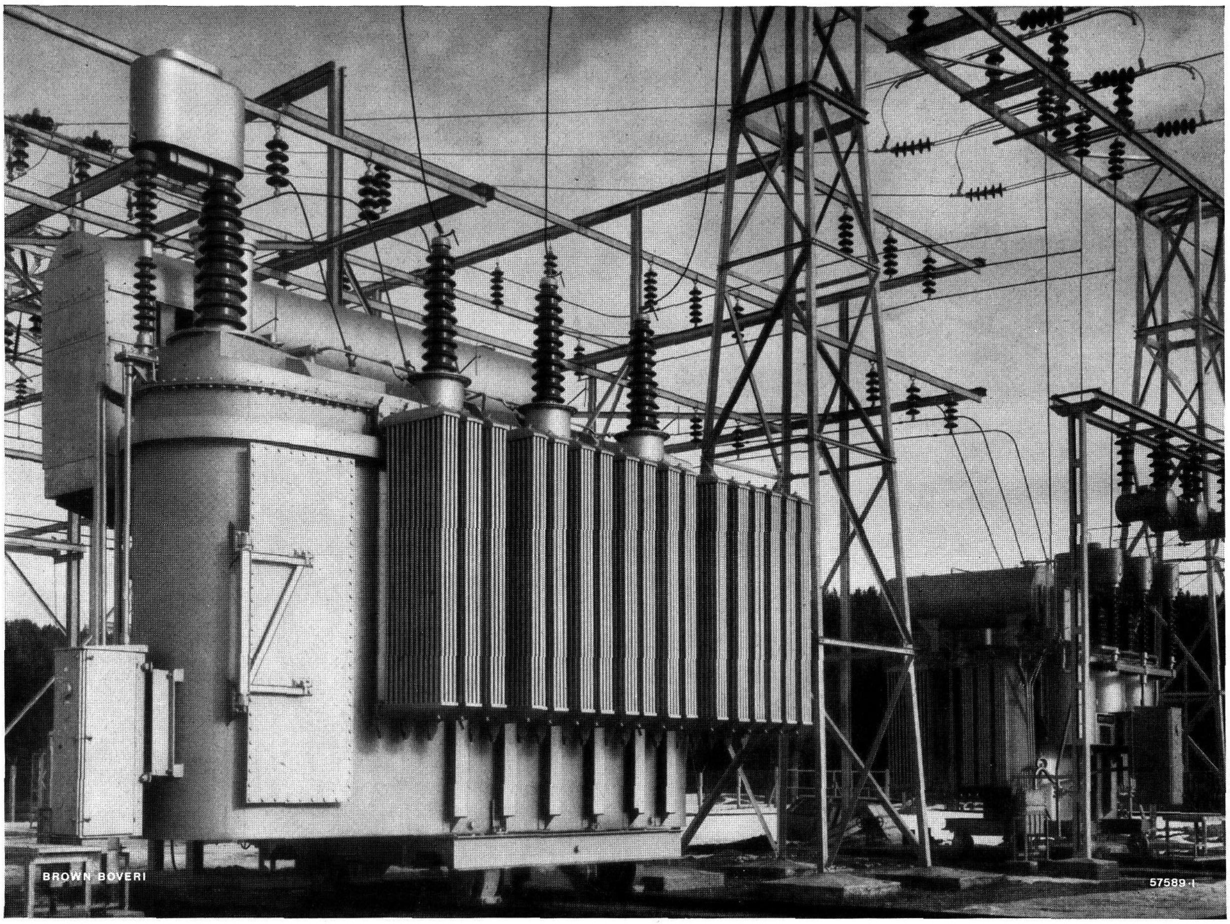
THE BROWN BOVERI REVIEW



Power Transformers with On-load Tap-changing Switches

On left:

Three-phase Three-winding Transformer

20/20/13 MVA

150/50/16 kV

On right:

Three-phase Regulating Auto-transformer

25 MVA

50/65 kV

Both Transformers are designed for Natural Cooling

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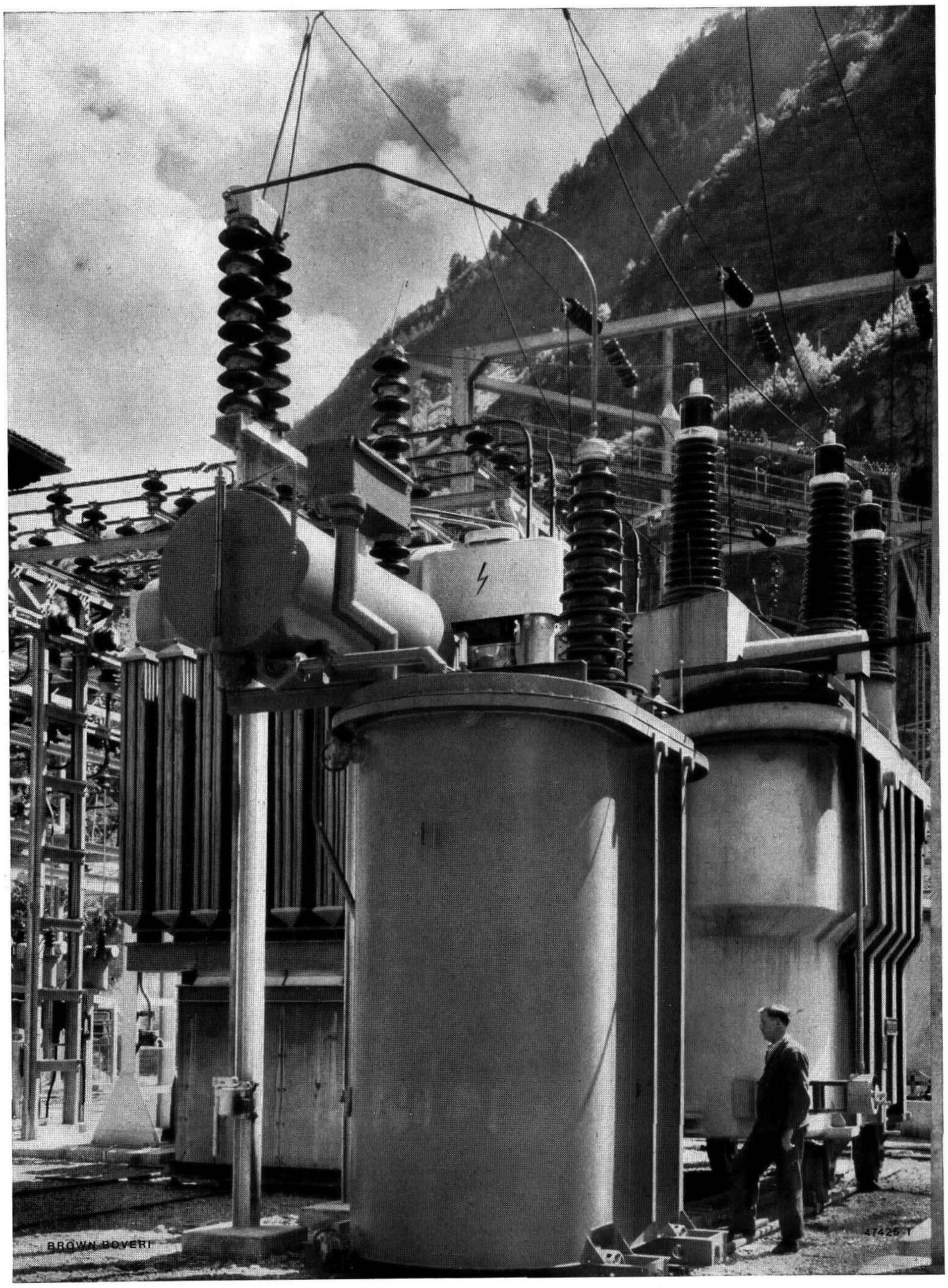
Printed in Switzerland.

In the Transformer Field



Piottino Power Station of the Aare-Tessin A.-G.

At front:

Arc Suppression Coil for the Protection of the Gotthard Transmission Line

12,000 kVA

$150 : \sqrt{3}$ kV

At rear:

Three-phase Transformer with built-on Bank of Coolers

46,000 kVA

8·2/159·3 — 145·1 kV

THE BROWN BOVERI REVIEW

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

VOL. XXIX | NOVEMBER/DECEMBER, 1942 | No. 11/12

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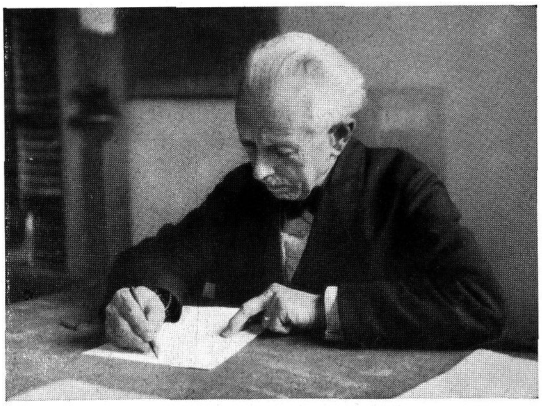
CONTENTS:

IN the autumn of 1941, Mr. Johann Kübler, for many years chief of our Transformer Department, retired on superannuation after more than thirty-eight years in our service. Before taking leave of us, Kübler read on the 12th December, 1941, a paper[1] on Brown Boveri transformer designs from the very early days of the firm in 1891. Kübler's reputation as a transformer specialist extends to far beyond the Swiss frontiers and for this reason we feel justified in reproducing his paper in abridged form here. We are convinced that it will be appreciated by all those to whom our branch of engineering is something more than a profession and also by everyone having the privilege of being counted among the personal friends of the genial Kübler.

[1] *Also published in extenso in brochure form.*



TRANSFORMER DESIGNS OF BROWN, BOVERI & COMPANY, LIMITED, BADEN, FROM 1891 TO 1941.

Decimal Index 621.314.21 (091)

I. DESIGNS PRIOR TO 1906.

Transformers which, referred to their rating, are now termed distribution transformers were at first chiefly of the air-cooled type with one, two, or three limbs arranged horizontally for single-phase service (Fig. 1) and vertically for three-phase applications (Figs. 2 and 3). In the latter case the limbs were arranged in triangular formation and provided with annular or Y yokes (Fig. 4). Even at that early date, however, oil-insulated transformers, arranged horizontally or vertically in cast-iron tanks (Fig. 5), were built.

The limbs were of circular cross-section, being either turned down or built up from finely-stepped laminations to give as close an approximation to a circle as possible. The low-voltage winding was of coarse wire, round or rectangular in cross-section, with cotton insulation, the high-voltage winding of round wire, insulated entirely with paper or, in the case of thin wires, with cotton or two or three layers of silk.

The turns of both windings were arranged in layers, being wound continuously over the whole length of the limb (even in the case of the high-voltage winding) or divided into two halves stepped at the ends and thus giving the winding a trapezoidal cross-section. Even at that time the arrangement with a large number of separate coils was already known. As insulation, both between the high- and low-voltage windings and between windings and cores, cylinders of thick paper simultaneously wound and glued in a lathe were originally employed. Such cylinders, however, were later chiefly only used to insulate the

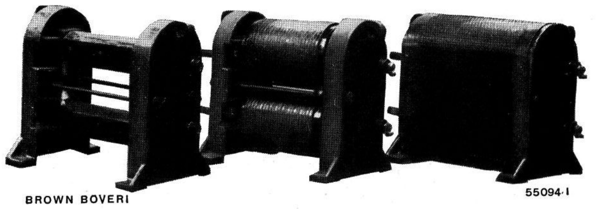


Fig. 1. — Single-phase air-cooled transformers with two limbs arranged horizontally, ratings up to approx. 40 kVA, 5000 V, built up till about 1902.

windings from each other. Horizontal windings had no end supports, whereas those on vertical limbs

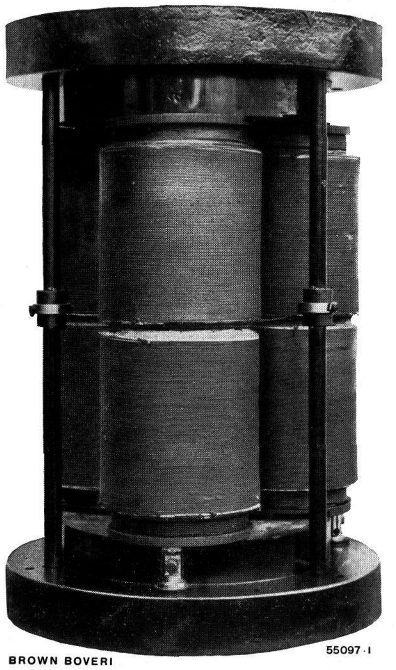


Fig. 2. — Three-phase air-cooled transformer with annular yoke, ratings up to approx. 50 kVA, 5000 V, built until 1902.

Fig. 3. — Three-phase air-cooled transformer with Y-shaped yoke, ratings up to approx. 50 kVA, 5000 V.

were provided with oil-impregnated, wooden or presspahn supports.

Medium-size, single- and three-phase transformers, i. e., with ratings between 100 and 200 kVA, were oil-insulated and had vertical limbs and cast-iron, oval or round tanks with smooth, ribbed (Fig. 6), or corrugated walls. Corrugated sheet metal was also frequently used for the walls, these being cast-welded directly into a cast-iron base and upper rim (Fig. 7). Occasionally, to obtain an increased output, the corrugated walls were sprayed with water. The terminals were fitted on the side.

Oil-immersed power station transformers with ratings of 300 to 600 kVA — by 1902 the latter figure had already been raised to 1150 kVA — had vertical limbs and for single-phase applications were of the shell-type with disc winding (Fig. 8), for which Brown Boveri were granted letters patent in 1892. Three-phase transformers had the core limbs in triangular formation (Fig. 9) with Y-shaped or annular yokes, tank of riveted boiler plate, cast-iron bottom, and water cooling on the jacket or copper cooling coil principle. The 1150 kVA transformers mentioned above (Fig. 10) had limbs arranged in the same plane. Their tanks were rectangular with rounded ends, while the cooling coil was built into the flared part at the top. Although the terminals of these transformers were already taken through the cover, on earlier models they had been brought out through the walls of the

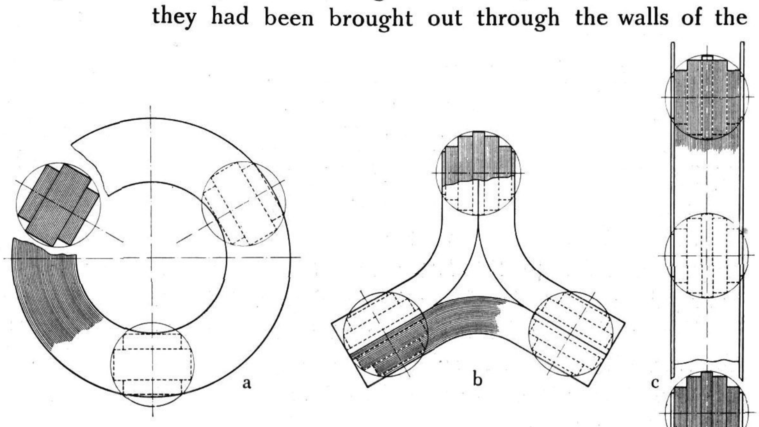


Fig. 4. — The three types of yoke for three-phase transformers.

a. Annular yoke, prior to 1902.
b. Y-shaped yoke, prior to 1902.
c. Straight yoke, from approx. 1902 onwards.

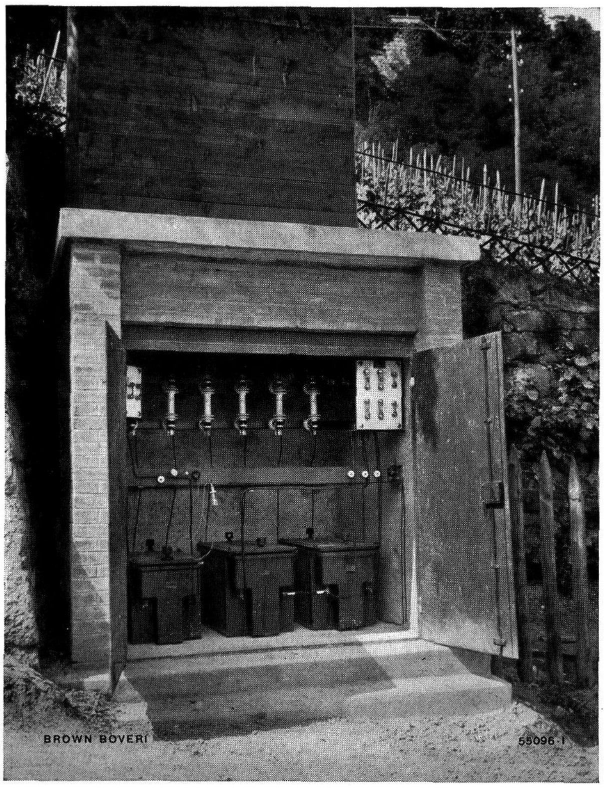


Fig. 5. — Single-phase oil-immersed transformers, horizontal pattern, rating 15 kVA, 2000 V, 40 cycles.
Old substation in Schlossbergweg, Baden. (Demolished about 1920.)

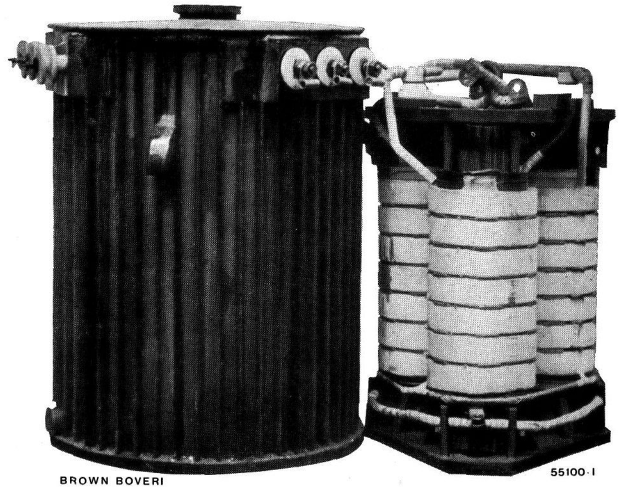


Fig. 6. — Three-phase oil-immersed transformer with round cast-iron tank, cooling ribs on walls, and Y-shaped yoke, rating approx. 60 kVA, 7600 V, 40 cycles, built up till about 1900.

tank. Both high- and low-voltage windings were usually sub-divided into sections, but the low-voltage winding was sometimes also wound in layers. The insulation of the wire and between the high- and low-voltage windings was similar to that of the small transformers.

Dr. Gallusser, who took over the Transformer Department in 1903, objected to the large amount of copper, which was frequently heavier than the

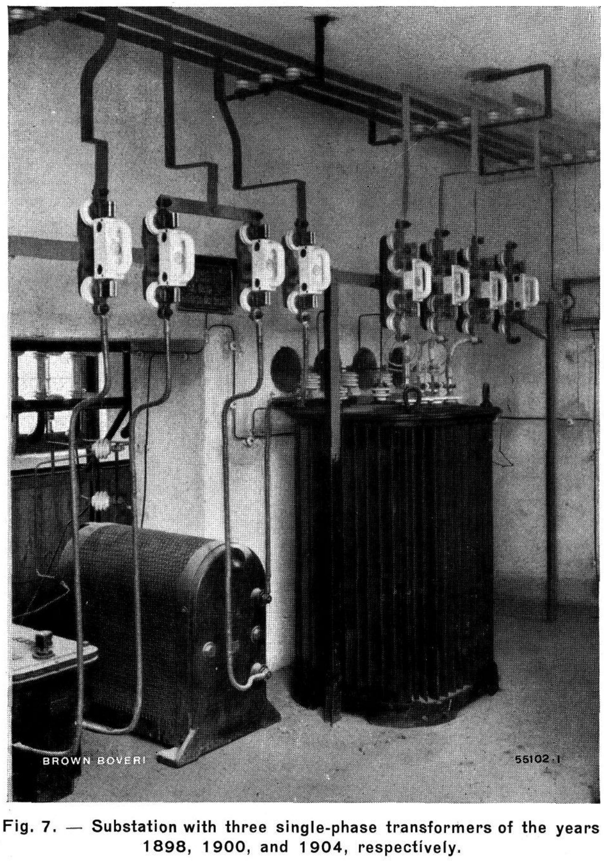


Fig. 7. — Substation with three single-phase transformers of the years 1898, 1900, and 1904, respectively.

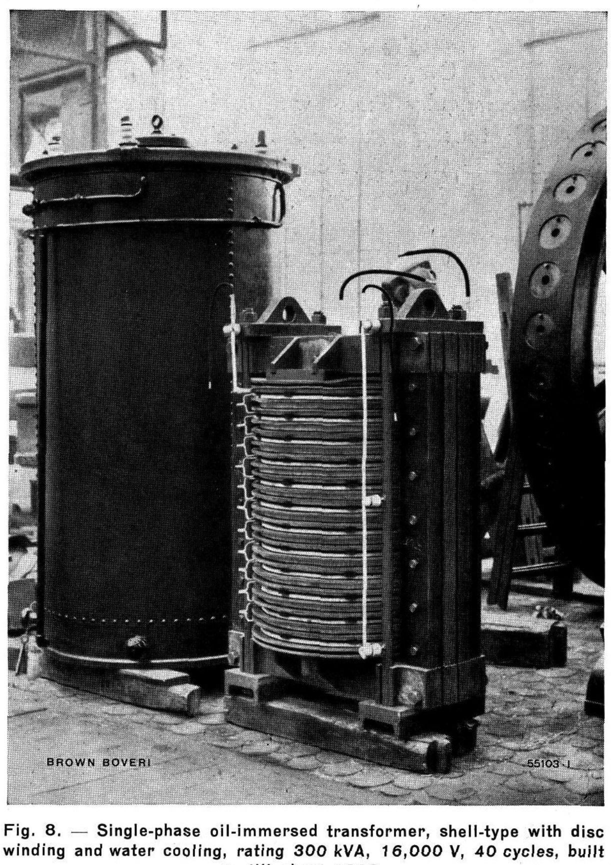


Fig. 8. — Single-phase oil-immersed transformer, shell-type with disc winding and water cooling, rating 300 kVA, 16,000 V, 40 cycles, built up till about 1898.

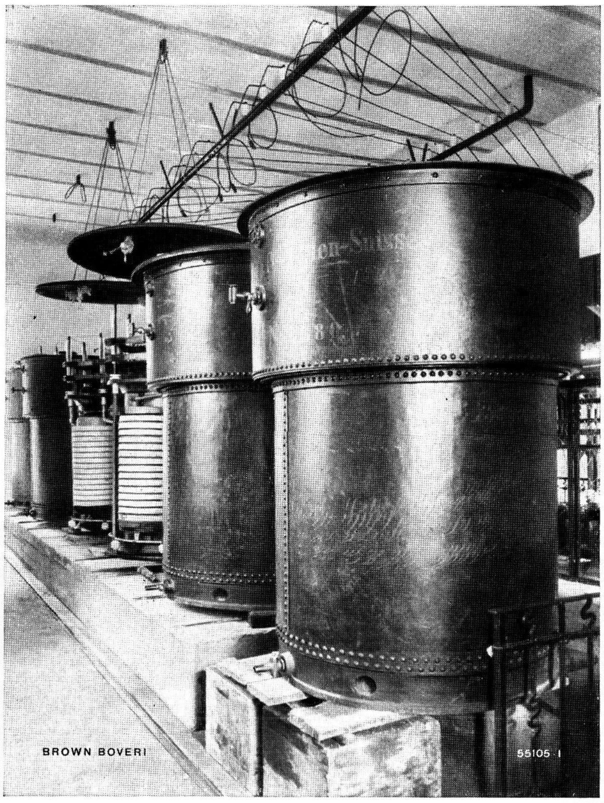


Fig. 9. — Large three-phase oil-immersed transformers rated 630 kVA, 4000/20,000 V, with Y-shaped yokes and water jacket cooling, installed in Como power station in 1902.

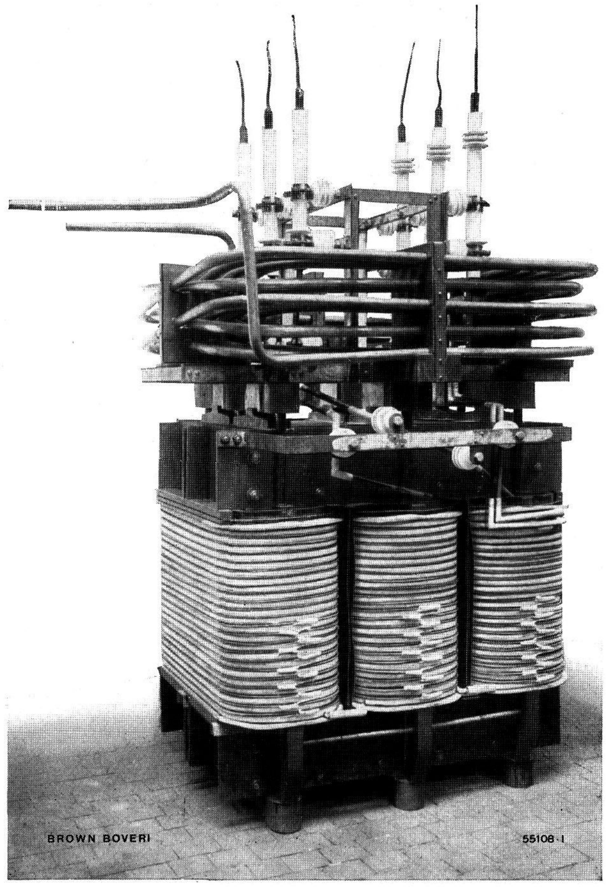


Fig. 11. — First three-phase oil-immersed transformer rated 1000 kVA, 25,000 V, 50 cycles, with rectangular limbs and copper cooling coils, built for Beznau hydraulic power station in 1903.

active iron. On the basis of calculations, he introduced rectangular limbs with a large cross-section (Fig. 11), thus substantially reducing material costs. Dr. Gallusser also replaced the copper cooling coils by cast, ribbed elements similar to those then used for central heating systems.

Already before Dr. Gallusser's time, however, heavy-current shell-type transformers with disc windings, and again under him, two-limbed core-type transformers for carbide furnaces, with current ratings of 6000—10,000 A, were built. At that early date extensive investigations had already led to their leads being transposed (Fig. 12), thus giving a low reactance and practically no additional losses. A bank of such transformers, however, gave far from satisfactory results in other respects under test. The cylindrical, externally arranged, low-voltage winding produced heavy additional losses. Later calculations showed that the edgewise-wound rectangular copper gave excessively large dimensions perpendicular to the leakage field. A heavy resinous oil was used. The induction was gradually increased from 6000—7000 to 9000—10,000 gauss and under Dr. Gallusser even to 12,000 gauss. The loading of the wire had also been increased from

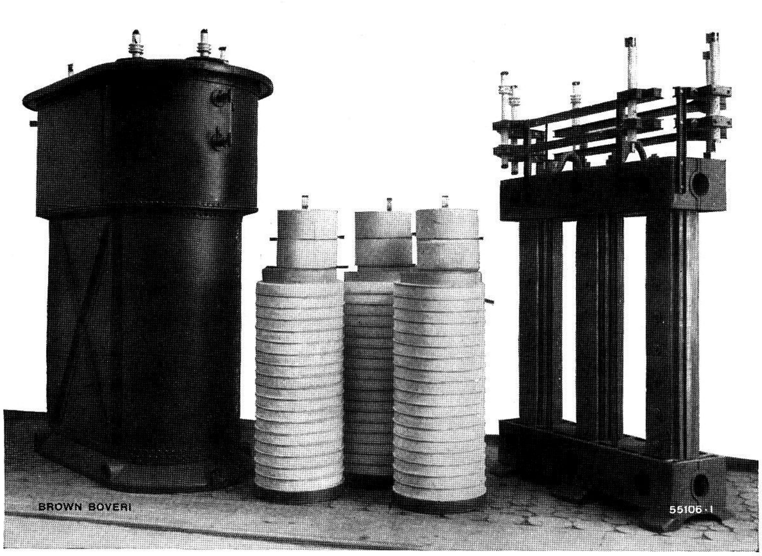


Fig. 10. — Three-phase oil-immersed transformer, rating 1150 kVA, 25,000 V, with straight yokes and copper cooling coils, for Fure et Morge station, built in 1901 and 1902.

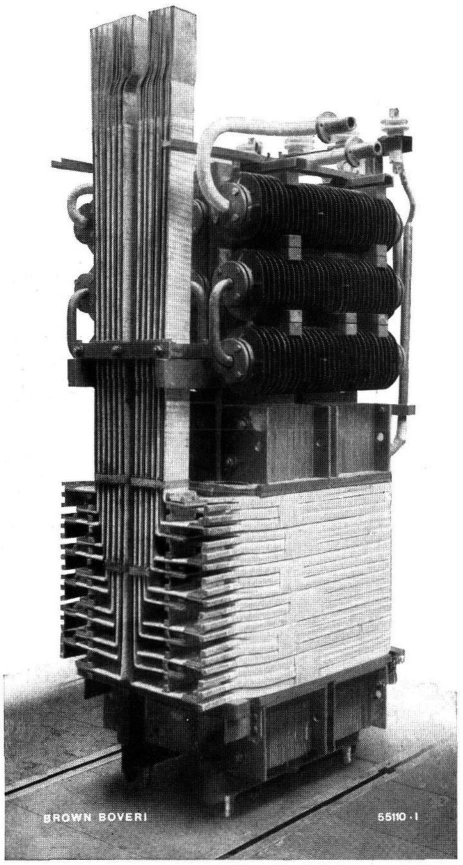


Fig. 12. — Heavy-current single-phase oil-immersed transformer with water cooling, cast-iron ribbed cooling elements, and transposed leads, built for a carbide furnace in 1904.

0·8—1·2 and again under Dr. Gallusser to 1·9—2·1 A/mm^2.

Dr. Gallusser left the firm in 1906 and the author then took over the Transformer Department.

Further developments will now be dealt with as they affected the different transformer components.

II. THE CORE.

As already stated the limbs of the first Brown Boveri transformers were circular. At the beginning they were turned down, later with finely graded laminations, then rectangular. In the case of large power transformers the rectangular form was not retained very long. In 1908/1909 circular limbs were reverted to, for the flat sides of the rectangular windings, with the resulting very low impedance voltages, proved not to be capable of withstanding the enormously increased short-circuit forces involved by the great rise in power station capacity which could be better coped with by the cylindrical form. Only distribution transformers, which were protected to a certain extent by the power transformers of the transmission system, were still constructed with rectangular limbs until about 1923. The laminations employed were so-termed dynamo sheets 0·3 mm thick. These were of as pure an iron as possible and by reason of their low resistance resulted in heavy eddy-current losses. The first alloyed laminations with a high resistance, i. e., with low eddy-current losses and, what is more, low hysteresis losses, came on the market round about 1905. Such sheets had a loss of 1·9—2·0 watts/kg at 10,000 gauss and 50 cycles. It was found impossible, however, to increase the induction to the extent which the losses would otherwise have allowed, inasmuch as the extremely high permeability obtained with low induction decreased to less than that of the old dynamo laminations as the induction rose. In consequence, to avoid excessive no-load currents, the induction could not be forced beyond approximately 12,000 gauss. Since that time improvements in insulation technique and core design have enabled the volume of iron to be greatly reduced, thus permitting the induction

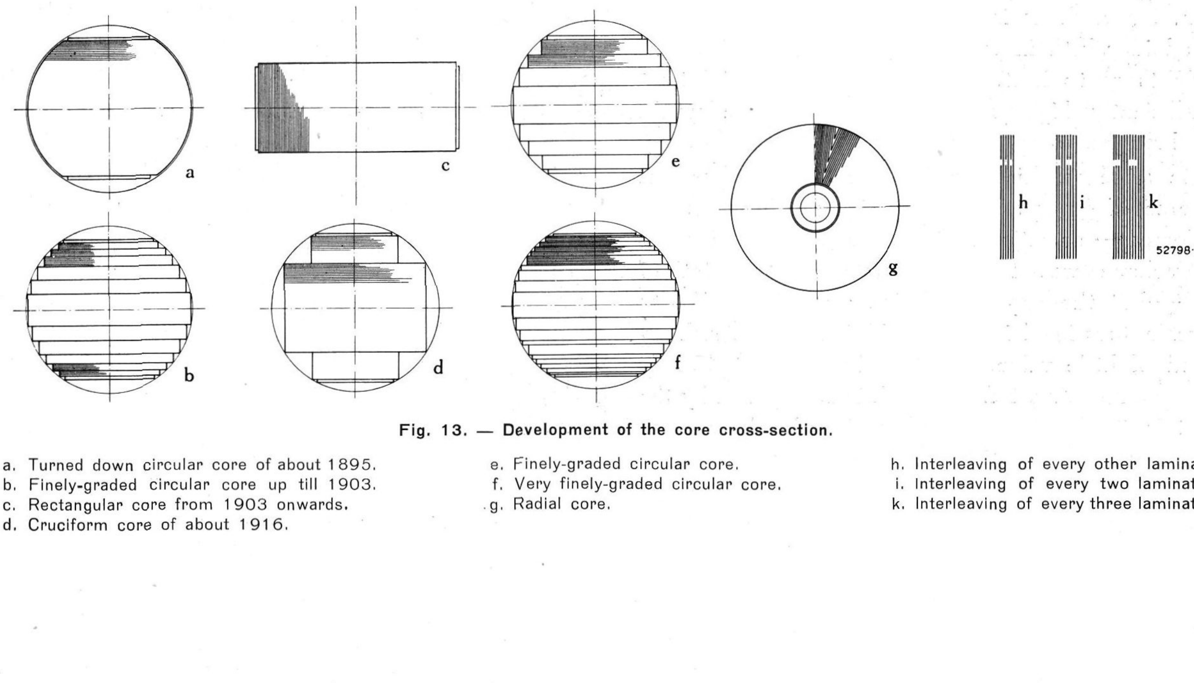


Fig. 13. — Development of the core cross-section.

a. Turned down circular core of about 1895.
b. Finely-graded circular core up till 1903.
c. Rectangular core from 1903 onwards.
d. Cruciform core of about 1916.
e. Finely-graded circular core.
f. Very finely-graded circular core.
g. Radial core.
h. Interleaving of every other lamination.
i. Interleaving of every two laminations.
k. Interleaving of every three laminations.

to be augmented to the present value of about 15,000 gauss without increasing the no-load current.

In order to keep the requisite winding material down to a minimum, cruciform cores, which had been introduced to diminish the cost entailed by different sizes of laminations, were abandoned, and finer and finer graded cores reverted to. These had become possible in the interim through improvements in the original stamping and cutting process (Fig. 13). In this way a practically circular cross-section was achieved, while the amount of scrap was also enormously reduced.

The evenness of the laminations has a great influence on the utilization factor of the limb cross-section. Pressure had to be brought to bear on the rolling mills for a long time, however, before they could be induced to produce smooth, pimple-free sheets. It is unfortunate that much of this progress should have been nullified by the last war and again by the present conflagration, but to obtain laminations at all one was, and is, obliged not to be fastidious.

From the very beginning our laminations were paper insulated. It was only after exhaustive tests that a thin, but strong paper was discovered which would save space and not be perforated by "pimples" in the laminations. If the laminations are not absolutely flat, however, even the best paper will be crushed at certain points, thus leading to additional losses. On one occasion, in the case of a 30,000 kVA transformer, this cause offset the use of the specially employed 1·45 watt sheets to such an extent that as far as losses were concerned we might just as well have employed 1·6 watt sheets.

It was suggested at different times that we should resort to varnish as insulating medium for the laminations. Apart from the fact that the initial outlay for the requisite plant would have been very high, we had no valid reason for departing from paper insulation, inasmuch as in all our long experience it had proved its worth in every respect, even on the score of resistance to heat. As proved by exhaustive tests a sufficiently high-quality varnish insulation would have brought no saving in space.

The scale resulting from the rolling process was a source of great trouble. Not only did it increase the losses — sometimes up to 10 % of the lamination volume was lost from a magnetic point of view — but the paper insulation also flaked off with the scale, thus involving much additional work. Pickling proved of little value, for pickled sheets rusted easily in the stores. Apart from conditions imposed by the war this trouble has now disappeared. Scale once played us a nasty trick. Certain locomotive transformers had been constructed with bare windings. These broke down due to short circuits in the windings. The trouble was first put down to over-voltages, but scale which had flaked off during the interleaving of the laminations proved to be the real cause. A remedy was eventually found by sewing the winding up in a cloth jacket.

The annealing of the sheets after processing was also given much attention. Exhaustive tests, however, proved that very little was to be gained, especially in the case of large cores. Here, too, the high initial outlay, together with that entailed by the necessary varnishing process, was not considered worth while.

Core defects were a source of great anxiety at one time. Thicker washers, larger nuts on the core and yoke clamping bolts, oil ducts perpendicular to the laminations (Fig. 15) which were introduced after extensive tests (Fig. 14), and perhaps more carefully machined butt-joint surfaces finally resulted in the complete elimination of these, however. In the case of large power transformers a contributing factor may also have been the forced cooling of the yokes.

With the increasing of the induction beyond 14,500 gauss losses in the fittings and end laminations became very pronounced, the loss curve rising very steeply from this point onwards. End laminations of non-magnetic material or screening with copper covers formed a remedy here. The burning of bolt insula-

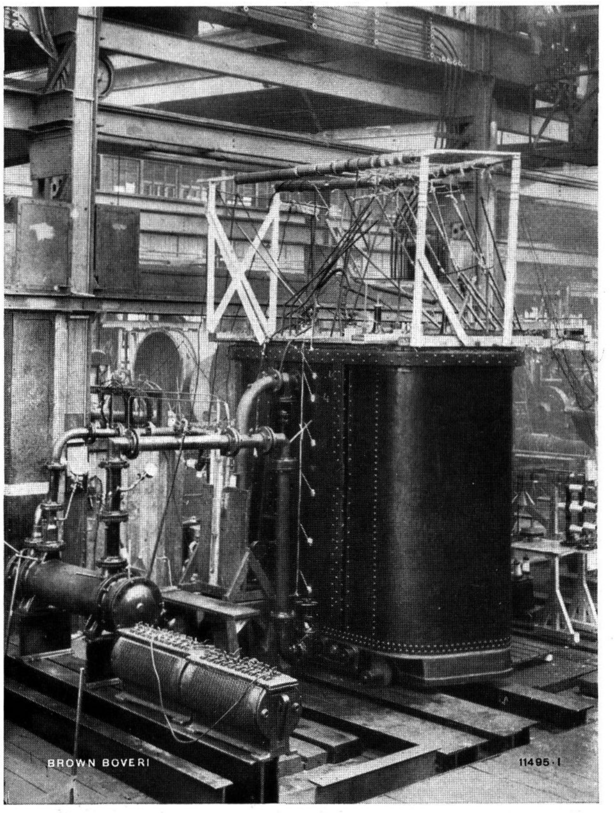


Fig. 14. — Temperature rise tests on a three-phase oil-immersed transformer rated 5200 kVA, 8000/45,000 V, 50 cycles, with forced oil circulation and water cooling carried out in 1920.

tion, however, proved to have another cause, viz., the bridging of the insulation between both the individual laminations and bundles of laminations by burrs resulting from the stamping process. Since that time laminations are usually ground after stamping, thus obviating this potential source of trouble.

At the beginning, on account of the core defects and later from the point of view of magnetizing current, losses, and noise, the question arose as to whether the core and yoke system should be interleaved or provided with butt joints. Extensive tests showed that on the score of noise there was very little difference between the two methods, but that with small core and yoke systems an up to 10 % improvement in magnetizing-current and loss conditions could be achieved, whereas in the case of large transformers very little was to be gained. Thereupon, we began interleaving voltage and distribution transformers (Fig. 16), but retained the butt-joint method for large core and yoke systems. It is strange that interleaving should only gradually have been introduced in Switzerland, for abroad it was widely adopted

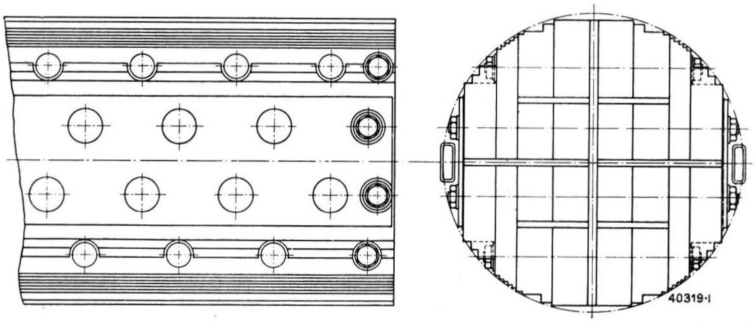


Fig. 15. — Section through core of a large power transformer with oil ducts perpendicular to laminations.

Fig. 16. — View of distribution transformer shop in 1926, showing interleaving operation.

at a relatively early date. When the increased height involved by butt joints does not permit of a transformer being transported completely assembled by rail, however, we now also interleave large transformers.

Many another interesting detail in connection with cores could be recalled, but space will not allow. A new development worthy of special mention, however, is the radially laminated core. Originally provided for a small regulator it now offers enormous possibilities. It enables reactors to be constructed for regulation by variation of the air gap of the core and, moreover, permits transformers of even the highest output and voltages to be built for rail transport.

III. THE WINDING.

Copper, or when lacking as at present aluminium, is the classical material for windings. Zinc, which was tried during the last war, proved to be too brittle and resulted in many winding breakdowns. Windings have undergone very little fundamental change. Single-, double-, multiple-concentric, and disc windings are still employed. The windings are either wound in layers or built up from a large number of separate coils. In the case of aluminium windings in particular, but also with copper windings, special processes have been evolved to avoid soldered joints between the individual coils. In order to ensure a constant voltage, electricity supply undertakings began specifying low impedance voltages instead of the initially high values, and this led to the simple concentric arrangement being abandoned for the double concentric. The growth and interconnection of power stations and the incapacity of circuit-breakers to withstand the high short-circuit currents made a return to the high — and even higher — impedance voltages imperative. For a long time past, values of 10 and even 15 % are standard practice for large power transformers, 3—5 % only being retained for distribution transformers.

As already stated paper tape was used very early as insulation for the high-voltage winding of transformers. This is therefore no innovation. In order to be able to employ the same wires for both transformers and motors the paper insulation was later abandoned for cotton. Poor experience quickly brought about a return to paper, however. As early as 1904, under Dr. Gallusser, cotton braiding was introduced to protect the paper. For considerations of space and also through the shortage of cotton, pure paper insulation has now been reverted to with excellent results. For high voltages, twenty to thirty layers of paper are employed.

Fear of breakdown due to surge voltages led to excessive reinforcement of the insulation of the end turns, the insulation between two single turns having to stand up to the full service voltage (Fig. 17). Investigations at first carried out with ultra-violet-rayed sphere gaps in 1922/23, later with cathode-ray oscillographs, enabled the insulation to be reduced to the values encountered to-day, i. e., about 40 % of the service voltage for the main insulation and 60 % for the end coils. These degrees of insulation have proved satisfactory over a long period of years.

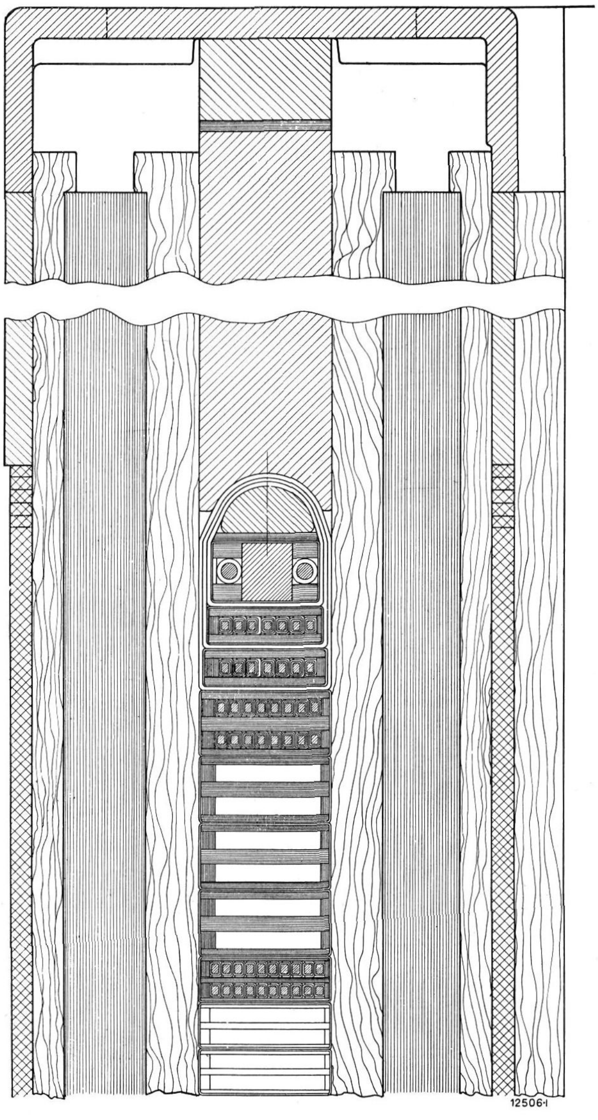


Fig. 17. — Section through winding of a large power transformer with heavily reinforced end turn insulation, constructed about 1912.

At first the individual coils were stacked one on top of another, being separated by presspan rings and bound together with cotton tape. The increased current density of 3 A/mm^2 and over rendered improved cooling imperative. The cotton braiding was dispensed with and the coils supported on distance pieces around 50 % of their periphery. On the advent of higher impedance voltages this was gradually reduced to 25 %, thus leaving virtually 75 % of the coil free for cooling purposes. In the case of large power transformers great care is now taken that at least one side of each wire is directly in contact with the oil.

A question which always demanded great attention was that of the additional winding losses caused by skin effect. At the beginning these losses could not be calculated, but a graphical method of mastering the problem was soon forthcoming and technical literature quickly brought the necessary formulæ. For many years past, therefore, it has been possible to keep these losses low. In order to be able to employ wires of small cross-section for high currents, many individual coils had to be connected in parallel, an arrangement which is still the only one possible in many cases to-day. Coils are now also wound with many parallel wires superposed (Fig. 18). These are transposed from layer to layer, however, as in the Rœbel bar winding.

Although it proved possible to determine winding losses at a relatively early date the temperature rise necessitated countless tests. The thermal currents in the oil are extremely involved and notwithstanding the numerous tests new phenomena are continually cropping up which cannot always be satisfactorily explained.

The heavily increased current forces attendant on the higher short-circuit powers led to winding trouble, chiefly in the end supports. Round about 1908, therefore, we introduced sprung supports (Fig. 19) which completely remedied this defect. The high impedance voltages introduced some years ago to safeguard the installation, however, also protect the transformers, and this fact, coupled with the improved pre-treatment of the windings, now renders simple, but good, springless supports again possible.

The continually rising high voltages — 30,000 V in 1902, now 220,000 or even 400,000 V — made greater and greater demands on the insulation between the high and low-voltage windings. Moderately increased cylinder thicknesses and greatly lengthened distances between the windings and the ends of the cylinders proved

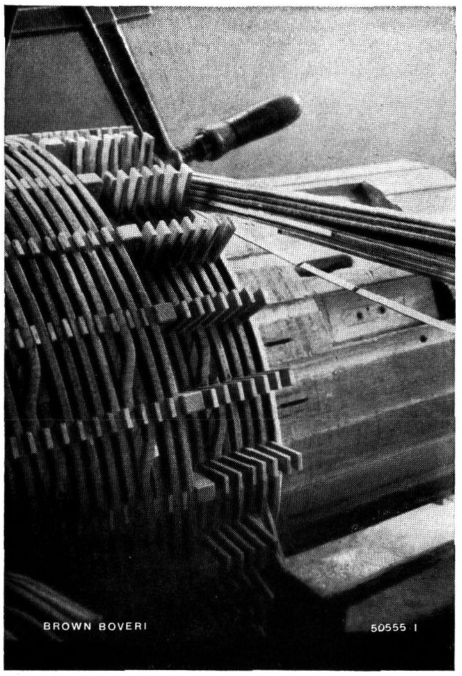
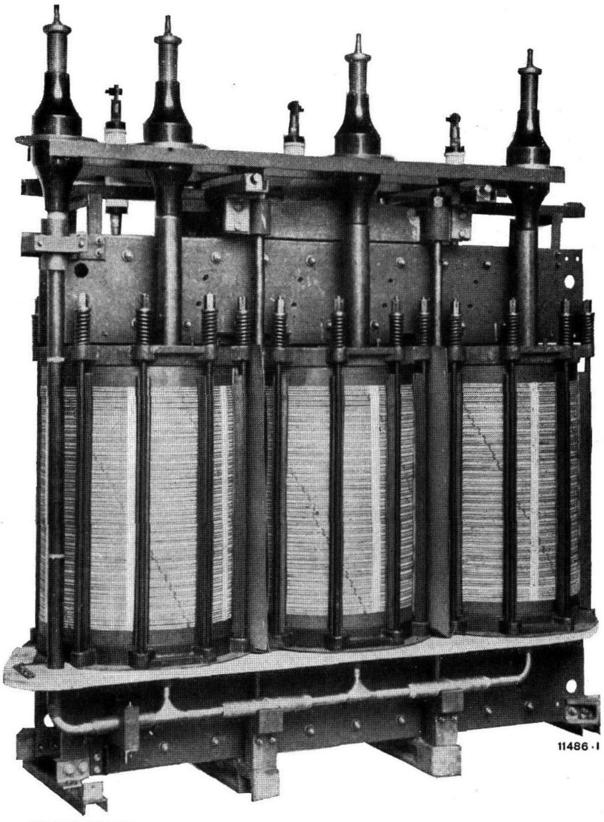


Fig. 18. — Cylindrical winding, with a large number of parallel wires superposed, in machine.



BROWN BOVERI

Fig. 19. — Core and yoke system with winding held by spring-loaded clamping rings, for a three-phase oil-immersed transformer rated 12,000 kVA, 10/60 kV, 50 cycles, with forced oil circulation and water cooling.

Bakdura high-voltage bushings.

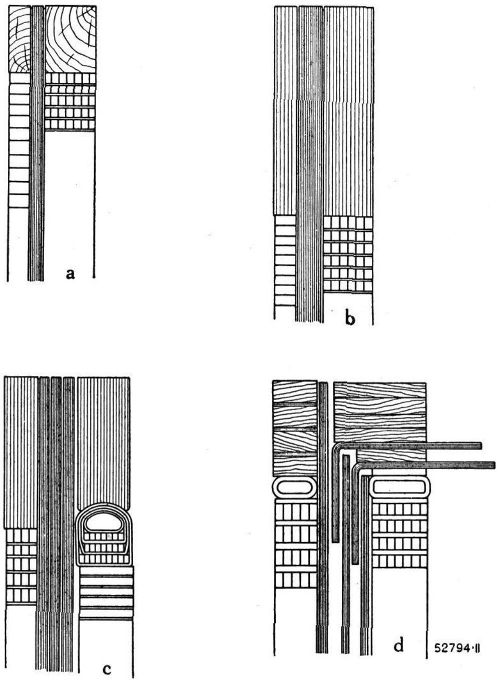


Fig. 20. — End spacing arrangement of windings.

a. Original arrangement up till 1903.
b. Unsatisfactory arrangement for high voltages, about 1905.
c. Improved arrangement for high voltages from about 1909 onwards.
d. Shielded arrangement of about 1927.

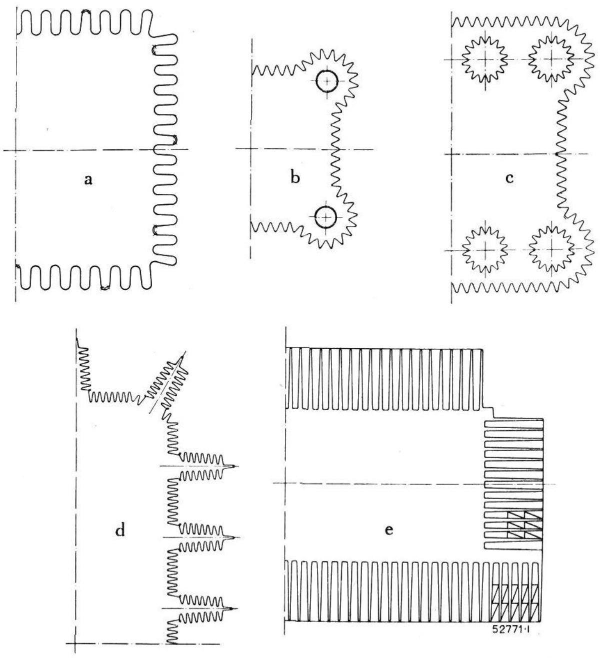


Fig. 22. — Oil tank patterns.

a. Original shape of corrugations up till about 1902.
b. Shape of corrugations and smooth cooling tubes up till 1908.
c. Shape of corrugations and corrugated cooling tubes up till about 1908.
d. Tank with corrugated radiators 1909.
e. Tank with rectangular corrugations and in certain cases corrugated corners. Present form of corrugations.

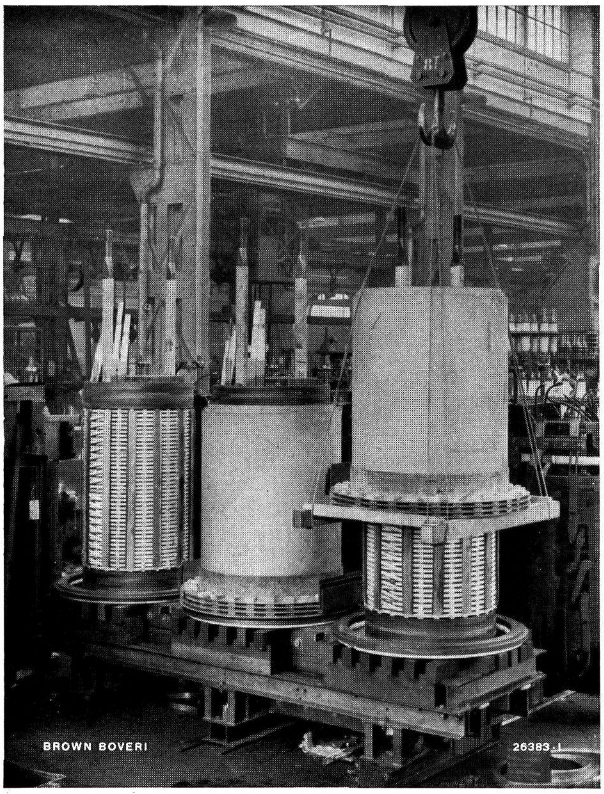


Fig. 21. — Assembly of shielded winding of three-phase transformer rated 20,000 kVA, 8/150 kV, 50 cycles.

not to be sufficient (Fig. 20). About 1908 the rounded insulating end protecting ring was introduced. From 1903 onwards the cylinders were improved by making them of bonded paper treated in special machines, first with cherry-resin varnish, then with synthetic resin varnish. As with many other insulating materials, however, the synthetic resin, which was quite the vogue at the time, resulted in very many failures until its limits were recognized.

Finally the shielded cylinder construction was introduced (Fig. 21). This has layers of insulation perpendicular to the lines of the field at the ends of the windings. With this arrangement it was possible to reduce the distance between the high- and low-voltage windings and inasmuch as the weight of the core was reduced to retain the same impedance voltage, much lighter transformers were the result. The small distances possible in cable-making, however, were far from achieved. Quite new features had to be introduced before the distance between the two windings could be further diminished and a corresponding reduction in core weight attained, thus again considerably decreasing the overall weight of the transformers. Two examples will serve to illustrate the progress achieved:

1926 25,000 kVA transformer with oil 87 tons.
1940 30,000 kVA transformer with oil 64 tons.

It is due to this enormous reduction in weight, combined with the corresponding decrease in bulk, which has enabled very large extra-high-voltage power transformers to be designed for transport by rail practically completely assembled and dried out, thus eliminating the drawback of re-erection at destination.

Further details of windings are beyond the scope of this article, although much must be left unsaid that would doubtless prove of interest.

IV. TANKS AND COOLING APPLIANCES.

Important components of oil-immersed transformers are the tank and cooling appliances. In order to conduct away the heat generated large cooling surfaces or forced cooling are necessary. Many designs were tried (Fig. 22). Corrugated tanks, however, became standard for small transformers up to about 3000 kVA (Fig. 23), although the corrugations themselves differed considerably in shape. Above the foregoing rating smooth tanks of commercial boiler plate 4—10 mm thick are employed, these being equipped with tubular radiators for natural cooling (Fig. 24).

As in the case of the corrugated tank, radiators of various forms (Fig. 25) were tried out during the course of extensive tests before the two present forms were decided upon, i. e., tubes of small diameter for natural cooling and of large diameter for forced cooling. The construction of corrugated tanks and radiators was given a big impetus by the introduction of the autogenous welding process in 1908. Since approximately 1922 boiler-plate tanks are also electrically welded, thus considerably simplifying their manufacture. The heavy cast base has been replaced by a bottom of boiler-plate with an underframe of rolled section iron, thus eliminating the trouble due to leaky rivets.

Large power transformers (in 1900 transformers of 300—600 kVA) were water-cooled, either on the jacket or copper cooling coil principle. Much trouble was unexpectedly encountered with the latter method due to *corrosion*. Then followed cast ribbed elements (Fig. 26), later wrought-iron elements (Fig. 27), and

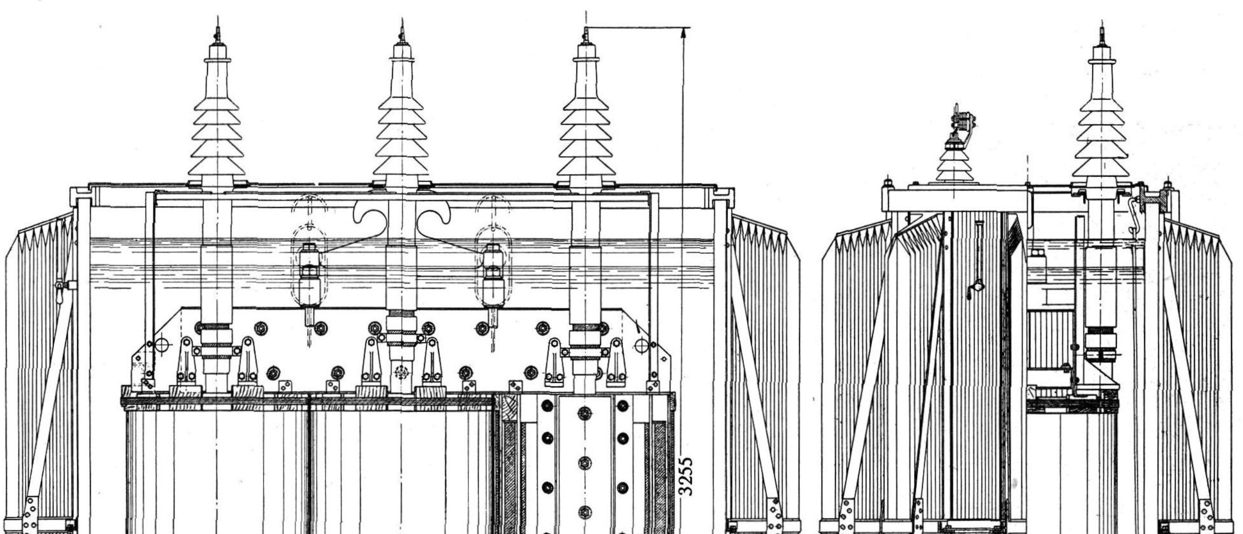


Fig. 23. — First three-phase 2000 kVA, 25,000/8000 V, 50-cycle, oil-immersed transformer with natural cooling, corrugated tank, and corrugated radiators supported by iron framework, supplied in 1909.

Fig. 24. — Single-phase outdoor-type transformer rated 3000 kVA, 60,000/15,000 V, 16 2/3 cycles, with tubular radiators for natural cooling, in a Swiss Federal Railways substation.

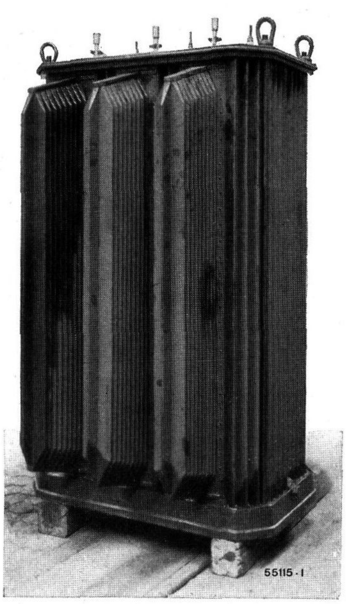


Fig. 25. — First corrugated tank with radiators and riveted and soldered seams, built in 1906.

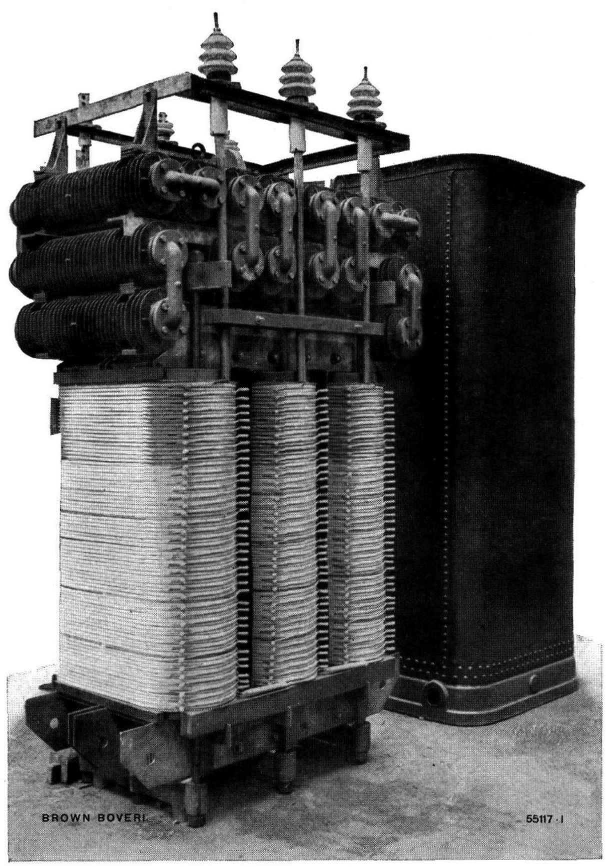


Fig. 26. — Three-phase oil-immersed transformer rated 3200 kVA, 8000/25,000 V, 50 cycles, with cast-iron ribbed cooling elements. 1905.

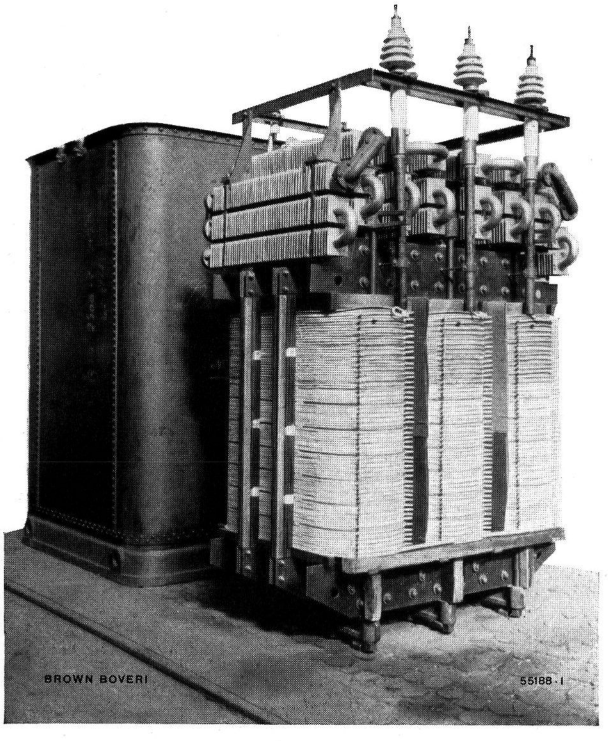


Fig. 27. — Three-phase oil-immersed transformer rated 4600 kVA, 8000/25,000 V, 50 cycles, with wrought-iron ribbed cooling elements, from 1905 onwards.

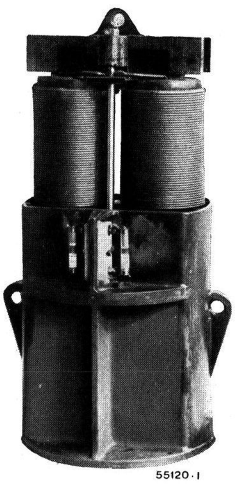


Fig. 28. — First single-phase outdoor-type oil-immersed transformer, for the Burgdorf-Thun Railway.

Year of construction 1898.

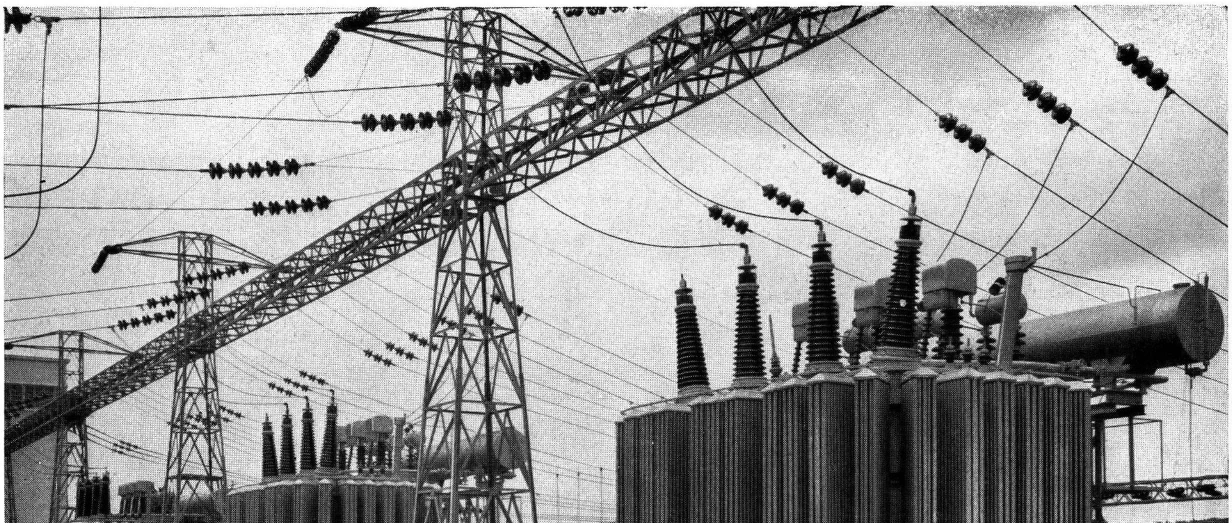


Fig. 29. — Large outdoor-type three-phase transformer with three windings, regulating gear, and forced air-cooled radiators, rating 25,000 kVA, 150/54 $\pm$ 4 $\times$ 1·25/8 kV, 50 cycles.

ultimately, round about 1908, external cooling with forced oil circulation. For a period transformers with natural or forced air cooling were given preference: water involved expense and there was always the risk of freezing. With the help of radiators no difficulty was experienced in building transformers up to 30,000 kVA and over without water cooling. Just recently, transformers with water cooling and oil circulation are again preferred by certain undertakings, due to the high overload capacity of such transformers, which is even higher than with forced air cooling.

In the case of outdoor transformers in particular, repainting is necessary from time to time. With welded-in radiators this work is very awkward. For this reason and to facilitate transport, the radiators had to be made detachable. The cast-iron cocks projected too far out to enable this to be done, so that wrought-iron cocks had to be evolved. Many thousands of these have proved extremely satisfactory in service.

To conclude this subject, which could be dealt with much more fully, a few remarks on outdoor transformers would not be out of place. Our first outdoor transformers with oil insulation (Fig. 28) were built for the Burgdorf-Thun Railway round about 1898. Then followed shortly afterwards distribution transformers and finally from 1918—20 onwards large power transformers (Fig. 29). The question of condensation was continually raised. All of our tests in this connection, however, showed that no trouble arising from this phenomenon was to be feared in outdoor transformers. In point of fact, all defects put down to condensation, or even to over-voltages, were positively traced to ingress of rain at leaky cemented joints, welding seams, bolt-holes, etc. Typical examples could be quoted here. The oil conservator was originally introduced to obviate condensation and it was only as a result of operating experience that its more important property, i. e., that of preventing decomposition of the oil, was recognized.

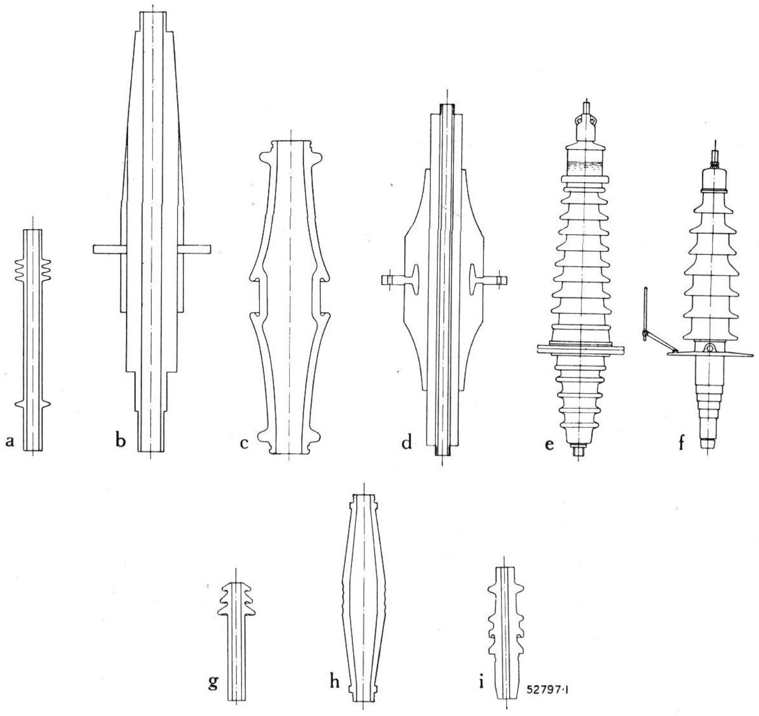


Fig. 30. — Bushings.

a. Porcelain tube, original bushing for high voltages of 30 kV, fitted up till about 1902.
b. Bonded paper bushings for 60 kV.
c. Porcelain bushing for oil or compound filling, 60—80 kV.
d. Bakdura bushing up to 110 kV.
e. Oil-filled porcelain bushing for 220 kV and over.
f. Condenser-type porcelain bushing up to 220 kV.
g. Original porcelain insulator for medium and low voltages, 16 kV.
h. Plain compound-filled porcelain bushing for medium voltages, 24 kV.
i. New porcelain bushing for medium voltages up to 24 kV.

V. BUSHINGS.

A transformer component which has always given food for thought is the bushing (Fig. 30). Initially fitted on the side of the tank, it was frequently taken through the cover after 1902, while from 1905 onwards this arrangement became standard practice.

The first high-voltage bushings were really primitive: a porcelain tube with collars top and bottom and a through-going copper wire as conductor. With increasing voltage the bushing problem became more and more acute. Multiple-tube porcelain bushings were introduced. As early as 1910 designs were evolved on the basis of the distribution of the electric field, although all of the conclusions drawn from this were not put into effect; the dimensions appeared to be too large. Nevertheless, from these investigations resulted the "Bakdura" bushings, which were excellent from the standpoint of form and dimensions, but did not prove satisfactory in service, due to cracking of the synthetic resin (with filling agent) from which they were made. The compound-filled porcelain bushings behaved, if anything, even worse. The compound overflowed, dirtying the porcelain or even causing it to split, due to incorrect selection of the melting point or the formation of internal hot spots by reason of air bubbles and glow discharges.

Finally, came the large oil-filled porcelain bushings, first without, then with condenser elements, and the pure bonded-paper bushing on the condenser principle. To-day, both types are employed, for both have proved highly satisfactory on the whole. Medium- and low-voltage bushings also underwent changes from time to time, first cemented, then clamped, with continual form modifications, a design has now been evolved which may safely be claimed to give entire satisfaction.

VI. OILS AND THEIR SUBSTITUTES.

The medium serving both to transfer the heat from the active material to the ambient air and as insulation is of extreme importance for the transformer. It is usually mineral oil or, more recently, so-termed non-inflammable synthetic oil, or even compressed air or gas.

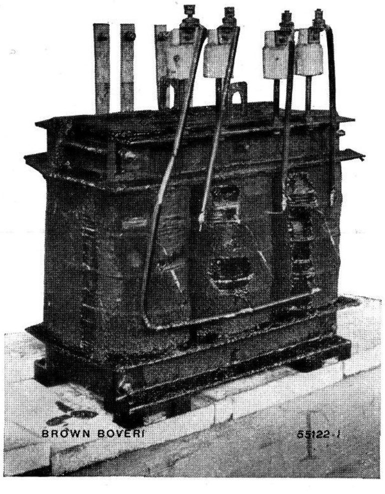


Fig. 31. — Three-phase oil-immersed transformer showing deposit of poor-quality mineral oil.

At the beginning, Brown Boveri employed resinous oil which contained, apart from the oil proper, a large percentage of colophony. Its viscosity was too low for efficient cooling and in service it became thicker and thicker. The mineral oil offered in its stead, however, at first failed completely. It not only formed a deposit (Fig. 31) which rendered effective cooling impossible, but it impaired the paper and cotton insulation. Each new kind of oil had to be tested. The method employed was to heat the oil in a copper vessel at a thermostatically controlled temperature of 110 °C for 700 hours. As it proved later a better metal could not have been selected for the vessel, inasmuch as copper acts as catalyser in the decomposition process. It was also quickly found that it is the oxygen in the air which causes decomposition of the oil. Sludge tests were introduced in England and Germany, but neither the English nor the German method satisfied us. We retained our heating test which had been still further improved in the interim. In this way we gradually obtained high-quality oils. Unfortunately the first World War nullified much of this progress and the present conflict is again having the same effect.

As already stated, the oil conservator was employed to prevent decomposition of the oil. Our experience has shown, however, that it is possible to dispense with this accessory and all its inherent complications if good oil is used.

In recent years attempts have been made to replace natural oils by synthetic products, so-termed non-inflammable oils, chlorinated hydrocarbons (e. g. Clophen, Diélectrol, etc.), which, however, are only really non-inflammable under certain conditions. They are much more expensive than mineral oils and have not uniformly good properties, so cannot be used as a substitute for mineral oil in every case.

Just recently, air or gas under pressure has also been used, although, on account of the high air pressures, solely for small power transformers, voltage transformers (chiefly for use with oil-less switchgear) etc. For large transformers the air receivers would at present be too big and the rate of heat dissipation hardly sufficient.

VII. DRYING OF INSULATING MATERIALS.

It was already known from experience with the electrostatic generator and the induction coil that great care must be paid to the drying of all organic insulating material. At an early date it was also found that such materials, even when dried to the degree of humidity of air, still contained up to 10 % of water. We were therefore not surprised to extract over 100 litres of water from a large power transformer on one

Fig. 32. — Transport of a large three-phase oil-immersed transformer in 1908.

occasion. Inasmuch as one single drop of water greatly impairs the insulation of a transformer, however, due attention had always to be paid to its drying. Originally the transformers were heated over an open fire or by electrical resistances, but it was soon recognized that the safest method was in a vacuum pan. Only on the erection site had the old method to be retained until such time as the oil tanks could be made vacuum-tight. More recently drying has been carried out in stoves with forced air circulation, a system which only has to be supplemented by drying under vacuum in the case of very high voltages.

The oil also contains moisture and must be dried out. At first it was found difficult to get oil to stand up to 50 kV in the standard test vessel with electrodes 5 mm apart, but nowadays, due to better drying and cleaning methods, values of 80 — 100 kV are attained. In addition to the drying of the oil attention is now also paid to its deaeration. This only serves to eliminate the last traces of air with a view to obviating the formation of sources of glow discharge, a process practised in cable manufacture for many years past.

VIII. TRANSPORT PROBLEMS.

The time is not very remote when large power transformers still had to be dismantled for transport. The re-assembly and re-drying processes not only did the transformers no good, but time was lost in getting them into service.

Due to the decrease in bulk for a given output and by utilizing railway clearances to the full it has been possible for some years past to construct even the largest transformers for dispatch practically fully assembled. Progress was continuously made: when the weight was a drawback unimportant parts were detached and the transformer filled with dry air or gas instead of oil for transport. At destination, therefore, very few components now have to be refitted, while the re-drying process can also be dispensed with if due care is taken when substituting the oil for the dry air filling.

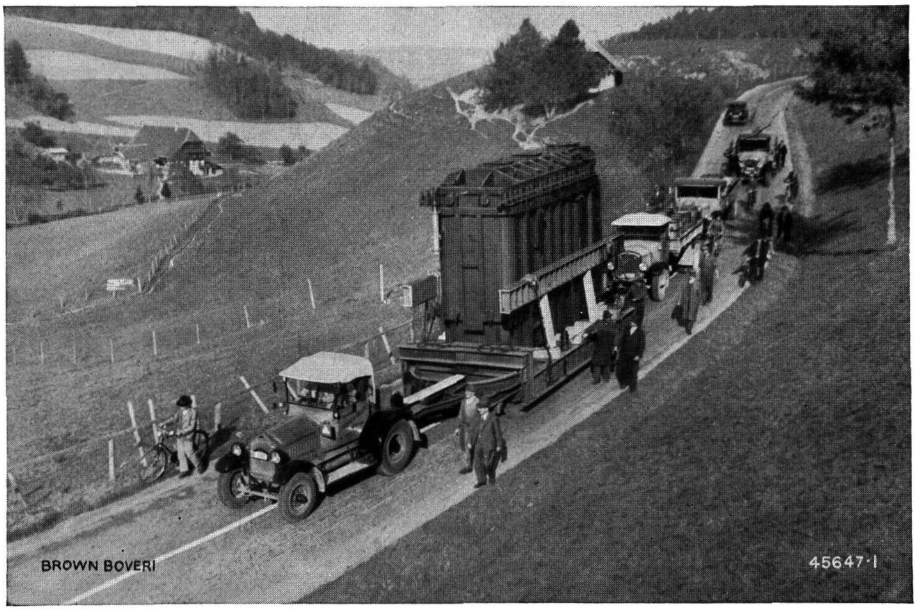


Fig. 33. — Transport of a large three-phase oil-immersed transformer with regulating gear rated 20,000 kVA, 167—120/49·5—33 kV, 50 cycles, in 1937.

In many cases transformers have to be conveyed to their erection site by road from the receiving railway station (Figs. 32 and 33). Special road vehicles had to be built to carry loads of up to 100 tons. Frequently, too, objections of civil engineers had to be overcome before certain roads and bridges could be traversed. Figs. 34 and 35 show that the transformers did not always arrive at destination without incident.

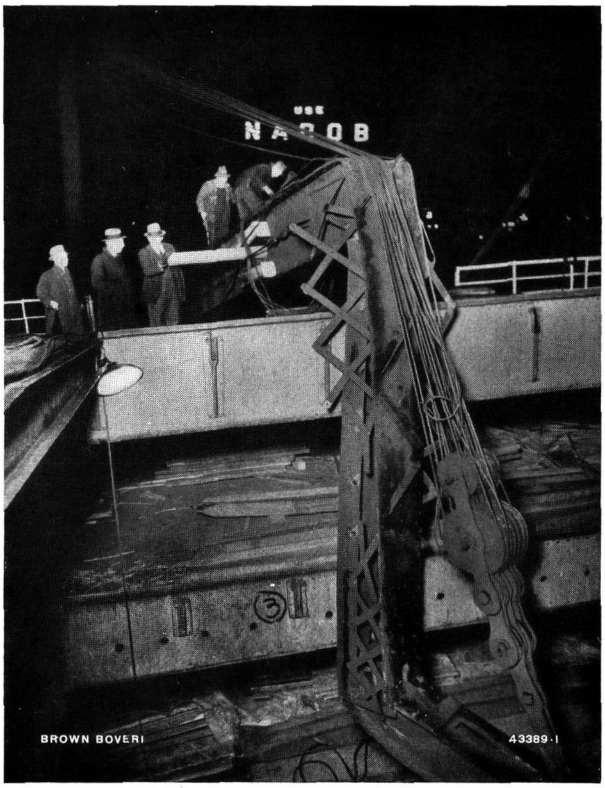
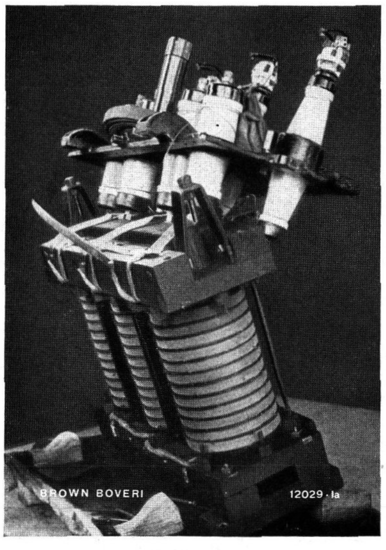


Fig. 34. — This crane broke during the unloading of a large mutator transformer from the ship in Canada. Through the fall the transformer was so badly damaged that a new one had to be supplied.

IX. THE DEVELOPMENT OF TRANSFORMER THEORY.

Very little has so far been said of the development of transformer theory. In point of fact this can be traced throughout technical literature, although much could be added from our own experience. The scope of this article, however, will only allow of our touching on two noteworthy points. Firstly, as early as 1915 our method of calculating voltage transformers was so carefully elaborated that calculations gave more accurate results than could subsequently be proved by test. For instance, our voltage transformers manufactured on mass production lines were more accurate than the standard transformer, supplied by a well-known maker, serving for calibration purposes. Secondly, for the very first order covering a multiple-winding transformer we elaborated on a sound theoretical basis the necessary data for the calculation of the impedance voltages, a field to which much attention was paid later in technical literature.



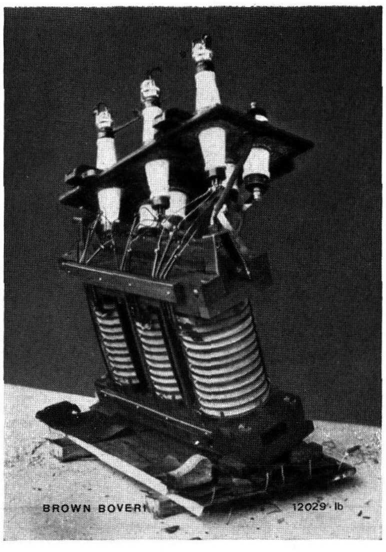


Fig. 35. — Small three-phase oil-immersed transformers upon arrival in Asia.

X. STATISTICAL.

Much of interest concerning the development of Brown Boveri transformers could be given in the form of curves and tables, but here, too, one single figure must suffice. Up to the celebration of the fiftieth anniversary of the foundation of the firm 80,000 transformers (including voltage, but not current transformers) went out of the Baden works alone.

(MS 915) *J. Kübler. (E.G.W.)*

THE EXTINCTION OF THE ARC IN SINGLE- AND MULTIPLE-BREAK AIR-BLAST HIGH-SPEED CIRCUIT-BREAKERS.

Decimal Index 621.316.57.064.45

Maximum rupturing reliability and breaking times are achieved with air-blast high-speed circuit-breakers when the opening operation is sub-divided into distinct arcing and disconnecting contact movements. By employing a potential-controlled multiple break all breaks function in their most favourable capacity range. This arrangement gives the arcing chambers a high electric strength and permits circuit breakers to be tested up to the full guaranteed capacity.

THE two chief demands placed on modern high-voltage circuit-breakers are short breaking time and maximum switching reliability from both the electrical and mechanical point of view. These two requirements can be met in an ideal manner with air-blast hollow contacts, although the basic design of the circuit-breakers must be selected so as to exploit all of the advantages of air-blast extinction to the full.

One of the most striking features of this method of arc extinction is that the capacity of the hollow contacts not only depends on the nozzle diameter and the air pressure, but also to a very high degree on the travel of the contacts. The capacity, however, does not rise uniformly with increasing contact travel, but approaches an optimum value and then diminishes

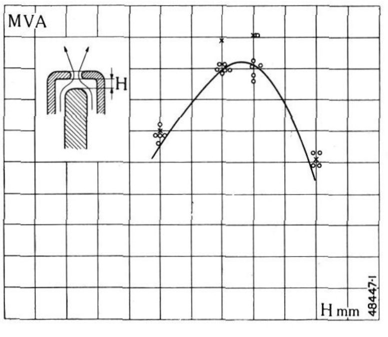


Fig. 1. — Rupturing capacity of a hollow contact in relation to the gap.

o. Satisfactory rupturing operations.
x. Operation with persisting arc.

Maximum rupturing reliability is achieved through the most favourable extinction gap being maintained under all working conditions.

rapidly if the distance between the contacts becomes still greater (Fig. 1). This most favourable extinction distance is relatively small and does not give a sufficiently high electric strength between the circuit-breaker contacts when the stream of air ceases. With certain designs of circuit-breakers, therefore, the travel of the arcing contacts must be made substantially greater than is actually necessary and desirable

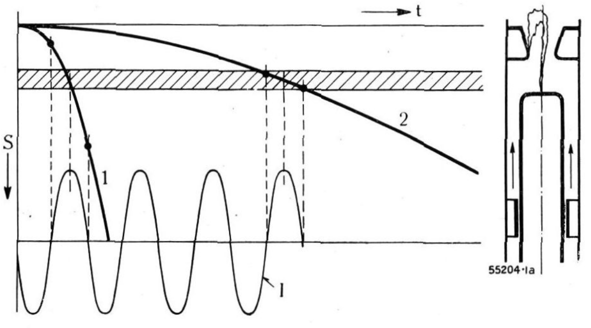


Fig. 2a. — *Curve 1 shows that when the arcing contact moves too quickly it is already beyond the arc extinction zone at the passage of the current through zero, while when moving slowly (curve 2) favourable extinction conditions obtain at the moment of passage of the current through zero, but the arcing time becomes long.*

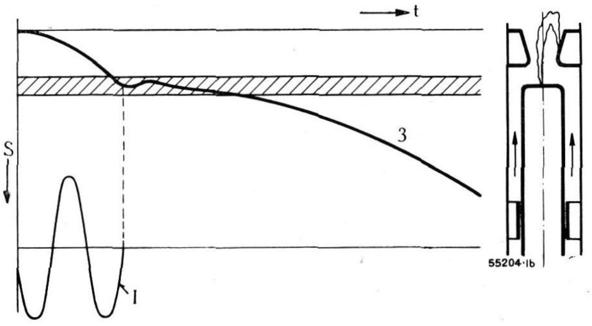


Fig. 2b. — This curve corresponds to a circuit-breaker with very irregular contact movement; the above-mentioned drawbacks are avoided, but design difficulties are encountered.

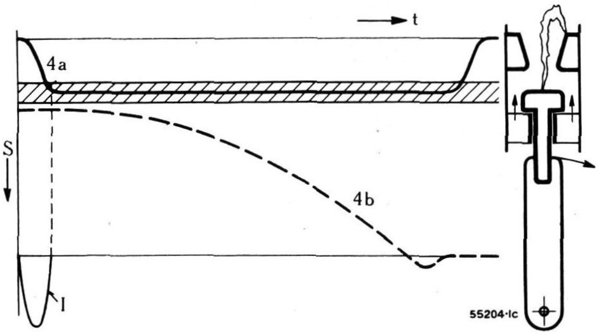


Fig. 2c. — This curve shows how in the case of the Brown Boveri air-blast high-speed circuit-breaker the separation of the movement of the arcing contact (curve 4 a) from that of the disconnecting contact (curve 4 b) ensures both contacts operating under optimum conditions.

Fig. 2. — Influence of movement of arcing contact on arc extinction capacity and arcing time.

Hatched section. Most favourable arc extinction zone.
t. Time. S. Contact travel. I. Current.

for the extinction of the arc. In consequence, a continuous opening movement of the contacts as is usual with other types of circuit-breakers is quite unsuitable here. With high contact speeds the arc extinction zone is traversed so rapidly that, given certain conditions, it has already been passed when the most suitable moment for extinction, i. e., the passage of the current through zero, is attained (Fig. 2 a, curve 1). On the other hand, low speeds may lead to undesirably long arcing times (Fig. 2 a, curve 2).

An improvement can be achieved by grading the rupturing characteristic (Fig. 2 b, curve 3). The contact is moved fairly rapidly into the extinction zone and made to remain there for several half-cycles by means of special braking devices. These have to satisfy very stringent requirements, the chief of which being extremely accurate operation under all temperature conditions likely to be encountered in service.

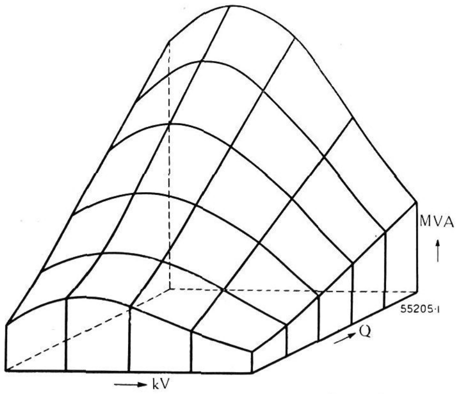


Fig. 3. — Admissible rupturing capacity of air-blast hollow contact in relation to nozzle cross-section at various service voltages.

By employing potential-controlled multiple breaks all contacts operate to optimum capacity in the voltage range. Such circuit-breakers thus have small dimensions and minimum air consumption.

A much more reliable arrangement has been successfully applied to Brown Boveri air-blast high-speed circuit-breakers for some years past. The rupturing operation is completed in two separate movements, that of the arcing contacts and that of the disconnecting contacts (Fig. 2 c). The travel of the arcing contacts is positively limited so that the most favourable extinction zone is always definitely utilized. The opened disconnecting contact, however, forms a reliable, visible, and creep-free insulating gap with the circuit-breaker open. The biggest advantage of the arrangement described is that the mass of the arcing contacts to be moved is very small. In consequence, the extinction zone is reached in the shortest possible time, i. e., the arcing time is extremely short. The principle of sub-dividing the rupturing operation into two distinct movements has proved particularly important in the case of extra-high-voltage circuit-breakers. By employing a potential-controlled multiple break the mass and travel of the individual arcing contacts has been still further reduced. This ensures all of the advantages of air-blast extinction being fully exploited even at the highest service voltages.

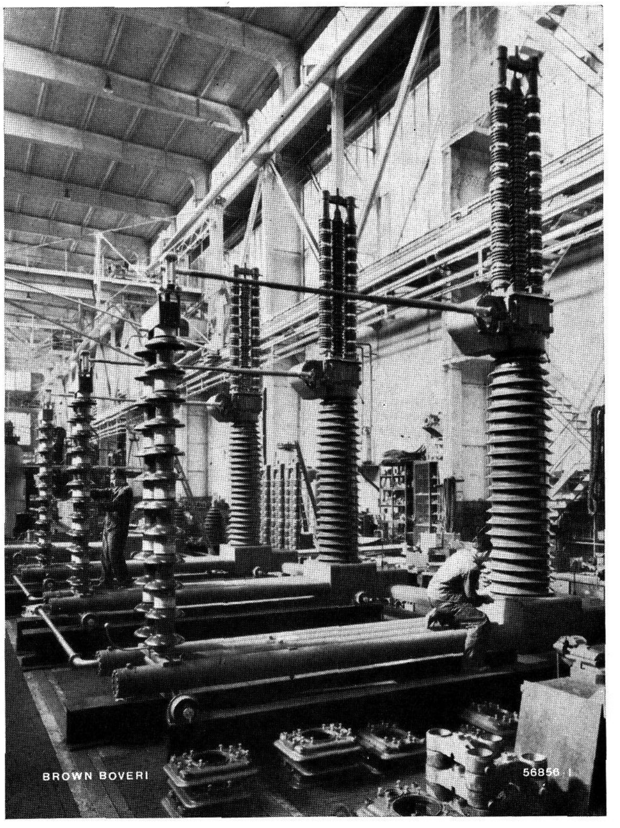


Fig. 4. — Air-blast high-speed circuit-breaker with multiple break for 300 kV maximum service voltage. Rupturing capacity 2500 MVA.

The multiple break with potential control permits the arcing chambers to be tested to the full guaranteed capacity and, moreover, gives them a high electric strength.

From thousands of rupturing tests the extinction capacity of air-blast hollow contacts is now known over a wide range (Fig. 3). With increasing contact cross-section the rupturing capacity rises comparatively rapidly at all service voltages. An interesting fact disclosed by the tests is that the efficiency of such contacts is greatest in a quite definite voltage range. This property can also be infallibly proved theoretically. In order, therefore, to obtain circuit-breakers utilizing the arc extinguishing air as efficiently as possible, several breaks, all functioning in the above-mentioned most favourable voltage range, must be connected in series. The introduction of potential-controlled multiple breaks has enabled this to be achieved in a reliable manner for the highest service voltages. The described arc extinction principle results in minimum air consumption and maximum rupturing capacity.

Fig. 4 is a workshop view of a circuit-breaker with potential-controlled multiple break for a maximum service voltage of 300 kV. This circuit-breaker is designed for high-speed reclosing. By reason of the small mass of the moving arcing contacts reclosing is effected simply and at high speed. The connection of several breaks in series gives the arcing contacts finite, pre-determined power. For this reason, by dealing with one break at the time, circuit-breakers of the highest rupturing capacity can be fully tested in the existing test bays.[1]

Fig. 5 is an oscillogram of the opening, reclosing, and final rupturing of a circuit-breaker on a dead short circuit. This case makes very heavy demands on the contacts, but is coped with by the air-blast high-speed circuit-breaker without difficulty. The rupturing time between the imparting of the impulse to the trip coil and completion of the opening operation was 0·046 second the first time and 0·052 se-

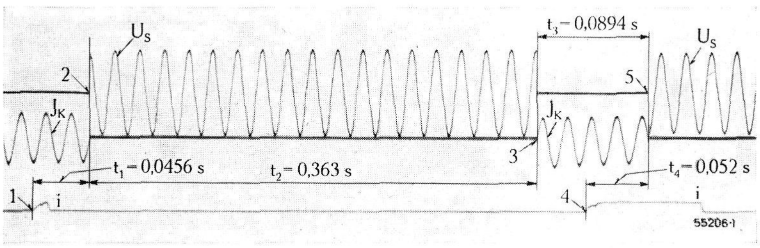


Fig. 5. — Oscillogram of rupturing operation and subsequent reclosing on a dead short circuit with an air-blast high-speed circuit-breaker for a maximum service voltage of 300 kV.

U_s. Voltage across circuit-breaker contacts. J_k. Short-circuit current.
i. Current in trip coil.

t_1. Rupturing time at first opening operation.
t_2. Reclosing time.
t_3. Duration of short-circuit current after reclosing.
t_4. Rupturing time at second opening operation.

1. Voltage impressed on trip coil.
2. Switch interrupts short-circuit current.
3. Moment of reclosing.
4. Second tripping impulse imparted to trip coil (due to short-circuit persisting).
5. Circuit-breaker opens definitively.

It will be noticed that the opening times t_1 and t_4 are very short.

The air-blast high-speed circuit-breaker is particularly adapted to high-speed reclosing, due to the blast of air rapidly evacuating the gas generated between the contacts.

a high electric strength. This is particularly important where lines have to be disconnected under no-load conditions or a number of lightning discharges occur immediately after opening. The characteristic feature of circuit-breakers with potential-controlled multiple break is that each individual break interrupts a de- cond on the final occasion. As already pointed out in earlier articles[2] such short opening times are extremely important from the standpoint of network protection, while for high-speed reclosing they are imperative.

(MS 891) *H. Thommen. (E. G. W.)*

[1] For particulars of more detailed research work in this field see: H. Thommen: "The latest Development of the Air-blast High-speed Circuit-breaker." The Brown Boveri Review, June, 1941, p. 137.

[2] H. Thommen: "The further Development of the Air-blast High-speed Circuit-breaker up to the Highest Voltages encountered in Service and for Outdoor Erection. Increased Protection of Systems by Short Rupturing Times and Rapid Reclosings in Cases of Short-circuit Trouble." The Brown Boveri Review, March, 1939, p. 55.

"Reduction in the Number of Network Service Breakdowns by means of automatic quick-acting Reclosing of Circuit-breakers or by using Protector Tubes." The Brown Boveri Review, April, 1940, p. 84.

"Der Druckluftschalter und die Bedeutung seiner kurzen Ausschaltzeit für den Netzschutz." Bulletin SEV, 1939, p. 702.

WHAT DOES IT COST TO START UP A VELOX BOILER.

Decimal Index 621.182.91 : 621.181.65

The Velox boiler presents the advantage for test departments and technical schools that it can be quickly and easily put into service, and that it can be readily shut down during operating pauses. Re-starting, and starting-up from the cold state, take only a few minutes, and require very little fuel. Measurements of the consumption during starting were effected on the Velox boiler in the boiler house of the test department of Brown, Boveri & Co., Ltd., in Baden.

These measurements showed that the fuel consumption for a single start from the cold state amounted to 60—80 kg, that the efficiency for a run of for instance one hour was still 87·5 %, compared with 92 % for continuous service. Extracts from operating diagrams show the typical heavy load variations and the interruptions of service occurring during such operation.

THE Velox boiler is more suitable than any other boiler for starting-up from the cold state in the shortest possible time in case of necessity. Because of this high degree of readiness one will therefore not keep the fire of a Velox boiler going when its steam output is temporarily not required but will shut the boiler down. In this manner fuel and attendance costs are saved during the period of waiting. This procedure is particularly convenient in technical schools and turbine manufacturing works where the characteristic fluctuating steam demand of test service may for various causes often undergo unexpected changes of programme. Thus, for example, the existing coal-fired water-tube boilers in the boiler house of the test department of Brown, Boveri & Co., formerly often had to be kept under fire for days, in anticipation of large load tests, when for some reason the carrying out of the tests was delayed. In the year 1938 an oil-fired Velox boiler having an output of 20 t/h was installed as a permanent addition to the two 15 t/h coal-fired boilers of the boiler house, by means of which the supply of steam necessary for test purposes was considerably facilitated and cheapened. Fig. 2 shows a typical load diagram of this boiler taken during governing tests on large marine turbines. Fig. 3 shows the boiler load and the variation of pressure during a series of tests when an interruption of one hour and 10 minutes had to be interposed to change over the test arrangements. The boiler was shut down and started up again five minutes before the new series of tests.

This possibility of shutting down the boiler during short interruptions of service is of great convenience in practical operation. Restarting is effected by depressing a few push buttons; it takes only a few minutes and requires very little effort. The fuel

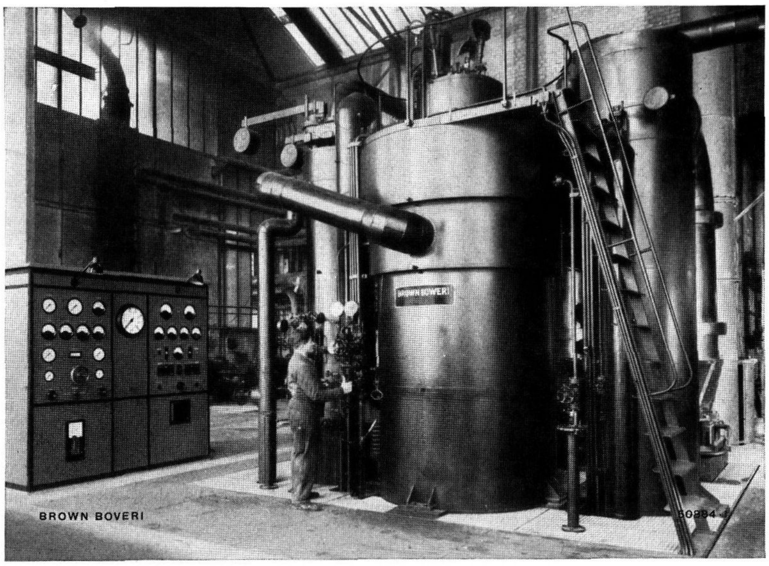


Fig. 1. — Velox steam generator for 20 t/h at 40 kg/cm², 450° C, in the boiler house of the test department of Brown, Boveri & Co., Ltd., Baden.

The simple and quick starting of this steam generator, together with the possibility of immediate shut-down, make it particularly well suited to the service requirements of test departments. The small space requirements facilitate the accommodation of the boiler in existing boiler houses, or even in the test department itself.

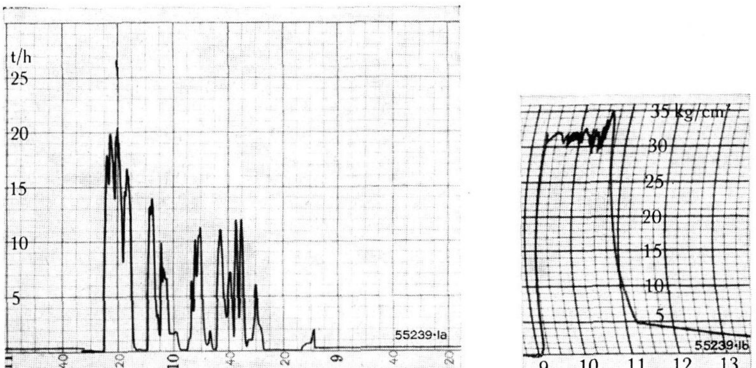


Fig. 2. — Steam output and steam pressure during a governing test on a large marine turbine.

In spite of large fluctuations in the steam flow the variation of steam pressure is insignificant.

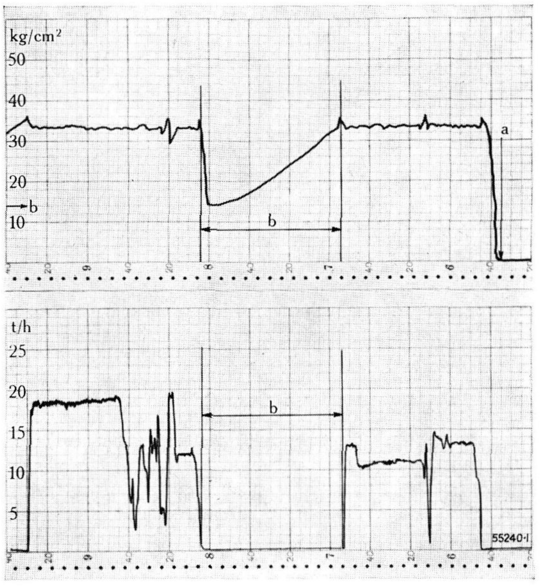


Fig. 3. — Typical load diagram during a test with an unexpected interruption.

In spite of the unknown duration of the interruption, the boiler is shut down. Only 1—2 minutes are required for restarting, especially when the boiler is still under pressure. The interruption therefore does not entail any additional costs.

consumed during restarting the still warm boiler is exceedingly small. It depends on the degree of cooling, and hence on the duration of the interruption. From the commercial point of view it is important to know what quantity of fuel is necessary for starting the completely cold boiler. If quick starting for a short test run were obtained at the expense of a high fuel consumption, it would certainly detract from the suitability of the boiler for intermittent fluctuating load service. The small mass of the Velox boiler and the absence of any brick walls would immediately lead one to believe that only a small heat quantity is required for starting. Repeated measurements on the 20 t/h Velox boiler of the test department showed the quantity of fuel required to start the boiler from the cold state to full-load output to be 63—80 kg. The fuel oil used had a lower calorific value of 10,000 kcal/kg. No measurable increased fuel consumption could be noticed after the boiler had begun to deliver full-load output. It could therefore be assumed that warming up was at that moment practically completed, and that the steady state had been almost attained.

Under steady conditions, the efficiency of this boiler at full load is 92 %. Allowing the measured amount of fuel of 80 kg the overall efficiency, including starting, can be calculated for short operating periods.

Efficiency of the 20 t/h Velox boiler for short operating periods, including starting consumption.

Operating time hours	Efficiency %
1	87·5
2	89·8
3	90·5
4	90·8
5	91·1
6	91·3
7	91·5
8	91·8

Even for an operating period of only one hour, the efficiency of the Velox boiler allowing for the consumption at starting is over 87 %. The cost of each start from the cold state based on a fuel oil price of Fr. 110.— per ton is only about Fr. 9.—.

These considerations show clearly the valuable characteristics of this boiler for service in test departments and in similar fields of application.

(MS 842) *A. Spoerli. (Hv).*

SEVEN YEARS' CONTINUOUS SERVICE WITH VELOX STEAM GENERATORS.[1]

Decimal Index 621.181.65

Towards the end of summer 1935 a Velox steam generator of 18—20 t/h output with combined natural gas and oil firing was put into service in a Roumanian chemical plant. Three years later a second identical boiler was installed. The two boilers assure uninterruptedly the steam supply of the continuously operating plant.

The following article describes briefly the installation and gives an account of the operating experience obtained up to the present.

IN the year 1934, the technical management of a large chemical undertaking in Roumania, saw itself faced with the modernization and adaptation of its manufacturing plant to the steadily increasing production. In place of the six antiquated water-tube boilers, each of 4 t/h output at 12 kg/cm² and 280° C, there was to be installed a modern steam boiler, and the various reciprocating steam engines, together with the obsolete transmission gear were to be replaced by a turbo-set and electric drives. The new boiler was to be built for a steam quantity of 18—20 t/h at 36 kg/cm² and 400° C. Moreover, it was desired if possible, to install the new boiler and the turbo-set

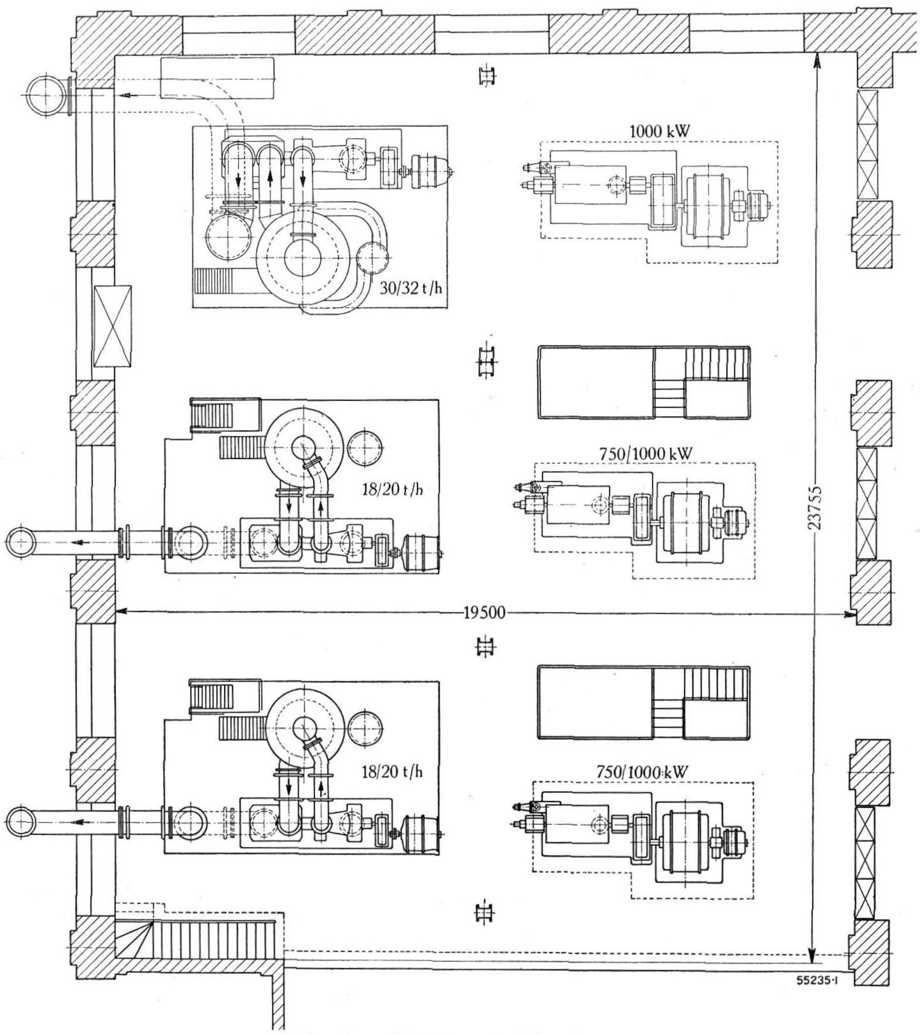


Fig. 1. — Arrangement of the plant.

Each Velox boiler constitutes a unit with the corresponding turbo-set which can be looked after by the same attendant.
The proposed third boiler for 32 t/h steam and the corresponding extraction back-pressure turbo-set of 1000 kW output are drawn in thin lines.

[1] W. G. Noack: "Druckfeuerung von Dampfkesseln in Verbindung mit Gasturbinen." Zeitschrift VDI 1932, p. 1033.

"Veloxkessel." Techn. Mitteilungen, Essen, Fachheft für Hochdruckdampf 1938, p. 575.

"The present-day Design of the Velox as result of the Experience gained in several Years' Practice." The Brown Boveri Review 1941, p. 221 and Zeitschrift VDI 1941, p. 967.

A. Stodola: "Leistungs- und Regelversuche an einem Velox-Dampferzeuger." Zeitschrift VDI 1935, p. 429.

E. Klingelfuss: "Der heutige Stand der Entwicklung des Velox-Dampferzeugers." Die Wärme 1937, p. 831.

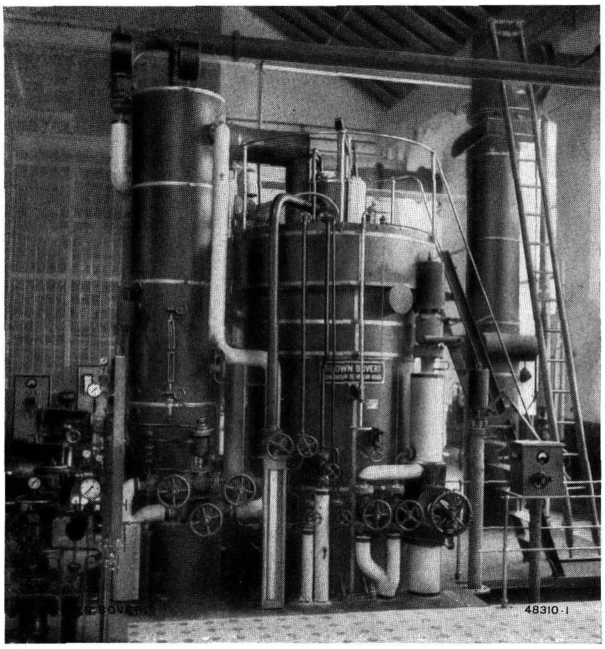


Fig. 2. — Velox steam generator for 18/20 t/h steam at 36 kg/cm² abs., 400° C with combined natural gas and oil firing.

All valves for the gas fuel, the oil fuel, the feed water and the steam are together and located at the front of the boiler, thus considerably facilitating the attendance.

in the old engine room where the reciprocating engines used to stand. The old boiler house, after dismantling of the boilers, was to be used as a machine shop.

No other type of boiler could suit this requirement better than the Velox steam generator. Thanks to its small dimensions, it was possible not only to erect the boiler together with the turbo-set in the old engine room, but there was enough space left for extension by a second, and, if necessary, by a third plant of the same capacity (Fig. 1). The management, therefore, decided on the purchase of a 18—20 t/h Velox boiler (Fig. 2), and of an extraction back-pressure turbo-set, having a terminal output of 750-1000 kW at 0·7 power factor. Three years later, the plant was extended by a second installation of the same capacity (Fig. 3).

I. FUEL.

Normally, natural gas (methane) is used as fuel, but oil may also be burnt in the boiler. It was therefore specified that the change-over from one fuel to the other, should be capable of being effected without interrupting the service.

The natural gas is supplied to the chemical works at a pressure of 6—8 kg/cm² gauge through a pipe line 80 km long. Its pressure is reduced in the central gas distributing station of the plant by means of a regulating device to 2 kg/cm² gauge, at which pressure it is supplied to the Velox boiler. The gas-fuel regulating valve of the boiler, which is controlled by the steam pressure regulator, automatically regulates the flow of fuel according to the momentary load.

As known, combustion takes place in the Velox combustion chamber under pressure. In the case of these Velox boilers, the combustion chamber pressure at full load is 1·5 kg/cm² gauge (Fig. 4). In case the pressure in the supply pipe should fall below this value due to a large demand on the part of other consumers, there is provided a cellular-type compressor having a maximum power of 40 kW, to enable the gas to be brought to the required pressure.

The natural gas, as received, is clean. It has a lower calorific value of 8500 kcal/Nm³ or 11,720 kcal/kg; the theoretical air requirements are 9·235 m³ per m³ of natural gas. With an excess air of 25 % ($\lambda = 1 \cdot 25$) and at full load, the time available for the complete combustion of the mixture during its transit from the burner to the base of the combustion chamber is 0·174 second.

This condition must be complied with by the burner (Fig. 5). In actual fact, it assures perfect combustion with an excess air of only 4—5 % ($\lambda = 1 \cdot 04 — 1 \cdot 05$). As, however, upon the occurrence of a sudden increase of the load of the boiler, the excess air may fall even below this value, due to the time required for the acceleration of the charging set, necessary to deliver the increased air quantity, and, because of

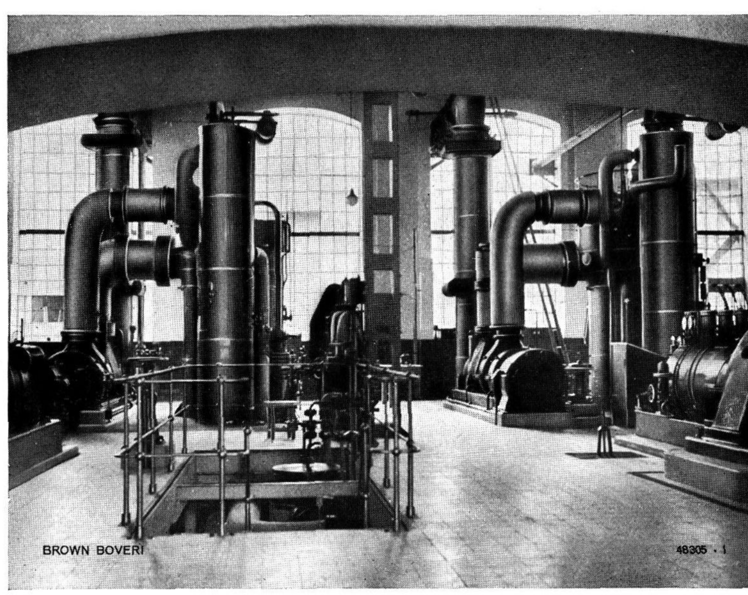


Fig. 3. — Velox power plant. Two Velox steam generators each for 18/20 t/h of steam per hour at 36 kg/cm² abs., 400° C, and two extraction back-pressure turbo-sets, each for 750/1000 kW at 0·7 power factor.

In spite of the small space available, the plant is very accessible and in no way cramped. Velox I (on the left) has now over 46,000 hours of service to its credit, Velox II over 11,000.

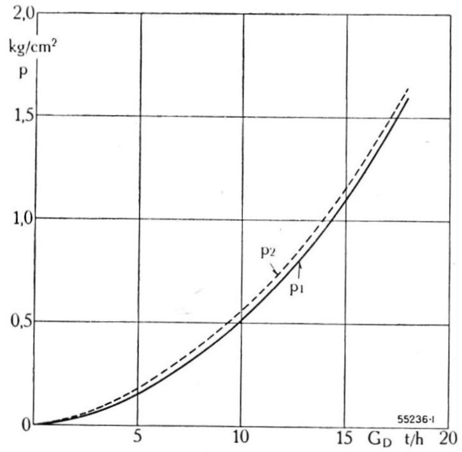


Fig. 4. — Velox steam generator for natural gas firing and for an output of 18/20 t/h. Curve showing the increase of the charging pressure with the load.

p_1. Gauge pressure in the combustion chamber.
p_2. Minimum admissible pressure of the gas fuel before the burner.
G_D. Steam quantity in t/h.

Combustion takes place in the Velox boiler under pressure, which increases proportionally to the square of the load. The gas fuel must therefore be supplied to the combustion chamber at a certain minimum pressure depending on the load.

For example, at a steam output of 10 t/h, a gas fuel pressure of 0·56 kg/cm² gauge is sufficient.

Fig. 5. — Burner and guide vane system for natural gas and oil.

The guide vanes for the combustion air are hollow. The gas fuel flows through a large number of small holes in the vanes, thereby ensuring an intimate mixture with the combustion air. The oil enters through the usual central nozzle. The change over from gas to oil firing and back again may take place during service.

the fact that natural gas tends to extinguish readily if insufficient air is present, the mixture regulator is for safety's sake, adjusted for a somewhat greater excess air, namely for 8—10 %. In order, however, to allow of operation with as low an excess air as possible, the regulating principle of the second boiler supplied later, was altered somewhat. Contrary to the first boiler, the steam pressure regulator adjusts first, not the gas quantity, but the air quantity, this being achieved by varying the speed of the charging set. The mixture regulator then adjusts the gas quantity to suit the quantity of air, whereby the gas control valve follows the impulses of the mixture regulator instantaneously. Thus, even with the highest load peaks, the excess air cannot fall below that which the mixture regulator is set to maintain, and the danger of extinction of the flame is eliminated, in spite of the low excess air setting of the regulator.

Operation of the Velox steam generator with oil fuel takes place only on rare occasions of failure of the gas supply, and lasts as a rule but for a few hours. Oil quantity and air supply are then regulated by hand, a check on the combustion being maintained by the Brown Boveri photo-electric smoke indicator.[1]

The oil injection nozzle, which cannot be left exposed continuously to the radiation of the gas flame, is lowered into the combustion chamber during operation with oil. Whilst the fuel oil quantity is being increased by hand, the steam pressure regulator automatically closes the gas fuel regulating valve, so as to keep the steam quantity constant. It opens it automatically, when, conversely, in changing back to gas firing, the fuel oil quantity is reduced by hand, and the steam production therefore tends to fall. The oil fuel injection nozzle is thereupon withdrawn from the combustion chamber.

During seven years of service, the boilers had to be changed over to oil fuel twenty-eight times. The shortest period of operation with oil lasted 1 hour, the longest 46 hours, and the total time of service with oil amounted to 270 hours.

II. FEED WATER.

The manufacturing methods of the chemical plant require that the entire steam quantity, after it has developed energy during its partial expansion in the steam turbine, be used in manufacturing processes. No condensate is therefore available for feeding the boilers, and the feed water consists of 100 % treated raw water, taken from a near-by stream. This river water contains large quantities of finely divided clay and is rich in silica, which separating out as calcium silicate, produces the most dangerous type of boiler scale. The feed water from the existing treating installation, in which the sediment was precipitated by aluminium sulphate, and the hardness reduced by the addition of caustic soda to 1—2 degrees (German)[2]

[1] H. S. Hvistendahl: "The Brown Boveri Photo-electric Smoke Indicator." The Brown Boveri Review, June, 1937, p. 166.

[2] 1 German degree of hardness corresponds to 1·25 English or 1·79 French degrees.

would have been quite adequate for a plant operating with condensate, and where only the make-up feed water consists of treated water. When used for supplying the entire feed water quantity, it leads, however, to a rapid increase of the residual hardness in the boiler. After approximately one month of continuous operation with this water, a few tube failures due to the formation of boiler scale, did indeed take place in the Velox boiler. The failures of the defective tubes all occurred at the same spot, namely, at the lower end of the evaporator elements. Investigation showed that sludge, rust, and flakes of boiler scale, which apparently had pealed off during shutdowns and during the putting into service trials, had accumulated there. Evidently, the water circulation at this spot was not sufficiently intensive to prevent collection and caking of this deposit. The entire remaining surface of the evaporator tubes was covered with a coating of boiler scale 0·1—0·2 mm thick, consisting mainly of calcium silicate. Its rate of growth would have allowed the boiler to continue to be operated for quite a long period. The trouble was eliminated by improving the water flow conditions at the inlet points of the evaporator elements and by the use of the well-known conditioning process of the feed water, consisting in the maintenance of a definite phosphate excess in the boiler water which causes the residual hardness to be precipitated as harmless sludge.

The water treatment proper is as follows:— First, aluminium sulphate is added to the raw water. Aluminium hydroxyde is formed, which acting as a coagulant, absorbs the fine clay particles.[1] The sludge collects in a conical sludge trap and is drained off from time to time. The water is then thoroughly filtered in two consecutive sand filters. The alkaline earth bicarbonates are separated out by the automatically regulated addition of caustic soda. The temperature of the water during this treatment is 80° C. This is followed by a conditioning of the water with tri-sodium phosphate at a temperature of 95° C, the amount of phosphate added being such as to ensure an excess of P_2O_5 in the boiler water of at least 15—20 mg/l. The hardness of the water thus treated, fluctuates between 0 and 0·3° (German).[2]

To keep in the boiler water a soda figure of 500,

$$(\text{Soda figure} = \text{mg/l NaOH} + \frac{\text{mg/l } Na_2CO_3}{4\cdot 5})$$

about 10% of the feed water supplied to the boiler, has to be blown down. The heat contained in the blown-down water amounts to about $2^1/_2$%. It is used in a heat exchanger for pre-heating the raw water supplied to the feed-water treating plant.

After installing this water treatment plant, a continuous run of 500 hours was made with the Velox boiler, after which an evaporator element was removed and cut open for inspection; it was found to be absolutely free from scale. Thus this difficult question of the feed water had been solved entirely satisfactorily by the chemical experts. No further difficulties of any kind occurred after this due to the feed water.

The sodium figure of 500 had been specified to prevent priming of the contents of the separator and the carrying over of water droplets into the superheater. There is a tendency for the salt contained in the carry-over to separate out at the first superheater bend, and to endanger the latter.

In the first three years of service, during which the steam output varied between 8 and 12 t/h, the boiler could be operated with soda figures of 550 and, for short periods, even more, without any superheater failure taking place. In 1938 the steam output rose to 13—16 t/h. With the considerably increased steam velocities then prevailing in the separator, salt-containing water droplets were carried over into the superheater, which led to a few failures of individual superheater elements. The soda figure was thereupon reduced at high outputs, so that the danger of salting up of the superheater was considerably lessened. It may here be mentioned that the built-in superheater has the great advantage that individual elements can be quickly replaced; a shut-down of 2—3 hours being ample for the exchange of a few elements.

In the case of the second Velox boiler delivered in 1938, it was specified that it should be capable of operating with soda figures of 800 to 1000, in order to reduce the blow-down losses. A first attempt at improving the separator was not successful. After a three weeks' trial run, with soda figures of 800 to 900, superheater failures again occurred, some superheater bends having become completely blocked with salt and failing due to insufficient cooling. Thereupon, a steam dryer which had been developed in the meantime, was built into the steam separator. This completely stopped the salting up troubles. In this steam dryer, which is fitted at the outlet of the separator, the steam flows at high velocity along the spiral path of an internal helix. The droplets are thrown out; they creep along the edge of the spiral guide strips and are drawn off by a drain connection. To check the separative action of this steam dryer,

[1] For some years now, aluminium sulphate is replaced by the cheaper iron chloride, whereby iron hydroxide falls out as a heavy sludge effectively cleaning the water.

[2] The costs of chemical amount to 7·5 Cts per ton of treated feed water (pre-war costs).

exact measurements of the moisture in the steam were carried out which gave the excellent results reproduced in the following table:—

TABLE I.

Steam quantity	Boiler water		Condensed live steam	Steam moisture
t/h	Soda figure	Cl mg/l	Cl mg/l	%
10	795	955	Traces	—
14	990	1173	„	—
18	1061	1310	„	$<0{\cdot}03$
18	1114	1327	„	$<0{\cdot}03$

Moisture of the live steam.
The steam dryer built into the steam separator delivers practically absolutely dry steam.

The method of determining the chlorides in the condensed live steam would have enabled 0·4 mg/l of Cl to be traced, which corresponds to a steam moisture of 0·03 %. As, however, the result of the titration was negative, the amount of moisture in the steam must have been less than 0·03 %. The qualitative test for chlorides showed the steam moisture at an output of 18 t/h to be 0·02 %.

The steam flowing to the superheater is now dry at all loads. The boiler can be operated with soda figures of 1000 and over. The blow-down quantity with soda figures of 800—900 is only 5—6 %.

The fact that no deposits of salt could be found in the steam pipes, water traps and valves, or in the turbines of either of the two Velox plants, is a further proof of the perfect separating action of the Velox separator.

TABLE II.

Composition	Average values: Raw water	Feed water	Boiler water
Phenol-phthalein alkalinity in cm^3 n/10 H Cl	—	0·8	19·9
Methyl-orange alkalinity in cm^3 n/10 H Cl	2·0	2·1	19·5
Temporary hardness (German degrees)	5·6	—	—
Total hardness (German degrees)	8·7	0·22	—
Cl in mg/l	27·6	33·7	378
SO_3 in mg/l	53·5	53·7	588·8
SiO_2 in mg/l	14·0	14·2	157·5
CaO in mg/l	65·0	1·5	1·8
P_2O_5 in mg/l	—	5·4	49·9
Soda figure	—	—	800

Average values for raw water, feed water and boiler water.
The feed water supplied to the Velox steam generators consists of 100 % chemically treated river water.

III. STARTING AND AUXILIARY MOTOR.

Extra quick starting is not required in the case of this plant. A starting power of 80 kW which is delivered by a three-phase shunt commutator motor is therefore amply sufficient. With it, the steam generator can still be brought from the cold state to full-load steam output in 10—15 min.

IV. EFFICIENCY OF THE PLANT.

According to the conditions of the contract, acceptance tests on the first plant were to be carried out after one year of continuous service. Measurements on the Velox steam generator and on the turbo-set were made simultaneously. The guaranteed efficiencies were not only attained but exceeded, especially in the case of the Velox boiler (Fig. 6); even taking into account the relatively large blow-down loss of 1 1/2 to 2 1/2 % the guarantee values were still maintained. In addition to the low excess air, the low exhaust gas temperature also contributes to the attainment of this favourable result; during the acceptance tests measurements showed the exhaust-gas temperature to be 134 °C, corresponding to an exhaust-gas loss of only 5·8 % (Fig. 7).

The auxiliary electrical power is made up as follows:— At a steam output of 18 t/h the power taken by the circulating pump is 21·1 kW and that of the feed pump 48·3 kW. The power of the auxiliary motor of the charging set decreases with increasing boiler load, and becomes negative at approximately half load, i. e., the gas turbine delivers power via the auxiliary motor now operating as a generator to the supply. This excess power can reach 20 kW at full load.

The acceptance tests on the second plant could not be carried out owing to the outbreak of the war. The service records show, however, that the efficiencies attained are at least equal to those of the first plant.

V. BOILER OVERHAULS.

Up to the present date Velox boiler I has been subjected to two thorough overhauls. The first took place after about 21,000 hours of service. The only abnormal effect observed during the period of the boiler operation just preceding the overhaul, was a slight surging of the compressor in the region of lower speeds. The cause of this disturbance was found to lie in severe obstruction of the first row of guide blades of the axial compressor, due to dust drawn in with the air. The entire charging set had never been dismantled since it was first installed. The total work of overhaul consisted of:

1. Cleaning of the compressor.
2. Replacement of a ball bearing on the gear between the auxiliary motor and the charging set.
3. Cleaning of the auxiliary motor and smoothing of the commutator.

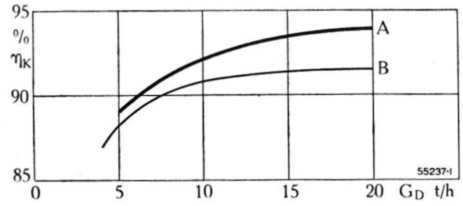


Fig. 6. — Boiler efficiency of Velox I measured during official tests after one year of continuous service.

A. Measured efficiency.
B. Guaranteed efficiency.

$$\eta_{boiler} = \frac{G_D\ (i_D - i_{sp})}{G_B \cdot H_u}.$$

G_D. Total steam quantity produced in kg/h.
i_D. Heat content of live steam at superheater outlet.
i_{sp}. Heat content of incoming feed water.
G_B. Weight of fuel supplied in kg/h.
H_u. Lower calorific value of fuel.

As the power required to operate all the boiler auxiliaries (excluding the boiler feed pump) is only 22 kW, the plant efficiency is very nearly equal to the boiler efficiency.

In the higher load region, the gas turbine supplies more power than is required for charging the set; if this power is fed into the supply network the plant efficiency may even exceed the boiler efficiency.

4. Repacking of the glands of the circulating pump.
5. Cleaning of the feed water economiser by means of a pickling solution[1]. The tubes were covered on the water side with a layer of calcium phosphate 0·8—1 mm thick.

The second overhaul was made after 39,000 hours of service when the following work was carried out and the parts mentioned below were replaced:

1. Cleaning of the compressor.
2. Cleaning of the feed-water economizer with a pickling solution.
3. Smoothing the commutator of the auxiliary motor.
4. Replacement of a roller bearing of the gas turbine.
5. Replacement of a ball bearing of the auxiliary motor.
6. Replacement of a diaphragm of the mixture regulator.
7. Replacement of the spindle of the automatic feed regulator valve.

These operations were carried out in a few days, whereby it should be mentioned that with the Velox boiler it is possible already about one hour after shutting down to begin with the work of overhaul. With usual types of boilers, up to one week may elapse until the brickwork has cooled down sufficiently to enable the boiler to be entered.

In conclusion it can be said that for these first two plants built for combined natural gas and oil firing, no difficulties were experienced due to the use of the Velox principle. The only real troubles were caused in the beginning by the unfavourable feed-water conditions. They would have been experienced with any other type of high-pressure boiler. That it was possible entirely to overcome these difficulties was due to no small extent to the most effective cooperation of the customer. On September 1st, 1942, the total operating time of Velox I was 46,780, that of Velox II was 11,545 hours. Moreover, the fact that plans for a third still larger plant have been considered by the customer, the realization of which has been deferred by the war conditions, confirms the very satisfactory operating results of these Velox installations.

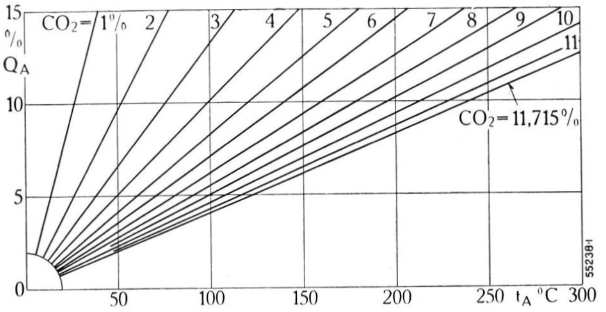


Fig. 7. — Heat lost in the exhaust gases with natural gas firing (methane) in function of the exhaust gas temperature.

Q_A. Exhaust gas loss in %.
t_A. Exhaust gas temperature °C.

The main source of loss of a boiler is the exhaust gas loss. Low exhaust gas temperatures and low excess air considerably reduce this loss in the case of the Velox boiler. The exhaust gas loss measured during the official tests was 5·8 %, the excess air being 9 % (CO_2 content of gases = 10·7 %) and the exhaust temperature 134° C.
(Feed water temperature 88° C.)

It is of interest here to refer just briefly to the operating experience obtained with two other Velox boilers equipped with exactly the same combined burner for oil and gas fuel which since their placing into service in June, 1938, have operated continuously with oil. These are the two boilers of the San Lorenzo plant of the Argentine State oil fields which were built for an output of 28 t/h at 16 kg/cm² abs. and 300° C which have to supply the steam requirements of a continuously operating oil refinery[2]. Up to July 1st, 1942 (last report received) the service hours of Velox I amounted to 31,340 and those of Velox II to 30,550. Between October 1st, 1940 and September 30th, 1941, the one boiler operated during 8356, the other during 8521 hours corresponding to service factors of 95·4 % and 97·3 %, respectively.

(MS 836) *E. Gugler. (Hv.)*

[1] The pickling solution used, consisted of:
23 % hydrochloric acid (35 %)
20 % pyroligneous acid (with 11·4 % acetic acid)
57 % water
100 %

[2] H. S. Hvistendahl: "The Velox Power Plant of the San Lorenzo Refinery of the Argentine State Oil Fields." The Brown Boveri Review, November, 1940, pages 211 to 217. See also the Brown Boveri Review, January/February/March 1940/41/42 numbers.

ON THE RELATIONSHIP BETWEEN THE SALT CONTENT AND THE CONDUCTIVITY OF THE BOILER WATER IN ELECTRIC BOILER OPERATION.

Decimal Index 621.181.646.004

An important factor for the dimensioning and operation of electric boilers is the conductivity of the boiler water. The deciding relations between the salt content, the temperature and treatment of the boiler water, their effect on the conductivity, as well as their dependence on the design of the boiler are discussed here.

I. GENERAL.

IN the electrode type of boiler, the electric current flows between two or more electrodes under voltage through the boiler water, whereby the latter is heated or evaporated. Among the electrode-type of boilers should be included the high-voltage water-jet boiler built by Brown Boveri. It is suitable for single- or three-phase alternating current of the usual frequencies of $16^2/_3$ to 60 cycles. Direct current cannot be used in electric boilers because hydrogen and oxygen would form at the electrodes, which upon mixing would constitute a dangerous explosive mixture.

II. THE CONDUCTIVITY OF THE FEED AND BOILER WATER.

Pure water is a practically non-conductor of electric current. In order that it shall become conductive, salts, bases or acids must be dissolved in it. Such solutions are called electrolytes. Except in the case of pure condensate, water always contains a greater or less quantity of substances in solution. If there is not sufficient of these present, it is possible by the addition of compounds, such as soda or tri-sodium phosphate, to obtain the necessary conductivity for boiler operation, and at the same time to improve its quality for preventing boiler scale.

Not all molecules in an electrolyte participate in carrying the current, but only those dissociated into ions. The formation of ions depends on the nature of the dissolved substance, on its concentration in the water, on the presence of other substances, and on the temperature of the solution. It would be going too far to discuss in detail the complicated relationships of the electrochemistry of solutions. We therefore limit ourselves to the important ones.

(a) *Method of Measurement.* — Contrary to solid substances, for which the definition resistance may be assumed to be familiar to all, it is usual in the case of liquids, to refer to the conductivity. If a cylinder of fluid of length l cm and of cross section q cm^2 has a resistance R, then its specific resistance is:

$$\varrho = \frac{R \cdot q}{l} \; \Omega\,\text{cm}.$$

The specific conductivity $\varkappa$ of this solution is given by the reciprocal of ϱ:

$$\varkappa = \frac{1}{\varrho} = \frac{l}{R \cdot q} \; \Omega^{-1}\,\text{cm}^{-1}$$

This value is equal to the conductivity of a cube of unit length (cm) of side.

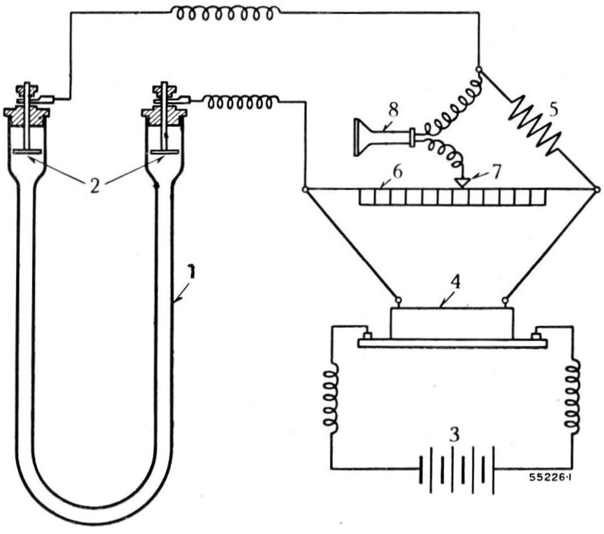


Fig. 1. — Diagram of the arrangement for measuring the specific conductivity of electrolytes.

The use of a resistance bridge in connection with an oscillator enables very exact results to be obtained without precision instruments.

1. Calibrated measuring column.
2. Electrodes.
3. Battery.
4. Oscillator.
5. Resistance.
6. Bridge measuring wire.
7. Sliding contact.
8. Telephone.

For measurements on electrolytes, the arrangement shown in Fig. 1 has proved satisfactory. The solution to be measured is filled into the measuring column and the specific resistance or conductivity is measured with the help of a Wheatstone-Kirchhoff bridge. The use of an oscillator for the production of alternating current, instead of the direct measurement by means of continuous current, is necessary, in order that no substances shall separate out at the electrodes which would falsify the result due to polarization. For approximate measurements, an alternating-current resistance meter is often used in practice in place of a measuring bridge.

(b) *Effect of the dissolved Substances.* — The conductivity relations of electrolytes have been the subject of research by well-known investigators, and the relationships, especially in the domain of dilute water solutions, to which the water in electric boilers also belongs, have been elucidated. Thus the classical dissociation and ionization theory of Arrhenius throws light on the behaviour of electrolytes. Detailed investigations have shown that part of the molecules present in a solution decompose into ions (electrolytic dissociation) and that only these ions participate in carrying the current. The percentage of molecules decomposed is called the degree of dissociation. If, for instance, ordinary salt is dissolved in water, simultaneous dissociation takes place according to the following equation:—

$$\mathrm{Na\,Cl} \rightleftarrows \mathrm{Na}^{\bullet} + \mathrm{Cl}'$$

A singly, positively charged sodium ion (cation) and a singly, negatively charged chlorine ion (anion) form. In the case of polyvalent substances, for instance sodium sulphate, three ions form according to the equation:

$$\mathrm{Na_2\,SO_4} \rightleftarrows \mathrm{Na}^{\bullet} + \mathrm{Na}^{\bullet} + \mathrm{SO_4}''$$

that is, two cations and one doubly charged anion.

Between the ions and the concentration of the substance, that is, between the number of ions and of molecules contained in a solution there holds, for example, in the case of a solution of ordinary salt:

$$k \cdot c_s = c_i^{\ 2}$$

where c_i is the concentration of the ions and c_s that of the undissociated molecules. If c is the total concentration $(c = c_i + c_s)$ then it follows that:

$$k = \frac{c_i^{\ 2}}{c - c_i}$$

k is called the dissociation constant. If α is the degree of dissociation, that is $c_i = c \cdot \alpha$, then it follows that:

$$k = \frac{c^2 \cdot \alpha^2}{c(1-\alpha)} = \frac{c \cdot \alpha^2}{1-\alpha}$$

The determination of the concentration and of the nature of the ions and molecules present in a solution is a very considerable help for chemical investigations. In the case of electric boiler operation, it is especially the conductivity of the feed water and boiler water which is interesting; it is also possible to obtain therefrom valuable deductions in regard to the composition and the salt content.

With the same concentration, different substances have different conductivities. According to Kohlrausch, this fact is due to the ionic mobility. As shown by Fig. 2, hydrogen ions (acids) and OH ions (bases), be-

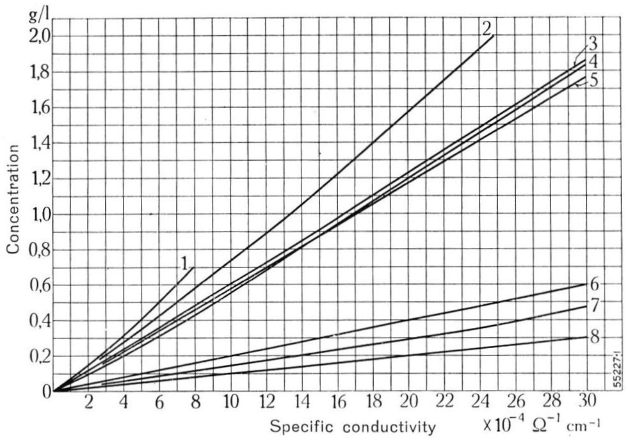


Fig. 2. — Specific conductivities of electrolytes at 18° C as function of the concentration (according to Landolt-Börnstein).

The conductivity of the electrolytes at the same concentration is very different, due to varying ion formation. Up to concentrations of about 2 g/litre the specific conductivity varies in an almost linear manner with the concentration.

1. $CaSO_4$ Calcium sulphate.		5. NaCl	Sodium chloride.
2. Na_2SO_4 Sodium sulphate.		6. NaOH	Caustic soda.
3. KCl	Potassium chloride.	7. H_2SO_4	Sulphuric acid.
4. Na_2CO_3 Sodium carbonate.		8. HCl	Hydrochloric acid.

cause of their greater mobilities compared with metal or salt radical ions, result in good conductivities. According to newer theories the difference in the behaviour of individual electrolyte groups is due to the characteristics of the pure undissolved substances. The one group comprises all compounds which already as crystals exhibit a definite ionic lattice. The second group contains mainly either compounds which have a molecule lattice in the solid state, or those to which a unipolar constitution has to be ascribed as waterfree substances: only upon dissolution do such substances supply ions due, for instance, to the formation of electrolytically dissociated hydronium salts. In the first case the ions are already present in the undissolved substance, in the second case their formation must be preceded by a chemical reaction on the completeness of which the number of ions depends.

(c) *Effect of the Concentration.* — The specific conductivity increases first with increasing concentration, because the number of ions increases; it does not, however, increase proportionately with the salt content at high concentrations, because the degree of dissociation decreases with increasing concentration. As shown by Fig. 3 this behaviour is particularly marked in the case of sulphuric acid (H_2SO_4). The maximum

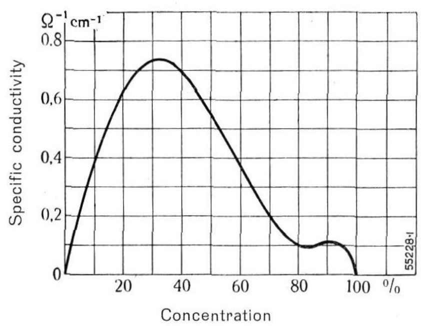


Fig. 3. — Specific conductivity of sulphuric acid (H_2SO_4) as a function of the concentration.

In all electrolytes, the dissociation decreases with increasing concentration and therefore also the percentage of ions formed. At higher concentrations, the specific conductivity no longer increases proportionately. It finally reaches a maximum and thereafter decreases.

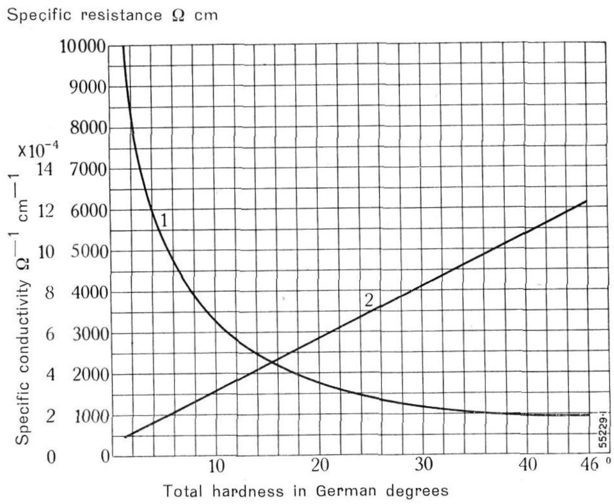


Fig. 4. — Specific resistance and conductivity of raw water at 20° C as a function of the total hardness (Alpine and Jura regions).

1. Specific resistance. 2. Specific conductivity.

The specific conductivity of raw water from the Alpine and Jura regions increases in a linear manner up to the maximum degrees of hardness met with, as all salts contained therein exhibit the same characteristics.

conductivity is reached at about 30 % concentration, falling to a minimum for a composition $H_2SO_4H_2O$ (82 %). This monohydrate must therefore be considered as a relatively badly conducting pure substance. On adding further H_2SO_4, the curve rises again to a maximum at about 92 % after which it falls to practically zero. The solubility in water is usually so small that maximum conductivity is not attained. In the case of very dilute water solutions such as those included in Fig. 2, the conductivity increases with the concentration in an almost linear manner. For the same reason the decrease in dissociation does not appear in the case of the low concentrations of 0·2—1 g/l present in electric boiler waters.

(d) *Effect of other Substances.* — If equal volumes of two solutions are mixed, the conductivity of the mixture does not correspond to the arithmetic average of the two individual values, provided the substances concerned are not practically completely dissociated, apart from the fact that depending on the composition of the solution, chemical reactions causing a change of conductivity may take place. It is therefore possible to determine the total salt content of a solution, only when a single salt is present. This is, however, rarely the case with electric boiler water. On the other hand, conductivity measurements enable the salt content of solutions to be determined with sufficient accuracy when all the substances dissolved therein behave in a similar manner, such for instance, as is the case with raw waters. The curves of conductivity and of specific resistance illustrated in Fig. 4 represent the average values of about fifty analyses. In spite of the very different ratios of temporary to permanent hardness of the individual water samples, the electrolytes clearly behave in a uniform manner, which is proved by the maximum departure of 10 % from the curve. It is often possible to make determinations of the salt content with sufficient accuracy by means of conductivity measurements, when a known substance strongly preponderates in a solution so that the conductivity is mainly determined by it.

(e) *Effect of the Temperature.* — The conductivity of electrolytes increases considerably with the temperature. The temperature coefficient is positive and decreases with the temperature, that is to say, the increase in conductivity per 1° C increase in temperature is smaller at high temperatures than at low ones. Fig. 5 shows the variation of the conductivity with temperature for a number of normal solutions. Not all substances have the same temperature coefficient; the relationship between conductivity and temperature is expressed by the following formula:—

$$C = \frac{1}{\varkappa_{18^\circ}} \cdot \frac{\varkappa_2 - \varkappa_1}{t_2 - t_1}$$

where $\varkappa_2$ and $\varkappa_1$ represent the conductivities at the temperatures t_2 and t_1, $\varkappa_{18^\circ}$ the conductivity at 18° C and C the temperature coefficient. The latter amounts to 0·02 to 0·023 for weak salt solutions, to 0·009 to

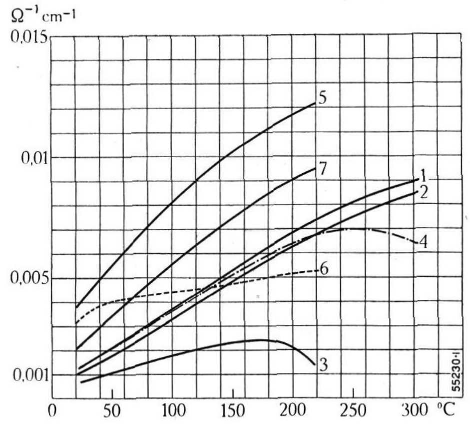


Fig. 5. — Specific electric conductivity of aqueous 0·01 normal solutions in function of the temperature (according to Landolt-Börnstein).

The conductivity increases considerably with increasing temperature, about 2 % per °C in the case of electric boiler water.

1. KCl Potassium chloride.
2. NaCl Sodium chloride.
3. $MgSO_4$ Magnesium sulphate.
4. K_2SO_4 Potassium sulphate.
5. HCl Hydrochloric acid.
6. H_2SO_4 Sulphuric acid.
7. NaOH Caustic soda.

0·016 for acids and some acid salts, and to 0·019 to 0·02 for strong bases. Allowing for the salts and bases usually dissolved in electric boiler water a coefficient of 0·02 may be assumed with sufficient accuracy. The conductivity of boiler water therefore increases about 2 % per °C.

III. COMPOSITION OF THE BOILER WATER AND ITS EFFECT ON THE CONDUCTIVITY.

In addition to the above-mentioned influences on the conductivity of individual dissolved substances, of their concentration and of the temperature of the boiler water, reference is here made for the sake of completeness to the variability of the composition of the water, and the phenomena taking place during service.

When a boiler is supplied with raw water of a definite hardness and conductivity, already the effect of heating and of the pressure, causes chemical reactions to take place which alter the composition and the conductivity of the water. In the case of the water of the Alpine and Jura regions, the bicarbonates of calcium and magnesium present are, for instance, decomposed as follows:—

$$Ca(HCO_3)_2 = CaCO_3 + CO_2 + H_2O$$
$$Mg(HCO_3)_2 = MgCO_3 + CO_2 + H_2O$$

The bicarbonates present before the decomposition of the solution result, as shown in Fig. 4, in a definite conductivity. After the reaction, there are formed the insoluble calcium carbonate ($CaCO_3$), or the partially soluble magnesium carbonate. The carbonic acid liberated escapes with the steam. The ions, necessary for carrying the current are no longer present, or only to a lesser extent, thus causing a reduction in the conductivity. For instance, the conductivity of a raw water of a total hardness of 9·2 German degrees, of which 7·5° were due to temporary or bicarbonate hardness was reduced after a short period of boiling at atmospheric pressure from 3 to $2{\cdot}3 \times 10^{-4} \Omega^{-1} cm^{-1}$.

The treatment of the feed or boiler water to prevent the formation of sludge or scale, has, depending on the process or the chemicals added, an important effect on the conductivity.

In general, care will be taken in choosing the softening process so as to insure that the treated water shall contain as little salts or bases as possible, in order that the conductivity of the water shall not attain too high a value. Even in cases where the electric boiler allows the use of water of a high conductivity, it should be remembered that only pure water escapes in the form of steam, thus causing the content of salts and bases in the boiler water to increase. The removal of the salts must therefore be effected more frequently in the case of a boiler fed with a water of high conductivity, than in the case of one fed with water of low conductivity. The kind of salts or bases entering into the boiler is also important. For instance, as shown by Fig. 2 caustic soda (NaOH) has at the same concentration about 3·5 times the conductivity of sodium sulphate (Na_2SO_4). In addition to the above considerations, the price of the softening plant and the cost of the chemicals used must also be taken into account, which is especially important in the case of electric boilers with their relatively small installation costs.

IV. DEPENDENCE OF THE ADMISSIBLE CONDUCTIVITY OF THE WATER ON THE CONSTRUCTION OF THE BOILER.

The admissible concentration of the salts and bases in the boiler water, and hence also the maximum value of the conductivity, depends to a considerable extent on the construction and arrangement of the electrode system. If a certain maximum value is exceeded, arcing takes place, leading to unsteady operation and to flash-overs. At the same time the water is decomposed and an explosive gas mixture is formed. The simplest system, which is one still used to-day for low voltage boilers, consists of an immersion electrode, which for simplicity is shown in Fig. 6 as single phase. The current flows from the fixed inner electrode through the water to the outer electrode which is constituted by the boiler shell via the earth and back to the supply. In the three-phase arrangement the three electrodes are symmetrically disposed in a triangle in the cylindrical shell and may also take the form of flat plates. Because of the variation of the cross section of the water along the path of the current between the concentric electrodes in the disposition shown in Fig. 6, the resistance per unit length of current path varies correspondingly according to the equation

$$\frac{dR}{dr} = \frac{\varrho}{2 \cdot \pi \cdot h} \cdot \frac{1}{r}$$

where ϱ is the specific resistance of the water.

Evidently this resistance increases rapidly in the neighbourhood of the inner electrode, so that the voltage drop there is very large.

The voltage per unit length of path is represented by the formula:

$$\frac{dV}{dr} = \frac{V}{r \cdot \log_e \frac{r_2}{r_1}}$$

and the voltage loading of the water in percentage of the average loading by:

$$\frac{r_2 - r_1}{V} \cdot \frac{dV}{dr} = \frac{r_2 - r_1}{\log_e \cdot \frac{r_2}{r_1}} \cdot \frac{1}{r} \text{ (curve 2 in Fig. 6)}$$

The load density is:

$$\frac{dL}{dv} = \frac{J^2 \cdot \varrho}{(2 \cdot \pi \cdot h)^2} \cdot \frac{1}{r^2}$$

It therefore varies with the square of the reciprocal of the distance from the centre of the boiler.

The variation of the load density in percent of the average load density is expressed by the equation:

$$\frac{V}{L} \cdot \frac{dL}{dv} = \frac{1}{2 \cdot \pi \cdot \log_e \frac{r_2}{r_1}} \cdot \frac{1}{r^2} \text{ (curve 3 in Fig. 6)}$$

The curve showing the variation of the voltage along the radius has been drawn in Fig. 6. The voltage loading of the water in percent of the average loading and the density are represented by the curves 2 and 3. The steep variation in the neighbourhood of the inner electrode can be clearly seen.

The above reflections show distinctly that the maximum power per unit volume occurs at the surface of the electrode so that the maximum steam evolution also takes place there. The steam bubbles so formed displace the water so that the load distribution is affected even more unfavourably. In order to avoid an excessive specific loading of the water

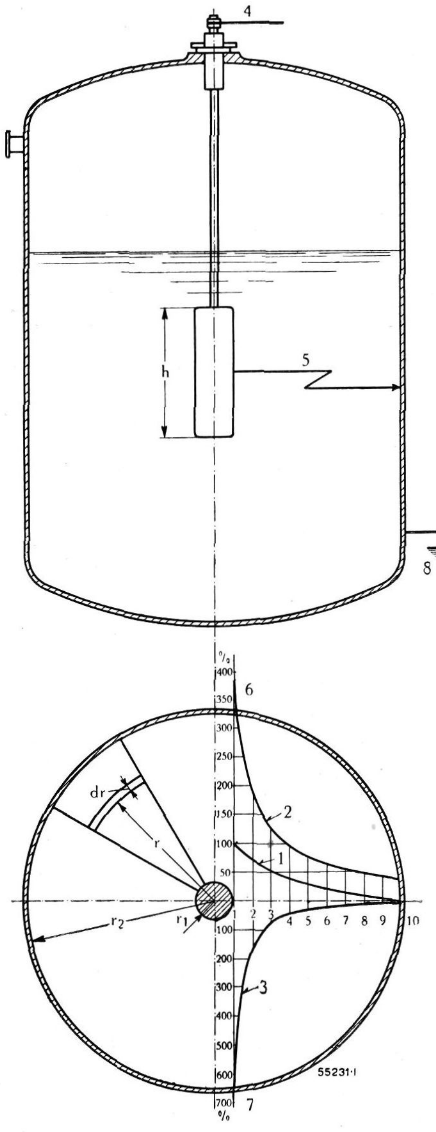


Fig. 6. — Variation of the voltage and power density in a single-phase electric boiler with immersion electrode.

Curve 1. Variation of the voltage in the water between concentric electrodes.
Curve 2. Voltage loading of the water in % of the average voltage loading for a radius ratio of 1 : 10.
Curve 3. Variation of the power density in % of the average density.
4. Supply.
5. Current path.
6. Voltage.
7. Power density.
8. Earth.

The voltage drop and therefore the energy conversion is a maximum in the neighbourhood of the inner electrode. In order that arcing shall not take place, *the boiler water must have a low conductivity.*

in the neighbourhood of the electrodes and undesirable arcing, the conductivity of water and therefore the salt content has to be kept small. In the case of high voltages the values are so low that they cannot be attained in practice, so this electrode system cannot be used for a high voltage.

In the majority of electric boiler types, ceramic displacement bodies of various forms are built into the boiler, which reduce the cross-section of the water between the electrodes. An example of such a construction is illustrated in Fig. 7. Only relatively small

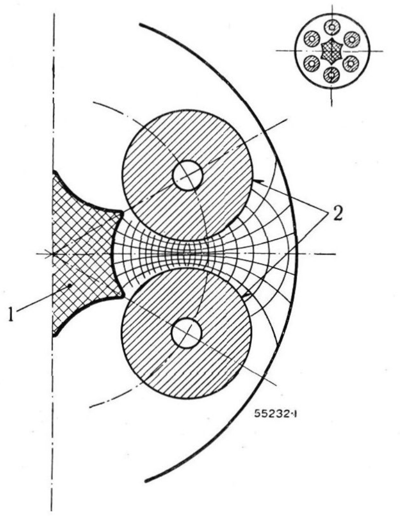


Fig. 7. — Immersion electrode with displacement bodies for increasing the length of the high-resistance current path.

The highest current density exists in the channels between the displacement bodies, so that higher water conductivities may be allowed than in the case of ordinary immersion electrodes, and higher voltages may be used. The presence of ceramic parts in the boiler water is a disadvantage.
1. Electrode. 2. Displacement bodies.

slits remain free for the passage of current the sum of whose sections is smaller than that of the corresponding electrode surface. In this manner the high resistance current path is artificially lengthened. The conversion of energy takes place mainly in the reduced water sections.

In spite of the fact that these improved electrode systems are built for high voltages and that they allow of a higher conductivity of the water, they all have the common disadvantage that they require ceramic bodies built into the boiler. Ceramic bodies are however subject to a more or less rapid corrosion depending on the quality of the water, the corrosion being particularly marked in the case of alkaline boiler waters. Moreover, when a lime deposit has formed on the insulating body, mechanical stresses may occur, due to differences in the thermal expansion of lime covering and of the base body, which may lead to the formation of cracks. The Brown Boveri water-jet electric boiler developed in 1933, for the construction and operation of which the reader is referred to previous publications[1], avoids these disadvantages in that the current is conducted by water jets. With the exception of the insulators mounted in the steam space, which are effectively shielded, there are no ceramic parts in the boiler, and especially none in the water. Contrary to the case of the electrode boiler, the voltage varies in an almost linear manner along the water jets, as the cross-section for the current flow is there everywhere the same. The steam evolution also takes place uniformly and along the whole length of the jets. For this reason a much higher conductivity is admissible in the jet boiler than in a boiler with immersion electrodes.

This higher admissible content in salts and bases allows of a freer choice of the method of softening, reduces the amount of blow-down, and the heat loss connected therewith.

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[1] E. Soldati: "The Brown Boveri Water-jet High-voltage Electric Boiler." The Brown Boveri Review 1935, p. 71—76.

A. Strub: "Measurements carried out on the Electric Boiler in the Zuckerfabrik und Raffinerie Aarberg (Switzerland). The Brown Boveri Review 1937, p. 167/168.

E. Soldati: "Electric Boilers." The Brown Boveri Review 1938, p. 231—236.

A. Strub: "Brown Boveri High-voltage Electric Steam Boilers for High Pressures and Automatic Regulation." The Brown Boveri Review 1940, p. 139—141.

(MS 844) *A. Strub. (Hv.)*

A REMOTE-CONTROLLED HYDRAULIC POWER STATION.

Decimal Index 621.398:621.311.21

Attention is drawn to an equipment of extremely simple construction and relatively low first cost, which is eminently suitable for the remote control of electrical installations over comparatively short distances.

BROWN BOVERI has supplied a remote control equipment for a hydraulic power station in Italy which permits the two 5000 kVA hydro-electric sets to be started up, shut down, regulated, and supervised from a control station three kilometres away, thus enabling attendants to be dispensed with in the power station itself.

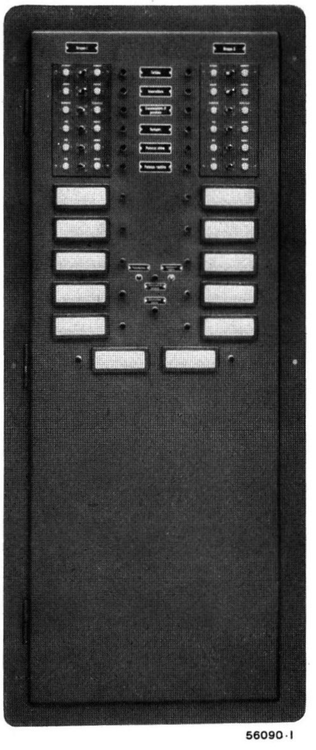

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Fig. 1. — Remote control equipment in the transmitting station.

A large station with two hydro-electric sets is remote-controlled and supervised from this panel. Such equipment is particularly suitable for the remote control of hydraulic and thermal power stations, substations, mutator plants, and pumping stations.

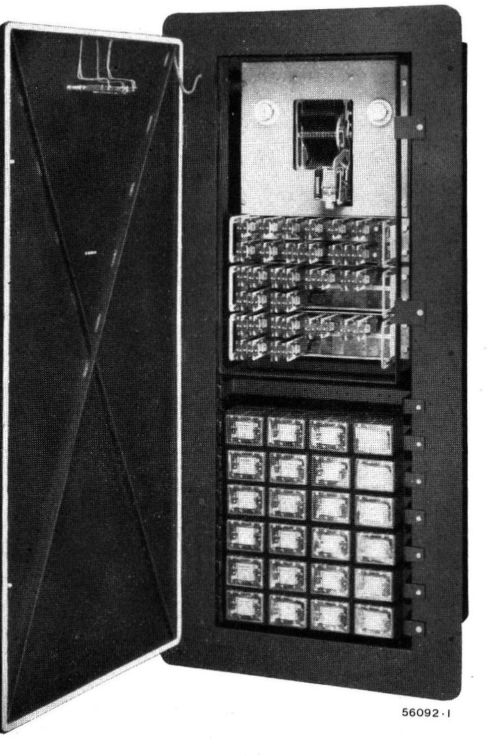

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Fig. 2. — Remote control equipment in the receiving station.

This simple selector and relay gear receives impulses from the distant control station and transmits them to the electrical apparatus to be operated. The equipment illustrated permits twenty-four control, twenty-four position indicating, and twelve fault indicating impulses to be transmitted over six lines, so that the power station can be left unattended and control and supervision effected from the control station.

Control is on the line combination principle, which system is eminently suitable for the operation of electrical plants over relatively short distances where it is not absolutely necessary to keep the number of pilot wires down to a minimum. In the ordinary way, at least six connecting lines are required between the transmitting and receiving stations. These permit of the carrying out of fifty different operations (for which four free lines are invariably available) and suffice for the remote control of fairly large plants. The remote transmitting gear is very simple in construction and, in consequence, inexpensive. Since in a given selector position several lines are available for every control operation, remote control and position indication or remote control and metering are simultaneously possible in the same selector position. In this way, standard remote control and metering apparatus can be extensively used without recourse having to be had to special connections to reduce the number of pilot wires.

The scheme of the installation is such that no remote metering equipment is required, each of the two alternators supplying its own overhead line through a transformer. These lines terminate on the busbars in the control station, where a metering station is installed for each incoming line to enable the state of the individual hydro-electric sets to be immediately recognized at any time.

Figs. 1 and 2 show the control equipment in the transmitting and receiving stations, this comprising selectors with the appertaining relays and control apparatus accessibly mounted in a dust-tight metal casing. Remote control is effected by calling the attended station selector into one of the twelve control positions by means of the push-buttons. Thereupon, the selector in the receiving station automatically moves into a corresponding position, thus directly connecting the two stations by four lines over which impulses can be transmitted. Each hydro-electric set is allotted the following six control positions: —

Position 1: Starting up and shutting down of water turbine.
Position 2: Closing and opening of alternator switch.
Position 3: Switching in and out of automatic synchronizer.
Position 4: Governing of water turbine.
Position 5: Remote control of active load of set.
Position 6: Remote control of reactive load of alternator.

The different operations are initiated by means of tumbler switches, while pilot lamps are provided for position indication. Each hydro-electric set has also six fault indicating devices. Abnormal conditions are automatically indicated in the control station where a klaxon sounds and luminous signals announce the nature of the trouble. A push-button beside each signal permits the fault indication to be cleared and the klaxon to be cut out. In the arrangement of the connections position indication is given preference over control operations, while position indicating impulses imparted simultaneously are accumulated. Moreover, direct telephone communication can be established between the two stations. A supervisory device incorporated in the remote control equipment indicates interruptions in the transmission lines and also failure of the auxiliary supply.

(MS 829) *W. Kissling. (E. G. W.)*

THE CALCULATION OF TRANSIENT PHENOMENA IN SIMPLE CIRCUITS WITH RESISTANCES VARYING WITH THE APPLIED VOLTAGE.

Decimal Index 537.311.3

In the present article, it is shown how the calculation of transient phenomena in simple circuits containing resistances varying with the applied voltage can be carried out in a very clear manner, if the resistance characteristic is expressed in the form of a logarithmic function.

I. INTRODUCTION.

THE great advances which have been made in the last few years in the manufacture of Brown Boveri arrestors, have been due mainly to the continued development of resistances, the value of which varies with the applied voltage.[1] Variable resistances have shown themselves to be absolutely reliable components for this application, and it is not beyond the bounds of possibility that they may also prove serviceable and appropriate for other applications. Before, however, being able to consider such applications seriously, it is essential to be able to understand the nature of the stresses occurring and of the phenomena taking place, and to be able to determine them as accurately as possible. The treatment by exact mathematical methods of problems relating to electric circuits with variable resistances is not usually possible, because only in the rarest of cases is it feasible to solve the fundamental differential equations involved: nor can the superposition principle be applied to circuits containing such resistances. Recourse has therefore to be taken to methods of approximation such, for instance, as graphical integration, or step by step calculation. If, however, a suitable formula can be found to fit the resistance characteristic, then, as shown below, an accurate calculation is possible, at least for the simple, but important cases of circuits containing an EMF, an inductance and the resistance, the value of which varies with the impressed voltage, or a circuit containing an EMF, a capacity and the variable resistance.

It is usual, in technical literature, to express the characteristic of the resistance by a power law in the form $u = k \cdot i^b$, and Th. Brownlee[2], basing on this assumption, has worked out the solution for the above two cases. The results thus obtained are, however, very unwieldy (for instance, time is expressed as a power series function of i). As, however, every

[1] The Brown Boveri Review 1940, No. 12, p. 243. Bull. SEV 1941, No. 25, p. 692.

[2] Gen. El. Rev. Vol. 37, 1934, p. 179.

mathematical formulation of the characteristic represents merely a close approximation to the real characteristic over a more or less extended range, it might prove advantageous to choose another form of expression. The condition to be observed is that it shall represent the characteristic sufficiently closely over the range under consideration and that it shall provide a simple and clear solution for the most important phenomena. In the following we shall represent the resistance characteristic by the logarithmic function

$$u_w = \alpha \log_e (\beta i + 1) \qquad (1)$$

where α and β are the constants of the resistance, and it will be shown that this formula allows of a practical and clear representation of the phenomena studied.

II. CIRCUIT CONTAINING AN EMF, AN INDUCTANCE AND A VARIABLE RESISTANCE IN SERIES.

We consider a circuit according to Fig. 1, where a variable resistance W, an inductance L and an EMF e, which latter may assume the value 0, are connected in series.

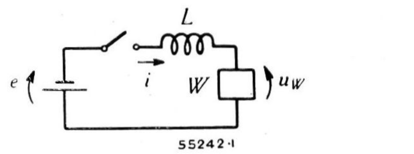

Fig. 1. — Series circuit containing an EMF, an inductance, and a variable resistance.

e. EMF. *W*. Variable resistance.
L. Inductance. u_w. Voltage across resistance.

The calculation of this particular case has already been published elsewhere[1] in connection with a special problem; the solution is, however, briefly repeated here for the sake of completeness as well as for explaining somewhat more closely the validity of solution range.

The differential equation applying is

$$L \frac{di}{dt} = e - u_w \qquad (2)$$

If the following substitution is made for the EMF

$$e = -\alpha \log_e \mu \text{ i. e. } \mu = \varepsilon^{-\frac{e}{\alpha}} \qquad (3)$$

then we obtain upon integration:

$$\underline{\mathrm{li}\,[\mu(\beta i + 1)] = \frac{\alpha\mu\beta}{L}(t - t_0)} \qquad (4)$$

The function $y = \mathrm{li}\,(x)$ is known as the logarithmic integral, and equation (4) gives the required general relation between the current i and the time t. The time scale is, in this representation, linear, and the current scale is also linear at least in the higher ranges ($\beta i >> 1$). As shown by Fig. 2, the logarithmic integral function presents a discontinuity extending to

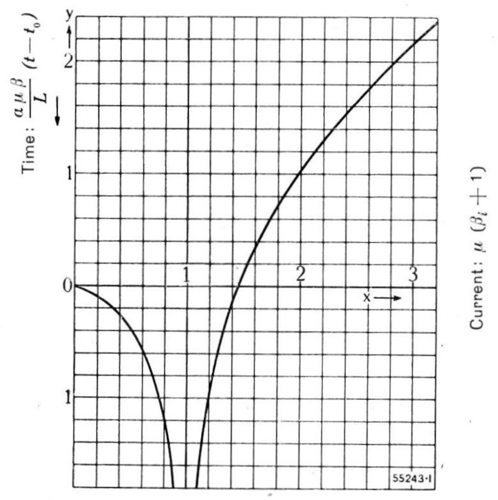

Fig. 2. — Logarithmic integral $y = \mathrm{li}\,(x)$.

The curve contains the relation between current and time for the circuit of Fig. 1.

infinity for the abscissæ $x = 1$; the value of the current i_∞ corresponding to this point where $x = \mu\;(\beta i_\infty + 1) = 1$ is, therefore, only attained after an infinite time. This is simply the steady current: $i_{stat} = i_\infty$ flowing under the influence of the EMF e. Depending upon the initial conditions, i. e., on whether the initial value i_o of the current i is smaller or greater than the final value i_{stat}, the current follows the corresponding part of the curve to the left or to the right of the vertical asymptote $x = 1$, to approach the final value.

It remains to be shown, that the relation (4) enables the entire range of possible currents to be covered. In this connection, it should be noted that the equation (1) representing the characteristic of the resistance

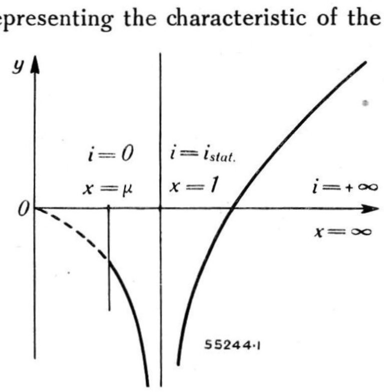

Fig. 3. — Diagram showing the range of positive currents for the curves of Fig. 2.

This range corresponds here to the part of the curves drawn in heavy line.

[1] Bull. SEV 1942, No. 4, p. 94.

is not symmetrical relatively to the origin; it would therefore yield different voltages for positive and negative currents and it is accordingly defined as applying to positive currents only. In consequence, equation (4) is only valid for positive currents, i. e., between the limits $i = \infty$ and $i = 0$ or $x = \infty$ and $x = \mu$, as illustrated in Fig. 3. Negative values of the current i can be handled by substituting into equation (2) the value $-i'$ for i and $-u'_w$ for u_w. Hence

$$-L\frac{di'}{dt} = e + u'_w = \alpha \log_e \left(\frac{\beta i' + 1}{\mu}\right).$$

This gives the same result as the former derivation, if μ is replaced by $\frac{1}{\mu'}$, that is if the sign of the EMF is reversed in the previous calculations, as can also

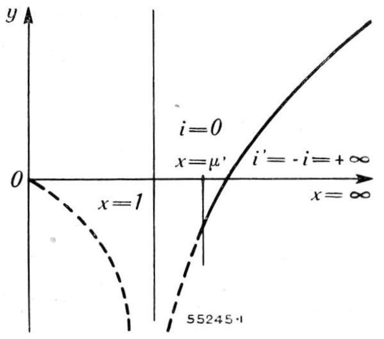

Fig. 4. — Diagram showing the range of negative currents of Fig. 2. This range corresponds to the part of the curve drawn in heavy line.

be seen from an inspection of Fig. 1. The range of negative currents is, therefore, represented by the part of the curve between the values $x = \infty$ and $x = \mu'$, and the reciprocal of μ' must be substituted for μ in the scales for current and time (Fig. 4).

III. CIRCUIT CONTAINING AN EMF, A CAPACITY AND A VARIABLE RESISTANCE IN SERIES.

We consider next a circuit according to Fig. 5, wherein a variable resistance W, a capacity C and a constant EMF e, are connected in series. Let the

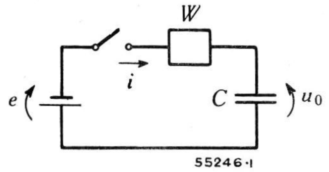

Fig. 5. — Series circuit containing an EMF, a capacity and a variable resistance.

e. EMF. *C.* Capacity. *W.* Variable resistance.

capacity be charged to an initial voltage u_o. Then assuming a resistance characteristic according to equation (1), the following relation holds for the transient phenomena:

$$(e - u_o) = \alpha \log_e (\beta i + 1) + \int \frac{i}{C}\, dt \qquad (5)$$

$$0 = \frac{i}{C} + \frac{\alpha\beta}{\beta i + 1}\frac{di}{dt} \qquad (6)$$

From which we obtain by separation of the variables and by integration

$$-\int \frac{\alpha\beta C}{(\beta i + 1) i}\, di = \int dt$$

$$-\alpha\beta C \log_e\left(\frac{\beta i}{\beta i + 1}\right) = t - t_o \qquad (7)$$

or written in a different form:

$$t - t_o = \alpha\beta C \log_e\left(\frac{\beta i + 1}{\beta i}\right) = 2\alpha\beta C \operatorname{arc\,coth}(2\beta i + 1) \qquad (7a)$$

Whence $$2\beta i + 1 = \coth\left(\frac{t - t_o}{2\alpha\beta C}\right)$$

$$i = \frac{1}{2\beta}\left[\coth\left(\frac{t - t_o}{2\alpha\beta C}\right) - 1\right] \qquad (8)$$

The variation of the current can, therefore, in this case also be represented by a common curve, valid for every case, namely by a hyperbolic cotangent curve.

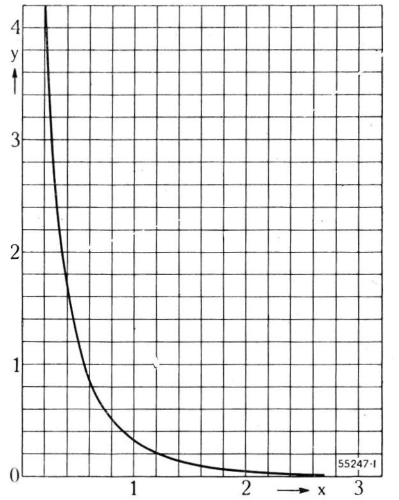

Fig. 6. — Curve showing the function $y = \coth x - 1$. The curve represents the relation between the current and the time for the circuit illustrated in Fig. 5.

The curve illustrating the function $y = \coth x - 1$ has been plotted in Fig. 6. By suitably choosing the scale, this curve can be used to represent the behaviour of the current in every case; the current and time scales are here linear. According to this curve, the current always falls to 0, whether or not the condenser possessed an initial charge or whether or not in the first case an EMF was present. This includes, therefore, also the important case of a surge generator in which a capacity is discharged through a resistance, the value of which is a function of the voltage. In addition to the case already considered of $e > u_o$, the result also holds good for the case $u_o > e$, as the differential equation is independent thereof; this is evident, as the problem is just the same, whatever the direction in which the equalization of the two voltages takes place.

The following relation for the duration of semi-amplitude is also of interest. Inserting for the current the values $i = i_o$ and $i = \frac{i_o}{2}$, and for the times $t = t_1$ and $t = t_2$, then $T_H = t_2 - t_1$, and we obtain

$$\underline{T_H = 2\,\alpha\,\beta\,C \operatorname{arc\,coth}(2\,\beta\,i_o + 3)} \qquad (9)$$

or written in other form

$$\underline{T_H = \alpha\,\beta\,C \log_e \left(\frac{\beta\,i_o + 2}{\beta\,i_o + 1}\right)} \qquad (10)$$

The semi-amplitude duration can, therefore, be quite easily calculated from the resistance constants α, β, the capacity C, and the value of the initial current i_o, which with given initial values of the voltages e and u_o, can immediately be obtained from the characteristic (1). For direct calculation equation (10) would be convenient; with the aid of Fig. 6 and of equation (9) the semi-amplitude duration may be determined directly as follows. In Fig. 6 the function $y = \coth x - 1$ has been drawn, therefore, $x = \operatorname{arc\,coth}(y + 1)$ and the required value $\frac{T_H}{2\,\alpha\,\beta\,C}$ is therefore given by the abscissæ value of x corresponding to the ordinate $y = 2\,\beta\,i_o + 2$.

IV. OTHER TYPES OF CIRCUIT.

As already mentioned in the introduction, it is not usually possible to treat transient phenomena in more complicated circuits by mathematical means. It has, in particular, hitherto not been possible to solve the important cases of circuits containing both inductance and capacity in a similar general manner, and in such cases only methods of approximation remain available. Moreover, it is clear that a mathematical solution, even if attainable, would assume a highly complicated form, because due to the variation of the resistance with the voltage, several transitions from periodic to aperiodic behaviour or vice versa might take place during the course of a single event. In the two relatively simple cases in which a constant resistance of such magnitude that it cannot be neglected, is added to the circuits shown in Fig. 1 and Fig. 5, the solution is most simply obtained by expressing the *resulting* characteristic of the combined resistances in the form of an equivalent characteristic according to equation (1).

(MS 868) *Dr. H. Meyer. (Hv.)*

ADDITIONAL LOSSES IN TRANSFORMERS AND MACHINES FEEDING MUTATORS.

Decimal Index 621.314.21 : 621.314.65
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The electrical phenomena occurring in transformers and machines supplying mutators are described and expressed mathematically with the help of Fourier's analysis. A number of test results prove the correctness of the theoretical considerations.

INTRODUCTION.

AN alternating-current system generally comprises elements such as synchronous machines, transformers, overhead lines, underground cables, induction machines, and apparatus having the same effect as load resistors (e. g., lighting equipments, radiators, and furnaces). Notwithstanding their diversity all of these apparatus have something in common, viz., that, given no-load conditions, all electrical magnitudes, voltages and currents, occurring at any point in the system are sinusoidal functions of time at the fundamental frequency of the system. This remarkable property is a result of the linear function of the three following fundamental laws which ultimately govern all of these phenomena:—

Ohm's law:	$e = r \times i$
The law of induction:	$e = -l \times \frac{di}{dt}$
The law governing the displacement currents in dielectrics:	$e = \frac{1}{c}\int i \times dt$

One single apparatus, which made its appearance in industrial systems scarcely twenty years ago, has upset these harmonious conditions. This is the mutator. By reason of its valve action this must be treated as a current interrupting apparatus with special properties. From its very nature, therefore, the mutator can only take "chopped" currents, or in other words produce harmonics. This is the chief obstacle the mutator had to surmount to conquer a place in a field previously monopolized by transformers and machines.

The purpose of this article is to describe the effect of mutators on the transformers and machines feeding them and to enumerate the measures necessary to confine the drawbacks to an admissible degree.

It is only just recently that the questions raised here have really become of any great importance, for as long as mutator ratings represented only a small proportion of the installed power of the system there was no reason to fear any noxious effects. With the advent of electrolysis plants with ratings up to 100 MW, more attention was paid to this problem. However, it is direct-current transmission over long distances, with double conversion from a.c. to d.c. and d.c. to a.c. by means of mutators, which presents the problem in all its acuity, at least as far as machines are concerned. In point of fact, it cannot now be left out of consideration that at some future date the whole of the three-phase power generated by a power station — or even a group of stations — may possibly be fed into a d.c. transmission line.

I. GENERAL.

In this first part the principles governing the current distortion in a system supplying mutators will be briefly described and an effort made to explain how this distortion produces abnormal additional losses.

(a) *Current Distortion in Systems supplying Mutators.*

This question has frequently been dealt with in technical literature[1] and for this reason only a cursory recapitulation of generally accepted facts will be given here. In order to determine the currents in the system the anode currents must be taken as base. These are periodic rectified currents and apart from numerous harmonics, therefore, have a mean value differing from zero. This harmonic of zero order leads one to presume that harmonics of even power are also present, which is corroborated by closer study of these phenomena.

The transformer currents on the mutator side are obtained simply by superposing the anode currents. During this operation certain harmonics may compensate one another, but no new ones can occur.

The transformer currents on the three-phase side, as well as the line currents, are determined in a similar manner in virtue of the law of compensation of the ampere-turns on each limb (this law is rigorous except for the magnetizing current). In the course of this additive operation certain harmonics may also disappear, but new ones cannot arise. These elementary considerations will suffice to show that the current distortion becomes less pronounced the greater the distance from the mutator and the shorter the distance to the alternators. In order to keep this study general neither the capacity of the systems nor the resulting displacement currents will be taken into account. This does not preclude these phenomena having to be taken into consideration (at least partially) in certain special cases, however.

In all these instances it is indispensable to take account of the overlapping, i. e., the phenomenon occurring in a mutator when the arc passes from one anode to another. The interval of time involved is termed the angle of overlap, expressed in electrical degrees. Due to this overlapping the anode-current wave fronts and tails become much less steep and the amplitude of the higher harmonics is thus substantially reduced.

In this respect, direct-current transmission with conversion from three-phase a.c. to d.c. and back again to a.c. by means of mutators, deserves special mention. If, for instance, the alternators and transformers have the same ratings as the mutators they feed, the reactance of the three-phase system as far as the mutator terminals and referred to the rated impedance (i. e., the quotient obtained by dividing the rated voltage by the rated current) is very high — of the order of 30 % —

[1] See:

L. Lebrecht: "Stromrichterbelastung der Hochspannungsnetze." ETZ 56 (1935), p. 957.

W. Leuckert and E. Kübler: "Oberwellenbelastung von Drehstromnetzen durch Stromrichter." E. & M. 54 (1936), p. 37.

E. Kübler: "Oberwellengrundgesetze der Stromrichtertechnik in physikalischer Ableitung." E. & M. 55 (1937), p. 457.

G. Laurent: "Le redresseur à vapeur de mercure envisagé dans ses rapports avec le réseau d'alimentation." RGE 44 (1938), p. 47.

E. Fässler: "Die Stromoberwellen auf der Wechselstromseite von Stromrichtern." Arch. f. Elektrotechn. 32 (1938), p. 640.

E. Fässler: "Der Einfluss von Oberwellen im Drehstromnetz auf die Harmonischen der Gleichspannung und des Netzstromes von Stromrichtern." Arch. f. Elektrotechn. 34 (1940), p. 209.

Schilling: "Die Gleichrichterschaltungen."

because the leakage reactances of the alternators are added integrally to the short-circuit reactances of the transformers. Under these conditions an exceptionally large angle of overlap is to be anticipated, inasmuch as a large reactance necessarily involves slow commutation from one anode to the other.

As an example of the foregoing the spectrum of the harmonics of the three-phase currents of a mutator with twelve-phase connection is shown in Fig. 1, the

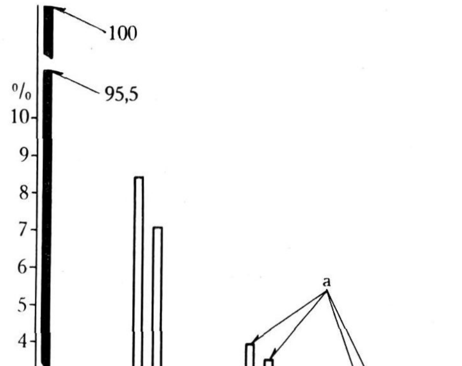

Fig. 1. — Influence of overlapping on the harmonic spectrum of the three-phase currents of a mutator set with twelve-phase connection. Ideal conducting period of anode = 180°.

Abscissa: Order of harmonics.

Ordinate: Amplitude of harmonics expressed as multiple of fundamental wave.

a. Harmonic spectrum for an angle of overlap of 0°.

b. Harmonic spectrum for an angle of overlap of 45°.

This diagram shows how a large angle of overlap reduces the amplitude of the higher harmonics. The amplitudes of the fundamental wave are not to scale.

anode conducting period being the ideal one of 180°. The harmonic analysis was made under the assumption of angles of overlap of 0° and 45°. Comparison of the two curves in Fig. 1 shows very clearly the reduction in the amplitude of the higher harmonics with increasing angle of overlap.

(b) *Additional Losses involved by distorted Mutator Currents.*

In the preceding section it was seen that mutators betray their presence in a three-phase system through the different currents encountered being more or less deformed. In the very first place, therefore, an effort must be made to discover what effects such currents will have on transformers and machines. The resulting phenomena are of a very diverse nature, but only the additional load losses will be chiefly considered here.

Inasmuch as these losses are caused by the variation of the current in time the effect will be all the more pronounced, i. e., the current all the more deformed, the greater the rapidity of the variations. In consequence, it is to be anticipated that mutators will cause non-negligible additional losses in transformers and machines feeding them.

In studying these phenomena it is particularly convenient to have recourse to Fourier's analysis both for predetermining the losses mathematically and for experimental research. As long as the saturation phenoma are neglected it can be assumed that the density of the eddy currents at any point equals the sum of the densities resulting from each harmonic separately. Moreover, it is known that the root mean square of a sum of sinusoidal functions of mutually different frequencies equals the sum of the root mean square values of each sinusoidal function. Hence one is justified in determining the losses for each harmonic separately and adding the individual results to obtain the true losses accruing from the distorted currents.

A diagrammatic example, making use of the foregoing method, will serve as an illustration of the additional losses involved by distorted currents.

Let it be assumed that an anode current with a trapezoidal characteristic is flowing through a rectangular bar of copper lying in the open slot of a machine

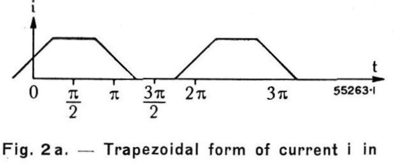

Fig. 2a. — Trapezoidal form of current i in conductor in function of time t.

Cycle = 2π.
Ideal conducting period of anode = π.
Overlapping = $\pi/2$.

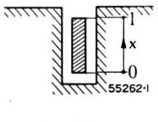

Fig. 2b. Arrangement of conductor in slot; x = Running coordinate.

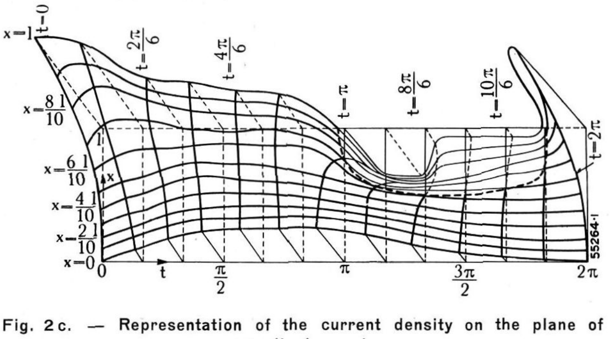

Fig. 2c. — Representation of the current density on the plane of coordinates x, t.

It will be noticed that the tendency is for the current to be forced away from the base of the slot and to be concentrated towards the exterior. Further it will be seen that the phenomenon is much more pronounced for the higher harmonics than for the fundamental wave.

Fig. 2. — Concentration of the current lines in a rectangular current conductor embedded in an open slot and carrying a trapezoidal current.

(Fig. 2a), the anode conducting period being the ideal one of 180° and the angle of overlap 45°. For every level x of the bar in the slot and every time t there is a definite current density which has been calculated for each harmonic successively in accordance with Field's classical method. The result is represented in Fig. 2 as follows:—

At each point x, t on the plane of the coordinates x, t a vector proportional to the current density at the point in question is drawn perpendicular to this plane and thus a surface obtained. An axonometric representation of this surface is given in Fig. 2 by means of a double family of curves for $x =$ constant and $t =$ constant. It will immediately be clear that on the whole the current is repelled from the base of the slot (zone $x = 0$) and concentrated near the opening (zone $x = l$). It will also be noticed that this phenomenon is all the more pronounced the higher the order of the harmonics, practically only the fundamental wave being found at the base of the slot. Finally, the opinion widely held that the concentration of the current only takes place during commutation, is proved to be entirely erroneous.

II. ADDITIONAL LOSSES IN MUTATOR TRANSFORMERS.

An attempt will now be made to show how these phenomena can be determined mathematically and subsequently how the experimental method may be usefully applied. This part will be concluded with the enumeration of measures capable of reducing the additional losses and also of suggested rules for incorporation in mutator transformer test specifications.[1]

(a) *The Leakage Fields in Mutator Transformers.*

In order to obtain as clear an idea as possible of the phenomena occurring in a transformer feeding one or several mutators recourse will be had to Fourier's analysis. No effort will be made to represent the variation of the true leakage field, however, the

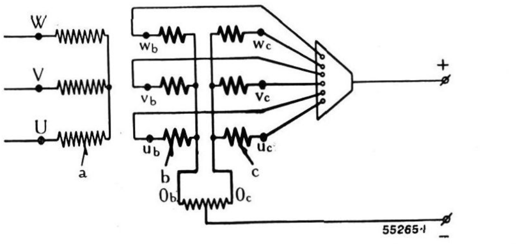

Fig. 3. — **Connection of mutator transformer in star/double-star with interphase transformer.**

a. Winding on three-phase side.
b. First winding on mutator side.
c. Second winding on mutator side.

This connection is frequently employed for heavy currents, e. g., for electrolysis plants.

analysis of the phenomena being confined to each harmonic separately.

It is intended to consider the star/double-star connection with interphase transformer (Fig. 3) which is frequently used in conjunction with heavy-current mutators for electrolysis plants, i. e., the very cases in which the question of additional losses is of greatest importance on account of the big copper cross-sections. Fig. 4 shows in diagrammatic form the arrangement of the windings on one limb of such a transformer. The two windings on the mutator side are strictly symmetrical with regard to the three-phase winding.

The anode currents delivered by the windings b and c are of the same magnitude, one being merely

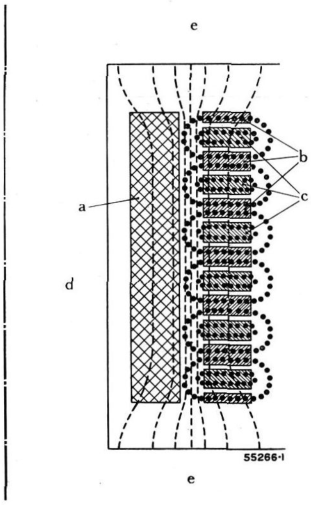

Fig. 4. — **Diagrammatic arrangement of windings of a mutator transformer on one limb.**

a. Winding on three-phase side.
b. First winding on mutator side.
c. Second winding on mutator side.
d. Core.
e. Yoke.

.... *Lines of force of leakage field produced by even harmonics.*
----- Lines of force of leakage field produced by odd harmonics.

The leakage field produced by the even harmonics lies radially, that of the odd harmonics axially.

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[1] J. Kübler: "Ueber die Messung der Einzelverluste bei Mutator-Transformatoren." Bulletin SEV, 25th May, 1938. Correspondence concerning above article, Bulletin SEV, 17th August, 1938.

P. Waldvogel: "Beitrag zur Frage der Kupferverlustmessung bei Mutator-Transformatoren, speziell mit Gabelschaltung." Bulletin SEV, 9th November, 1938.

H. G. Nolen: "Die Kupferverluste bei Mutator-Transformatoren." Bulletin SEV, 19th July, 1939.

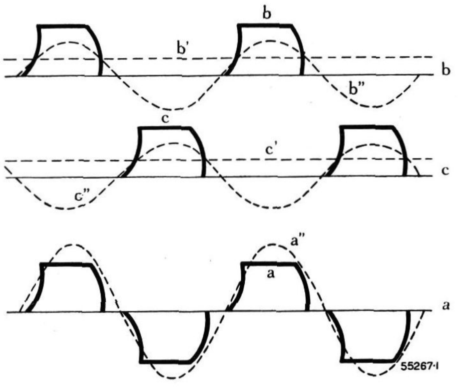

Fig. 5. — **Form of currents in windings of a mutator transformer on the mutator and three-phase sides.**

b. Form of current in the first winding on mutator side.
c. Form of current in the second winding on mutator side.
b—c = a. *Form of current in three-phase winding.*
b' and c'. D. C. components (even harmonic).
a", b" and c". Fundamental wave (odd harmonic).

The compensation of the even harmonics is achieved by combination of the two windings on the mutator side, that of the odd harmonics by combination of the two windings on the mutator side on the one hand and of the three-phase winding on the other.

displaced by half a cycle in relation to the other. (In conformity with Fig. 2 these currents are to be considered as positive in the direction neutral → anode). If the ampere-turns of the windings *b* and *c* are now considered as a whole, i. e., if the difference between the two currents is determined (Fig. 5), it will be found that the even harmonics (including the d. c. components) offset one another and that the odd harmonics (including the fundamental wave) sum up integrally. Inasmuch as, in virtue of the law of compensation of ampere-turns, the difference between the two anode currents gives the current on the three-phase side it can be concluded that:

1. The compensation of the even harmonics is achieved through the combination of the two windings on the mutator side.
2. The compensation of the odd harmonics is achieved by the combination of the two windings on the mutator side on the one hand and the three-phase winding on the other.

With the arrangement of the windings shown in Fig. 4 the leakage field of the odd harmonics occurs in the axial channel existing between the three-phase winding on the one hand and the two windings on the mutator side on the other. The leakage field of the even harmonics, however, is located in the lateral channels between the two windings on the mutator side.

(b) *Calculation of the Additional Losses.*

Now that a clear representation of the leakage field of each harmonic has been obtained the calculation of the losses corresponding to each of these harmonics by Field's classical theory will present no difficulties.

By way of example we have calculated the copper losses of a 7900/11,100 kVA, 16,000/6 × 612 V, 25-cycle transformer with star/double-star connection and interphase transformer delivering a direct current of 10,700 A. The anode currents were assumed to be trapezoidal in form, although an anode current characteristic more in conformity with actual conditions might just as well have been taken. The angle of overlap Θ was selected as parameter. The method of calculation is then as follows:—

A value is assumed for the anode current and the different even and odd harmonics determined. Given the arrangement of the windings *b* and *c* in alternate coils, the "reduced height" of the copper must first be determined in accordance with Field's theory for each harmonic separately, and then the loss increment factor referred to the ohmic losses and subsequently the true losses entailed by these harmonics, deduced. Thereupon, in view of the concentric arrangement of the winding *a* on the one hand and windings *b* and *c* on the other, the "reduced height" of the copper *a* and *b* or *c* must be determined for each odd harmonic separately by the same method, and then the loss increment factor referred to the ohmic losses and subsequently the true losses entailed by these harmonics, deduced. The true losses are obtained by simple superposition of the losses of each individual harmonic, as illustrated by the stepped curves in Fig. 6. The ordinate at the origin gives the ohmic losses of the d. c. component, while the "steps" in the values of the ordinates represent the effective losses due to the corresponding harmonics.

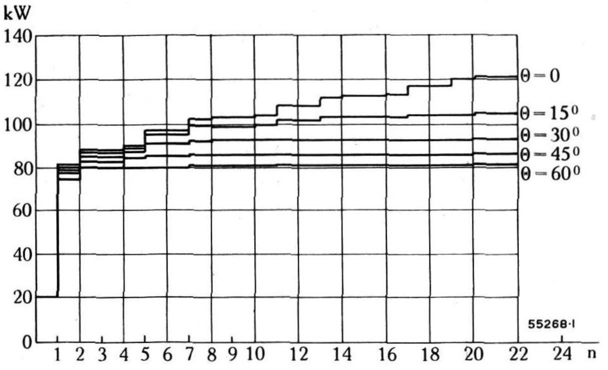

Fig. 6. — **True copper losses of a mutator transformer calculated for each current harmonic.**

Abscissa n. Order of harmonic.
Ordinate kW. Calculated true losses.
Parameter Θ. Angle of overlap.

The "steps" on the ordinates represent the losses actually due to the harmonics in question. The limits towards which the loss curve for $n = \infty$ tends give the true total losses. This diagram clearly shows the effect of overlapping on the losses.

These calculations were made for five values of the angle of overlap. The limiting value towards which the curves tend asymtotically for n = infinity represents the true losses of a transformer feeding mutators.

From Fig. 5 it will immediately be clear that overlapping has a decisive bearing on the additional losses. In point of fact, its importance is such that if calculation is limited to the twentieth harmonic, for $\Theta = 0°$, the possibility of the cessation of the rises in the loss curve is not perceptible, although it is possible to prove mathematically that such a point exists. After all, this result was only to be anticipated from the general considerations under subheading (a) of part I.

The final results of the above-mentioned calculations are as follows:—

For $\Theta = 0°$ true losses = ?
(extrapolation impossible).
For $\Theta = 15°$ true losses = 106 kW
of which 21·3 kW additional losses.
For $\Theta = 30°$ true losses = 94 kW
of which 13·0 kW additional losses.
For $\Theta = 45°$ true losses = 87 kW
of which 9·6 kW additional losses.
For $\Theta = 60°$ true losses = 82 kW
of which 8·1 kW additional losses.

(c) *Results of a Number of Tests for the Determination of Additional Losses.*

Inasmuch as it is hardly possible to contest the validity of the principle of superposition employed in the method of calculation indicated in the foregoing section, it was only natural that the experimental investigations should also be conducted with a view to determining the additional losses involved by each individual harmonic.

For the transformer connections in Fig. 3, for instance, pairs of diametrically opposite terminals on the mutator side were coupled together ($u_b\,u_c$ — $v_b\,v_c$ — $w_b\,w_c$), and then

in a first series of tests the three-phase terminals UVW,

in a second series of tests the terminals $u_b\,u_c$ — $v_b\,v_c$ — $w_b\,w_c$ (leaving open the terminals UVW) connected to a three-phase supply with rising frequency.[1]

It will be seen that the first series of tests fulfils the conditions of the odd harmonics and the second those of the even.

The only difficulty inherent in these measurements is the high degree of accuracy involved. (For low frequencies, for instance, the additional losses are rendered practically imperceptible by the ohmic losses.) For this reason, we resorted to our zero method with bridge connection which has already amply proved its worth[2]. Figs. 7a and 7b give, for example, the results of measurements carried out on the transformer serving as basis for the calculations in the foregoing section. Calculations and measurements agree to an entirely satisfactory degree.

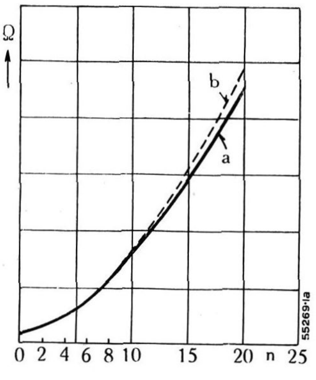

Fig. 7a. — Three-phase winding supplied, two half-windings on mutator side short-circuited.

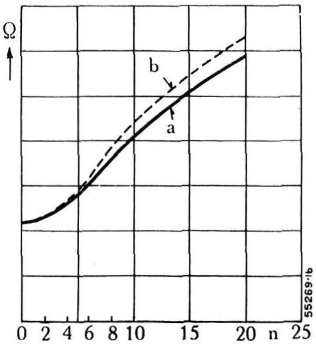

Fig. 7b. — Two half-windings on mutator side supplied in opposition, three-phase winding open.

Curves a: Measured results. Curves b: Calculated results.

In the case of the transformer considered the effective resistance increases rapidly with the frequency of the harmonics when the concentric arrangement of the winding is adopted and relatively slowly with disc windings. The agreement between the calculated and measured results is very gratifying.

Fig. 7. — Effective resistance of one phase of a short-circuited mutator transformer in function of the supply frequency or order n of harmonics considered.

Apart from the tests described above, which were repeated on a certain number of transformers, an effort was made to measure the copper losses of a mutator transformer directly. This test was carried out on a limb with three windings, the one being a three-phase winding and the two others those on the mutator side arranged symmetrically to the first winding in accordance with the standard three-phase/six-phase connection. The three-phase winding was short-circuited and the two windings on the mutator side were made to carry the anode currents of two opposite phases of a six-phase

[1] The idea of conducting tests of this kind doubtless originated with J. Kübler who wrote in the previously mentioned article (Bulletin SEV, 25th May, 1938, p. 279) as follows:—

"If it is desired to measure the additional losses produced by the even harmonics, parts of the secondary winding should be fed with current of the corresponding higher harmonics and other, correctly selected parts of the winding short-circuited."

[2] P. Waldvogel: "A new High-precision Method for Short-circuit Measurements on Transformers." The Brown Boveri Review 1942, p. 126.

mutator plant (Fig. 8a). This arrangement corresponded exactly to the working conditions of a mutator transformer with the exception of the flux in the core and the losses involved thereby, which were not present. The losses, which might be termed "load losses", were measured at the terminals of the two windings on the mutator side with two wattmeters and checked by a calorimetric method, every precaution being taken to ensure the requisite accuracy. Finally, in order to magnify the additional losses as compared to the ohmic losses a supply frequency of 100 cycles was selected. Three different tests with three different angles of overlap Θ were carried out, during which the ideal conducting period was left unchanged at

This test thoroughly corroborated both the preceding theoretical considerations and the method of calculation employed, and also fully confirmed the important influence of overlapping on the additional losses.

(d) *Practical Methods of Experimental Determination of Additional Losses.*

The question of the experimental determination of the additional losses in a mutator transformer is certainly very delicate, and for this reason much has already been written on the subject. The problem is to find a simple practical method by which the losses occurring in a transformer operating in conjunction with mutators can be derived from tests with

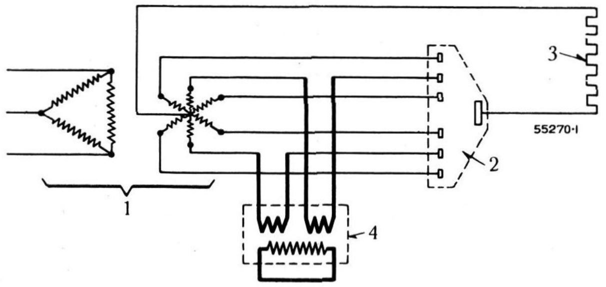

Fig. 8. — **Measurement of load losses in one limb of a mutator transformer, i. e., with currents in windings corresponding to operation in conjunction with mutators.**

Fig. 8a.

1. Auxiliary transformer feeding a mutator.
2. Six-phase mutator.
3. Load resistor for d. c.
4. Limb of test transformer with two windings on mutator side and one three-phase winding short-circuited on itself.

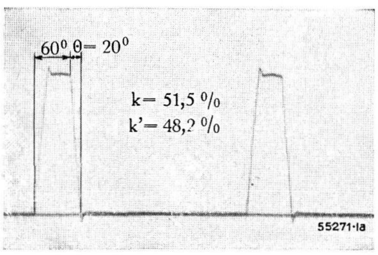

Fig. 8b.

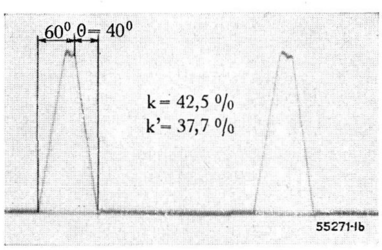

Fig. 8c.

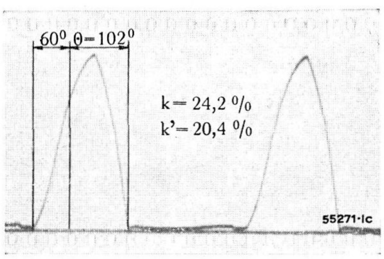

Fig. 8d.

Oscillogram of anode currents flowing in test transformer.

k. Value of measured additional losses in percentage of ohmic losses.
k'. Value of calculated additional losses in percentage of ohmic losses.
Θ. Value of angle of overlap.
60°. Ideal conducting period of anode.

This test shows how, with other conditions unchanged, the losses depend on the angle of overlap. It forms an excellent check on the method of calculation mentioned.

60^0 and the effective currents in the three windings maintained constant. As a result the following values k for the additional losses, expressed as a percentage of the ohmic losses, were obtained:—

	$\Theta = 20^0$	$\Theta = 40^0$	$\Theta = 102^0$
k (measured value)	51·5	42·5	24·2
k' (value calculated by method in section IIb)	48·2	37·7	20·4

sinusoidal currents (the only form of current which can be readily generated). The method sought must be capable of application to all designs, inasmuch as only one which fulfils all these conditions can be embodied in rules governing acceptance tests.

Only two methods, conforming to the decisions of the experts of Committee No. 22 of the I. E. C. at Zurich in 1938, will be mentioned here: With the one only half of the windings on the mutator side are short-circuited, with the other all of the windings. The following notes, which can be applied to the special case of the double-star six-phase connection, will show that neither the one nor the other are entirely satisfactory. The first method produces a leakage field which is neither that of the odd nor that of the even harmonics, while the second only produces the leakage field of the odd harmonics without taking that of the even into account.

The principle of a new method will now be expounded which, although recourse must be had to a number of approximations, has at least the advantage of being built up on an entirely scientific basis. The connections to be established are shown in Fig. 9. The anode terminals which are mutually opposed in the voltage vector diagram are connected in pairs by three mutually insulated short-circuiting connections denoted u, v, and w. In the first test the three terminals U, V, and W of the three-phase side are connected to a supply at the fundamental frequency; after deduction of the ohmic losses the additional losses ΔP_I, corresponding to the current of the fundamental wave, are obtained. In the second test, with terminals U, V, and W open, a supply with twice the fundamental frequency is connected to terminals u, v, and w; in this way, after deducting the ohmic losses, the additional losses ΔP_{II}, corresponding to the current of the second harmonic, are obtained. (It will be quite clear that there is no current through the interphase transformer in either case.)

Let $p \ldots$ now represent the series of whole numbers denoting the order of the harmonic currents flowing on the three-phase side and designated x_p; these are referred to the current of the fundamental wave. Further, let $q \ldots$ represent the series of whole numbers denoting the order of the harmonic currents only flowing on the mutator side, i. e., not affecting the three-phase side, and designated y_q; these are referred to the current of the second harmonic. With these denotations the losses involved by the harmonic p would then be $\Delta P_I \times x_p^{\,2}$ if the apparent increase of resistance due to the eddy currents were independent of the frequency. In reality, as results from Field's formulæ, this magnitude increases with the square of the frequency as long as the skin effect is not very marked and with the square root of the frequency should the skin effect be extremely pronounced. For the sake of simplicity, assume an exponential law p^{α} with a constant exponent α between $\frac{1}{2}$ and 2, e. g., $\alpha = \frac{3}{2}$. Given these conditions the additional losses produced by the harmonic p are $\Delta P_I \times p^{\frac{3}{2}} \times x_p^{\,2}$. Analogously, the harmonic q produces the additional losses $\Delta P_{II} \times \left(\frac{q}{2}\right)^{\frac{3}{2}} \times y_q^{\,2}$, so that the total additional losses in mutator service are

$$\Delta P = \Delta P_I \times \sum_p p^{\frac{3}{2}} \times x_p^{\,2} + \Delta P_{II} \times \sum_q \left(\frac{q}{2}\right)^{\frac{3}{2}} \times y_q^{\,2}$$

The two sums

$$\sum_p p^{\frac{3}{2}} \times x_p^{\,2} = x \text{ and } \sum_q \left(\frac{q}{2}\right)^{\frac{3}{2}} \times y_q^{\,2} = y$$

can be calculated as soon as the form of the anode currents has been laid down, i. e., in particular the value of the angle of overlap if trapezoidal currents are retained. A table of the values x and y could thus be set up for all of the more usual transformer connections and the additional losses calculated by the simple formula:

$$\Delta P = x \times \Delta P_I + y \times \Delta P_{II}$$

An example taken from the measurements mentioned in part II c will illustrate the application of the method just outlined. What are the load losses of the transformer previously considered, assuming it delivers a direct current, $I_g = 10{,}700$ A with an angle of overlap of 30°?

A table calculated in advance once and for all and which ought to be incorporated in test specifications in extenso gives the following values:—

Effective value of fundamental wave of anode current

$$= \frac{0{\cdot}2728}{\sqrt{2}} \times I_g$$

Second harmonic of anode current $= \dfrac{0{\cdot}1318}{\sqrt{2}} \times I_g$

Coefficient $x = 1{\cdot}38$. Coefficient $y = 1{\cdot}69$.

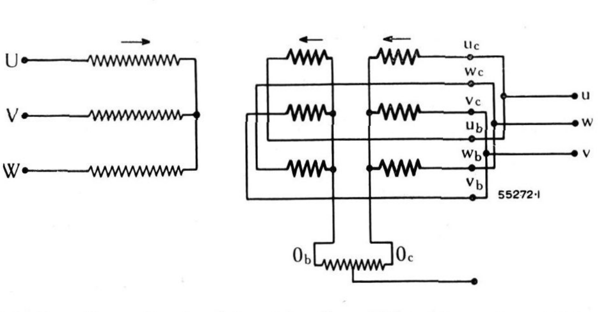

Fig. 9. — Connection for determining the additional losses in a mutator transformer by means of two measurements with sinusoidal currents.

U, V, W. Three-phase terminals.

u_b, u_c, v_b, v_c, w_b, w_c. Anode terminals.

One measurement is made with the fundamental frequency applied at U, V, W and the second with twice the fundamental frequency at u, v, w.

After having established suitable short-circuit connections measurement I is made at 50 cycles with $\frac{0{\cdot}2728}{\sqrt{2}} \times 10{,}700 = 2061$ A, then measurement II at 100 cycles with $\frac{0{\cdot}1318}{\sqrt{2}} \times 10{,}700 = 995$ A.

After deducting the corresponding ohmic losses the additional losses $\Delta P_I = 7{\cdot}240$ kW and $\Delta P_{II} = 0{\cdot}370$ kW are obtained, whence the additional losses in mutator service are

$$\Delta P = 1{\cdot}38 \times 7{\cdot}240 + 1{\cdot}69 \times 0{\cdot}370 = 10{\cdot}6 \text{ kW}.$$

It is an easy matter to calculate the coefficients x and y for other angles of overlap and to deduce the corresponding additional losses, employing the same two tests as previously. These results are tabulated hereafter so as to facilitate comparison with those of other methods.

TABLE I.

Additional Copper Losses in a Transformer

rated 7300/11,100 kVA, 16,000/6×612 V, 25 cycles with star/double-star connection and interphase transformer delivering 10,700 A d. c.

Angle of overlap (electrical degrees)		0°	15°	30°	45°	60°
Additional losses measured by different methods (kW)	α	11·3	10·6	10·2	9·7	9·2
	β	8·2	7·8	7·5	7·2	6·8
	γ	27·8	15·4	10·6	8·5	7·3
Exact losses (kW)	δ	?	21·3	13·0	9·6	8·1

(α) First method proposed by de Blieux with which half of the windings on the mutator side are short-circuited.

(β) Second method with which all of the windings on the mutator side are short-circuited.

(γ) Third, new method involving two three-phase measurements.

(δ) Losses calculated from section II (b) and which can be considered as the exact losses on the basis of the experimental investigations described in section II (c).

From comparison of rows γ and δ in the above table it will be seen that only the new method gives anything like a true idea of the influence of the angle of overlap on the losses. In point of fact, the influence of overlapping is practically imperceptible with methods α and β.

In conclusion, it would perhaps not be out of place to add an experimental justification to the considerations leading to the adoption of this new method, which, notwithstanding its essentially qualitative nature, is extremely convincing. Instead of carrying out tests I and II in succession terminals U, V, and W, and u, v, and w, were simultaneously connected to supplies at the fundamental and twice the fundamental frequency, respectively. The currents flowing through the three windings of a limb under these conditions were oscillographed (Fig. 10). It will be seen that apart from the d. c. component the currents flowing through the different windings have the same form as those actually occurring in mutator service.

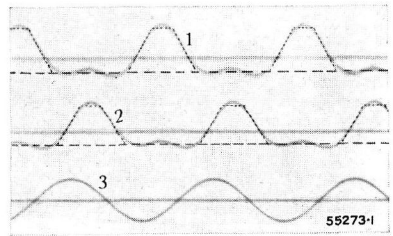

Fig. 10. — Oscillograms of the currents in the three windings of one limb of a mutator transformer when supplied simultaneously with once and twice the fundamental frequency as per diagram in Fig. 9.

1. Resultant current in winding u_b.
2. Resultant current in winding u_c.
3. Current in winding u.

The dotted curves represent the currents in actual mutator service which are approximately similar to those occurring during the tests.

These oscillograms show that the proposed test measurement reproduces true service conditions.

III. ADDITIONAL LOSSES IN SYNCHRONOUS MACHINES OPERATING IN SYSTEMS INCORPORATING MUTATORS.

In this third part the field in the air gap of a machine feeding mutators will be considered in relation to both the stator and rotor, and the leakage fields of such a machine briefly discussed. Thereupon, the question of the pre-determination of the additional load losses and the measures necessary to reduce them will be dealt with, while in order better to be able to substantiate the theoretical considerations a number of experimental results will be given. Remarks on effects other than the increase in losses will finally conclude these notes.[1]

[1] Dr. P. Pohl: "Gefährdung von Generatoren durch Dauerbelastung des Dämpferkäfigs." E. & M. 20th January, 1935.

Dr. P. Pohl: "Belastbarkeit von Generatoren bei Betrieb auf Stromrichter." E. & M. 28th April, 1935.

Erwin Kübler: "Stromrichterbelastung von Generatoren und Drehstromnetzen in vektorieller Darstellung." Wissenschaftliche Veröffentlichungen aus den Siemens-Werken 1939, No. 1.

(a) *The Field in the Air Gap of a Machine feeding Mutators.*

If t denotes time and T a cycle of the fundamental wave the current i_1 of phase 1 can be represented by the following Fourier series:—

$$i_1(t) = \sum_{n=1}^{\infty} a_n \times \text{sine}\left(2\pi n \frac{t}{T} + \varphi_n\right)$$

If x is taken to denote the peripheral abscissa and X the perimeter of the air gap the ampere-turns per centimetre A_1 resulting from the passage of the current i_1 through the winding of phase 1 can be written as follows:—

$$A_1(x,t) \cong \cos\left(\frac{2\pi}{X} \times x\right) \times i_1(t)$$

$$= \cos\left(\frac{2\pi}{X} \times x\right) \times \sum_{n=1}^{\infty} a_n \times \text{sine}\left(2\pi n \frac{t}{T} + \varphi_n\right)$$

This applies to an "ideal" machine which is characterized by the geometrically sinusoidal distribution of the ampere-turns per centimetre.

The expression for the induction B_1 in the air gap produced by the ampere-turns of phase 1 is derived, as is well known, from the expression of the ampere-turns per centimetre A_1 by simply integrating for the variable x:

$$B_1(x,t) \cong \int A_1(x,t) \times dx$$

$$\cong \text{sine}\left(2\pi \frac{x}{X}\right) \times \sum_{n=1}^{\infty} a_n \times \text{sine}\left(2\pi n \frac{t}{T} + \varphi_n\right) \text{ [1]}$$

The windings 2 and 3, geometrically displaced by $\frac{2\pi}{3}$ and $\frac{4\pi}{3}$ compared to the winding 1, carry currents i_2 and i_3 displaced in time by $\frac{2\pi}{3}$ and $\frac{4\pi}{3}$, respectively, compared to i_1, from which result the two fields $B_2(x, t)$ and $B_3(x, t)$. The expressions of these can be readily formulated from the example of the expression for $B_1(x, t)$. The resultant field in the air gap is:

$$B(x,t) = B_1(x,t) + B_2(x,t) + B_3(x,t).$$

After conversion of the sine products of this sum into sums it is seen that only the terms with $n = 3h + 1$ and $n = 3k - 1$ remain (h and k denote all positive whole numbers), all other terms being eliminated.

$$B(x,t) = \frac{3}{2} \sum_{\substack{n = 1, 4, 7, 10, \ldots \\ \text{in general: } n = 3h+1}}^{\infty} a_n \times \cos\left[2\pi \frac{x}{X} - 2\pi n \times \frac{t}{T} - \varphi_n\right]$$

$$- \frac{3}{2} \sum_{\substack{n = 2, 5, 8, 11, \ldots \\ \text{in general: } n = k - 1}}^{\infty} a_n \times \cos\left[2\pi \frac{x}{X} + 2\pi n \frac{t}{T} + \varphi_n\right]$$

The terms of the first sum represent fields rotating in the positive direction at the speed $(3h + 1) \times \frac{X}{T}$ and those of the second sum fields turning in the negative sense at a speed of $(3k - 1) \times \frac{X}{T}$.

Recapitulating, the electromagnetic phenomena in the air gap of a machine with distorted stator currents can be described as follows:—

The 1st, 4th, 7th, 10th, ... harmonics of the stator currents produce fields which are geometrically distributed over a pole pitch and rotate in the positive direction with speeds of 1, 4, 7, 10 .... times the

[1] It would be as well to refer here to the difference existing between an "ideal" and an "actual" machine, when the former delivers a distorted and the latter a sinusoidal current. The ampere-turns per centimetre in the second case are actually a product of a sine function of time, sine $\left(2\pi \times \frac{t}{T}\right)$, with a periodic distorted function of the locus x. The expression for the induction $B_1(x, t)$ in the air gap will therefore be:

$$B_1(x,t) = \text{sine}\left(2\pi \frac{t}{T}\right) \times \sum_{p=1}^{\infty} b_p \times \text{sine}\left(2\pi p \frac{x}{X} + \varphi_p\right)$$

The harmonic fields may be termed "geometrical" or of first order; these extend over fractions of the pole pitch $\left(\frac{X}{p}\right)$ and rotate at speeds which are fractions $\left(\frac{1}{p} \times \frac{X}{T}\right)$ of the synchronous speed.

In contradistinction thereto the expression $B_1(x, t)$ for the "ideal" machine with distorted currents leads to the notion of harmonic fields "referred to time" or of second order; these extend over the whole pole pitch (X) and rotate at speeds which are multiples $\left(n \times \frac{X}{T}\right)$ of the synchronous speed.

In reality the hypotheses set up for the "ideal" machine are never fulfilled, so that the induction in the air gap of an "actual" machine which delivers distorted currents is as follows:—

$$B_1(x,t) = \sum_{p=1}^{\infty} \sum_{n=1}^{\infty} b_p \times a_n \times \text{sine}\left(2\pi p \frac{x}{X} + \varphi_p\right) \times \text{sine}\left(2\pi n \frac{t}{T} + \varphi_n\right)$$

There result, therefore, harmonic fields of the first order for $n = 1$ and any value of p or harmonic fields of the second order for $p = 1$ and any value of n. Furthermore, harmonic fields of so-termed third order are found for $p \neq 1$ and $n \neq 1$. These fields extend over fractions of the pole pitch $\left(\frac{X}{p}\right)$ and rotate at speeds $\left(\frac{n}{p} \times \frac{X}{T}\right)$ which can be above or below the synchronous speed.

synchronous speed, their amplitude being directly proportional to the harmonics of the corresponding currents. The 2nd, 5th, 8th, 11th .... harmonics generate analogous fields rotating, however, in a negative sense at speeds of 2, 5, 8, 11 .... times the synchronous speed. Current harmonics with an order of multiples of three produce no field whatsoever. Indeed, such harmonics cannot occur in a balanced system without neutral wire.

In order subsequently to be able to study the effect of the stator current on the rotor an idea must be obtained of the characteristic of the field in the air gap as seen by an observer turning with the rotor, i. e., in the positive direction, at a speed of $\frac{X}{T}$. The running ordinate x on the periphery of the stator is connected to the running ordinate x' on the periphery of the rotor by the relation $x = x' + \frac{X}{T} \times t$ which inserted in the expression of the field B gives:

$$B(x' t) = \frac{3}{2} \sum_{\substack{n = 1, 4, 7, 10 \dots \\ \text{in general: } n = 3h + 1}}^{\infty} a_n \times \cos\left[2\pi \frac{x'}{X} - 2\pi(n-1)\frac{t}{T} - \varphi_n\right]$$

$$- \frac{3}{2} \sum_{\substack{n = 2, 5, 8, 11, \dots \\ \text{in general: } n = 3k - 1}}^{\infty} a_n \times \cos\left[2\pi \frac{x'}{X} + 2\pi(n+1)\frac{t}{T} + \varphi_n\right]$$

This expression shows up two series of rotating fields turning at speeds of 3, 6, 9 .... times the synchronous speed, the one in the positive and the other in the negative direction.

It is often an advantage to group the field harmonics in pairs rotating at the same speed and to write the expression for the field in the following manner:—

$$B(x', t) = \frac{3}{2} a_1 \times \cos\left(2\pi \times \frac{x'}{X} - \varphi_1\right)$$

$$+ \frac{3}{2} \sum_{\substack{n = 3, 6, 9, 12, \dots \\ \text{in general: } n = 3l}}^{\infty} (a_{n-1} + a_{n+1}) \times \text{sine}\left(2\pi \frac{x'}{X} + \frac{\varphi_{n-1} - \varphi_{n+1}}{2}\right)$$

$$\times \text{ sine}\left(2\pi n \frac{t}{T} + \frac{\varphi_{n-1} + \varphi_{n+1}}{2}\right)$$

$$- \frac{3}{2} \sum_{\substack{n = 3, 6, 9, 12, \dots \\ \text{in general: } n = 3l}}^{\infty} (a_{n-1} - a_{n+1}) \times \cos\left(2\pi \frac{x'}{X} + \frac{\varphi_{n-1} - \varphi_{n+1}}{2}\right)$$

$$\times \cos\left(2\pi n \frac{t}{T} + \frac{\varphi_{n-1} + \varphi_{n+1}}{2}\right)$$

In this form an observer attached to the rotor would see the resulting field as a superposition of elliptical fields rotating at 3, 6, 9, 12 .... times the synchronous speed. In the special case where the amplitudes of the two current harmonics belonging to a group are mutually equal the simplified elliptical field corresponds to a pulsating field with fixed axis. Special mention must be made of the fundamental wave of the stator current which, as was to be anticipated, produces a constant field.

Before concluding this section it must be stated that the foregoing considerations have been kept quite general in that all of the harmonics (n = total of all positive whole numbers) were assumed to be present in the stator currents. In a three-phase system incorporating mutators, however, only a certain number of harmonics are to be found. The orders divisible by three disappear for reasons of symmetry, while those divisible by two are eliminated by the choice of a suitable transformer connection. For instance, in the case of six-phase mutators the stator currents of the machines will contain, apart from the fundamental wave, the harmonics 5, 7, 11, 13, 17, 19 .... to the exclusion of all others. In the air gap there will be fields rotating in the positive direction at speeds of 1, 7, 13, 19 .... times and in the negative direction at speeds of 5, 11, 17 .... times the synchronous speed. Referred to the rotor there will be various elliptical rotary fields — apart from the constant field of the fundamental wave — turning at speeds of 6, 12, 18 .... times the synchronous speed.

(b) *The Leakage Fields of a Machine feeding Mutators.*

A discrimination will be made between leakage fields forming in the stator slots and those forming around the coil heads of the windings.

The leakage fields which form in the stator slots are characterized by the fact that in the general case where all of the conductors in a slot belong to the same phase the field lines are produced by ampere-conductors having strictly the form of the stator currents; the skin effect phenomena are thus the same as for a transformer.

The leakage fields forming around the coil heads of the rotor windings are of quite a different nature, i. e., they rotate due to the fact that the winding coil heads are displaced 120° geometrically and the currents flowing in them likewise by 120° in time. The considerations in the foregoing section relevant to the field harmonics in the air gap can thus be integrally applied to the leakage fields around the coil heads.

(c) *Calculation of Additional Load Losses.*

Notwithstanding the arbitrary nature of such a division a discrimination will be made between three classes of additional load losses: Those having their origin in the slot conductors, those in the coil heads and neighbouring solid parts, and, finally, those in the rotor.

(α) The additional losses in the slot conductors due to the distorted currents can thus be calculated in the same way as for transformers, i. e., by determining the losses for each individual harmonic according to Field's theory and subsequently integrating these individual losses.

Results of such calculations naturally depend chiefly on the arrangement of the conductors in the slot, on whether they are split up into leads of small cross-section, and on the measures adopted to obtain maximum possible symmetry of the individual strands. They also depend to a high degree, however, on the form of the current delivered by the machine, i. e., in particular on the number of phases and the angle of overlap of the mutators. The latter factor is of such a decisive nature that, as stated in section II (b) for transformers, calculations based on the assumption of an angle of overlap of 0^0 (stator currents formed by superposed rectangles) lead to extravagant results.

By way of example a number of figures concerning a 38 MVA turbo-alternator feeding mutators with twelve-phase connection are given. Under these conditions the currents delivered by the machine contain the harmonics 1, 11, 13, 23, 25, 35, 37... Table II shows the true losses (i. e., ohmic and additional losses together), expressed as a multiple of the ohmic losses for the fundamental wave. The upper line corresponds to an angle of overlap Θ of 45^0, whereas the second assumes commutation to be instantaneous, i. e., $\Theta = 0^0$.

Although the series in the upper line converges very rapidly, the same does not apply to that in the lower one. In other words, where the true losses for $\Theta = 45^0$ are 1·0671 they would be much greater than 1·4380 for $\Theta = 0^0$. The difference between the two results is such that the assumption of $\Theta = 0^0$ has no practical value.

This calculation shows, moreover, that the increase in the additional losses in the slots involved by the distortion of the stator currents presents no great difficulty.

(β) In calculating the additional losses in the coil heads and neighbouring solid parts great difficulties are encountered in that the configuration of the lines of force in the leakage field is very complicated; in point of fact very little is known about it at all. With the help of the following fundamental considerations, however, it is at least possible to arrive at an estimate of the losses.

The latter have their origin in the magnetic fields produced by the stator currents of the machine which induce electromotive forces in the whole of the surrounding space. These e. m. f. 's produce eddy currents of such magnitude in the conducting parts that their ohmic voltage drops offset the electromotive forces. Hence, the additional losses are proportional to the square of the primary currents and the square of the frequency. If P_n denotes the additional losses involved by the harmonic I_n of the frequency n, and P_1 the additional losses entailed by the fundamental wave I_1, the following is arrived at:

$$P_n = \left(\frac{I_n}{I_1}\right)^2 \times n^2 \times P_1$$

In reality the mechanism of the formation of the eddy currents is greatly complicated by the fact that these currents produce further magnetic fields themselves which are superposed on the primary field and tend to weaken it. The approximation, therefore, can only result in excessive loss values.

TABLE II.

True Losses in the Slots of a 38 MVA Turbo-alternator feeding a Set of Mutators with Twelve-phase Connection. Values calculated and expressed as Multiples of Ohmic Losses of Current of Fundamental Wave.

Order of harmonic	1	11	13	23	25	35	37	$\sum_{n=1...}^{37}$
Angle of overlap $\Theta = 45^0$	1·0594	0·0030	0·0028	0·0008	0·0006	0·0003	0·0002	1·0671
Angle of overlap $\Theta = 0^0$	1·0594	0·0681	0·0660	0·0620	0·0617	0·0605	0·0603	1·4380

Here again, the assumption of an angle of overlap of zero is futile, for in this case $\frac{I_n}{I_1}$ would be equal to $\frac{1}{n}$ and P_n to P_1, so that $P = \sum_n P_n$ would become infinite.

From experience we are now in a position to estimate with a high degree of accuracy the additional losses in the coil heads, clamping plates, and protective casings of our machines for a sinusoidal current (i. e., the losses P_1 with the denomination adopted). The above-mentioned procedure permits, therefore, an upper limit to be estimated for the additional losses P when a machine has to operate in conjunction with mutators:

$$P = \sum_n P_n < P_1 \times \sum_n \left(\frac{I_n}{I_1}\right)^2 \times n^2$$

For loads comprising mutators in twelve-phase connection and with an angle of overlap $\Theta = 45^0$ the following result is arrived at:—

$$P < 1 \cdot 11 \times P_1$$

whence it can be concluded that here, too, the increase in the additional losses due to the distortion of the stator currents is of little importance.

(γ) A question is now touched upon which is far more important than the two preceding ones, viz., that of the additional losses in the rotor.

In an "ideal" machine, i. e., with sinusoidal distribution of the stator ampere-turns, and assuming pure sinusoidal currents, there would be no other losses than the ohmic losses of the excitation current. In the case of an "actual" machine it is known (section IIIa) that harmonic fields of the first order exist. Their pole pitch is very small and their speed of rotation low. In consequence, compared to the rotor, these fields turn at a speed deviating very little from the synchronous. If the rotor (or at least the pole shoes) are laminated these fields involve no very great loss. The same applies if the rotor has amply-spaced damping bars. If, however, the damping bars are very close together or the rotor has a solid core (as is generally the case with turbo-alternators), the harmonic fields produce eddy currents which must be taken into consideration. Nevertheless, all these currents have frequencies of about the same magnitude as the fundamental frequency, i. e., relatively low, which of course is an advantage.

In section III (a) it was seen that in a machine delivering non-sinusoidal currents the air gap is the seat of rotary fields of the so-termed second order which are distributed over the whole pole pitch and rotate at a very high speed. It has also been seen how these fields are to be considered from the point of view of the rotor, so that the effect they will have on the latter can now be gone into. In all of the closed metallic circuits existing on the surface of the rotor, currents are induced which tend to oppose the main ampere-turns. For two reasons, however, the induced ampere-turns must be inferior to the exciting ampere-turns; firstly, because the voltage induced by the common lines of force of the primary (stator) and secondary (rotor) circuits cannot be zero, but must cover the ohmic and inductive drops in the secondary circuit; secondly, because the resultant field magnetization necessitates a certain number of ampere-turns. If calculation of the losses is based on the assumption that the periphery of the rotor is the seat of opposing ampere-turns equal to those of the stator an excess error will therefore certainly be committed.

A difficulty not to be under-estimated lies in the determination of the true resistance of the various rotor circuits. If a machine is provided with a good damping winding it can be assumed that the currents in the solid core are negligible, while the skin effect in the conductors of the damping winding can be calculated by the same method employed for the copper in the stator slots. If a damping winding is not provided, the rotor currents pass through the core and the true resistance can be calculated by Rosenberg's method.[1] This is based on the hypothesis that throughout the whole depth of a thin layer on the surface of the core (termed "conducting skin") the magnetic induction remains constant and the current density diminishes linearly from the exterior to the interior. The most frequent case encountered in practice lies midway between that of a damping winding with a very low resistance and that where only the solid core is employed to obtain the required damping effect. In consequence, it is advisable to apply both of the above methods of calculation, the one for the winding and the other for the solid core. Inasmuch as the two circuits are connected in shunt the one with the lower resistance will take the higher current.

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[1] Rosenberg: "Wirbelströme in massivem Eisen." ETZ, 31st May, 1923.

Rosenberg: "Massive Eisenleiter und Wirbelstrombremsen." ETZ, 6th December, 1923.

Taking the example already considered of a 38 MVA turbo-alternator feeding a bank of mutators in twelve-phase connection and with an angle of overlap $\Theta = 45^0$ the following will be found on the rotor:—

For the 12^{th} harmonic 22 $A_{r.m.s.}$ per cm.
For the 24^{th} harmonic 5·4 $A_{r.m.s.}$ per cm.
For the 36^{th} harmonic 2·4 $A_{r.m.s.}$ per cm.

Each of these values applies to the most heavily stressed zones.

By way of comparison it might be mentioned that the full-load excitation corresponds to a direct current of more than 1000 A per centimetre. All that is necessary, therefore, is to arrange in each slot a damping winding with a cross-section not exceeding a few per cent of the excitation winding. If on the other hand, the solid core is required to carry alone the ampere-turns induced in the rotor a "conducting skin" thickness of 0·2 mm is obtained for the 12^{th} harmonic in accordance with Rosenberg's method; from this the specific losses per surface unit, which attain approximately 10 % of the ohmic losses of the excitation current in the most severely stressed zone, can be derived.

(d) *Suggested Measures for Diminishing the Additional Losses.*

The foregoing considerations, illustrated by a number of examples, show that the additional losses in a synchronous machine exclusively feeding mutators, are chiefly governed by the following factors:—

Number of phases
Value of angle of overlap
Arrangement of conductors in stator slots
Arrangement of coil heads and clamping plates
Design of rotor.

In principle, by doubling the number of phases the first two and by tripling the number of phases the first four harmonics of the three-phase current are suppressed. When the transformer connection is not absolutely symmetrical, however, the anticipated elimination of certain harmonics does not take place. In point of fact the multiplication of the number of phases (in certain installations the record figure of 60 phases has been attained!) involves more and more complicated transformers. Nevertheless, from the numerical examples given in the previous section of this article it should not be necessary to go beyond twelve phases for normal cases.

The increasing of the angle of overlap is a measure from which the best results may rightly be anticipated. To this end it is advisable to design machines and transformers with a sufficiently high reactance; this also simplifies their design. The fact that a larger angle of overlap involves a larger reactive power consumption for the same d. c. output, however, sets a limit in this direction.

As regards the arrangement of the conductors in the stator slots the designer now has adequate means available to enable these additional losses to be reduced to practically as low a value as desired, even when the stator currents are distorted.

The design features to be incorporated in the rotor affect on the one hand its active core and on the other its damping winding. There can be no doubt that laminated poles have the advantage of eliminating all difficulties. Nevertheless, it would be a grave error to affirm that solid poles are entirely unsuitable for mutator service. The previously mentioned numerical example has shown that in the case of a turbo-alternator, for instance, where purely for mechanical reasons solid cores are highly desirable, the additional losses at the surface of the core do not provide an insurmountable obstacle. To keep to general considerations: every conscientious designer adopting solid poles must necessarily predetermine by calculation the magnitude of these additional losses. It has been seen how such a calculation can be carried out.

A damping winding, if it is liberally proportioned, will always be of advantage in that it prescribes certain definite paths for the induced currents instead of allowing them to stray about more or less freely in the core. This must not be interpreted to mean that a damping winding is absolutely indispensable. On the contrary, a machine without damping winding should give entire satisfaction in conjunction with mutators, especially when the poles are laminated. In this case induced currents could only occur in the excitation winding, these being superposed on the d. c. current without causing any appreciable additional losses. One thing is absolutely certain: A damping winding with an inadequate cross-section or a high effective resistance constitutes a real danger.

(e) *Results of Tests for the Determination of Additional Losses involved by Mutators.*

The experimental determination of the additional load losses in a synchronous machine is not an easy matter. Proof of this is that no national or international specifications exist on the subject. Moreover, it seems hardly possible to make measurements which would accurately check the theoretical considerations as in the case of transformers.

An attempt made on a 1100 kVA machine with laminated salient poles is, however, worthy of mention. This was connected so as to feed a six-phase mutator with interphase transformer. The current flowing in the ring

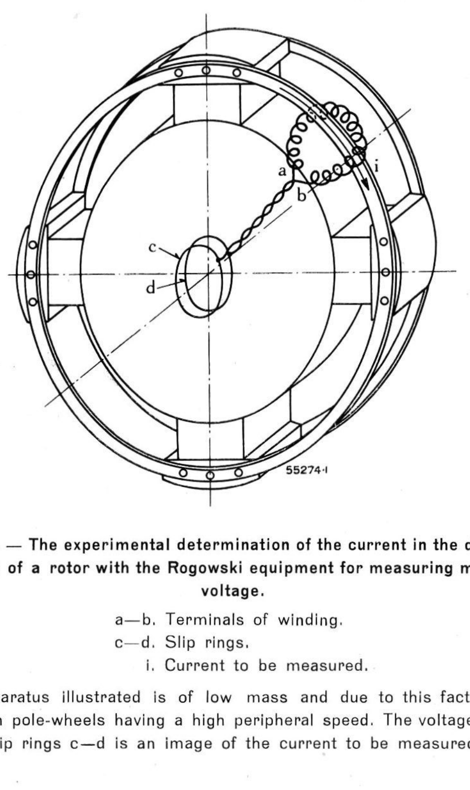

Fig. 11. — The experimental determination of the current in the damping winding of a rotor with the Rogowski equipment for measuring magnetic voltage.

a—b. Terminals of winding.
c—d. Slip rings.
i. Current to be measured.

The apparatus illustrated is of low mass and due to this fact can be fitted on pole-wheels having a high peripheral speed. The voltage on the slip rings c—d is an image of the current to be measured.

of the damping winding was measured with the Rogowski apparatus for measuring the magnetic voltage (Fig. 11). It is known that the voltage induced between the terminals *a* and *b* of the winding of the apparatus, and which is accessible on the rings *c-d*, is an image of the current embraced, i. e., of the current in the ring. The advantage of this apparatus is that, due to its small mass, it can be mounted without difficulty on a pole wheel having a high peripheral speed. The oscillograms in Fig. 12 show the results of these tests. As was to be anticipated from the theoretical considerations, the sixth

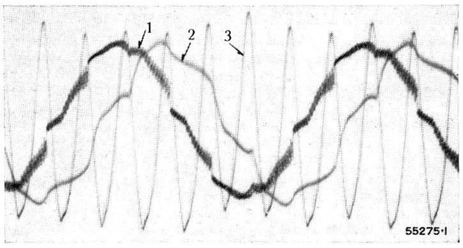

Fig. 12. — Oscillogram of 1100 kVA alternator with damping winding supplying a six-phase mutator with interphase transformer.

1. Stator line voltage.
2. Stator current.
3. Rotor current in ring of damping winding.

The current in the damping winding contains chiefly the sixth current harmonic.

harmonic can be clearly seen. An interesting point is that the current calculated from the measured stator currents by the method described in section III (c) agrees by less than 12 % with the measured current.

The measurement of the currents in the damping windings is nevertheless not entirely satisfactory unless an attempt is made directly to measure the losses involved by the harmonics of the stator current. In this respect it would appear indicated to follow the lines leading to the successfull results obtained for transformers and to resort to measurements with the stator winding fed by a three-phase current at harmonic frequencies. During these measurements the excitation winding must be short-circuited and, on principle, the rotor turned at normal speed, although experience has shown that the losses

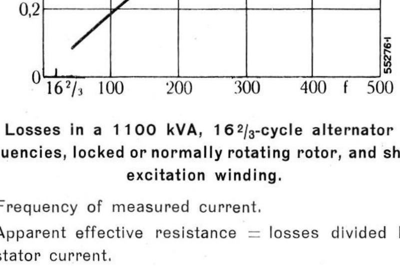

Fig. 13. — Losses in a 1100 kVA, $16^2/_3$-cycle alternator on test with various frequencies, locked or normally rotating rotor, and short-circuited excitation winding.

Abscissa: Frequency of measured current.
Ordinate: Apparent effective resistance = losses divided by square of stator current.

Three-phase currents of different frequencies applied to the stator winding of the alternator produce losses which rapidly increase with the frequency. These phenomena are of exactly the same nature as those which would occur in the machine if it were supplying a mutator with currents distorted through the presence of harmonics.

remain practically the same if the rotor is locked as long as the impressed frequency is sufficiently high compared to the normal frequency. Fig. 13 gives the results of similar tests and clearly shows the increase of the losses with the frequency for a given current.

(f) *Secondary Effects of Mutators on Working Conditions of Machines.*

So far only the additional load losses caused by mutators in machines have been considered, this question doubtless being the most important. Mutators, however, produce other peculiar phenomena in machines which must not be neglected.

The voltage across the terminals of a machine can be considered as induced on the one hand by the field in the air gap and on the other by the leakage fields in the slots and coil heads. The field in the air gap is obtained by superposition of the exciting, stator, and reaction ampere-turns in all of the closed rotor circuits. If the latter were completely to offset all of the harmonics of the stator ampere-turns, as was assumed in the calculation in section III (c), the electromotive force induced by the field in the air gap would be purely sinusoidal. In reality, this will never be the case so that the presence of a mutator will necessarily lead to distortion of this e. m. f. What is more, the distortion of the stator currents involves even greater distortions of the voltage induced by the leakage field, so that finally the voltage at the terminals of the machine is quite appreciably distorted.

Another aspect of this question is the increasing of the iron losses. In point of fact, as has just been seen, the resultant field in the air gap is not free from harmonics. The same, therefore, applies to the induction in the core. One naturally wonders what losses will take place in a core which is the seat of a flux varying in accordance with a non-sinusoidal law. The reply is simple as far as the eddy current losses are concerned in that the losses of all of the individual harmonics are superposed. For the hysteresis losses the problem is much more difficult. It is highly improbable, however, that harmonics cause no increase in these losses.

Finally, it should be remembered that every flux harmonic in a core may produce a shrill magnetic noise in the machine, a phenomenon which has been observed on various occasions.

IV. CONCLUSION.

Since the advent of mutators in three-phase systems fears have been expressed as to the possible adverse effects on transformers and machines. This question is at present important where large electrolysis plants occur; in future it may be still more important in the event of energy being transmitted over long distances by direct current.

The current distortions caused by mutators chiefly involve increased additional losses. The best means of solving this problem is to split the currents up into their harmonics and strictly to apply the principle of superposition for the determination of the losses.

In the case of mutator transformers the currents of the odd harmonics have quite a different characteristic from those of the even orders for most of the connections, i. e., geometrically displaced leakage fields occur in one and the same limb. The additional losses involved by each of these fields can be calculated for all of the harmonics by Field's classical theory. The result shows the extraordinarily favourable influence of the angle of overlap. These conclusions have been corroborated by tests either with sinusoidal currents at different frequencies or with three-phase currents such as occur under conditions of mutator operation. Finally, the question of the workshop testing of mutator transformers for checking the fulfilment of guarantees as far as they affect load losses, is dealt with. After establishing suitable short-circuiting connections, currents at the fundamental frequency are first applied at three different points, thereupon currents at twice the fundamental frequency at three other points, and finally the additional losses under mutator operation determined by a very simple formula from these two measurements. The correctness of the fundamental construction and results of this method have been corroborated by various tests.

The magnetic field in the air gap of an alternator delivering distorted currents due to the presence of mutators comprises a synchronously rotating field and a certain number of fields of the width of a pole pitch and turning at speeds of odd multiples of the synchronous speed; compared to the rotor these fields appear as elliptical fields rotating at speeds of even multiples of the synchronous speed. The additional losses involved by the harmonics of the currents originate in the slot conductors, in metallic parts in the vicinity of the coil heads, and in the rotor. The first can be calculated in accordance with Field's theory, the second liberally estimated by means of a simplifying hypothesis, and the third determined by assuming that the ampere-turns per centimetre of the rotor exactly offset the harmonics of the ampere-turns per centimetre of the stator and calculating the effective resistances of the various closed rotor circuits (damping windings or solid core).

The different measures permitting the additional losses involved by operation of machines in conjunction with mutators to be reduced to a value not appreciably affecting the rating of the machine are: Increasing of number of phases, increasing of angle of overlap, stranding of slot conductors, and provision for heavily damping the rotor by means of an appropriate winding or by its own core. As alternative must be mentioned the entirely laminated rotor with, in consequence, no damping effect. In general, the different measures indicated enable the number of phases to be kept down to twelve, which represents a big advantage as far as the transformers are concerned, in that they become simpler. The considerations on the configuration of the fields in the air gap and on the value of the currents circulating in the damping windings have been corroborated by test. It is possible to draw useful general conclusions of the behaviour of a machine under conditions of mutator operation by measuring the losses resulting from the application of sinusoidal currents at harmonic frequencies to the stator. Apart from the increase in the additional losses mutators cause distortion of the voltage at the terminals, an increase in the iron losses, and in certain cases the emission of a shrill magnetic noise.

(MS 883) *Dr. P. Waldvogel. (E. G. W.)*

BRIEF BUT INTERESTING

Economical Utilization of available Water Power in Industrial Plants.

Decimal Index 621.311.21

THE undermentioned example illustrates how a small heavily fluctuating water power supply can be utilized to the full.

The wood grinding mill lineshafting of a paper mill, requiring 100—150 kW, is driven by two old-type water turbines with a maximum output of 300 kW. These have no automatic governing gear and when load fluctuations occurred had to be regulated in a far from easy manner by hand. What is more, however, the available water power could not be fully utilized for the greater part of the year

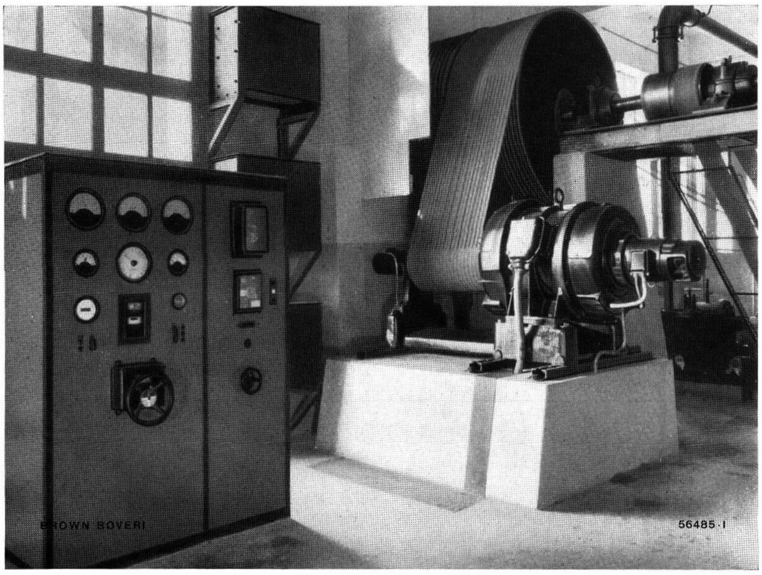

Fig. 1. — 265 kVA three-phase synchronous machine capable of operation as generator or motor for economically utilizing the heavily fluctuating water power supply of a paper mill.

The machine is coupled by vee-belts to the grinding mill lineshafting driven by the two water turbines of the paper mill. Since the turbines have no governors, an automatic electrical equipment was supplied to keep the speed of the lineshafting constant in the event of faults occurring in the overhead supply system.

Some time ago, therefore, a 265 kVA synchronous machine was installed. This is driven from the lineshafting by vee-belts and operates in parallel with the existing mill installation which takes its supply from an overhead transmission system. The revolutions of the machine are thus maintained constant by the supply frequency. When plenty of water is available the machine operates as generator and at times of low water level as motor to help drive the lineshafting, the necessary energy being obtained from the supply system.

The following special condition had to be taken into account in the design of the plant:—

During the summer months faults are liable to occur in the overhead supply network which is then disconnected from the mill system. In such cases the synchronous machine is likewise isolated from the latter. If the machine was operating as generator prior to the fault, the throwing off of its load would cause the turbine revolutions to rise to an impermissibly high value, and, in consequence, also the speed of the machines, e. g., centrifugal pumps, driven from the lineshafting. To obviate this, the machine is automatically switched on to loading resistors, its excitation and load being controlled by a quick-acting regulator influenced by a tachometer dynamo in such a manner that its revolutions remain practically unchanged.

In view of the present shortage of electrical energy the possibility of utilizing the available water power to the full at all times is particularly welcome.

(MS 882) *Richard Schnitzer. (E. G. W.)*

Contact-wire Thawing Equipment.

Decimal Index 621.369.6:621.332

EARLY on winter mornings difficulties are sometimes encountered with hoar frost on the contact wires of trolley bus systems. Current collectors with special ice scrapers, however, spoil the polish of the wires and thus shorten the life of both the wires and the carbon sliding pieces. The thawing of the ice electrically not only avoids these drawbacks, but permits the desired end to be achieved in a shorter time. With this process the contact wires are loaded by means of resistors connected across their end to give a current density of 4—5 A per mm^2, the supply being taken from the substation. The layer of ice is positively melted within 10—30 minutes, according to the air temperature.

After exhaustive tests the Berne Municipal Tramways ordered two such contact-wire thawing equipments which were put into commission just recently. Each equipment (Fig. 1) comprises loading resistors, ventilating appliances, an overload switch, and individual switches for increasing the load in steps from 250—800 A, all enclosed in a sheet-metal cubicle suitable for outdoor erection. The equipment is characterized by simple control and adaptability of the loading current to actual conditions.

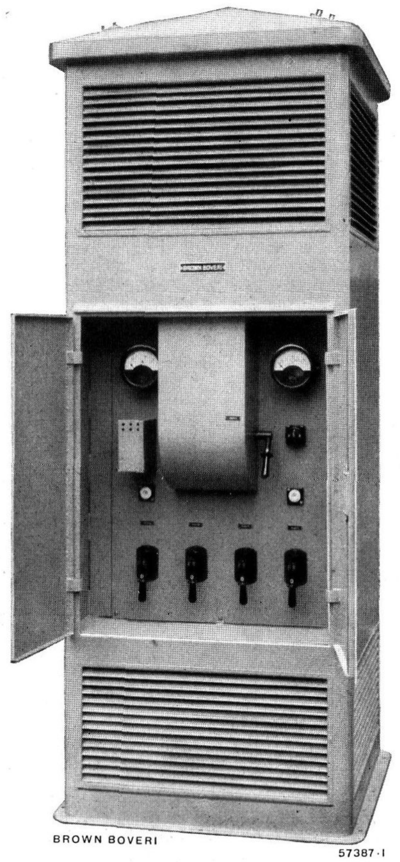

Fig. 1. — Contact-wire thawing equipment for Berne Municipal Tramways trolley-bus system.

Electrical thawing equipment enables any contact-wire system to be reliably freed from ice or hoar frost in the shortest possible time.

The initial outlay for the thawing equipment is rapidly recuperated through the trouble-free service in cold weather, reduced wear and tear on the contact wires and carbon sliding pieces of the current collectors, and the decreased interference with wireless reception.

(MS 920) *G. Manta. (E. G. W.)*

500 Cycles in Transformer Test Bay.

Decimal Index 621.317.2:621.314.21

TRANSFORMER test specifications call for a turn test with twice the rated voltage to prove the insulation between adjacent turns. At normal frequency this would entail doubling the magnetic induction, which is impossible due to the limit set by the saturation point of the iron. In consequence, the frequency must be increased, preferably to a multiple of the rated value, inasmuch as for a given product of the flux and the frequency the iron losses diminish with rising frequency.

Notwithstanding this artifice powers which are beyond the capacity of orthodox testing equipment are required for the testing of large transformers.

For the test bay at Baden we have built a special "medium-frequency" alternator. Comparative investiga-

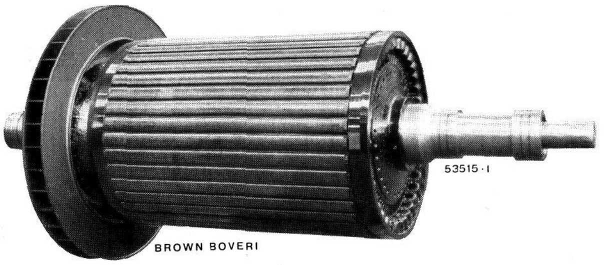

Fig. 1. — Rotor of forty-pole 500-cycle alternator.

The excitation winding lies between the pole shanks. The rings over the coil heads also serve as short-circuiting rings for the damping winding.

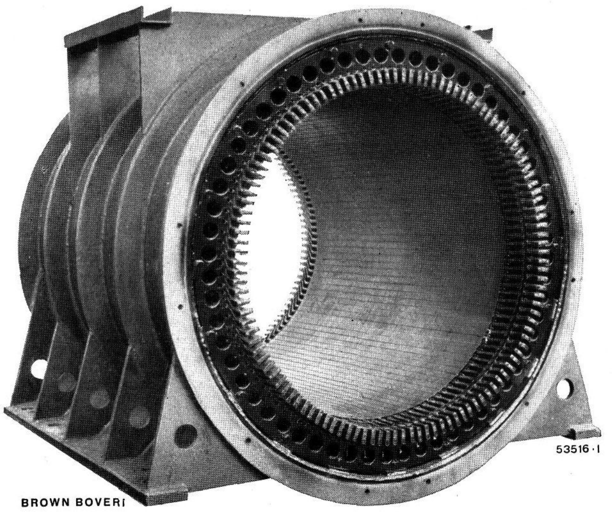

Fig. 2. — Stator of 500-cycle alternator.

The winding is of the two-layer transposed-bar type. The stator is cooled by means of axial ducts in the stator laminations to which the air flows through the holes visible in the retaining ring of the coil heads.

type of rotor winding to that of turbo-generators (Fig. 1). Each pole is wound and the two halves of adjacent coils, which completely fill the slots, are held by metallic wedges inserted under the pole shoes. Dampers let into the latter complete the damping winding formed by the wedges.

The stator winding has two transposed bars per slot. By inclining the slots the same effect is obtained as with a finely distributed winding, although only one slot is available per pole and phase (Fig. 2).

Due to the large number of poles, as well as for mechanical reasons, the yoke is much higher than actually necessary from a magnetic point of view. This fact, however, enabled axial cooling to be adopted, which simplifies the design of the laminated rotor through the elimination of the troublesome radial ducts, and results in a more compact machine.

The iron losses do not exceed the calculated values and full advantage was taken of the special low-loss sheets employed. I^2R and other losses are also moderate.

The alternator, together with its 1000 kW, 1500 r. p. m. driving motor, is depicted in Fig. 3. It will be noticed that the air cooler and its admission branches, through which the cooling air is forced by a radial fan fitted at the opposite end to the motor, is mounted on top of the alternator. This arrangement had to be adopted due to the set being installed in a basement.

The driving motor also embodies special features (chiefly affecting the ventilation) which have enabled its dimensions to be considerably reduced compared to earlier designs.

(MS 884) *Dr. O. Hess. (E. G. W.)*

tions proved 500 cycles to be the most suitable frequency. The alternator is designed for a continuous three-phase load of 2000 kVA at 0·2 power factor and 4000 V; the corresponding single-phase rating is 1150 kVA. An overload of 75 % is permissible for a short period.

In order to obtain still higher powers it is intended to switch condensers in parallel with the machine.

Great care had to be taken to keep the form of the voltage as nearly sinusoidal as possible.

The most pronounced harmonic, as determined with a frequency analyser, represents only 0·5 % of the fundamental wave, while the other harmonics are no more than fractions of this value. The excellent form of the voltage curve — notwithstanding the salient poles of the rotor — was achieved through careful design of the pole shoes. The high peripheral speed of about 80 m/s involved a similar

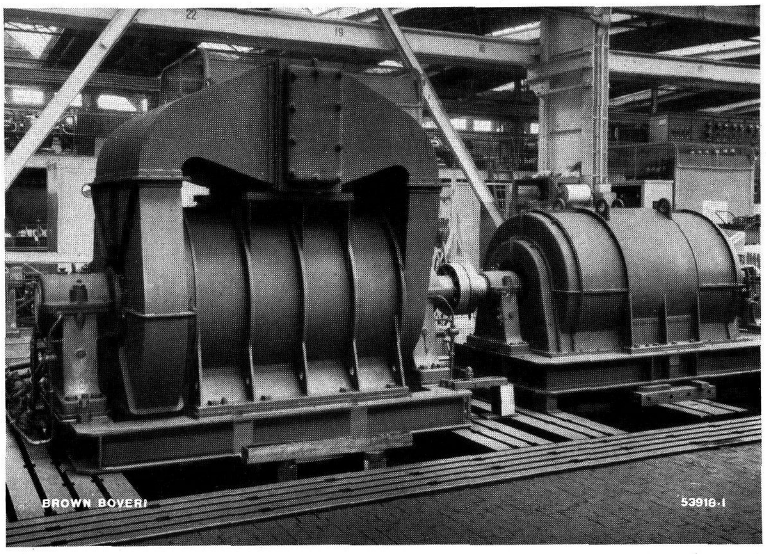

Fig. 3. — Forced air-cooled 1500 r. p. m., 500-cycle alternator continuously rated at 2000 kVA, with 1000 kW driving motor, in test bay.

The alternator can be overloaded up to 3500 kVA for a short period. Notwithstanding the exacting requirements placed on the form of the voltage curve, the design is simple, robust, and thoroughly reliable. Such machines are also suitable for industrial applications.

Remote Control simplifies Operation.

Decimal Index 621.398

AUTOMATIC mutator stations have been widely adopted. They are usually found at points of concentration of the load in traction systems where the little attention they require — the closing of circuit-breakers sufficing to put this class of equipment into service in the morning — renders them particularly suitable. Ingenious apparatus switch such substations in and out at pre-determined times, supervise the sets, and indicate faults. In large municipal systems incorporating a number of substations, heavy and unforeseen load fluctuations have to be reckoned with and to ensure efficient working it is highly desirable that lightly loaded convertor sets should be cut out in good time. These requirements, however, involve continual supervision and remote metering and regulation either from a central office or an attended substation.

A typical example of the simplification in operating conditions accruing from remote control is afforded by the modernization of the "Promenade" Substation of the Zurich Municipal Electricity Supply. This station which was equipped in 1926 with three 1000 kW, 575 V mutator sets, feeds an important section of the municipal tramway system in the centre of the town. Twenty-four feeders distribute the energy to the various points of consumption.

The new remote control gear, put into service about twelve months ago, enables the three mutator sets and the outgoing feeders to be supervised and controlled from the attended "Drahtzug" Convertor Station. Inasmuch as a six-core pilot cable already existed, the line combination system was selected for the transmission of the signals over the short distance between the control and controlled stations. Features of this method of control are simplicity and reliability. Two selector switches and a number of relays — components which have been developed to a high degree of perfection and have already proved their worth in telephone applications — are provided for the transmission of the control impulses and the accomplishment of the metering operations in the two stations. The time taken for the entire sequence is at most three seconds, one selector supervising the operation of the other during the whole of the time they are rotating. The number of signals which can be transmitted depends on the number of lines available. Given a six-core cable, for instance, sixty signals can be transmitted. In each position of

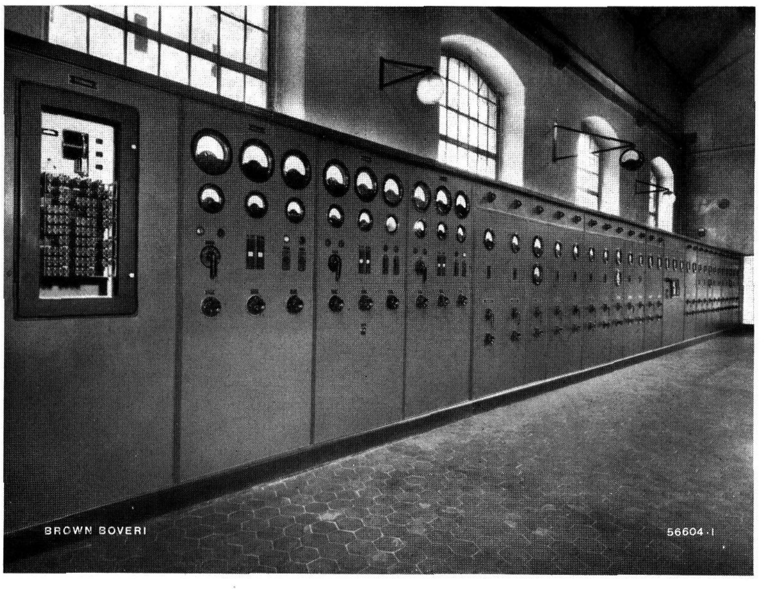

Fig. 1. — "Promenade" Substation of Zurich Municipal Electricity Supply.

Switchboard with control gear and instruments for three mutator sets and twenty-four d. c. feeders. The first panel carries selector switches and telephone relays for remote control purposes. The sets and feeders can be changed over to hand control at any time by means of multiple-unit switches.

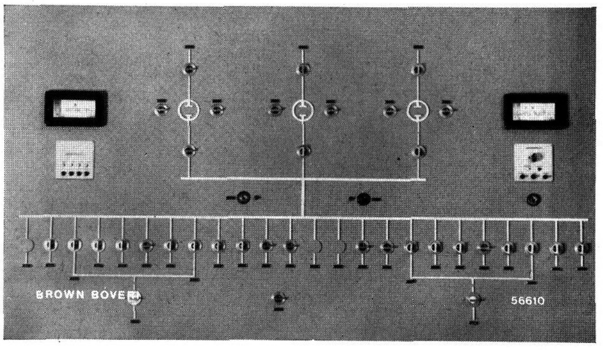

Fig. 2. — Switchboard in "Drahtzug" Control Station for the remote control of the "Promenade" Mutator Station.

The control gear of the three mutator sets and the twenty-four feeders are incorporated in the mimic diagram. Symbol switches indicate the positions of the circuit-breakers in the substation. If the positions of the symbol switch and the circuit-breaker associated with it do not coincide, e. g., in the event of the latter opening on overload, this is indicated by the intermittent glowing of the pilot lamp embodied in the control switch. The instruments are provided for the remote indication of the current and voltage.

the selectors three lines are required for supervising the control gear itself, while the others are used for the transmission of impulses and signals or to form a metering circuit. The remote supervisory control gear in the "Promenade" Substation is designed to switch in and out the three mutator sets, meter the voltage and current of each unit, and indicate faulty cooling, impaired vacuum, and excessive temperatures. When switching impulses are imparted to the feeder circuit-breakers the due accomplishment of the operation is accurately recorded back at the control station. Pilot lamps and switch symbols in the control room enable a permanent check to be kept on the condition of the mutator installation.

Inasmuch as mutator substations require so little general supervision the duties of the attendants are chiefly confined to the carrying out of switching operations. The installation of remote supervisory control gear, therefore, liberates such men for other work. This advantage is naturally greater the more substations can be remote-controlled from the one central point.

(MS 872) *M. Rossé. (E. G. W.)*

A new Record.

Decimal Index 621.165.004

MORE than twenty years ago a Brown Boveri set was installed in a corn-mill at Vila Franca (Portugal), this being the only source of energy the mill has. It works day and night, Sundays and weekdays, without interruption, and further serves to supply the current for the lighting of the local town.

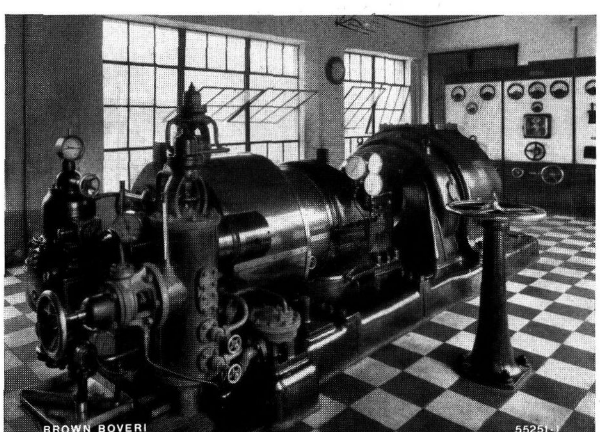

Fig. 1. — The 300 kW Brown Boveri turbo-set installed in a corn mill at Vila Franca de Xira (Portugal).

During a twenty years' period this set was running for more than 170,000 hours; in other words for 97 % of the time since it was first started up.

About every three years the set is inspected, as was also the case in July last. For practical reasons this is done simultaneously with the annual cleaning of the mill, for which purpose the whole plant is closed down for a few days. The last inspection of this kind revealed that the complete blading of the turbine is still in first-class condition and that the set, since its first start on the 7th July, 1922 until the 30th July, 1942, had been running for more than 170,000 hours without the slightest trouble. This is new proof of the high degree of reliability of our machines and shows how little attention they require in service.

(MS 921) *E. A. Kerez.*

Efficiency unchanged after 19,000 Hours' Operation.

Decimal Index 621.165:621.515

Results of Acceptance Tests on Turbo-compressor Set.

IN 1939 a turbo-compressor, complete with 6600 kW steam turbine and condensing plant and having an output of 72,000 m³/h at a delivery pressure of 8·0 kg/cm² abs, was purchased by the Oranje-Nassau Coal Mine, Heerlen (Holland).

The new power station in which the set was to be installed had not been completed by the time the machine arrived at destination. The customer urgently needed the compressor, however, so it was erected on a temporary foundation out-of-doors. The final acceptance test was postponed until the machine could be definitely installed in the power station.

Owing to the prevailing conditions it was impossible to begin re-erection until 1942, after the set had been running practically continuously for twenty-seven months or approximately 18,000 hours. On this occasion the opportunity was taken to clean the rotors and guide blades of the compressor and turbine, as well as the air coolers and condenser. Otherwise, no adjustments were made to blading and glands. The acceptance tests were carried out in May, 1942, after the set had run for a further 1000 hours in its new situation and during which time the condenser had again been somewhat dirtied by slightly oily steam. The results of these tests were as follows:—

Load	Deviation of steam consumption from guaranteed value
73,350 m^3/h	+ 0·9 %
61,600 m^3/h	+ 1·6 %
40,800 m^3/h	— 9·6 %

Notwithstanding the fact that the set had already been running for 19,000 hours, the mean steam consumption was still well below the guaranteed values, i. e., the efficiency of the turbine and compressor had not varied during this long working period. Commenting on the steam consumption measurements in his letter of acceptance the customer writes: "This is a splendid result for a machine already having 19,000 working hours to its credit."

These results afford further proof of the excellent design of Brown Boveri turbine and compressor blading and labyrinth glands, which ensure a virtually unchanged efficiency after years of service.

(MS 916) *R. Walthard. (E. G. W.)*

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(* Review of Progress)

FRONTISPIECES AND SEPARATE ILLUSTRATIONS.

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