of the arcing distance as well as of multiple-component insulators as a function of the equivalent arcing distance

$$S_E = \Sigma s.$$

Curve 1a – 2a. Built-up insulators.
Curve 1a (test points +). 1 intermediate fitting, 120 mm long.
Curve 1b (test points ×). 2 intermediate fittings, 120 mm long.
Curve 2a (test points △). 1 intermediate fitting, 350 mm long.
Curve 3. One-piece insulators.
Curve 4. Required arc-over voltage according to REH as a function of the corresponding minimum arcing distance.

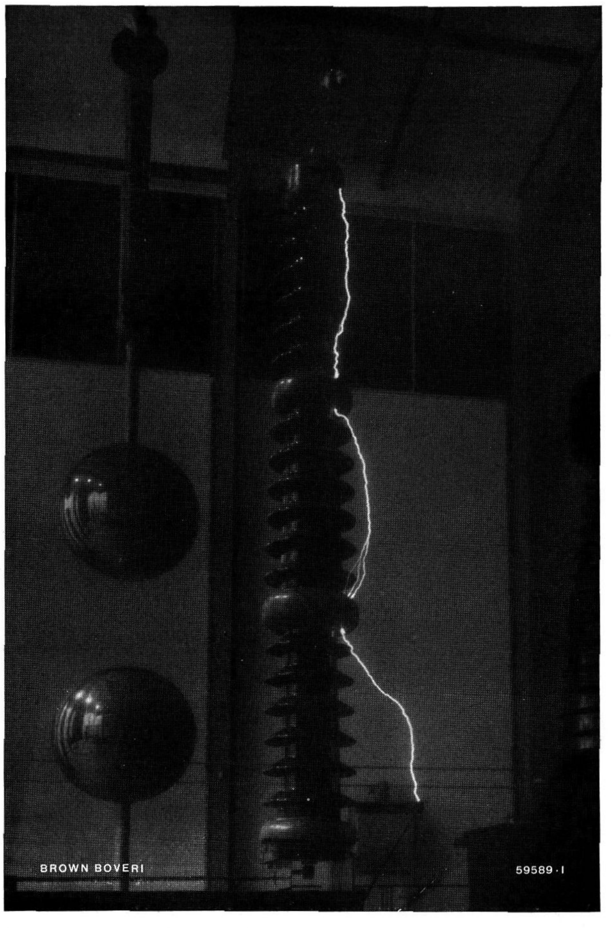
Not a single point lies below the limit curve 4.
There is in all cases compliance with the regulations.

obtained for an intermediate length of fitting of 120 mm, curves 1b for two such fittings. Such short fittings will be normal. Curves 2a and 2b show the effect of the arc-over voltage with longer fittings, curve 2a referring to a single fitting of 350 mm length, curve 2b to two such fittings. In regard to the type of stress the families of curves for the built-up insulators show an essential difference: The differences of the characteristics for the two arrangements are very much greater with alternating-current voltage (Figs. 4 and 5) than with impulse voltages (Figs. 2 and 3).

In order to show which formula is correct for the equivalent arcing length, the diagrams also include the measured arc-over voltages for single-piece insulators (curves 3). The formula will be right if the curves of arc-over voltage drawn to a basis of equivalent arcing distance coincide with the curves for a single-piece insulator. As shown by the figures, formula (3) gives for impulse as well as for alternating current voltages (Figs. 2 and 4) too large a value for the equivalent arc-over distance, since the arc-over voltages actually measured are smaller than those deduced from the calculated equivalent arcing distance obtained from curve 3. The values according to formula (1) are therefore much too high; for this reason they have not been included in the diagrams. Formula (2) shows, however, in the case of the impulse test a very good agreement (Fig. 3), whereas with alternating current voltage the formula gives rather too large values (Fig. 5).

The VDE (REH)-Rules for high voltage alternating current apparatus demand that the equivalent arcing distance according to formula (3) shall not be less than the minimum required for single-piece insulators. In order to test the suitability of this regulation, there have been included in Figs. 2 to 5 the minimum values of the arc-over voltage plotted as a function of the minimum value of the arcing distance, according to the VDE (curve 4). Now it will be seen from Figs. 2 and 4 that the minimum arc-over voltage according to REH with impulse and alternating-current tests is generally reached if the equivalent arcing distance according to formula (3) agrees with the minimum value according to REH. In individual cases — particularly with long intermediate fittings — the arc-over voltage remains, however, somewhat below the required minimum value. If the equivalent arcing distance according to formula (2) is equal to the minimum REH-value, the required arcing voltage is reached or exceeded in all cases (Figs. 3 and 5).

(MS 978) *Fr. Beldi and E. Uhlig. (Hv.)*



Impulse test on 400 kV isolating switch (model).

The clearance of the protective spark-gap is greater than the standard clearance, so that flash-overs occur on intermediate fittings. Flash-over voltage 1800 peak kV.

INVESTIGATIONS INTO RELIABILITY OF MARGINS BETWEEN COORDINATED INSULATION LEVELS.

Decimal Index 621.316.93 : 621.3.048

Extensive investigations into the tolerance of impulse flash-over voltages have shown that in the coordination of insulation strengths an absolutely safe margin is economically impossible. For a given insulation step, therefore, the probability of failure is required to be known. In the present article probability calculations are made which justify the margins specified by the Swiss Coordination Committee. The theoretical considerations are substantiated by numerous test results.

1. *Introduction.*

"Insulation coordination" is a comprehensive term for all of the measures adopted in electrical systems to obviate puncture of insulation in the event of over-voltage and — when the cost of the necessary preventive means is prohibitive — to confine flash-overs to points at which they are likely to do no harm and not interrupt service. Such measures include grading of the insulation strength of the various parts of the system so that under impulsive voltage conditions some parts flash over, while others do not. If three insulation levels are adopted grading is effected twice, viz., on the one hand between the lower and intermediate level and on the other between the intermediate and upper levels. The lower level is usually held by lightning arrestors, the intermediate by gaps of some kind, and the upper partly by clearances in air partly by a liquid or solid dielectric. In the following notes it is intended to investigate the margins between the lower and intermediate levels and between the intermediate level and the clearances in air of the upper level.

To begin with let us consider the conditions under which an arrestor prevents flash-overs across the gaps of the intermediate insulation level. At first sight the problem appears very simple: the operating breakdown and residual voltage of the arrestor must be lower than the flash-over voltage of the gaps. In point of fact, however, no definite value can be given to either the breakdown or flash-over voltage, inasmuch as both arrestors and gaps are subject to a big tolerance in performance characteristics. The coordination can therefore only be termed safe when the maximum value of the arrestor breakdown voltage is lower than the minimum flash-over voltage of the gaps.

Even this requirement does not appear to present any difficulties, but due to the magnitude of the tolerance of performance already referred to it cannot be fulfilled in practice. Impulse flash-over tests carried out on rod-gaps [1] at the instigation of the Swiss Coordination Committee have given voltages varying by as much as $\pm$ 26 %. Since as far as can be ascertained no systematic investigations have ever been made with the gaps of the intermediate level the same maximum tolerance will be assumed here. In the case of arrestors the tolerance of performance seems to be somewhat smaller, although it may still attain $\pm$ 20 %. To fulfil the above requirement under these conditions the mean breakdown voltage of the arrestors would have to be roughly 40 % lower than the mean flash-over voltage of the gaps. If an arrestor is also expected to provide adequate protection for gaps located at some distance from it the margin would have to be made even greater. In consequence, the mean breakdown voltage of the arrestors should only be about half the mean flash-over voltage of the gaps. This, however, is impossible to realize in practice, while a further margin of this magnitude is even less feasible between the intermediate and upper insulation levels.

One has therefore no other resource than to select smaller steps with the knowledge that in certain cases gaps will flash over in lieu of arrestors operating. The probability of such failures, which should only be very slight, will now be investigated for a given insulation step.

2. *The Probability of Gap Flash-overs in Relation to the Voltage with $^1/_{50}$ μs Impulse Waves.*

The results of tests undertaken by the Swiss Coordination Committee will be taken as base. Fundamentally, there are two distinct tolerances to be taken into consideration, viz., on the one hand that between the 0 % and 100 % flash-over voltages and on the other that of the 50 % flash-over voltage when testing a gap in different laboratories or at different times.[2] The first tolerance can be represented by an S-shaped curve (cf. Fig. 1, curve 1) which gives the probability of flash-over in relation to the peak value

[1] Bulletin SEV 1943, No. 8, p. 193.

[2] This only refers of course to the tolerance remaining when the individual test values of the flash-over voltage are reduced to standard atmospheric conditions (air pressure, temperature, and humidity).

of the impulse voltage. If, therefore, the test object flashes over at the peak value of 100 % in 50 % of a large number of tests with the standard impulse wave of $^1/_{50}$ μs, at a peak value of 95 % it will only flash over in 12 % of the tests, and so on. Curve 1 in Fig. 1 is the mean of twelve different test curves (six different gap clearances tested each time with both polarities).

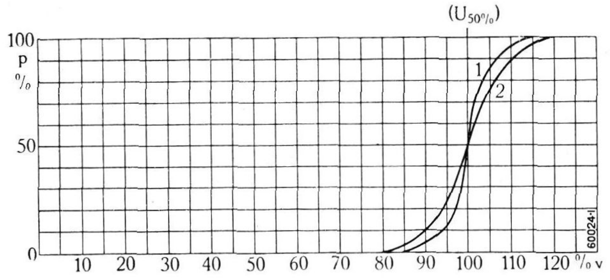


Fig. 1. — Probability of flash-over p of rod-gaps in function of voltage v with voltage surges of standard 1/50 μs wave-form. The peak value of the impulse voltage v is given as a percentage of the 50 % flash-over voltage.

Curve 1. Mean value of twelve different test curves (gap spacing 140 to 1150 mm, both polarities).

Curve 2. Probability resulting from curve 1 for a given 50 % flash-over voltage when latter subject to tolerance given by equations (4) and (1a.)

The second type of tolerance can be represented by the law of Gauss. If the deviation of the individual test values of the 50 % flash-over voltage from the mean value (referred to this mean value) is denoted by ξ the probability of test values falling within the range of ξ and $\xi + d\xi$ is

$$dW = \frac{h}{\sqrt{\pi}} e^{-h^2 \xi^2} d\xi \quad \ldots\ldots (1)$$

whereby from the investigations of the Swiss Coordination Committee a mean value of

$$h = 16 \quad \ldots\ldots\ldots\ldots (1a)$$

results. This probability curve is represented by 1 in Fig. 2.

If a large number of tests are made on a gap at different times or at different places and the mean of the recorded flash-over voltages is taken, it can be assumed that further test values will be symmetrically grouped about this mean value, giving the distribution represented by curve 1 in Fig. 2. When, however, only one single test* is made — as should be standard practice for the adjustment of coordinating gaps — the resultant voltage will not lie exactly in the middle of the probability curve (Fig. 2), but somewhere in the vicinity, e. g., at O in Fig. 3 with the distance δ** from the centre of the Gauss curve. If one single test is carried out on each of a large number of similar gaps the same law applies to the distance δ of all of the test values from the middle point of the curve as for the distribution of the values resulting from repeated tests on one single gap. The law of probability for the distance δ obtained from one single test, therefore, is given by substituting δ for ξ in equation (1):

$$dW_1 = \frac{h}{\sqrt{\pi}} e^{-h^2 \delta^2} d\delta \quad \ldots\ldots (2)$$

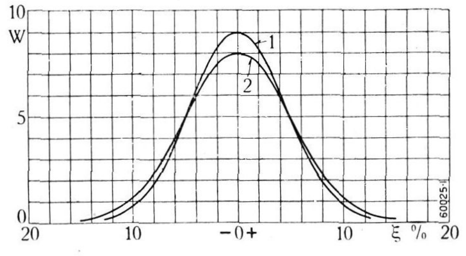


Fig. 2. — Gauss curves for tolerance of 50 % flash-over voltage of rod-gaps and 50 % breakdown voltage of lightning arrestors

(graphical representation of equation 1).

Curve 1. Mean value of Swiss Coordination Committee's tests with rod-gaps.

Curve 2. Mean value of Brown Boveri's tests with lightning arrestors.

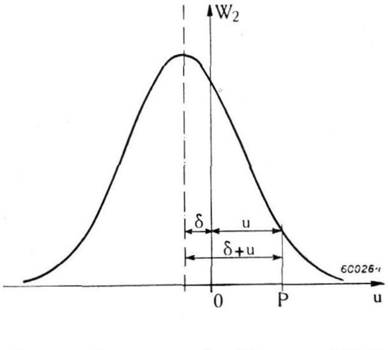


Fig. 3. — Gauss curve for tolerance of 50 % flash-over voltage of rod-gap adjusted to a required value by one single test.

O. Required value of voltage.

P. Value at later test.

u. Deviation of test value from required value referred to latter.

δ. Deviation of centre point of probability curve from required value, referred to latter.

W_2. Probability of occurrence of deviation u.

* The one single test can of course comprise many test points; of chief importance is that tests are not repeated at different times or places.

** δ is a relative value, i. e., the deviation of the required value from the mean value divided by the required value.

A gap adjusted to a certain required value by one single test* will now be investigated. Referring to Fig. 3 this required value is at O. If any number of subsequent tests are made the distribution of the resulting values will be represented by the same Gauss curve as in Fig. 2 (curve 1), except that the centre point is shifted towards the required value by the amount δ. Assuming the deviation of any test value (P in Fig. 3) from the required value (referred to the latter) to be denoted by u the relative deviation from the centre point of the probability curve will be $(\delta + u)$. In the case of curve (1) in Fig. 2 the relative deviation from the centre point is represented by ξ. To obtain the equation for the curve in Fig. 3, therefore, $(\delta + u)$ need only be substituted for ξ in equation (1) applying to curve 1 in Fig. 2:

$$d W_2 = \frac{h}{\sqrt{\pi}} e^{-h^2 (\delta + u)^2} du \quad . \; . \; . \; . \; (3)$$

For the case of several gaps each adjusted to the same required value by one single test there is again a law of probability for the quantity δ in equation (3), viz., equation (2). Hence, with the deviation u from the required value, the probability of a 50 % flash-over voltage occurring on any of several gaps adjusted to the same required value, is

$$dW = \int_\delta dW_1 \, dW_2 =$$

$$\frac{h^2}{\pi} e^{-h^2 u^2} du \int_{-\infty}^{+\infty} e^{(-2h^2\delta^2 - 2h^2\delta u)} d\delta$$

or simplifying

$$dW = \frac{h}{\sqrt{2}\sqrt{\pi}} e^{-\left(\frac{h}{\sqrt{2}}\right)^2 u^2} du \quad . \; . \; . \; (4)$$

In lieu of h in equation (1), $h/\sqrt{2}$ appears as accuracy term in equation (4). Even with a large number of gaps each adjusted to the same 50 % flash-over voltage by one single test, therefore, the values to be expected from subsequent tests also follow a Gauss curve, except that, as was to be anticipated, the tolerance is greater than that of a single gap referred to the mean value of its 50 % flash-over voltage.

On the one hand, therefore, the probability of flash-over in relation to the voltage for a given 50 % flash-over voltage (curve 1 in Fig. 1) is now known and on the other also the laws of tolerance for the 50 % flash-over voltage itself (equations 4 and 1 a). These enable the probability of flash-over to be readily calculated for any voltage value when gaps are adjusted to a certain required value by one single test. Fig. 4 shows curve 1 of Fig. 1 plotted with its centre point, i. e., the 50 % flash-over voltage shifted by the amount u to the right of the required value. From Fig. 3 u is the deviation of the 50 % flash-over voltage from the required value for any test. If the curve 1 in Fig. 1 obtained experimentally is denoted

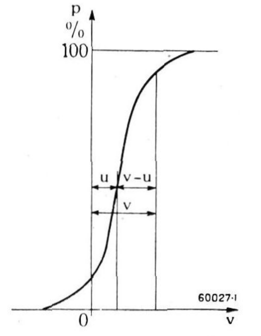


Fig. 4. — Probability of flash-over in function of voltage for rod-gap adjusted to a required value of the 50 % flash-over voltage by one single test.

Abscissa v. Voltage (plotted as deviation from required value, referred to latter).
Ordinate p. Probability of flash-over.
u. Deviation of 50 % flash-over voltage from required value, referred to latter.
O. Required value.

$$p = S\ (v)$$

the equation for the curve in Fig. 4 will be

$$p = S\ (v - u) \quad . \; . \; . \; . \; . \; . \; . \; (5)$$

For the case of a large number of gaps adjusted to the same required value the distance u of the centre point of the S curve from the required value will follow the law of probability represented by equation (4). Given the value v, therefore, the probability of flash-over for any of the gaps will be

$$p' = \int p \, dW = \frac{h}{\sqrt{2}\sqrt{\pi}} \int_{-\infty}^{+\infty} S(v-u) \cdot e^{-\frac{h^2}{2}u^2} du \quad (6)$$

Since the function S is only given graphically the integral can only be found graphically. The result of this operation is represented by curve 2 in Fig. 1. This characteristic, therefore, gives the probability of flash-over for any voltage value when several gaps have each been adjusted to the same required value of the 50 % flash-over voltage by one single test. Curve 2 is similar in form to curve 1 and hereafter will be briefly styled the "S′ curve".

* See foot-note in first column on page 260.

3. *Margin between Breakdown Voltage of Arrestors and Flash-over Voltage of Horn-gaps of Intermediate Insulation Level.*

The tests and arguments employed with respect to the horn-gaps of the intermediate insulation level can now also be applied to the lightning arrestors as regards their breakdown voltage. In this case extensive test data of our own are available. The mean S curve (without taking into account the tolerance of the 50 % operating voltage at different places and times) is represented by curve 1 in Fig. 5. The tolerance of the 50 % operating voltage can be given by a Gauss function in accordance with equation (1) as

$$h = 14 \quad . \; . \; . \; . \; . \quad \text{(1b)}$$

The corresponding Gauss curve is shown in Fig. 2 (curve 2). From these fundamental data the S′ curve was derived as in the preceding section and plotted in Fig. 5 as curve 2. It shows the probability of operation of arrestors at various voltages when the arrestors have each been adjusted to the same required value of the 50 % breakdown voltage by one single test.

Fig. 6 again shows the probability curves (S′ curves) for arrestors and horn-gaps, whereby the required value of the 50 % breakdown voltage of the arrestor lies 15 % below the required value of the 50 % flash-over voltage of the gaps. These curves give the probability of flash-over of the gaps (p_1) and non-breakdown of the arrestor ($1-p_2$) for any voltage value.

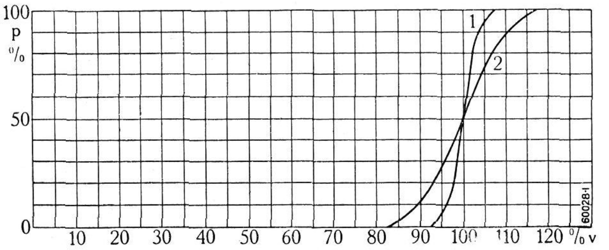


Fig. 5. — Probability of breakdown p of lightning arrestors in function of voltage v with voltage impulses of standard 1/50 μs wave-form. The peak value of the impulse voltage v is given as a percentage of the 50 % breakdown voltage.

Curve 1. Mean value from various tests undertaken by Brown Boveri.
Curve 2. Probability resulting from curve 1 for a given 50 % breakdown voltage when latter subject to tolerance given by equations (4) and (1b).

The breakdown time-lag of a modern arrestor is very little less than the flash-over time-lag of horn-gaps. It can therefore be assumed with a good approximation that an arrestor — if it functions at all — will invariably break down before gaps can flash over. On the other hand horn-gaps can only operate when the decisive moment for the operation or not of the arrestor has passed. In consequence, there is practically no mutual effect between arrestors and gaps, i. e., the individual probabilities (p_1) and ($1-p_2$) are independent. Therefore the resulting probability of the non-operation of the arrestor and the flashing over of the gaps, i. e., the probability of failure of coordination, is given by the product

$$p = p_1 \; (1 - p_2) \qquad (7)$$

This probability of failure is plotted in Fig. 7, where the required value of the breakdown voltage of the arrestor is on the first occasion 15 % and on the second 20 % below the required value of the flash-over voltage of the gaps. In both cases the probability of failure with low or high-voltage values is nil, inasmuch as in the one case the gaps never flash over and in the other the arrestor invariably operates. In between there is a zone with a finite probability of failure, which, however, does not even attain 1 % for a margin of only 20 %. If it is considered how little probability there is of a voltage of this very magnitude attaining the arrestor and the gaps it protects, the resultant probability of failure is extremely slight, even with a margin of only 15 %. This result is remarkable when it is remembered that absolutely reliable coordination is only obtained with a margin of at least 40 %.

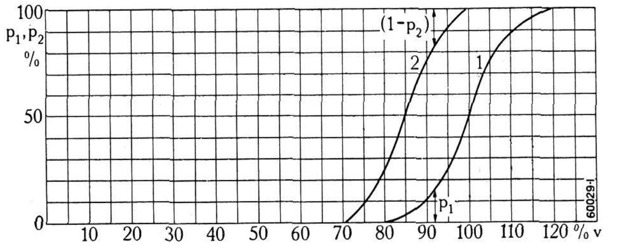


Fig. 6. — Probability of flash-over p_1 of a gap and probability of breakdown p_2 of an arrestor in function of voltage v. The peak value of the impulse voltage v is given as a percentage of the 50 % flash-over voltage of the gap.

Curve 1. Probability of flash-over of gap.
Curve 2. Probability of breakdown of arrestor.

4. *Margin between Residual Voltage of Arrestors and Flash-over Voltage of Horn-gaps of Intermediate Insulation Level.*

Apart from the breakdown voltage, the residual voltage of an arrestor must not be too high if the gap it is required to protect is not to flash over. Repeated measurement of the residual voltage of a given arrestor with a definite discharge current shows that it varies relatively very little, and by way of an approximation can be considered constant.[1] The gaps to be protected, when adjusted by one single test to the required value, have a flash-over probability in relation to the voltage as represented by curve 2 in Fig. 1. This curve is also plotted in Fig. 8, where the 80 and 85 % values of the 50 % flash-over voltage of the gaps are also given to show how the voltage across the gaps can rise when the residual voltage is limited to 80 or 85 % at the rated discharge current.

It will immediately be seen from this figure that the probability of a gap flash-over during the passage of the rated discharge current through the arrestor is of the order of 3 % when with this current the residual voltage lies 15 % below the 50 % flash-over voltage of the gaps. With a margin of 20 % no flash-over takes place across the gaps whatsoever. If it is considered that given a sufficiently high discharge capacity the full rated discharge current will only be attained very rarely, the probability of failure, even with a margin of only 15 %, is extraordinarily slight.

5. *Margin between Flash-over Voltages of Horn-gaps of Intermediate Insulation Level and Clearances of Upper Insulation Level.*

Since flash-overs can also occur across clearances in air in the upper insulation level the grading problems between the intermediate and upper levels are similar to those between the lower and intermediate levels. If it is assumed that the tolerance in performance characteristics of rod-gaps can also be applied to the

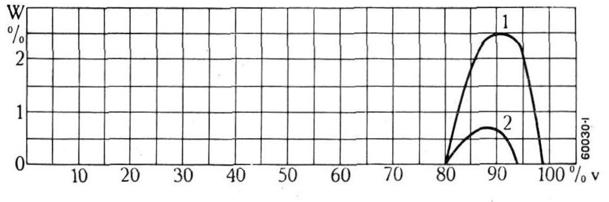


Fig. 7. — Probability of failure of a gap protected by arrestors.

Abscissa v. Voltage in percentage of 50 % flash-over voltage of gap.

Ordinate W. Probability of flash-over of gap notwithstanding parallel-connected arrestors.

Curve 1. 50 % breakdown voltage of arrestor set 15 % below 50 % flash-over voltage of gap.

Curve 2. 50 % breakdown voltage of arrestor set 20 % below 50 % flash-over voltage of gap.

clearances in air of the upper level, the probability of flash-over of both the upper and intermediate levels is given by curve 2 in Fig. 1. If the required value of the flash-over voltage for the upper level is set, for example, 15 % higher than that of the intermediate level the curve can be plotted once with the centre value at 100 % and a second time with this value at 115 %, whereupon the probabilities p_1 and $(1-p_2)$ can be found exactly as in Fig. 6.

The flash-over time-lag for the two coordinated clearances, however, is of the same order of magnitude, so that the probabilities p_1 and $(1-p_2)$ are therefore not mutually independent and the resulting probability for the upper level flashing over and the intermediate level not flashing over must not be taken as a product of the two probabilities. If this is done (which theoretically is not quite correct) the probability of failure of coordination is given by curves 1 and 2 in Fig. 9, the margins being 15 and 25 %, respectively.

From a theoretical point of view Strigel[2] has more correctly derived the probability of failure with coordinated, closely-spaced sphere-gaps and, taking the discharge time-lag characteristics into consideration, finds curves of the character represented by curve 2 in Fig. 10. The probability of failure increases with rising voltage and tends towards a value of about 50 %. Given such a characteristic all that is attained with two coordinated clearances is that some of the flash-overs take place across the clearance set to the lowest value; protection of the higher clearance by

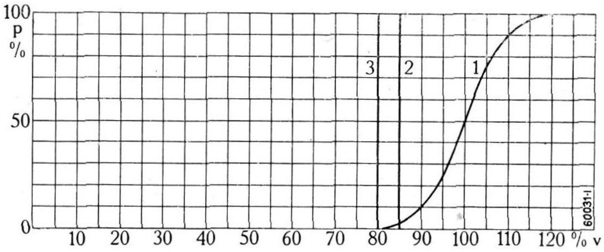


Fig. 8. — Probability of flash-over p of a gap in function of voltage v; voltage limited by residual voltage of an arrestor. The peak value of the impulse voltage v is given as a percentage of the 50 % flash-over voltage of the gap.

Curve 1. Probability of flash-over of gap.

Curve 2. Voltage limited by arrestor with residual voltage 15 % below required value of 50 % flash-over voltage of gap.

Curve 3. Ditto, for 20 % margin.

the lower is far from realized. Under these conditions coordination of clearances in air in the intermediate

[1] The manufacturing tolerances of several arrestors of the same rated voltage must be eliminated by never allowing the residual voltage to exceed the specified limit value.

[2] R. Strigel: "Elektrische Stossfestigkeit", Springer, Berlin, 1939, p. 52.

and upper levels would be ridiculous, and it would be *impossible to* protect high-voltage equipment against flash-overs by means of rod- or horn-gaps.

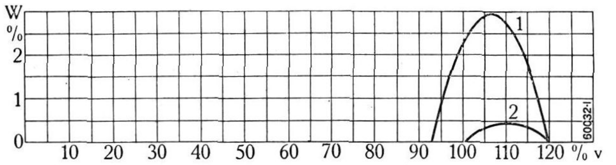


Fig. 9. — Probability of failure of two coordinated gaps.

Abscissa v. Voltage in percentage of 50 % flash-over voltage of gap with lower setting (intermediate insulation level).

Ordinate W. Probability of flash-over of gap with higher setting (upper insulation level) notwithstanding parallel connection of a gap with a lower setting.

Curve 1. Gap in upper level set to 15 % higher flash-over voltage than gap in intermediate level.

Curve 2. Gap in upper level set to 25 % higher flash-over voltage than gap in intermediate level.

Fortunately, however, all of our numerous measurements on high-voltage apparatus and rod-gaps prove that with an adequate margin of protection the failure curve has not the character of curve 2 in Fig. 10, but that of curve 1. The maximum probability of failure can be limited to a few per cent, or even less, by selecting a sufficiently large margin, and, what is more, the probability of failure decreases with increasing voltage after this maximum has been attained. No special stress need be laid on the significance of this fact from the point of view of insulation co-ordination.

Curves 1 and 2 in Fig. 9 cannot be conclusively confirmed theoretically until the discharge time-lag characteristics of clearances, such as occur in the intermediate and upper insulation levels of high-voltage equipment, are completely known. Investigations with this end in view are at present in progress. For the time being, however, the experimentally discovered fact that the probability of failure is really characterized by such wave-form curves and that for calculation purposes the individual probabilities of the upper level flashing over and the intermediate level not flashing over can be taken as though they were independent, must suffice.

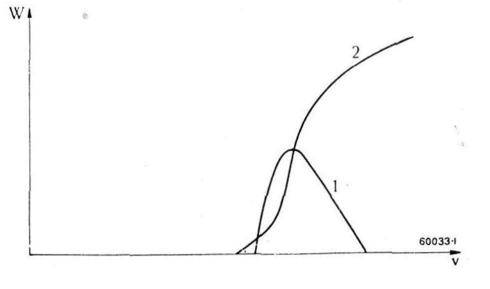


Fig. 10. — Different characteristics of probability of failure of two coordinated gaps.

Curve 1. Characteristic as invariably given by Brown Boveri tests with sufficiently large margin of protection.

Curve 2. Characteristic obtained from theoretical derivations based on Strigel's method of determining probability of failure of gaps.

It was hitherto assumed that the clearances investigated were each adjusted to the required value by one single test, i. e., when reckoning the probability of failure the entire tolerance resulting from tests at various places and at different times, was taken into consideration. If, however, high-voltage equipment is coordinated in itself, this tolerance can be largely eliminated. Take the example of a circuit-breaker with which the flash-over voltage between conductors and earth is set lower than that across the open contacts so that there is a greater tendency for a flash-over to take place to earth than across the contact: the two flash-over voltages can be measured one after the other, whereby the described tolerance is to a large extent eliminated. With a good approximation, therefore, curve 1 in Fig. 1 (and not curve 2) can be taken as base for the calculation of the probability of flash-over of each clearance and the distance between the two curves made equal to the distance between the required values of the flash-over voltages.

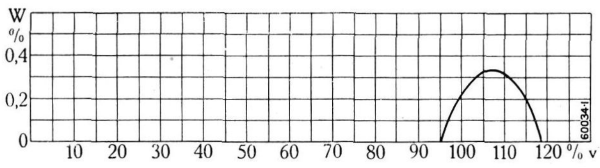


Fig. 11. — Probability of failure of two gaps with 15 % margin between mean values of 50 % flash-over voltage.

Abscissa v. Voltage in percentage of 50 % flash-over voltage of gap with lower setting (intermediate level).

Ordinate W. Probability of flash-over on gap with higher setting (upper insulation level) notwithstanding parallel connection of gap with a lower setting.

If the two curves for the probability of flash-over are combined in the usual way a wave-form curve is obtained for the probability of failure, but which is not so high as when calculating with the S′ curves. Another factor to be taken into account is the time-lag tolerance of the 50 % flash-over voltages which result in the peak value of the curve being still further reduced. The resultant curve for the probability of failure with a margin of 15 %, is shown in Fig. 11. The maximum probability of failure is much less than with the margin of 15 % in Fig. 9 (curve 1) and even still below that for the 25 % margin represented by the second curve in the same figure.

For the sake of clearness the different assumptions on which Figs. 9 and 11 are based will be repeated. In the first case the two parallel-connected gaps were adjusted to a given flash-over voltage by one single test absolutely independently, whereas in the second the tests were carried out at the same place simultaneously or in immediate succession. If even in this second case the tolerance of the 50 % flash-over voltage is perhaps not entirely eliminated, with the result that the probability of failure appears somewhat greater than in the curve in Fig. 11 derived under

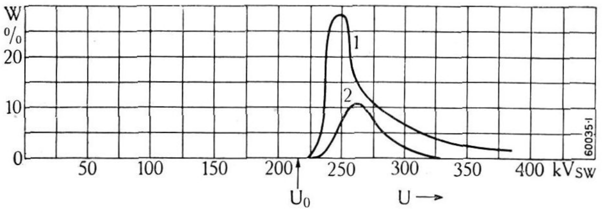


Fig. 12. — Test curves of probability of failure of two coordinated rod-gaps.

Abscissa U. Peak value of impressed impulse voltage of 1/50 μs wave-form.

U_0. 50 % impulse voltage of gap with lower setting.

Ordinate W. Percentage of flash-overs (incorrectly) occurring on gap with higher setting.

Curve 1. 50 % flash-over voltage of higher gap set 10 % above lower gap.

Curve 2. 50 % flash-over voltage of higher gap set 15 % above lower gap.

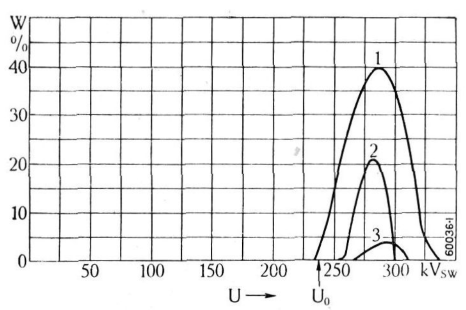


Fig. 13. — Test curves of probability of failure of two coordinated gaps.

Abscissa U. Peak value of impressed impulse voltage of 1/50 μs wave-form.

U_0. 50 % flash-over voltage of gap with lower setting.

Ordinate W. Percentage of flash-overs (incorrectly) occurring on gap with higher setting.

Curve 1. 50 % flash-over voltage of higher gap set 10 % above lower gap.

Curve 2. 50 % flash-over voltage of higher gap set 15 % above lower gap.

Curve 3. 50 % flash-over voltage of higher gap set 20 % above lower gap.

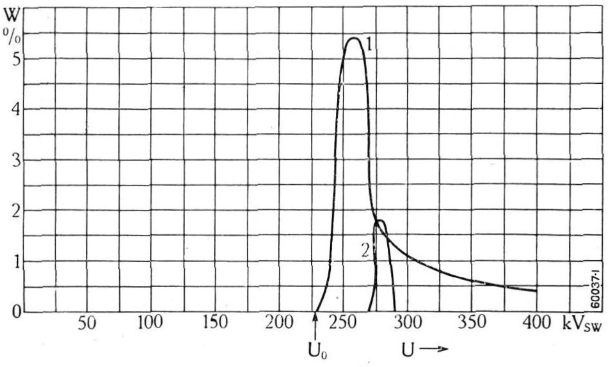


Fig. 14. — Test curves of probability of failure of two coordinated rod-gaps.

Abscissa U. Peak value of impressed impulse voltage of 1/50 μs wave-form.

U_0. 50 % flash-over voltage of gap with lower setting.

Ordinate W. Percentage of flash-overs (incorrectly) occurring on gap with higher setting.

Curve 1. 50 % flash-over voltage of higher gap set 10 % above lower gap.

Curve 2. 50 % flash-over voltage of higher gap set 15 % above lower gap.

extremely favourable conditions, the probability is at any rate much less than when the two gaps were tested independently. It is therefore strongly to be recommended that the intermediate and upper insulation levels be mutually stepped by simultaneous tests. This can be achieved most simply by coordinating the high-voltage equipment in itself. Under these conditions a margin of 15 % will generally suffice.

6. *Experimental Confirmation of Theoretical Considerations.*

The behaviour of coordinated gaps, in particular, had to be experimently confirmed due to the uncertain data on which the theoretical considerations were based. A very large number of tests were made, some over long periods. Typical results are given in Figs. 12—14.

The theoretically derived curves in Fig. 9 are based on mean values. The individual test curves in Figs. 12—14 do not agree with the curves of mean values throughout and even differ among themselves. The character of all of the recorded curves, however, conforms to the theoretical curves. The probability of failure in particular is nil both for low and high values of the impressed voltage and in the intervening zone is given by a wave-form curve the maximum value of which is lower the greater the margin of protection.

Even more instructive than the tests reproduced in Figs. 12—14 are the investigations in connection with completely assembled high-voltage equipment coordinated in itself, which are described in the following article.[1] The countless tests carried out all showed that the desired coordination of the clearances of the intermediate and upper levels is possible, inasmuch as given an adequate margin a curve of the characteristic of curve 2 in Fig. 10 was never obtained. In most cases a margin of 15 % proved sufficient to avoid failure if both clearances were tested as simultaneously as possible. Occasionally the margin had to be increased to 20 % to achieve this end. In the case of margins below 15 %, however, the failures were impermissibly numerous.

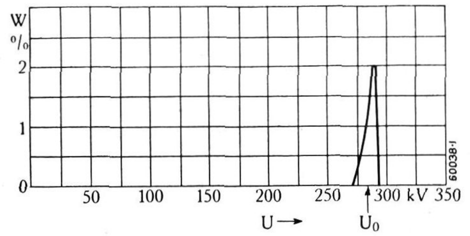


Fig. 15. — **Test curves of probability of failure of gap protected by arrestor when 50 % breakdown voltage of arrestor set 16 % below 50 % flash-over voltage of gap.**

Abscissa *U*. Peak value of impressed impulse voltage of 1/50 μs waveform.

U_0. 50 % flash-over voltage of gap.

Ordinate *W*. Percentage of flash-overs (incorrectly) occurring on gap.

The margin of protection between rod-gaps and arrestors was also investigated experimentally. At the outset a 60 kV arrestor was connected in parallel with a rod-gap and the 50 % breakdown voltage of the arrestor set to 16 % below the 50 % flash-over voltage of the gap (by two independent tests). About 300 impulses with a wave of $^1/_{50}$ μs were then applied at each of various voltages, whereby the failure curve of Fig. 15 was obtained. No failures occurred below 272 kV or above 292 kV.

Thereupon a test was made which perhaps more nearly conforms to practical conditions. After the 50 % breakdown voltage of the arrestor had first been set 10 % below the 50 % flash-over voltage of the gap (again by two independent tests), individual voltage surges were applied and their peak value gradually increased until the first discharge took place. The test was repeated thirty-five times, whereby the arrestor correctly operated thirty-four times, while at the thirty-fifth attempt the gap flashed over. Thereupon the 50 % breakdown voltage of the arrestor was set 14 % below the 50 % flash-over voltage of the gap and the same test repeated seventy times. The arrestor operated every time and thus adequately protected the gap.

On another occasion the arrestor and gap were tested *in immediate succession* to obtain a margin of protection of 9 %. In this case the relatively small margin sufficed to prevent failure with a total of about 3000 surges at various voltages. All of these tests prove that the theoretical considerations are also fundamentally correct for the case of arrestors and gaps in parallel.

7. *Application of Results of these Investigations to the Insulation Coordination of High-voltage Equipment.*

The theoretical and experimental data given in this article were made available to the Swiss Coordination Committee for fixing the margins of protection. The subsequent publication of these particulars is intended to justify the margins selected by the Committee.

A margin of at least 25 % would be necessary between the intermediate and upper insulation levels if the two levels were to be tested independently. The simultaneous tests specified by the Coordination Committee usually permit the margin to be kept down to 15 % without increasing the probability of failure.

In an emergency a margin of 15 % between the flash-over voltage of the intermediate level and the breakdown voltage of the arrestors would suffice, even with independent tests. Since, however, an arrestor is also expected to provide adequate protection for high-voltage equipment located some distance away it must be remembered that the voltage at the point of installation of the protected equipment can rise somewhat higher than the breakdown voltage of the arrestors. In consequence, the Committee justifiably specified a margin of at least 25 %.

A margin of at least 25 % has also been prescribed between the flash-over voltage of the intermediate level and the residual voltage of arrestors. Inasmuch as the flash-over voltage decreases with altitude, while the residual voltage remains constant, the margin diminishes until at 1000 m above sea level it is only of the order of 12 %, whereby the probability of failure is merely a few per cent. It is therefore to be recommended not to select the rated discharge capacity too small so that the maximum residual voltage is rarely attained. The resulting probability of failure will then also be sufficiently slight.

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[1] See page 267.

THE COORDINATION OF AIR-BLAST HIGH-SPEED CIRCUIT-BREAKERS AND ISOLATING SWITCHES.

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The nature and evolution of the coordination of air-blast high-speed circuit-breakers and isolating switches are described. Details are also given of a new horn-gap arrangement for indoor switchgear, the result of lengthy research, which results in considerably reduced switch dimensions and smaller space requirements. It is further shown that 100 % safety against faulty flash-over of coordinated switchgear cannot be achieved economically, but that the degree of safety is adequate for all practical purposes.

NEARLY ten years have elapsed since Brown Boveri began investigating the coordination of high-voltage switchgear. During this period countless fundamental tests on all classes of switchgear, insulators, and gaps were necessary under the most varied conditions before these important high-voltage engineering questions could be satisfactorily cleared up. The present article deals with only a small part of the large field investigated.

To solve successfully the problem of the coordination of high-voltage switchgear the following essential requirements must be fulfilled:—

1. Voltage test specifications must be complied with.
2. The apparatus should be coordinated in itself.
3. Dimensions should be kept as small as possible to obtain economic and competitive switchgear.

The second requirement is rendered more severe by the fact that the coordination of the apparatus should also remain independent of its mode of erection.

To fulfil the first requirement the insulation strength of the supporting insulators of the various types employed and the air clearances between contacts and between phases had to be determined by test. The progressive development of circuit-breakers from the point of view of rupturing capacity led to new forms of components and involved investigation into their insulation strength. For this purpose only impulse voltage tests on dry, clean insulators need be considered, inasmuch as the impulse strength is the chief criterion

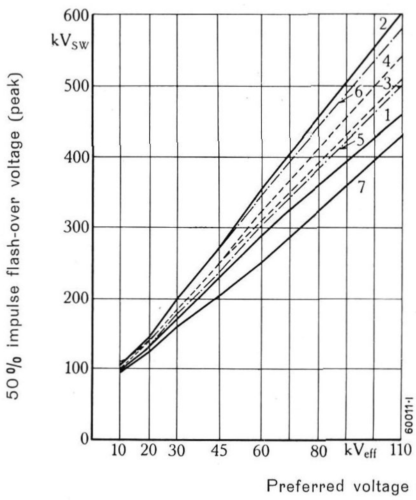

Fig. 1. — Indoor-type air-blast circuit-breaker. Minimum values of 50 % impulse flash-over voltage in relation to preferred voltages.

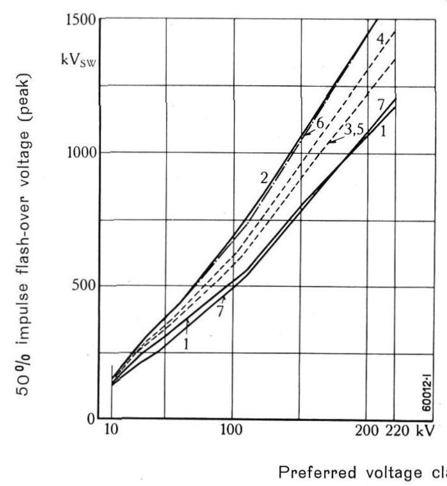

Fig. 2. — Outdoor-type air-blast high-speed circuit-breaker. Minimum values of 50 % impulse flash-over voltage in relation to preferred voltages.

The impulse flash-over voltages given are referred to the minimum gap spacings specified by the REH for the different preferred voltage classes. 1/50 μs impulse wave, test values reduced to 760 mm Hg, 20° C, and 11 g H_2O/m^3.

1. Break, brush to voltage, blade earthed, positive wave.
2. As 1, but negative wave.
3. Break, blade to voltage, brush earthed, positive wave.
4. As 3, but negative wave.
5. Phase spacing, positive wave.
6. As 5, but negative wave.
7. Supporting insulators, positive wave.

where coordination is concerned. To obtain fundamental data for the proportioning of clearances all flash-over test results had to be converted to uniform atmospheric conditions.

Exceptional difficulties were encountered in determining the clearances of circuit-breakers of the highest voltage classes, e. g., 150 and 220 kV, for which no apparatus had ever been constructed before. The supporting insulators and the fittings of the clearances in air, for instance, were copied from similar existing insulators and fittings. The circuit-breakers built with these components were then impulse tested and the final dimensions laid down on the basis of the corresponding gap spacings.

Figs. 1 and 2 show graphically the impulse strengths of the insulators and clearances in air of our air-blast high-speed circuit-breakers in relation to the corresponding voltage. For the sake of clearness the numerous individual test points have been omitted and replaced by curves which all represent the minimum values of the 50 % impulse flash-over voltages, inasmuch as the specifications are based on minimum insulation strengths.

The second important requirement, the coordination of switchgear in itself will now be dealt with.

Coordination went through several development stages as the different problems connected with the insulation strength of high-voltage apparatus were elucidated. At the outset high-voltage switchgear was generally coordinated without horn-gaps on the supporting insulators. Subsequently, a turned-down horn was provided on the earthed side of each insulator, the clearance being adjusted to that of the insulator. Now our indoor circuit-breakers are fitted with a special type of gap evolved from numerous tests to determine the flash-over voltage of gaps of various forms. Fig. 3 shows the impulse flash-over voltage of horns fitted on apparatus insulators in the same plane. For purposes of comparison the curve for the positive 50 % impulse flash-over voltage of a rod-to-plate gap is also given.

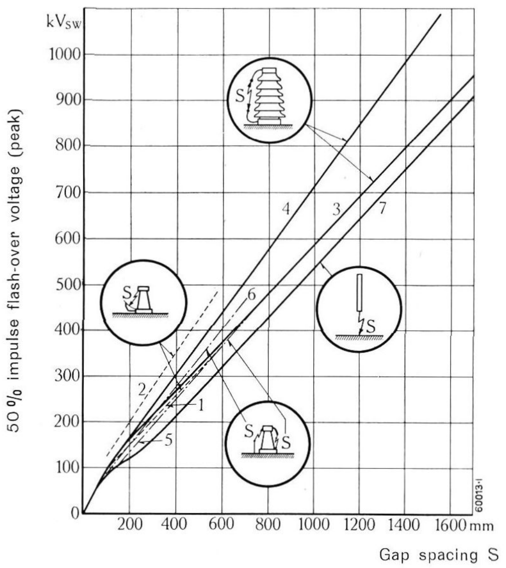

Fig. 3. — Minimum values of 50 % impulse flash-over voltage of horn-gaps in relation to gap spacing.

1/50 μs impulse wave, test values reduced to 760 mm Hg, 20° C, and 11 g H_2O/m^3.

1. Supporting insulator, with horn on earth side, positive wave.
2. As 1, but negative wave.
3. Insulator with horns top and bottom in same *plane*, *positive* wave.
4. As 3, but negative wave.
5. Insulator with horns top and bottom, displaced through 90°, positive wave.
6. As 5, but negative wave.
7. Rod-to-plate gap, positive wave.

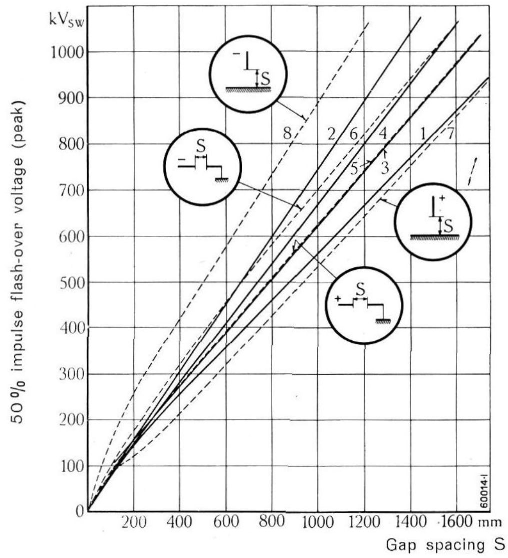

Fig. 4. — Indoor and outdoor-type air-blast high-speed circuit-breakers and isolating switches. Minimum values of 50 % impulse flash-over voltage of break in relation to gap spacing.

1/50 μs impulse wave, test values reduced to 760 mm Hg, 20° C, and 11 g H_2O/m^3.

1, 2. Brush to voltage, blade earthed, positive and negative waves.
3, 4. Blade to voltage, brush earthed, positive and negative waves.
5, 6. Rod-to-rod gap, positive and negative waves.
7, 8. Rod-to-plate gap, positive and negative waves.

In order to coordinate an air-blast circuit-breaker or an isolating switch in itself three different impulse tests must be applied. These are necessary to prove that the specified insulation strength is attained in every part of the apparatus and that flash-overs due to high surge voltages only occur between the apparatus and earth and not between phases or across the break. The latter test must be carried out in two operations, the voltage first being impressed on the contact brushes with the isolating switch blades connected to earth, whereupon the process is reversed. As will be seen from Fig. 4 it does not suffice to apply only one of the last-named tests. If, for instance, the voltage is impressed on the isolating switch blade and the contact brush earthed, the flash-over characteristic of this set-up is similar to that of a rod-to-rod gap, i. e., its polarity dependency is slight and with small gap spacings even disappears alltogether. When, however, the voltage is applied to the brush contact and the blade connected to earth quite a different characteristic is obtained: the positive flash-over voltage drops — particularly in the case of large gap spacings — practically to that of a rod-to-plate gap, whereas the negative flash-over voltage is of the order of that of a rod-to-rod gap. Tests on a large outdoor-type isolating switch showed that the characteristic of these curves can be varied within wide limits by modification of the contact brushes. When considering new designs, therefore, the insulation strengths must be determined for each individual case from tests with models.

In the preceding paragraph the impulse flash-over voltages of the individual insulated parts of our circuit-breakers and isolating switches were dealt with. To coordinate our switchgear from the test results, however, the margin between the protected and protectable levels must be fixed. From preliminary tests it was known that to achieve reliable coordination a margin of 15 to 20 % is necessary between the levels. Hereafter different possibilities of coordination are described.

If indoor switchgear were to be coordinated without gaps the big polarity effect and the large flash-over voltage tolerance entailed by the vagaries of porcelain unavoidable in the manufacturing process would involve inordinately large gap spacings for the parts to be protected (Fig. 5). More favourable results are obtained with a horn on the earth side of the insulator, although this method of coordination is not the most economical. A third arrangement with two horns in a vertical plane is not feasible, on the one hand because of its high degree of polarity dependency and on the other because, for reasons of design, the fitting of a gap would involve employing the next larger size of insulator.

As a result of exhaustive research and countless tests on gaps of various types it was found possible to overcome all of these difficulties and evolve an excellent arrangement which brings about a considerable reduction in switch dimensions. In lieu of one protective gap per insulator, two independent gaps, each comprising a single horn, are fitted, one at the top and the other at the bottom between two insulators, the latter being displaced 90° in the horizontal plane with respect to the upper one (cf. Fig. 9). The gap at the top operates on positive, the lower one on

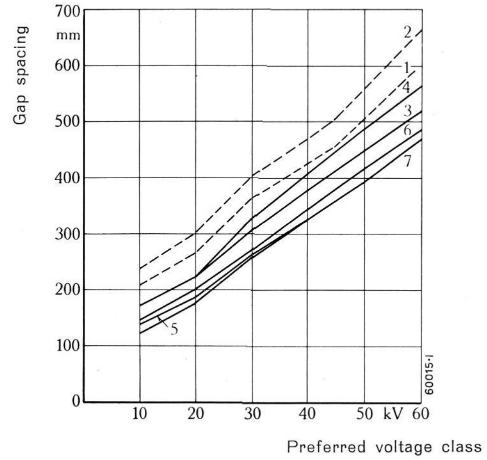

Fig. 5.— Coordination of indoor-type air-blast high-speed circuit-breakers and isolating switches. Minimum *necessary* gap spacing in relation to preferred voltages.

1, 2. Distances between phases and between contacts: coordination without horns.
3, 4. Distances between phases and between contacts: coordination with horn fixed on earth side of insulator.
5, 6. Distances between phases and between contacts: coordination with horns top and bottom, mutually displaced by 90° in horizontal plane.
7. Minimum insulation clearance specified by REH to earth and between live parts.

negative impulsive over-voltages. With this arrangement, therefore, the polarity dependency of the insulation strength to earth can be entirely eliminated or corrected to any desired degree. In consequence, to coordinate indoor air-blast high-speed circuit-breakers and isolating switches in themselves the minimum values specified by the REH rules, virtually suffice for all clearances in air (curves 5, 6, and 7 in Fig. 5).

Tests carried out at the same time showed that the protective action of the gap of such a circuit-breaker coordinated in itself, remains independent of its method of erection (on ground, elevated, or in a cell). Due to this fact manufacture can be restricted to one single, economical type of circuit-breaker or isolating switch with which the insulation clearances need not be altered from case to case. By way of example, Fig. 6 shows that the three isolating switches for the preferred voltage classes of 10, 20, and 30 kV remain coordinated independent of the mode of erection, whereby for the sake of simplicity only the coordination of the spacing between their phases is investigated; the same conditions, however, naturally also apply to the coordination of the break. Isolating switches normally mounted on the ground were first tested to ascertain the 50 % impulse flash-over voltages of the horn-gap and then, with the horns removed, between phases. It will be noticed that the levels are from 15 % to 60 % apart. Thereupon coordination was checked for other methods of erection and was found to be upheld, the horn-gap flash-over voltages, and in consequence the margins between the levels, only varying very slightly, as will be clear from Fig. 6.

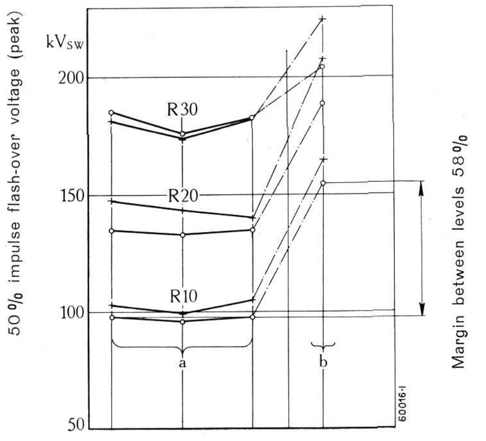

Fig. 6. — Indoor-type isolating switch for preferred voltages of 10, 20 and 30 kV classes. Influence of erection on coordination of clearance between phases.

a. 50 % impulse flash-over voltage to earth of three isolating switches coordinated with horns, for different methods of erection.

b. 50 % impulse flash-over voltage between phases of three coordinated isolating switches (to determine these voltage values the horns were removed from the insulators).

The margin between levels is the difference between the impulse flash-over voltage between phases (b) and the horn impulse flash-over voltage (a). The horn impulse flash-over voltages are virtually independent of the method of erection; coordination is upheld.

+ Positive wave test values.
o Negative wave test values.

R 30 = 30 kV preferred voltage class.
R 20 = 20 kV preferred voltage class.
R 10 = 10 kV preferred voltage class.

Recent exhaustive practical and theoretical investigations,[1] have shown that a 100 % safe margin between the protected and protectable insulation levels is not economically possible. Coordination tests with various voltage values proved that undesired flash-overs (failures) can occur across protectable clearances. Given inadequate margins between the levels the number of failures may be very high,[2] whereas with ample margins no failures whatsoever occur on high and low voltages, while around the 50 % impulse flash-over voltage of the protectable level the number of failures attains a maximum of a few per cent.

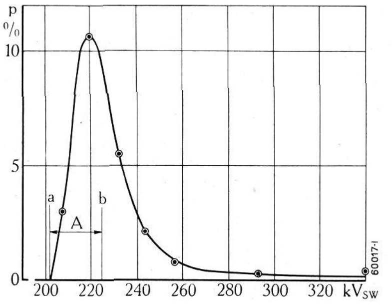

Fig. 7. — Percentage of faulty flash-overs p between the phases of a coordinated 50 kV air-blast high-speed circuit-breaker in relation to impressed voltage (peak). Margin between levels (A) 9 %. Tests with 1/50 μs positive wave.

a. 50 % impulse flash-over voltage of horn gap.

b. 50 % impulse flash-over voltage of insulation between phases.

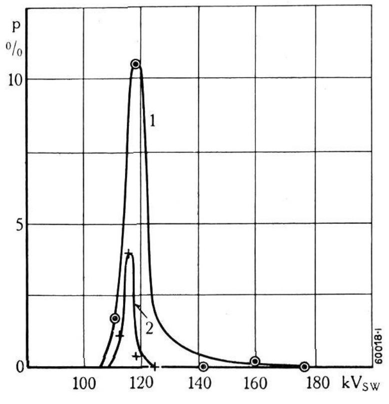

Fig. 8. — Percentage of faulty flash-overs p across the break of a coordinated 11 kV air-blast high-speed circuit-breaker in relation to impressed voltage (peak). Tests with 1/50 μs positive wave.

1. 5 % margin between levels.
2. 14 % margin between levels.

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[1] Cf. article: "Investigations into Reliability of Margins between Coordinated Insulation Levels" on page 259 of the present number of this journal and SEV-Bulletin No. 8, 21st April, 1943, p. 193: "Stossüberschlagspannungen an Stabfunkenstrecken".

[2] Cf. Fig. 10 of first article mentioned in foot-note [1].

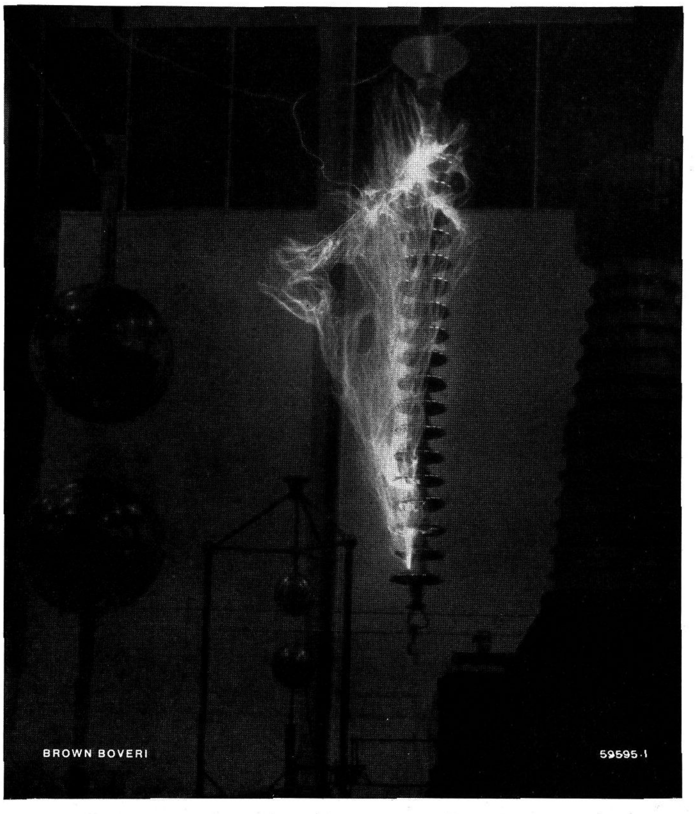
Fig. 9. — Coordinated 30 kV indoor-type air-blast high-speed circuit-breaker with horns top and bottom mutually displaced.

All of our investigations on air-blast high-speed circuit-breakers and isolating switches show that adequate safety is afforded by a margin of 15 to 20 % between the levels, which can be achieved economically. From the large number of tests carried out only two examples will be given. Fig. 7 shows the number of undesired flash-overs (failures) between the phases of a 50 kV air-blast high-speed circuit-breaker with a margin of 9 % between the levels. Upon the margin being increased to 20 % no undesired flash-overs whatsoever occurred in the course of the approximately 5000 impulses applied to the circuit-breaker. Fig. 8 represents the corresponding conditions in the break of an 11 kV air-blast high-speed circuit-breaker. The characteristic wave-form of the curves is clearly visible in both diagrams. These exhaustive investigations were naturally also applied to all of our air-blast high-speed circuit-breakers and isolating switches in the form of type tests.

From the foregoing it will be clear that particularly in the case of the coordination of indoor-type air-blast high-speed circuit-breakers and isolating switches the determination of the minimum permissible clearances enables switchgear to be constructed with the smallest possible space requirements and which, due to the small dimensions of its components, can be considered the best economical design. As a result of lengthy, untiring, and conscientious research work we have practically succeeded in fully elucidating this important problem of the coordination of high-voltage switchgear.

(MS 973) *H. Mataré. (E. G. W.)*

1100 kV a. c. flash-over on string of eighteen suspension insulators.



THE LATEST DEVELOPMENTS IN LIGHTNING ARRESTORS.

Decimal Index 621.316.933.3

After a short survey of ten years' development work on the Resorbit arrestor, an account of the latest progress is given, whereby lightning arrestors can be built for any rated voltage and discharge capacity.

THE modern lightning arrestor is a typical product of successful technical research in the high-voltage engineering field. This is, however, not the only reason why we wish to consider the development of the lightning arrestor in this special number; it is namely a happy coincidence that it is now just ten years ago since we introduced the modern Resorbit arrestor to the market.[1] In itself it is interesting after the lapse of a decade to take a retrospective view of the development of a technical product and to note the state reached, this being particularly so in the case of a field such as overvoltage protection, where in past years such great progress has been made.

I. SHORT RETROSPECT OF THE DEVELOPMENT OF THE RESORBIT ARRESTOR.

Research work in the field of over-voltages, which successfully commenced when the cathode-ray oscillograph was developed into a suitable instrument for recording high-speed phenomena, clearly revealed what conditions must be fulfilled by an effective lightning arrestor and it was found that arrestors of the horn, drum or disc type, as well as similar complicated apparatus, could not meet the requirements. The Resorbit arrestor which was developed as a result of the aforementioned research work, is based on the principle of the resistance which varies with the voltage and which is connected in series with an extinguishing spark gap. This principle has proved very successful and forms the basis for practically all modern designs of arrestor. The first Resorbit arrestors[2] were designed for a discharge capacity of 750 A; it is interesting to note that despite this — for present-day conditions — undoubtedly very low discharge capacity, the cases where arrestors were not capable of dealing with the impulse currents which occurred were really very rare. This naturally depends on the frequency of occurrence of the discharge currents. The newly developed Resorbit arrestor proved a great success in practice and from the very beginning helped very considerably to reduce disturbances due to overvoltages. It was, however, obvious that despite this success, development would have to continue. Already in 1936 the discharge capacity was therefore increased to 1500 A and this without altering the external dimensions of the apparatus. At the same time it was possible to raise the upper limit for the rated voltages of the arrestor series from 37 to 64 kV. These arrestors were capable of providing adequate protection against overvoltages due to indirect or direct lightning strokes occurring some considerable distance away. The main aim was, however, to develop an arrestor which would continue to operate and would offer adequate protection also for the discharge currents which are generated when lightning strokes occur nearer to the arrestor. Intensive work in this direction resulted in 1939 in an increase in the discharge capacity to 2500 A, in 1940 to 4000 A, and in 1941 to 10,000 A and more. In this connection it must be emphasized that this increase in the discharge capacity was not achieved at the expense of other important properties, but that for instance it was also possible to reduce the breakdown and residual voltages.[1]

In order to illustrate the progress which has been achieved, an arrestor of the series 10 from the year 1933 and one from the year 1943 are shown in Fig. 1; despite the fact that the new arrestor of the

[1] See: Progress in Brown Boveri Designs during 1933. The Brown Boveri Review 1934, Nos. 1/2, page 17.

[2] See: The Brown Boveri Review 1936, No. 3, page 82.

[1] It is to be noted that according to Swiss Rules the conception discharge capacity not only means the capacity for discharging the currents in question, but also at the same time includes the adherence to certain limiting values for the residual voltage.

Fig. 1. — Two stages in the development of lightning arrestors, series 10; on the left a 1943 design for a discharge capacity of 4000 A and on the right a 1933 design for a discharge capacity of 750 A.

The new arrestor is even smaller than its predecessor of 1933, despite a more than five times greater discharge capacity.

4000 A series has a discharge capacity more than five times greater than the old type, it is even slightly smaller than its predecessor from 1933.

II. THE LATEST DEVELOPMENT.

The main object of the latest development is to produce lightning arrestors for every rated voltage and every discharge capacity. In order to exceed the previous upper limit of 60 kV for the rated voltage it was only necessary in principle to increase the series connection of the active arrestor elements (voltage-dependent resistances and extinguishing spark gaps). With this increased series connection of elements due consideration had to be paid to the fact that the desired result can only be achieved if it is seen that each element takes up the right amount of stress. The natural earth capacity of the elements opposes this uniform stress distribution and thus necessitates special means for a capacitive control of the voltage stress. The desired result was obtained without undue expense by suitably arranging and dimensioning the active components inside the arrestor and by providing external control elements in the form of rings.[1] Such an arrestor with its characteristic control rings is shown in Fig. 2, these arrestors having been developed for higher rated voltages up to 220 kV.

The previous rapid development of arrestors as regards discharge capacity was due solely to the improvements made in the resistances which vary with the voltage. When examining possibilities for further development it was necessary to consider whether the limits of the extinguishing device, which from the very beginning and during all previous stages of development had been in the form of an extinguishing spark gap, had not been reached. A systematical investigation of the extinguishing spark gaps showed, however, that the discharge of the highest current impulses, contrary to the opinion often expressed, presented no difficulties for the extinguishing spark gap of the Resorbit arrestor, because only infinitesimal changes occurred in the external surface layer,[2] which did not affect operation. It is of interest perhaps to note that these arc traces on the extinguishing plates with impulse currents of 20 — 50,000 A, often revealed the beautiful designs known as Lichtenberg figures. Further detailed experiments with the extinguishing spark gaps were concerned with extinguishing capacity, minimum breakdown voltage, and optimum extinguishing distance. The systematic working out of innumerable tests carried up to a point where the stress was so high that a breakdown occurred, enabled a clear division to be made between causes of defects and the determination of extinguishing capacity limits as a function of the specific voltage stress and the extinguishing distance, which together with breakdown measurements resulted in the most favourable dimensions for the extinguishing spark gaps being fixed afresh. By this means it was found that these extinguishing spark gaps possess a considerably higher extinguishing capacity than was hitherto assumed, currents up to 200 A amplitude value being readily extinguished, as the oscillogram in Fig. 3 shows. Furthermore the properties of the extinguishing spark gaps were in no way detrimentally affected by these extinguishing operations, as was shown by the purely accidental distribution of successive discharge traces on the extinguishing plates.

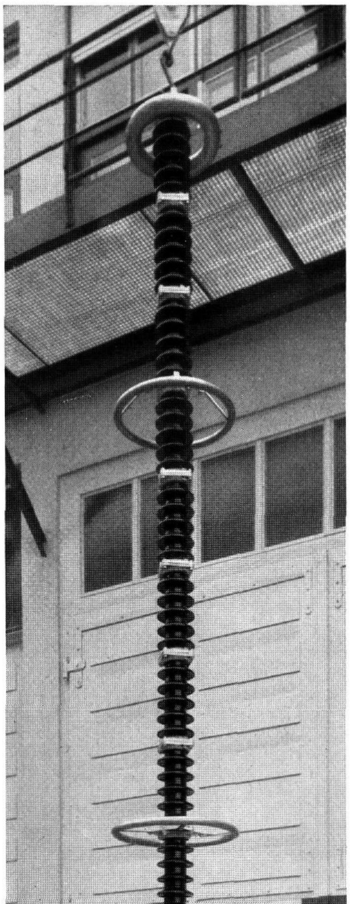


Fig. 2. — Lightning arrestor for 220 kV rated voltage and 10,000 A discharge capacity.
A characteristic feature of these arrestors for very high voltages are the control elements for obtaining uniform stress.

Although these tests had shown that the extinguishing spark gap possesses considerable reserves as an extinguishing element for the arrestor, it was nevertheless clear that there is a limit to the extinguishing capacity. This means, however, that there is also a limit to the discharge capacity which can be attained with this design of arrestor, because on the one hand by means of the resistance characteristic a definite ratio of maximum discharge current to the following power current is associated with a definite ratio of maximum residual voltage to rated voltage, and on the

[1] Bulletin SEV 1941, No. 25.

[2] See: The Brown Boveri Review 1941, No. 6, page 153.

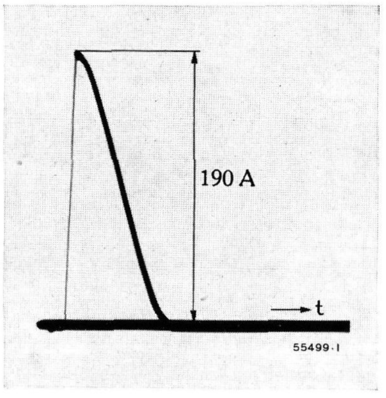


Fig. 3. — Extinction oscillogram for a perfectly interrupted current of 190 A amplitude.

Power currents of this magnitude are still extinguished without trouble.

other hand the resistance characteristic cannot be altered without affecting other important properties of the arrestor. In order to avoid these limitations without having to renounce the great advantages which result from the principle of the extinguishing spark gap, such advantages, as good breakdown characteristic, no attendance or maintenance, adaptability to all rated voltages, etc., it was necessary to follow a fresh course. Due to a more extensive knowledge of the extinguishing process[1] the chief possibilities were examined and verified by means of exhaustive tests. This resulted in the arrestor with cascade connection, which provides a safe solution to the problem in question and can be constructed for all rated voltages and any desired discharge capacity at reasonable cost. Fig. 4 shows diagrammatically the construction and Fig. 5 a view of such an arrestor for 45 kV rated voltage and 50,000 A discharge capacity.

Fig. 6. — Arrestor for 1500 V d. c. voltage, as successfully employed in d. c. railway networks for protecting substations and motor coaches.

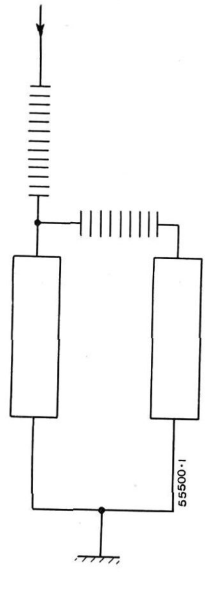


Fig. 4. — Basic diagram of an arrestor with cascade connection.

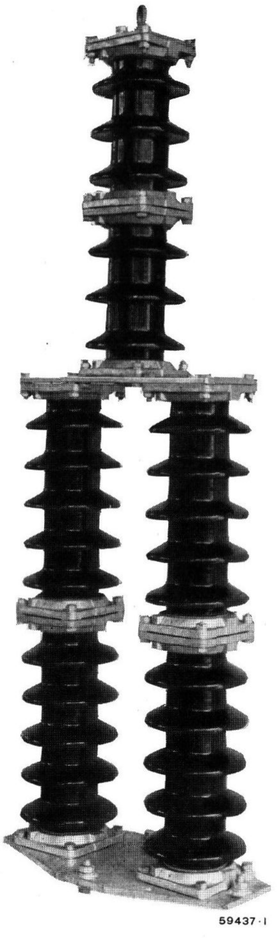


Fig. 5. — Arrestor for 45 kV rated voltage and 50,000 A discharge capacity according to the cascade connection principle.

This arrangement enables arrestors to be built for any rated voltage and discharge capacity.

For the sake of completeness it must also be mentioned that in addition to the lightning arrestors for alternating-current high-voltage networks dealt with in this short article, standard types for low-voltage and direct-current networks have also been constructed (Fig. 6), which have proved to be very satisfactory in service, whereby all the experience gained in the arrestor field was taken into account, due consideration being given to the correspondingly different conditions.

(MS 964) *Dr. H. Meyer. (Op.)*

[1] The Brown Boveri Review 1941, No. 6, page 153. Bulletin SEV 1942 No. 4, page 94.

RECENT INVESTIGATIONS INTO THE IMPULSE STRESSING OF POWER AND VOLTAGE TRANSFORMERS.

Decimal Index 621.314.21.015.33. 621.3.015.33 : 621.314.21

By means of improved theoretical considerations it is possible to realize the essential factors which govern the design of lightning-proof transformers. The conclusions thus reached have been confirmed by measurements and enable economical designs to be produced by co-ordinating both decisive factors — voltage distribution and insulation strength.

I. INTRODUCTION.

IT is known that impulse waves produce quite different stresses in transformer windings when compared with those caused by the voltages occurring during normal service, there not only being a difference as regards the duration of the stressing, but above all in the greatly diverging voltage and stress distribution in the winding. Whilst for normal operating voltages this voltage distribution is determined by the inductive linkage and is practically linear, when impulses occur it is at first entirely determined by the capacitances of the individual windings and coils relative to each other and to earth. The divergence between this initial voltage distribution and the inductive final distribution which is the only one possible for a long interval of time, causes equalizing oscillations in the winding, during which the transition from the initial to the final distribution occurs. Generally the highest winding stress is caused by the initial distribution, and the equalizing oscillations then displace the point of maximum stress in a somewhat reduced form from the beginning of the winding towards the inside of the winding.

Soon after these relationships were discovered, steps were taken to achieve an improvement by making the capacitive initial voltage distribution equal to the inductive final distribution by influencing the winding capacitances. Thus in the first place the excessive local voltage concentration and high stresses, and secondly also the equalizing oscillations, disappear with these so-called controlled or oscillation-free windings. All these arrangements, the best known of which for instance employs shields which extend along the entire leg and are connected to the input terminal, require a considerable amount of space and material and only have the desired effect if the star point is earthed. The main object in view is not, however, to control the winding and render it free from oscillations, but to obtain a transformer which is safe in operation and lightning-proof, so that it is questionable whether these measures really offer the best solution of the problem under consideration. When it is considered that the safety of the transformer as regards voltage impulses depends on the voltage distribution as well as on the dimensions of the insulation having to resist the resulting stress, then it is to be expected that by suitably correlating these two factors it should be possible to achieve a much simpler and more economical design, due consideration of course being given to existing designs which already afford considerable protection against the effects of lightning.

II. IMPROVING THE VOLTAGE DISTRIBUTION BY CAPACITIVE MEANS.

(a) *General.*

In order to judge the capacitive voltage distribution a winding completely cut open along a meridian plane is considered, where the individual turns form open rings lying in the electrical field. For a single-layer coil a simple equivalent arrangement in the form of a network of series and shunt capacitances is then obtained. This arrangement generally also forms the basis for considering practical windings which have a more complicated construction; the means used for a linear control of the capacitive voltage distribution referred to in the previous chapter were derived from such arrangements.

If, however, it is desired to determine the exact point where maximum stress occurs, or to deal with the much discussed question of reinforced line end coils, or even to calculate the stress distribution in a particular winding, it will soon be obvious, except in a few isolated cases, that the desired object cannot be achieved with this greatly simplified equivalent arrangement. Difficulties are immediately encountered particularly as regards determining the series capacitance of the coils which has to be introduced into the equivalent arrangement. When extending the equivalent arrangement in order to be better able to meet actual conditions, special attention must be paid to one point, namely the coil connections. These lead from the end turn of a coil or half coil to the first turn of the adjoining coil and connect coil turns by a short path, which, according to the aforementioned method of consideration where the winding is lying completely cut open in the electrical field, would under certain conditions have very different potentials. The differences in potential between these coil turns cannot, however, exist and an equipotential surface must pass through the end turn of one coil and the first turn of the next coil or half coil. This is at least exactly so in the vicinity of the connection which has been made. At other points along the circumference slight deviations may occur which, however, only help to make the potential distribution more uniform and are of no importance as regards the calculation which deals with the most unfavourable point. If it is assumed that these equipotential surfaces pass through the last and first turns of successive coils and that the flux of the displacement current is divided into part fluxes which flow to earth or to the next potential surface of the kind mentioned before and lying in the winding, a useful equivalent arrangement will generally be obtained.

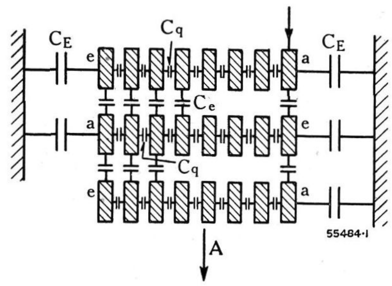


Fig. 1. — Cross-section through a double coil winding of a large transformer.

A. Direction of leg axis.
C_E. Earth capacitance.
C_e. Conductor capacitance over space between adjacent coils.
C_q. Capacitance between turns.
e. Last turn of a half coil.
a. First turn of a half coil.

(b) *Double Coil windings for Large Power Transformers.*

For these windings which are normally arranged in double coil connection and are composed of half coils with only one turn per layer, as shown for instance in cross-section in Fig. 1, when due consideration is given to the coil connections, an equivalent arrangement such as shown in Fig. 2 is obtained, where for the series capacitance C_2 an equivalent capacity is introduced which can be represented as a function of the capacitances C_1 and C_2. It is then not difficult to extend this equivalent arrangement to cover any potential end rings, parallel connections, etc., which may be present; in this article the considerations are, however, confined to the essential elements. The calculation made on the basis of this diagram now corresponds to actual conditions and it is therefore possible to ascertain the effects of the practical layout of the winding on the stress distribution or conversely to achieve the most favourable constructional arrangement for the winding. Furthermore, it is therefore also possible to discriminate between and to calculate the different kinds of stresses, namely turn insulation stress, stress across the space between adjacent coils and main insulation stress, which occur with surge phenomena and are of fundamental importance as regards the behaviour of the transformer under these conditions. In addition it is possible to strengthen the insulation just at the point where it is really necessary. The limited scope of this short article does not enable very many details to be discussed. Instead only the question of reinforced end coils for this type of winding will be briefly referred to. Careful examination and calculation shows namely that contrary to the usual assumption, generally the insulation between adjacent coils and not the insulation of the turns is mostly endangered. As a result of this the number of coils and not the wound length of the conductor determine the range over which the insulation should be reinforced, and the insulation does not necessarily have to be strengthened by reinforcing the turn insulation. The usefulness of reinforced turn insulation furthermore depends entirely on whether the cooling ducts are arranged in planes perpendicular to the transformer leg axis or in cylindrical surfaces which are coaxial with the core; in

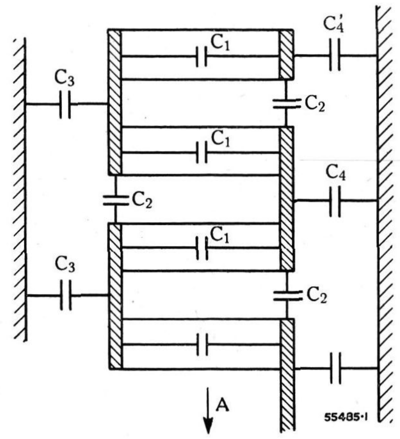


Fig. 2. — Extended equivalent diagram for the winding in Fig. 1.

A. Direction of leg axis.
C_3, C_4, C_4'. Earth capacitances.
C_1. Equivalent value for the coil turn capacitances.
C_2. Equivalent value for the coil capacitance.

This diagram enables such windings to be examined and calculated and the most favourable arrangement and dimensions for their insulation to be determined.

the former case the reinforced insulation has only a very slight effect on the voltage distribution and is entirely beneficial, whilst with the latter arrangement the voltage distribution is considerably influenced and each case must be examined individually so as to ascertain where the most favourable insulation strength is obtained in relation to the voltage distribution.

(c) *Voltage Transformer Windings.*

The windings of voltage transformers generally consist of fine wire coils having a large number of turns per layer and a large number of layers; the layers at the beginning and end are mostly wound with stronger wire. In order to be able to judge the behaviour of these windings use can be made of the known simple equivalent network of series and shunt capacitances, if due attention is paid to the fundamental considerations stated in the previous section 2a as regards determining the series capacitance. The parts of the equipotential surfaces limiting the series capacitances are to be assumed to pass through the last and first turns of successive coils and also to a large extent into the reinforced end layers. With such a conception it will immediately be obvious that there must be very great differences between an arrangement where the line end coils are in double coil connection with the beginning inside or outside, respectively, and the kind of connection where all the beginnings of the coils are inside or outside. There is thus an excellent opportunity of achieving improvements merely by altering the connections of the coils. With these windings it is also easily possible to improve the voltage distribution very greatly by means of ring shields inside or outside the coils at the line end of the winding in conjunction with a suitable connection of the coils (compare the oscillograms shown in Figs. 3 and 4). Fig. 5 shows the corresponding initial voltage distributions over the length of the winding and from these it is possible to determine the maximum coil stresses. The importance of the problem of the reinforced line end coil which should be noted here, is dealt with in section IV. With voltage transformers for high voltages it can happen that the aforementioned measures do not suffice for an adequate reduction of the coil stress and therefore it is for instance necessary to consider the question of introducing additional control condensers. Even in this case a complete linearization of the voltage distribution will not be attempted and according to the first section of this article the control will only be applied to the extent that the stress remains below the maximum allowable value. When due attention is paid to this point, it is possible to design the control with a minimum outlay and to achieve a very considerable saving in material and space.

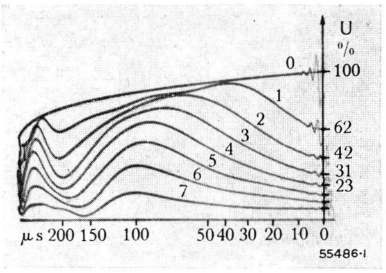


Fig. 3. — Voltage curves caused by impulse waves on a normal voltage transformer winding.

Oscillogram curves 0, 1, 2, etc., show the voltages at the terminal, after the first, second, third coils, etc.

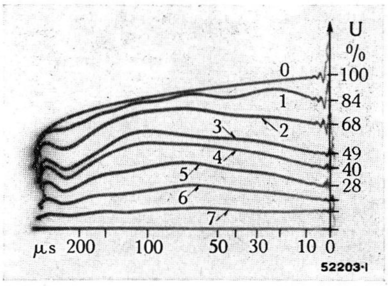


Fig. 4. — The result of improving the winding used for Fig. 3 by means of simple ring shields.

Oscillogram curves 0, 1, 2, etc., show the voltages at the terminal, after the first, second, third coils, etc.

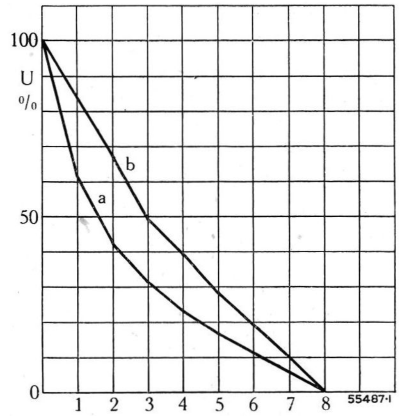


Fig. 5. — Initial voltage distribution resulting from the impact of an impulse wave on voltage transformer windings.

a. Winding composed of identical coils.
b. Windings with improved coil arrangement and simple ring shields.
The maximum coil stress can be determined from these curves and the improvement achieved by simple means is apparent.

Ordinates: Voltage.
Abscissae: Number of coils as a measure of the winding length.

III. CONTROL OF VOLTAGE DISTRIBUTION BY MEANS OF RESISTANCES.

For controlling the voltage distribution, it is also possible to use resistances instead of capacitances, these resistances being connected either only in parallel with the most highly stressed coils or as a control potentiometer in parallel with the whole winding. For an effective control the resistance should have a small value, whilst out of consideration for continuous loading at the operating coil voltage its value should, however, be high. Since the control effect is only necessary at high voltages and the operating load only occurs at smaller voltages, it is advisable to employ voltage-dependent resistances which with a low voltage have a high resistance coefficient and with a high voltage a low resistance coefficient. Contrary to capacitive control arrangements, whose effectiveness is not influenced by the amplitude and steepness of the voltage impulse wave, the effectiveness of a control with voltage-dependent resistances depends to a great extent on the amplitude and steepness of the applied impulse. Since, however, every voltage rise or fall takes at least an extremely short but nevertheless finite time and furthermore the time constant of the control arrangement in the region of overvoltages of dangerous magnitude can be kept small enough due to the use of voltage-dependent resistances, it is possible to guarantee the effectiveness of such control arrangements. Test results obtained with such control arrangements confirmed the expected good effect; in addition the material and space required are much less than with control systems employing special additional capacitances, so that the arrangement described will be of considerable importance in future.

C_E. Earth capacitance.
C_0. Equivalent capacitance value for the remainder of the winding.
C_S. Series capacitance of reinforced coil.
L. Inductance of reinforced coil.
W. Travelling wave.

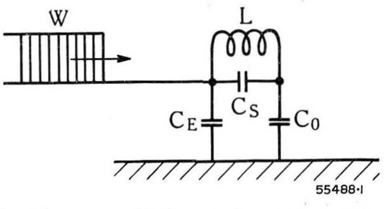


Fig. 6. — Diagram of the inherent oscillation of the reinforced line end coil of a voltage transformer winding.

IV. OSCILLATIONS OF REINFORCED COILS IN VOLTAGE TRANSFORMERS.

In the case of the windings of voltage transformers it is often usual to provide special line end coils with a reinforced wire section and reinforced insulation, these coils having only a small fraction of the number of turns of the normal coils (e. g., a tenth of the normal coil turns). Such a line end coil takes a relatively large share of the total impulse voltage during the initial voltage distribution. Immediately following the initial voltage distribution a phenomenon occurs which as far as we know has so far attracted very little attention, although it is of far-reaching importance. The equalization of the initial voltage at the line end coil can occur with a much smaller inductance than that of the standard coils, so that the equalization process for the latter takes much longer, the difference in the equalizing times being about in the ratio of the number of coil turns. This difference is still further increased by the fact that due to the equalization time being of the same order of magnitude the standard coils possess a stronger coupling. As regards the equalization process of the line end coil the rest of the winding is therefore still effective in a purely capacitive manner, and this coil thus performs according to the diagram of Fig. 6 the well-known oscillations of the impulse excited series oscillation circuit, this being very clearly shown in the oscillogram in Fig. 7. As a result, the beginning of the standard coil winding after half an oscillation is stressed with a considerably higher voltage than if this standard coil winding were connected directly to the terminal. With the windings of voltage transformers or transformers of similar construction (e. g., testing transformers and the like) such reinforced line end coils are very definitely detrimental. If it is impossible to dispense with a reinforced insulation for the line end coil, the transition from the line end coil to the standard coil must be very carefully graduated and balanced in order to prevent these very dangerous effects occurring.

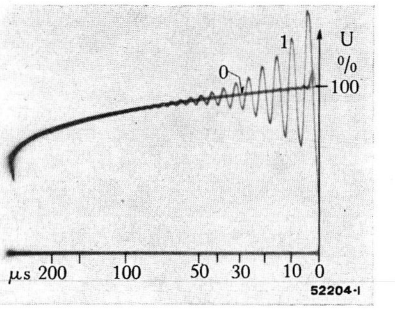


Fig. 7. — Oscillogram of the inherent oscillation of a reinforced line end coil.

0 and 1 indicate the characteristic of the voltage at the beginning of the winding and after the line end coil.

(MS 966) *Dr. H. Meyer. (Op.)*

THE BEHAVIOUR OF ROTATING MACHINERY WINDINGS ON THE OCCURRENCE OF TRAVELLING WAVES.

Decimal Index 621.313 045 : 621.3.015.34
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The windings of rotating machines behave differently from transformer windings on the occurrence of travelling waves. Whereas in transformers an initial voltage distribution is set up in the entire winding and followed by equalizing oscillations, there is in the case of rotating machines, a proper penetration of the waves. These penetrating waves retain a nearly constant amplitude, although the wave fronts become progressively flatter with increasing penetration. In the present article these characteristics are deduced theoretically and confirmed by comparison with test results, and conclusions are drawn as to the possibilities for the protection of such windings.

I. INTRODUCTION.

IN order to arrive at results of practical use in the theoretical treatment of the behaviour of windings on the occurrence of travelling waves, it is necessary to make certain simplifying assumptions. As it is not possible to apply the same assumptions to all types of windings, it is advisable not to start from general principles and to introduce the simplifications during the course of the theoretical treatment, but to distinguish right at the beginning the different types of winding according to their predominating characteristics, and to base the treatment on correspondingly simplified assumptions and methods, as in this manner, the fundamental principles are more clearly exposed and kept in view.

Whereas in the case of transformer windings the theory developed along these lines is generally well known and has been frequently described, this cannot be said to be true for other types of windings, and information in regard to the behaviour of the windings of rotating machinery windings in particular is rare. The object of the present article is to give a sufficiently complete account of the theoretical considerations applying, in order that a comparison with results obtained experimentally may enable a good idea to be formed of the characteristic behaviour of such windings and conclusions to be drawn as to the stresses to which they are submitted and the ways in which they can be protected.

II. THE CHARACTERISTICS OF THE WINDINGS OF ROTATING MACHINES.

The windings of rotating machines are characterized by the fact that a large part of their length lies embedded in the slots of the mass of iron. This results on the one hand in the fact that the capacity to earth of the winding is very large, and on the other in that the components of the winding (coils) are screened one from another. The remaining mutual capacity of the winding parts, for instance, of the coil ends, is therefore very small compared with the capacity to earth and is not able to influence appreciably the nature of the phenomena taking place in the windings; a state of affairs which is very different from that in transformers, where as is known, the mutual capacity of the coils, combined with the capacity to earth is of decisive importance for the behaviour of the winding at the beginning of surge phenomena*.

Moreover, it should be noted in the case of the very rapid phenomena in question, that because of the flux displacement, the magnetic flux practically does not enter into the iron at all, and hence no linkage can take place with the flux in the iron. With increasing duration, that is with a slowing down of the phenomena, the penetration of the flux into the iron, and hence the effect of the magnetic flux linkage steadily increases until at normal operating frequencies it plays the well known predominating role. As a result of these facts the couplings between the windings of different phases, as well as between coils of the same phase belonging to different poles are, in the case of the very short times here considered, very small and hence without appreciable effect on the behaviour of surge phenomena. We may, therefore, in our treatment, leave these couplings out of account and study mainly the behaviour of the individual phase windings independently of one another.

III. THE WINDING AS A CHAIN OF COILS.

(a) *Calculation of Voltage Variation inside Winding neglecting Dispersion of Velocities of Propagation.*

In accordance with what has been said above, we will now consider one phase winding separately and limit ourselves first to the investigation of its behaviour in the time interval before the return of a possible wave reflected from the star point. The effect of such reflected waves will be discussed later. The phase winding to be studied may now be represented by the equivalent diagram illustrated in Fig. 1, where L and C represent the inductance (without iron) and

* These considerations and hence the arguments of this article also apply to the windings of induction regulators although these cannot be classified as rotating machines.

the earth capacity of the coil groups per pole and per phase. For our later treatment we further simplify this representation by assuming, as shown in Fig. 2, that the entire earth capacity of a coil group is concentrated at the centre. This equivalent diagram represents a chain of coils built up of T-sections and

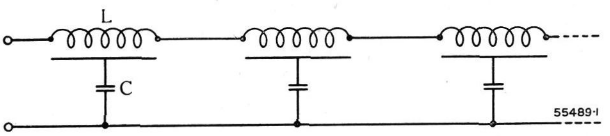

Fig. 1. — Equivalent diagram of the phase winding of a rotating machine.

L and *C* denote the inductances and the earth capacity of the coils per pole and per phase.

is well known in communications engineering*. For all frequencies below a certain cut-off frequency $\frac{\omega_g}{2\pi}$ given by the relation

$$\omega_g = \frac{2}{\sqrt{LC}} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

such a chain acts as a line. For all frequencies above this cut-off frequency, the chain acts as a barrier; it therefore only allows penetration of a voltage wave of limited steepness. The surge impedance measured at the terminals of a section in the chain is therefore

$$Z = \sqrt{\frac{L}{C}\left(1 - \frac{\omega^2 LC}{4}\right)} \quad . \quad . \quad . \quad (2)$$

It is real in the range of penetration $\omega < \omega_g$ and purely ohmic. Its magnitude over a considerable portion of the penetration range is approximately $Z = \sqrt{\frac{L}{C}}$ and falls rapidly to zero as the cut-off frequency is approached.

The time of travel T_ω through one section of a component frequency ω is equal to the reciprocal of the velocity of propagation and is given by the formula

$$T_\omega = T_o \frac{1}{\sqrt{1 - \eta^2}}^{**} \quad . \quad . \quad . \quad . \quad (3)$$

where $T_o = \sqrt{LC}$ is the boundary value of the period of travel for quite slow frequencies ($\omega = o$) and $\eta = \frac{\omega}{\omega_g}$.

In the present section we will follow the penetration of surge into the chain of coils making the simplifying assumption that all component frequencies of the range of penetration have the same duration of travel T_o and further that the surge impedance is equal to $Z = \sqrt{\frac{L}{C}}$ for all component frequencies. These assumptions apply over a considerable part of the range of penetration, but not in the neighbourhood of the limiting frequency.

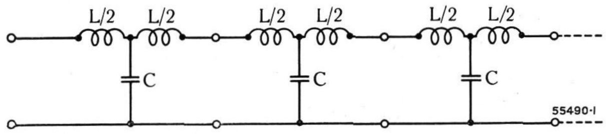

Fig. 2. — Simplified equivalent diagram of the winding according to figure 1.

If now a rectangular wave (a wave with an infinitely steep front and of infinitely long duration) is applied to the chain, the latter is penetrated by a wave, the height of which, as in the case of line bifurcations, is determined by the surge impedances of the winding and of the line, and with a velocity of propagation corresponding to the time of travel through a section T_o. Because of the property of limited penetration the form of the wave front inside the winding no longer corresponds to that of the applied wave, but is considerably flatter and, basing on the assumptions mentioned above, can be calculated.

Let e_w be the height of the entering surge

$$e_w = \frac{2Z}{Z + Z_L} \cdot e_L \quad . \quad . \quad . \quad . \quad (4)$$

where e_L is the height of the wave occurring on the line and Z_L the surge impedance of the latter. Then the wave front of the entering surge is given by the relation.

$$e = e_w \left[\frac{1}{2} + \frac{1}{\pi} Si\,(\omega_g\, t)\right]^{***} \quad . \quad . \quad . \quad (5)$$

The function $Si\,(\omega_g t) = \int_o^{\omega_g} \frac{\text{sine}\,\omega\, t}{\omega}\, d\,\omega$ in this

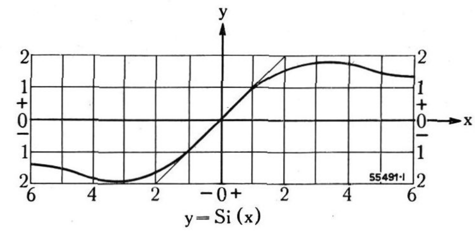

Fig. 3. — Integral sine $y = Si\,(x)$.

The wave fronts entering the winding can be expressed by this function.

* See for example Wallot: Theorie der Schwachstromtechnik.

** We are here concerned with the group velocity that is the resultant velocity of propagation of a whole frequency spectrum. See Wallot, l. c. § 226/241.

*** Similarly the wave front of the applied rectangular surge can be represented by the equation

$$e = e_L \left[\frac{1}{2} + \frac{1}{\pi}\int_o^{\infty} \frac{\text{sine}\,\omega t}{\omega}\, d\,\omega\right]$$

expression is known as the integral sine* and has the form shown in Fig. 3. If now a tangent is drawn to the wave front at half the height, then the duration time of the wave front measured at this tangent is given by the simple equation

$$T_s = \frac{\pi}{\omega_g} = \frac{\pi\sqrt{LC}}{2} \quad . \quad . \quad . \quad (6)$$

With the aid of the relations (3), (4) and (6) the behaviour of the winding can now be quite easily followed and a representation as shown in Fig. 4 can be obtained of the wave of limited steepness going through

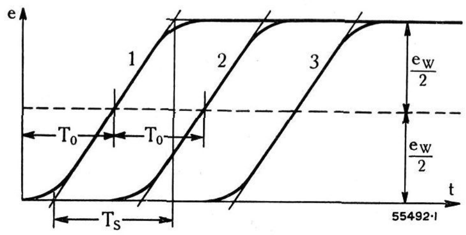

Fig. 4. — Diagrammatic representation of the travelling waves of limited steepness inside the winding.

T_o. Time of travel of the wave per section of the chain.
T_s. Time of rise on the wave front.
e_W. Height of the entering wave.
1, 2, 3. Wave front after passing through the first, second, and third sections.

the winding. (Note the difference compared with the behaviour of transformer windings. With rotating machines a proper penetration of the wave; with transformers, no penetration of the wave as such, but the simultaneous appearance of an initial voltage distribution over the entire winding followed by natural oscillation of the windings.)

(b) *Effect of the Dispersion of the Propagation Velocity.*

As shown by equation (3), the time of travel of the component frequencies even within the range of penetration is not constant, but depends on the frequency; the higher frequencies are propagated with a smaller velocity than the lower ones, their time of travel is therefore greater and the result is a progressive flattening of the wave front with increasing penetration. The variation of the function

$$\tau = \frac{T_\omega}{T_o} = \frac{1}{\sqrt{1-\eta^2}} \quad . \quad . \quad . \quad (3\text{a})$$

which corresponds to the equation (3) and which is made independent of the individual case by reference to the factor T_o, only the latter being considered as a fundamental constant of the winding, thereby enabling

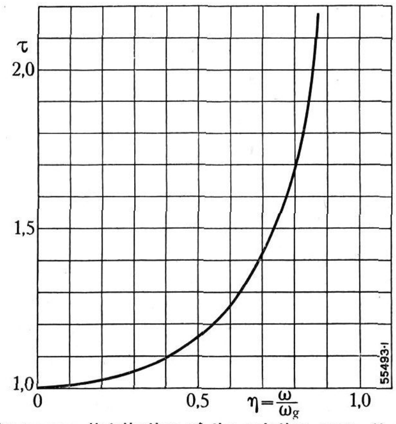

Fig. 5. — Frequency distribution of the relative group time of travel τ in the chain.

The higher frequencies are propagated with a smaller velocity and the limiting frequency has an infinitely large time of travel and, therefore, does not itself enter into the winding at all.

the expression to be brought to a general form, is illustrated in Fig. 5. It will be seen that the fundamental frequency has an infinitely long duration of travel and hence cannot itself penetrate the winding at all.

Unfortunately if these different times of travel of the different components of the original wave are taken into account, it is not possible to calculate exactly the shape of wave front. The following reasoning does, however, permit an approximate calculation and construction. We consider the wave front after each section of the chain, and replace it by a sine wave. Further, we make the assumption that the average time of travel of the wave thus represented through the immediately preceding section of the chain is equal to the time of travel of the frequency which corresponds to this sinusoidal shape of the wave front. Moreover, it should be borne in mind,** that the first noticeable effect at the end of a section occurs at an interval equal to the shortest duration of travel T_o, after the voltage starts to rise at the beginning of the section; that is, the beginnings of the wave fronts always occur at equal intervals of time T_o. These assumptions, together with the relations (1), (3) and (3a) allow the wave fronts at progressively increasing distances from the beginning of the winding to be calculated. By referring them to the fundamental constant T_o, the results of the calculation may again be expressed in a generally valid form. The following table gives

Number of sections n	τ_n	τ_{s_n}
1	1·27	1·62
2	1·185	1·85
3	1·15	2·04
4	1·12	2·22

* See Jahnke & Emde, Funktionentafeln, Wallot, l. c. § 389.

** Cf. Wallot, l. c. § 391.

for the first four sections of the chain, the relative travel

time $\tau_n = \frac{T_{s_n}}{T_o}$, as well as the relative steepness $\tau_{s_n} = \frac{T_{s_n}}{T_o}$ measured at the tangent to the steepest part of the wave front. The values of τ_{s_n} show clearly the progressive flattening of the wave with increasing penetration.

(c) *The Voltage Characteristic at the Beginning of the Winding.*

For times later than the duration of rise T_s, reckoned from the moment of the arrival of the wave, the voltage at the beginning of the windings (terminal) is given simply by the reflection formula (4). For earlier times, namely for frequencies higher than the cut-off frequency of the winding the input impedance of the chain is inductive and tends as ω increases — that is with decreasing time — towards the value $\frac{\omega L}{2}$. This causes the chain to act at first towards the incoming wave as an open line end and the voltage e_K at the beginning of the winding is first reflected to twice the height e_L of the incoming rectangular wave, thereafter decaying first according to the law

$$e_K = 2\, e_L \varepsilon^{-\frac{2\, Z_L}{L}\, t} \quad . \quad . \quad . \quad . \quad (7)$$

and afterwards attaining the value given by formula (4) $e_w = \frac{2\, Z}{Z + Z_L}\, e_L$, which gives the amplitude of the wave penetrating into the winding.

In practice the voltage at the beginning of the winding cannot suddenly spring to the value $2\, e_L$ as there is always a certain amount of terminal capacity C_o due, for instance, to bushings, terminals, leads, etc. which has to be charged by the incoming wave. The voltage at the beginning of the winding, therefore, rises first according to the equation

$$e_K = 2 e_L \left(1 - \varepsilon^{-\frac{t}{Z_L\, C_o}}\right) \quad . \quad . \quad . \quad (8)$$

and next falls according to the equation (7) attaining finally as shown in Fig. 6 the value given by equation (4). This is the cause of the characteristic bumps in the curve of the voltage at the entry of the winding as seen in the oscillograms reproduced in section III g. If these "inductance peaks" are very marked, they are also propagated, much flattened, into the inside of the winding just like an incoming external surge.

It is interesting to note that these "inductance peaks" may appear as two small bumps (see Fig. 8) in the case of a two-phase surge, but only as single bumps in the case of a single-phase or three-phase surge. This effect is explained by the coupling although small, between the individual phase windings, which causes in the limiting case of extremely weak coupling only one time constant to appear for single- and three-phase surges (as in equation 7), but two in the case of a two-phase surge.

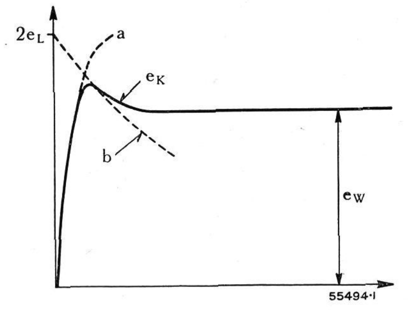

Fig. 6. — Diagrammatic representation of the voltage at the inlet to winding.

a. Voltage according to equation 8.
b. Voltage according to equation 7.
e_K. Voltage at the beginning of the winding.
e_L. Height of the oncoming wave.
e_W. Height of the penetrating wave.

The important conclusion to be deduced from the considerations of this section is the fact that the maximum value of the voltage at the beginning of the winding is not at all determined by the surge impedance of the winding, but occurs as an "inductance peak" due to the inductive input impedance of the chain.

(d) *The Voltage Conditions inside the Groups of Coils.*

The voltage curves calculated and drawn according to the considerations given above also readily enable the voltage rise across a section of the chain to be determined since the voltage at the beginning and the end of the section is known at every instant. As mentioned in the beginning, every section includes all coils per phase and per pole and it is naturally interesting to know also the voltage distribution within this section which usually consists of a number of coils arranged in different slots. In solving this problem, we recall that in practice the sections of a winding are not so concentrated as we have assumed so far for calculation purposes. The capacity, in particular, does not in fact act only at the middle of the section. It may, therefore, be assumed that the voltage will propagate itself also as a wave inside a section, so that the previously determined voltages at the beginning and end of the section may be interpolated. In the case of the first section, this interpolation must take into account the fact that voltages at intermediate points must start from the origin (instant of arrival of the wave) and then during increase, follow a curve parallel to the voltage variation after the first section (see section III g).

(e) *Voltage Distribution inside a single Slot Coil.*

The turns of coils in the same slot are very closely coupled, that is, the mutual inductance from the first to the last turn is of the same order as the self-inductance of the first turn (also in calculations not taking into account the effect of the iron). The result of this is that the voltage distribution within such a coil is made very nearly linear by the inductance and, contrary to the case of the transformer, is not determined at the beginning purely by capacity, because with such close magnetic coupling the charging current necessary for charging the earth and series capacities induces practically equal voltages in all turns. In fact, measurements made on such a coil showed the voltage distribution to be within the limits of experimental error, independent of the arrangement of the wires in the slot.

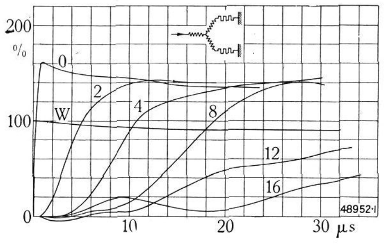

Fig. 7. — Penetration of a travelling wave into the stator winding of a high-voltage motor. Surge on one phase only.

W. Incoming wave.
O. Voltage at the terminal.
2, 4, 8, 12, 16. Voltage after the second, fourth, eighth, twelfth, and sixteenth coil.

Ordinates: **Voltage in percentage of the incoming wave.**
Abscissæ: **Time in micro-seconds.**

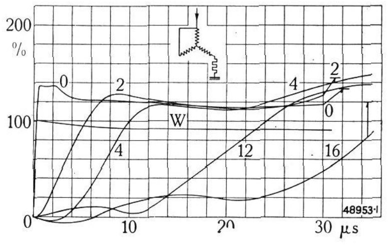

Fig. 8. — Penetration of a travelling wave into the stator winding of a high-voltage motor. Surge simultaneous on two phases.

W. Incoming wave.
O. Voltage at the terminal.
2, 4, 12, 16. Voltage after the second, fourth, twelfth, and sixteenth coil.

Ordinates: **Voltage in percentage of the incoming wave.**
Abscissæ: **Time in micro-seconds.**

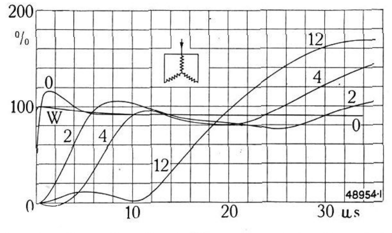

Fig. 9. — Penetration of a travelling wave into the stator winding of a high-voltage motor. Surge simultaneous on all three phases.

W. Incoming wave.
O. Voltage at the terminal.
2, 4, 12. Voltage after the second, fourth and twelfth coil.

Ordinates: **Voltage in percentage of the incoming wave.**
Abscissæ: **Time in micro-seconds.**

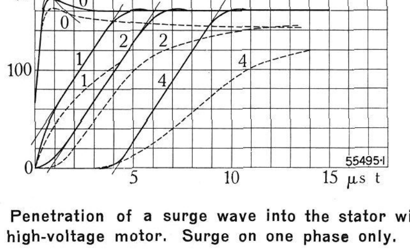

Fig. 10. — Penetration of a surge wave into the stator winding of a high-voltage motor. Surge on one phase only.

Comparison of the measured (dotted) and theoretically determined values (full lines). Notation as in figures 7—9.

Ordinates: **Voltage in percentage of the incoming wave.**
Abscissæ: **Time in micro-seconds.**

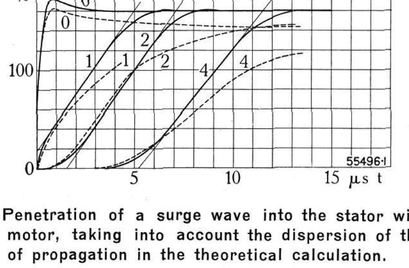

Fig. 11. — Penetration of a surge wave into the stator winding of a high-voltage motor, taking into account the dispersion of the velocity of propagation in the theoretical calculation.

Theory and measurement agree satisfactorily and show the progressive flattening of the wave with increasing penetration.

Ordinates: **Voltage in percentage of the incoming wave.**
Abscissæ: **Time in micro-seconds.**

(f) *Reflection at the Star Point.*

The penetrating wave is reflected and refracted at the star point, depending on the number of phases affected, according to the well known laws applying to line bifurcations.* If the surge is a three-phase one, and if the neutral is as usual not earthed, then it corresponds to an open line end, and total reflection occurs. In the case of a single-phase surge, the voltage is reduced at the star point to $^2/_3$ of the original height; with a two-phase surge it is increased to $^4/_3$ of the original value. Taking into account these relations and the resulting incoming and reflected waves, it is readily possible to complete the construction illustrated in Fig. 4. Consideration of a curve of the penetrating surge drawn in this manner, shows that due to the reflection at the neutral, a three-phase surge may result in an increased stressing of the winding insulation to earth, but not in additional stressing per member or per coil. On the other hand, with a single-phase surge, the reduction of the height of the wave causes a reduction of the stressing of the insulation to iron at the star-point; the stressing per member and per coil at the point of transition is, however, increased. Because of the considerable flattening to which the wave has already been subjected, the stressing of these star-point coils is, in spite of this, less than that of the coils at the beginning of the winding.

(g) *Comparison of the Results of Theory and of Tests.*

Figs. 7, 8, and 9 illustrate, as an example, the penetration of a surge into the winding of a high-voltage motor, as determined by the oscillograph. The motor is a six-pole, 6000 volt machine with two coils per pole and per phase. These curves show clearly the characteristic effects which may be expected on the basis of the above theory, for instance, the increasing flattening of the entering wave fronts, the "inductance peaks" of the voltage curve at the terminals and the reflection at the star point (voltage after the twelfth coil). In order to obtain a still closer comparison between theory and the test results, the case of a single-pole surge for the coils near the beginning of the winding is shown more in detail in the following Figs. 10 and 11. Fig. 10 illustrates the voltage curves as measured, as well as those calculated by the methods explained in sections IIIa, c and d. Fig. 11 shows the results of a similar process which, however, also takes into account the effect of the dispersion of the times of travel of the wave according to section IIIb. It can be seen that especially in the second case, there is a very good agreement between the measured values and the theoretically determined ones. There is a systematic discrepancy in the upper part of the wave fronts in that the measured values show a greater flattening. This can be explained by the growing effect of the iron into which the flux penetrates as the time increases causing a rise in the inductance, and hence a slowing down of the rate of rise of the voltage. To this effect and to the small capacitive coupling at the coil ends must be attributed also the negligible, smaller irregularities, at the beginning of the voltage rise in coils more distant from the beginning of the winding.

* See for instance, Rüdenberg: El. Schaltvorgänge, Chap. VIII.

IV. THE STRESSING OF WINDING INSULATION AND THE POSSIBILITIES OF REDUCING IT.

A fundamental distinction should be made between the two kinds of insulation stress, namely of the main insulation between the winding and earth and between phases on the one hand, and of the insulation between individual turns of the coils on the other. The proper control of these two forms of stress is of equal importance for the reliability of the machine. Depending on the type of winding and the design, the one or the other insulation will be most endangered. In the case of high-voltage motors of the usual sizes, special care will have to be given in particular to the insulation between turns, whereas in the case of large motors and generators, the main insulation is more likely to be the limiting factor.

(a) *Insulation of the Winding to Earth.*

According to both theory and measurement, the incoming wave is reflected and diffracted at the beginning of the winding due to the higher surge resistance of the chain, and a rise in voltage takes place which is further increased by the "inductance peaks" referred to above. This voltage rise depends naturally on the surge resistances of the line and of the winding, as well as on the number of phases affected, and may attain twice the value of the incoming wave. As a general rule, it will not, however, be necessary to reckon with the height of the incoming wave because a limit is set to the maximum terminal voltage by the arcing distance of the bushings, or by a surge arrestor (coordination) and hence the value thus fixed can be taken as a direct basis for the maximum terminal voltage. As it must be assumed that the surge is a three-phase one, allowance must accordingly always be made for the reflection at the star point. Theoretically, this causes the voltage to earth to be increased to twice the reference voltage at the terminals; a value which, however, because of the damping of the surge, and the appearance of the "inductance peaks" is not attained in practice and which rarely exceeds 1·8 times the terminal voltage. The to and fro movement of the wave causes the entire winding to be subjected to this stress to earth and not only the star-point end. This voltage rise can be avoided, and the voltage stress limited to the value at the beginning of the winding only if similar precautions, such as arcing gaps or surge arrestors, are applied to the star point. In the case of an earthed star point there is, independently of the number of phases affected by the surge, a reduction of the voltage down to zero. As, however, the over-voltage enters in the form of a wave, the entire winding must be insulated for the highest possible voltage and *no grading of the insulation towards the star point can be permitted.*

(b) *The Insulation within the Coil Groups, Coils and Turns.*

The first section at the beginning of the winding is the most highly stressed one and it must be capable of withstanding the full height of the voltage at the beginning of the winding. Within this first section, which comprises all the coils of a phase per pole, the distribution of the voltage stress over the individual coils is such that the first coil at the beginning of the winding is the most highly stressed one. The stress on it depends on the number of coils per pole and per phase, as well as on the cut-off frequency of the winding, and it must be assumed that for two or more coils per pole and per phase up to 75 % of the voltage at the terminals of the winding will have to be taken by this first coil (in the case of only one coil per pole and per phase, of course 100 %). Within a coil, it may be taken, according to the reasoning in section IIIe, that the voltage distribution is linear and the amount which has to be reckoned with for designing the winding insulation will depend on the arrangement of the turns within the coil.

The stressing of the coil and turn insulation may be definitely reduced, if care is taken to ensure that the voltage rise at the entry to the winding is not steeper than that of the penetrating wave. To achieve this, a suitable dimensioned condenser could, for instance, be connected in parallel to earth. (The theory exposed supplies the basis for dimensioning this condenser.) If, however, this measure is to be effective in all cases, it must be assisted by protecting a section of the line against direct lightning strokes and the condenser provided with a parallel connected arrestor. The same object may, however, also be achieved by other means, which are much simpler, because they can be provided in the machine itself. Their principle consists in not allowing the full steepness of the penetrating wave to fall directly down to the value determined by the limiting frequency of the winding, but to ensure a gradual transition which can be achieved, for instance, by reducing the inductance of the coils at the input end of the winding, as a function of the frequency or height of the voltage, e. g., by coupled turns closed through a condenser or through a voltage-dependent resistance.

The measures given in the preceding section IVa for limiting the voltage at the terminals of the winding, limit the stressing of the main insulation, as well as that of the coil and turn insulation. The most suitable solution of the problem of the winding stress and of the insulation is, therefore, clearly to be sought first by limiting the maximum voltage at the entry to the winding by suitable coordination of the insulation of the installation,* and secondly, by so dimensioning the insulation of the winding that it will under all conditions be able to withstand the voltages then possible, without any additional precautions.

V. SUMMARY AND CONCLUSIONS.

(a) In the case of rotating machinery windings, the individual phases behave during surges as though they were practically independent of one another, because the flux displacement occurring during such rapid phenomena results in only an extremely small magnetic coupling between the coils belonging to different phases and poles and the capacitive coupling because of the screening effect of slot iron is also very small.

(b) The voltage wave penetrates into the phase winding as into a chain of coils the sections of which are built up from the individual coils of each pole and phase; because of the barrier effect of the chain for frequencies above its cut-off frequency the surges entering the winding have only a wave front of limited steepness, which moreover is further flattened as the distance of penetration increases.

(c) Because the surge impedance of the winding (about 1500 to 2000 ohms per phase) is considerably higher than that of lines and busbars, and because this impedance is for all frequencies above the cut-off frequency of an inductive nature, there is a reflection at the beginning of the winding of the incoming surge with an increase of its voltage up to twice its original value accompanied by the appearance of so-called inductance peaks. As, however, the voltage at the beginning of the winding is in practice limited independently of the size of the incoming wave, it is only this limiting value which determines the stress in the insulation.

* See following article.

(d) At the star point, the waves entering the winding are reflected and diffracted according to the laws applying to the bifurcation of lines. Because of the reflection of a three-pole surge between 1·4 and twice the maximum value of the voltage at the terminals of the winding must be reckoned with for the stress of the winding insulation to earth; with an earthed star point only the simple value need be reckoned with. Because of the wave nature of the phenomena, it is not permissible to grade the insulation even with an earthed star point.

(e) The first section of the chain (coils per pole and per phase) receives the full voltage applied to the terminals of the winding. From 100 to 75 % of the voltage at the beginning of the winding should be reckoned per coil, according to whether there is only one, or two or more coils per pole and per phase.

(f) Within the individual coils it may be assumed that the voltage distribution is linear.

(g) The most suitable manner of providing over-voltage protection of the winding is by suitably fixing and systematically applying the principle of coordination, to limit definitely the over-voltage at the beginning of the winding and at the non-earthed neutral on the one hand, and to dimension the insulation on the other hand, so that it will safely withstand the overvoltages then occurring.

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PROPOSALS FOR THE ECONOMIC COORDINATION OF INSULATION IN SYSTEMS INCORPORATING ROTATING MACHINES.

Decimal Index 621.316.93 : 621.3.048
621.316.933.2 : 621.313

The Swiss Coordination Committee has temporary excluded rotating machines from the proposed rules for the insulation coordination of a. c. high-voltage systems due to the prohibitive cost. In the following article it is now shown that if modern lightning arrestors are employed, reliable coordination is also possible in the case of systems incorporating rotating machines. Even when directly connected to overhead transmission lines the machines are protected against over-voltages emanating from atmospheric disturbances without uneconomical reinforcement of their insulation proving necessary.

THE Swiss Coordination Committee (Advisory Committee 28 of the Comité Electrotechnique Suisse) has exhaustively studied the question of the grading of insulation in electrical systems and elaborated rules for the coordination of the insulation of high-voltage a. c. systems.[1] These rules only apply to systems incorporating no rotating machines. The aim of the present article is to investigate the insulation coordination of rotating machines.

At the outset the

draft of the Coordination Committee for high-voltage systems incorporating no rotating machines

will be considered.

Three impulse voltage levels are provided for, as represented by curves 1 a, 1 b, and 1 c in Fig 1. A striking feature of these curves is the big difference between the lower level 1 c (breakdown and residual voltage of the arrestors) and the intermediate level 1 b (impulse flash-over voltage of the equipment). Although at the higher rated voltages (not shown in the figure) the intermediate level is only 33 % above the lower level, at a rated voltage of 3 kV, for instance, it will be as much as 130 % higher.

There are two chief reasons for this enormous difference. Firstly, the range of protection of arrestors is greater the bigger the margin between them and the intermediate level. When economic reasons do not involve a smaller step, as in the case of the higher service voltages, it is therefore of advantage to select a fairly large margin. Secondly, the intermediate level (curve 1 b in Fig. 1) has been chosen relatively high for low rated voltages in order also to be able to employ the same equipment in systems where no lightning arrestors are employed. In this case, it is true, a comparatively high flash-over voltage is necessary, otherwise flash-overs will cause far too frequent service interruptions.

It will now be considered how the insulation strength could be reduced if arrestors were to be universally employed, whereby the possibility of substantially reducing the arrestor breakdown and residual voltage below curve 1 c in Fig. 1 will also be taken into account. In point of fact, the construction of arrestors with breakdown and residual voltages not exceeding three times the voltage rating (peak value of line voltage, curve 2 c in Fig. 1) now presents no difficulties. If the arrestors are installed close enough to the equipment to be protected the 50 % impulse flash-over voltage need not lie more than 33 % above it, as proposed by the Coordination Committee for the higher rated voltages. In this manner curve 2 b

[1] The draft of these rules will be published shortly.

is obtained for the intermediate level. Curve 2 a for the strength of the internal insulation of the equipment was then plotted 15 % higher, that is, by the same amount as curve 1 a above curve 1 b.

Fig. 1 shows, therefore, that within the range of voltage ratings considered and providing the possibilities of modern lightning arrestors are properly exploited both the internal and external insulation strength of the high-voltage equipment can be quite

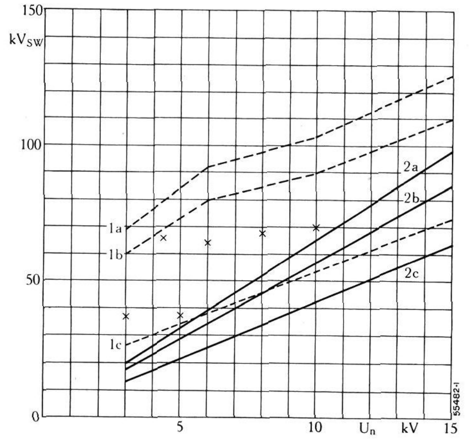


Fig. 1. — Insulation strength of high-voltage equipment (in peak kV) under impulsive conditions in relation to rated voltage U_n.

Curves 1a, 1b, 1c. Upper, intermediate, and lower insulation levels for systems incorporating no rotating machines, as proposed by the Swiss Coordination Committee.

Curves 2a, 2b, 2c. Upper, intermediate, and lower insulation levels for systems incorporating rotating machines as proposed by Brown Boveri.

a. Minimum value of internal insulation strength of equipment.

b. Minimum value of 50 % flash-over voltage of equipment.

c. Maximum value of breakdown and residual voltage of arrestors.

x. Measured impulse breakdown voltages of high-voltage motor and generator windings when tested with steep wave-front surges.

Abscissa : Rated voltage.

substantially reduced — compared to the proposals of the Coordination Committee — without affecting reliability (cf. curves 2 a and 2 b with 1 a and 1 b). The time does not appear to be quite propitious, however, for the introduction of this measure, inasmuch as operating engineers mostly desire also to be able to operate their medium-voltage systems without arrestors. If the high insulation strength represented by curves 1 a and 1 b is required in the case of busbars, circuit-breakers, isolating switches, transformers, etc., for systems *without* arrestors, it is definitely not worth while manufacturing a special model with reduced insulation conforming to curves 2 a and 2 b for systems *with* arrestors, since only a relatively small saving would be realized.

Insulation Coordination in Systems incorporating Rotating Machines.

Where rotating machines are concerned, however, conditions are quite different. Reinforcement of the insulation of coils and turns in slots and coil heads results in a poorer utilization factor in the case of both generators and high-voltage motors, and this is of no little significance.

If trouble-free operation is achieved with an insulation strength conforming to curves 2 a and 2 b the specification of a higher strength in conformity with curves 1 a and 1 b would be economically unwarranted. Compared to the additional expense involved by the reinforced insulation the cost of the arrestors can be neglected — at least for large and medium-size high-voltage machines. Moreover, even a machine with reinforced insulation would run great risk if connected to an overhead system without arrestors.

At this point investigation of the insulation strength of modern high-voltage machines of conventional design is of interest. To this end a number of impulse breakdown voltage test values are plotted in Fig. 1. Some of the tests were made many years ago on machines selected at random, so that the same results could be obtained with any standard designs without artifice, as long as the manufacturer has some knowledge of travelling wave phenomena in machine windings. When establishing general rules for insulation coordination it appears preferable not to base them on the very best impulse voltage strengths obtainable, if only because there are still many old machines in service the design of which does not conform to present-day knowledge, but which nevertheless must be protected against over-voltages.

The breakdown voltage test values in Fig. 1 all lie above curve 2 a*, but quite considerably below curve 1 a. From a technical point of view it would now be quite feasible to increase the insulation strength of high-voltage machines to above curve 1 a, although only at prohibitive cost. For this reason it is suggested that in systems incorporating rotating machines insulation coordination as per curves 2 a to 2 c should be adopted.

Where condensers are to be employed for the protection of machines a relatively low level is also indicated for the internal insulation, inasmuch as the price of such condensers depends even more than that of the machines themselves on the insulation levels. It must be emphasized, however, that with the proposed insulation steps reliable protection can also be achieved

* Two points lie only slightly above it, but for other test values the safety margin is very large. Within the whole range of rated voltages considered it is no difficult matter to insulate the machine windings, so that the breakdown voltage will lie, with a high degree of certainty, above curve 2 a.

without condensers. The breakdown voltage test values given in Fig. 1 were all measured with waves of steep front having a maximum time to crest of 1 μs. Even with such steep wave-front surges, therefore, rotating machines can be protected by arrestors against internal perforation without condensers having to be provided to reduce the steepness of the wave-front.

Fundamentally, two insulation levels, that of the arrestors and that of the internal insulation, would suffice to protect the latter against breakdown. To obtain an additional degree of safety, however, it is advisable to provide a third, intermediate level (curve 2b in Fig. 1). In this case, should an arrestor ever fail to operate, the internal insulation of the machines would not be endangered, because an external flash-over would take place (in the intermediate level) before the voltage could attain a value liable to endanger it. Suitable high-speed selective protective gear must of course be provided to interrupt the arc resulting from such flash-overs before it can do any harm.

Moreover, the point at which such possible flash-overs are required to occur should be carefully chosen. For instance, flash-overs must be avoided in the air inlet duct of generators, since the resulting arc may be blown into the machine. Investigation of existing plants has shown that the interior of practically all generators is shut off from the exterior in some way or can be in a simple manner, e. g., by means of a small barrier, if necessary. The horn-gaps which hold the upper limit of the intermediate level (curve 2b in Fig. 1) should be fitted on the outer side of the barrier, either on the outside of the bushings themselves or on any other insulators. All insulators on the innermost side of the barrier, however, should have an impulse flash-over voltage corresponding at least to the values of curve 2a in Fig. 1, to prevent flash-overs occurring in the interior.

The horns referred to must not be fitted too far away from the generator. If, as is usually the case, a cable connects the generator to the switchgear it is imperative that the horns be arranged on the generator side of the cable. The rate of propagation of electrical waves in cable is only about half as great as in busbars in air, so that a given length of cable corresponds to busbars twice as long. In consequence, the protective effect of the gaps might prove inadequate even with relatively short cables, should they be fitted at the end of the cable farthest away from the generator. The arrestors, of course, must also be installed at the generator end of the cable, so that their protective action will not be impaired.

In the case of high-voltage motors it will generally be preferable to fit the horns in the terminal box (cf. Fig. 2). This allows of correct adjustment in the manufacturer's works before delivery, thus ensuring that the desired margin is obtained. If the horns were to be fitted on special insulators in the plant this might not be the case, for motor manufacturers generally have no say in the layout of the switchgear. It could be objected that flash-overs in the terminal box are undesirable. This is true enough, but such flash-overs will be more the exception than the rule, i. e., will only occur when an arrestor fails to operate. It will be generally agreed, however, that a flash-over in the terminal box is to be preferred to punctured machine windings!

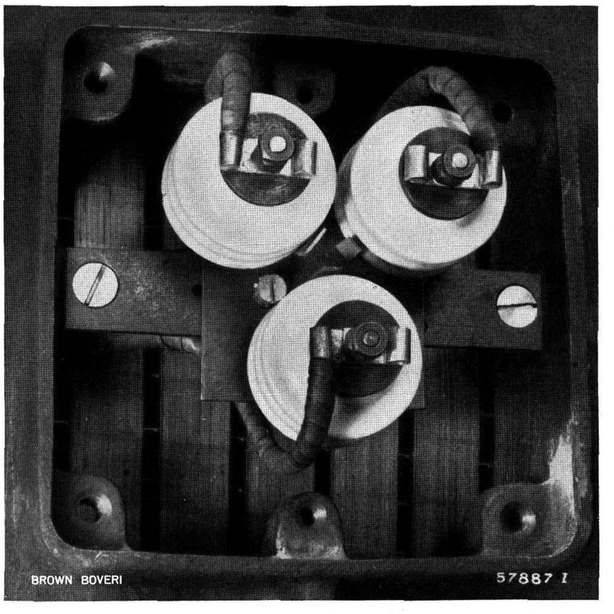


Fig. 2. — Terminal box of high-voltage motor.

The three iron bars between the insulators give positive and negative impulse flash-over voltages of the same magnitude.

The positive and negative impulse flash-over voltages of the horn-gaps of the intermediate level are advantageously set as nearly as possible to the same value, inasmuch as the breakdown and residual voltage of the arrestors (curve 2c in Fig. 1) is virtually independent of the polarity, so that the flash-over voltage of the gaps must be sufficiently above it for both polarities, i. e., at least as high as curve 2b in Fig. 1. If this flash-over voltage has the values represented by curve 2b for both polarities, the values given by curve 2a will suffice for the internal insulation. Should, on the other hand, the flash-over voltage of the horn-gaps be highly polarity-dependent, the values for one polarity would lie considerably above curve 2b, and the internal insulation strength would then have to be correspondingly higher than given by curve 2a. Fig. 2 depicts, for instance, how the negative impulse flash-over voltage can be reduced in a simple manner to the value of the positive in the terminal box of a high-voltage motor.

Fig. 3 represents flash-over voltage curves of horns suitable for mounting on insulators in the plant. The flash-over voltage naturally also depends on the mode of installation of the gaps, for which reason they are to be taken only as fundamental and not as cali-

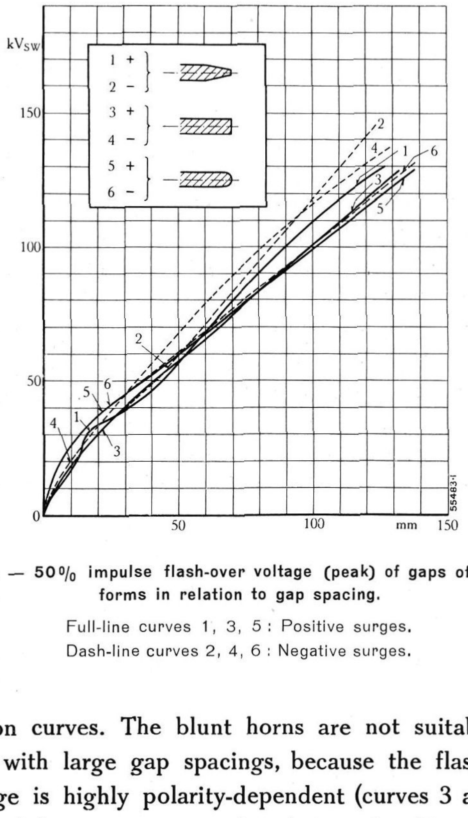


Fig. 3. — 50 % impulse flash-over voltage (peak) of gaps of varying forms in relation to gap spacing.

Full-line curves 1, 3, 5 : Positive surges.
Dash-line curves 2, 4, 6 : Negative surges.

bration curves. The blunt horns are not suitable, at least with large gap spacings, because the flash-over voltage is highly polarity-dependent (curves 3 and 4). Pointed horns are somewhat better in this respect (curves 1 and 2), although rounded horns finally proved to give the most regular curves and to be practically free from the influence of polarity (curves 5 and 6).

The degree of accuracy with which the horn-gaps can be adjusted to the desired flash-over voltage is of particular importance in the case of small gap spacings. For the lowest preferred high-voltage value of 3 kV the flash-over voltage should be of the order of 17 kV, the gap spacing varying according to the type of the horns between 5 and 9 mm. During tests with such gaps the spacing was adjusted by different persons within the above limits, the flash-over voltage being found to differ by a maximum of only $\pm$ 3 %.

This tolerance appears absolutely permissible and to obtain the correct margin with respect to the level held by the arrestors can be taken into account by setting the flash-over voltage somewhat higher than curve 2b in Fig. 1 from the very beginning. The flash-over voltage of rounded horns is very little affected by traces of burning due to arcs. After heavy short circuits it is nevertheless advisable to replace or touch up and re-adjust the horns.

Experimental confirmation of the correct coordination of the insulation of rotating machines can be obtained in the same manner as with other high-voltage equipment. It is shown that the breakdown and residual voltage of the arrestors remains below a specified maximum value (curve 2c in Fig. 1) and that the impulse flash-over voltage at least attains a specified minimum value (curve 2b). Moreover, with a voltage at least 15 % higher — when the terminals or other insulators or gaps provided for the purpose flash over — the internal insulation of the machine must neither flash over nor break down.

The coordination of the insulation of rotating machines is of course not to be taken to signify that only the insulation of the machines is coordinated as per curves 2a to 2c in Fig. 1 and that the remainder of the system is based on curves 1a to 1c. All parts of a system incorporating rotating machines must naturally conform to curves 2a to 2c. Nevertheless, circuit-breakers, isolating switches, transformers, etc., of standard design can be employed, inasmuch as only minimum values are specified for the strength of the internal insulation. If the latter satisfies curve 1a — as is invariably the case with standard high-voltage equipment — it will certainly satisfy curve 2a. The horns of this equipment need then only be adjusted to conform to curve 2b (instead of to 1b), to prevent the terminals of the machines forming the weakest point in the system.

As a result, somewhat different insulation coordination is obtained than for systems incorporating no rotating machines. It is, however, built up logically and gives reliable protection against over-voltages due to atmospheric disturbances. In the ordinary way arrestors discharge such over-voltages to earth without interruption of service. Even should an arrestor fail to operate, an external flash-over protects the machines against internal breakdown. The proposal exploits the possibilities of arrestors and therefore involves no greater internal insulation strengths than already provided by serious machine manufacturers.

(MS 977) *Dr. W. Wanger. (E. G. W.)*

BRIEF BUT INTERESTING

New Brown Boveri Voltage Measuring Device in Power Transformers.

Results of Tests by Swiss Association of Electrical Engineers.

Decimal Index 621.317.725:621.314.21

HIGH-VOLTAGE instrument transformers not only take up much valuable space in plants, but a large amount of material is also involved in their construction. At the very points in networks (e. g., substations, etc.) at which a record of the voltage is required, however, power transformers are usually available in which metering windings can be incorporated to produce an instrument voltage virtually unaffected by working conditions (magnitude of voltage and load current, power factor, direction of power transmission). This voltage is a true image of the transformer terminal voltage — the accuracy compares very favourably with that of voltage transformers — so that in many cases separate voltage transformers can be dispensed with. The construction and mode of operation of this new voltage measuring device has already been described in an earlier number of this journal (The Brown Boveri Review, October, 1941, p. 311 ff.) and will therefore not be dealt with here.

A device of this kind was embodied in a 20,000 kVA three-phase transformer put into service about six months ago, to measure the high voltage (rated value 144 kV), the rated and maximum permissible burdens being 3×100 VA and 3×3000 VA, respectively.

Transformer		Measuring device		
Mode of operation	Load %	Burden VA/phase	Transformation error in %	Phase angle error minutes
Stepping up	100*	0	+ 0·003	— 0·7
„ „	37	0	+ 0·036	— 2·4
	0	0	+ 0·061	— 3·4
Stepping down	19	0	+ 0·079	— 3·7
„ „	100*	0	+ 0·156	— 4·2
Stepping up	100*	100	— 0·263	— 6·7
„ „	37	100	— 0·229	— 8·7
	0	100	— 0·209	— 9·9
Stepping down	19	100	— 0·199	—10·2
„ „	100*	100	— 0·156	—10·7

* Values extrapolated from test results, since for operating reasons it was impossible to load the transformer with more than 19 or 37 % of its full rating.

An accuracy test undertaken on one phase by the Testing Department of the Swiss Association of Electrical Engineers (see table) has shown that the device fulfils accuracy requirements to a very high degree.

All errors are smaller than specified for the 0·5 voltage transformer class and the foregoing figures are striking proof of the extent to which the effect of the transformer load on the instrument voltage has been eliminated, the maximum transformation error between full load stepping up and full load stepping down being only 0·16 % and the phase angle error only 4·0 minutes.

Such measuring devices are now available for single and three-phase transformers.

(MS 968) *G. Wetten. (E.G.W.)*

Large Transformers of Lightweight Construction.

Decimal Index 621. 314. 21

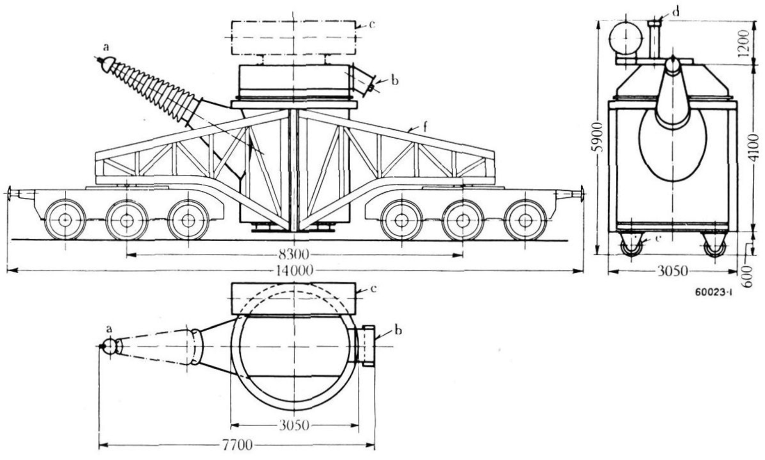
THE dimensions of distribution transformers have altered very little of recent years, inasmuch as it is difficult to build lighter transformers for voltages up to about 20 kV without affecting their quality and accuracy. Their small insulation clearances just suffice for the necessary flow of the cooling medium, so that little is to be gained by employing insulating material of improved quality.

Conditions are quite different in the case of large transformers for extra-high voltages, however, where the insulation clearances form a criterion for the design of the whole transformer and, in consequence, have to be made much larger than would actually be necessary for cooling purposes.

The distance between the primary and secondary windings, in particular, not only directly affects the size of the transformer, but also, together with the density of the ampere-turns, the magnitude of the leakage flux. The latter would generally have been greater than desirable if the designer had not increased the cross-section of the core to re-establish the specified ratio between the main and leakage fluxes. In the case of very large units in particular, however, a disproportion between the weights of the core and windings had to be tolerated, the oversize core being the predominating feature of the whole transformer.

This state of affairs provided a big chance to make outstanding progress, for if the distance between the primary and secondary windings could be substantially reduced, large transformers would become much lighter. Brown Boveri have now actually succeeded in reducing this distance to less than half the earlier value. Further details will be found elsewhere in the present number of this journal.[1]

[1] See page 235.



Single-phase oil-immersed transformer with radially-laminated single-limb core.

Dimensions and weight (including that of the oil) have been considerably reduced compared to earlier designs, thus greatly facilitating transport and erection.

Technical data: 80 (+24) MVA, 150 : $\sqrt{3}$/380 : $\sqrt{3}$/(10) kV, 50 cycles, with forced oil circulation and water cooling; for 240 MVA three-phase set, high-voltage neutral point solidly earthed. Weight for transport 88 t, weight of truck 30 t.

a. High-voltage bushing.
b. Low-voltage cable end box.
c. Oil conservator.
d. Safety valve.
e. Rollers.
f. Special transformer truck.

Year of construction	Rating MVA	Ratio approx. kV	Type rating = half sum of ratings of windings approx. MVA	Weight without oil t	Oil t	Overall weight t	Per MVA of type rating t
1930	32·5	10·5/48/116 ± 5%/**145 ± 5%**	73·5	143	57	200	2·72
1931	46	8·2/**152 ± 5%**	48	84·5	31	115·5	2·40
1941*	47·5	12·9+4×0·6/**160**	57	62	27	89	1·56
1941*	100 (+33)	**220**/110/(10)	140	158·5	33	191·5	1·37
Tender 1943*	80 (+24)**	150: $\sqrt{3}$/**380**: $\sqrt{3}$***/(10)	92	75	15	90	0·98

* New type of insulation.
** Single-phase transformer for 240 MVA three-phase bank.
*** Neutral point solidly earthed, insulation coordinated.

The effect of the measures taken is best illustrated by the above comparison of transformers manufactured.

The advantages of large transformers of lightweight construction on the score of transport and erection need no stressing, while the reduced weight of the oil will be particularly appreciated by operating engineers. Notwithstanding this great advance in transformer design the efficiency is not only unimpaired, but even enhanced.

Looking forward to the time when still higher transformer outputs and voltages will have to be reckoned with we seized a further opportunity of facilitating transport by introducing the radially laminated core.[1] This is particularly suitable for single-phase transformers which in banks of three will probably find application for the three-phase transmission of large blocks of power over long distances. Exhaustive studies and large-scale tests have put us in possession of reliable fundamental data which will permit us to solve post-war problems in the most favourable manner conceivable. The last item in the above table, a transformer with a radially-laminated single-limb core and a return magnetic path of special design, clearly shows what can now be attained in this respect. The weight per unit output and, in particular, the low weight of the oil are worthy of note when the high voltage of 380 kV is taken into consideration.

As the illustration shows, this powerful unit can be transported on a six-axle truck without great difficulty.

Maximum reliability coupled with minimum weight is and will continue to be our aim in transformer design.

(MS 992) *A. Meyerhans. (E. G. W.)*

[1] The Brown Boveri Review No. 10, 1941, p. 307.

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