PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

# Large Transformers

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# II. TRANSFORMERS

## Large transformers

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[Plates 10 and 11]

The design of power transformers is much more complicated today than it was some 30 years ago. The increased work load on the design engineer resulting from the economic necessity to operate materials at higher levels of stress has only been partially offset by the mechanization of calculation.

The economic growth of the electricity supply industry has been achieved by increasing the unit power of installations. There has also been an increase in transmission capability and short-circuit levels with a consequent increase in operating voltages, possibly projecting into the megavolt range. Problems which on small transformers are of little consequence become serious on large units. The areas in which the exigencies have become acute are weight, leakage flux losses and short-circuit strength. The necessity for the engineer to overcome these has created a demand for more basic knowledge, improved techniques, better materials and to a more economical use of materials. This in turn has led to revisions of test codes and the addition of new testing techniques which further complicate design and demand more from design engineers.

### 1. Introduction

The introduction of large power stations has made it necessary to provide high-voltage transmission networks to enable large blocks of power to be transmitted economically over long distances. A single 3-phase transformer or bank of three single-phase transformers handling the full output of a large generator has become commonplace. Figure 1, plate 10, shows a 710 MVA generator transformer which steps up the generator voltage from 21 kV to the desired transmission level of 345 kV. Typical transmission levels in common use vary from 300 to 500 kV. Future levels may be expected to reach as high as 1500 kV. At the receiving points step-down transformers are needed for distribution purposes to the consumers.

In the case of small transformers considerable latitude is available in design, and solutions are adopted which give the lowest cost, in terms of price or in terms of price weighted by the cost of supplying losses over the estimated life of the transformer. While cost still plays a part in the design of very large transformers, the emphasis changes and limits are introduced by the mechanical strength of the materials used, the permissible electric stresses for the insulating materials and their ability to withstand high temperatures without deterioration. In addition, the transformer has to be designed to meet limiting transport weights and dimensions so as to ensure that it can be transported from the factory to its ultimate destination.

We will discuss separately the major factors which influence these limiting features; but in this short paper it is not possible to deal with each factor in detail.

### 2. Transport weight

There is a relation between transformer power (usually referred to as MVA) and weight, and although some variation can occur due to choice of transmission voltage, impedance and losses, etc., there is a limit to the minimum weight that can be achieved.

Figure 2 indicates how the transport weight of a transformer depends on its MVA and also on its rated voltage. As the transformer rating increases, so does its weight. An 1100 kV unit is approximately 33 % heavier than a 275 kV unit of the same MVA.

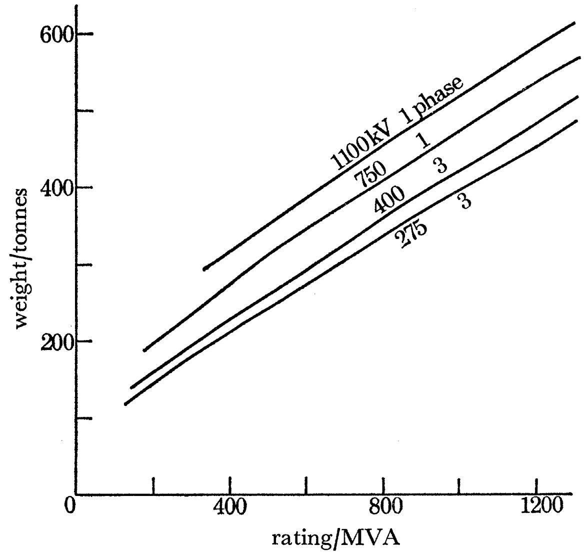


FIGURE 2. Transformer transport weights.

Only when the weight of a completed transformer without oil, coolers and bushings exceeds the transport limit is there any resort to assembly on site, and therefore an important point in any design is the weight that can be transported. In the U.K. large transformers are moved either by road transport or by a combination of road and sea transport. In North America and Europe rail transport is used extensively. In intermediate stages transfer from transporter to ship by crane or some other device may become a limit. Transformers having a transport weight of 110 tonnes net can be transported without restriction in the U.K. but large units having a net transport weight of up to 260 tonnes have been successfully transported. In the U.K. a new transporter is now available that is capable of moving loads of a net weight of 420 tonnes. Limitations are caused by bridges and culverts; air cushion equipment is used to surmount these limitations.

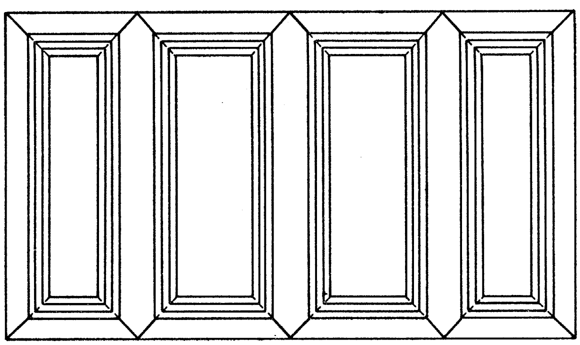

FIGURE 3. Arrangement of 5-limb 3-phase core.

Faced with these limits and with the growing need for larger units, manufacturers must continually be weight conscious. At some point the change from 3-phase to single-phase units must take place, although when this is done a cost penalty of approximately 20 % is incurred.

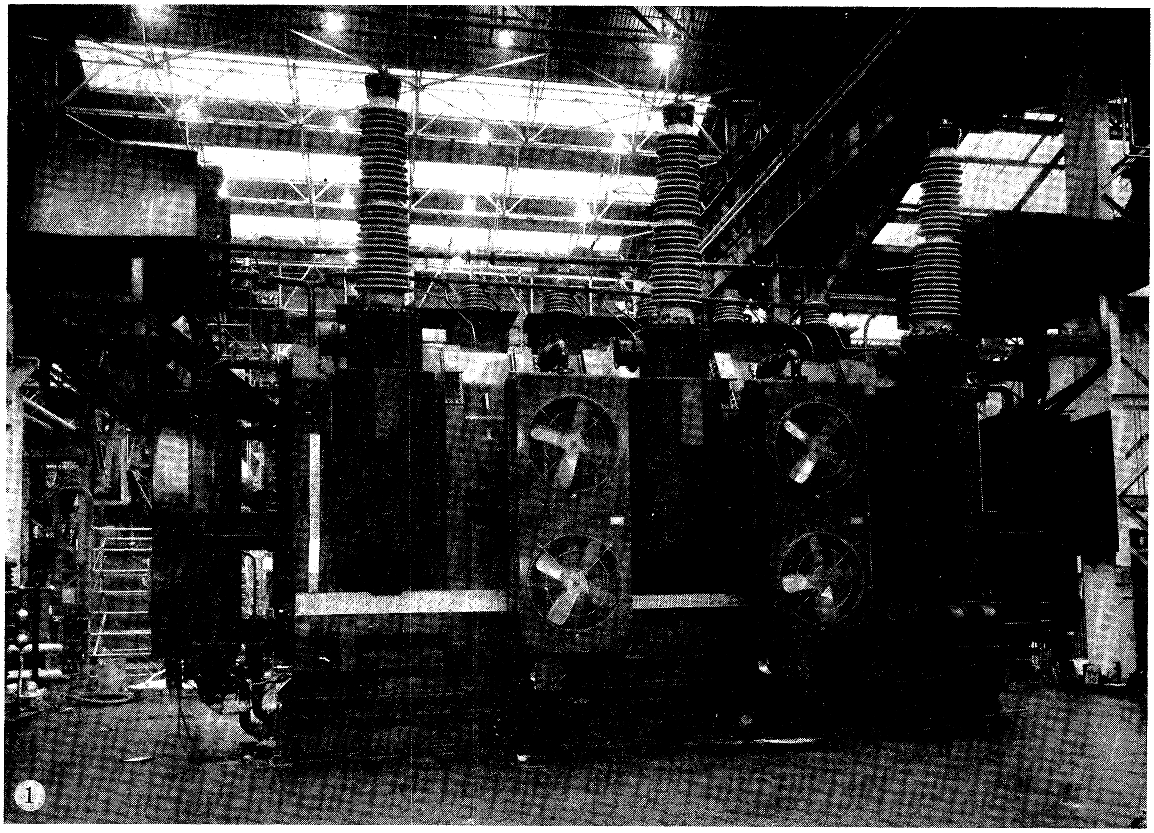

FIGURE 1. 710 MVA, 3-phase generator transformer. Delta/Star connected. Ratio 21/345 kV.

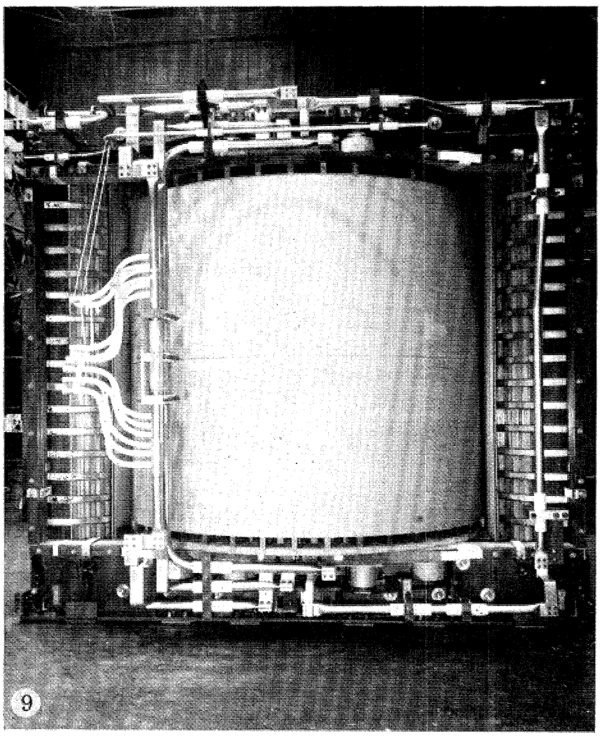

FIGURE 9. Core and coils of single-phase transformer fitted with horizontal magnetic shunts.

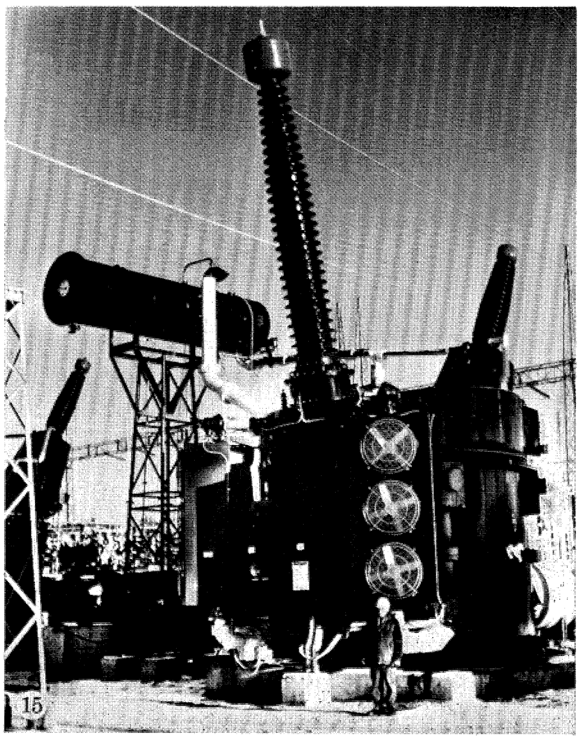

FIGURE 15. 700 kV single-phase auto transformer.

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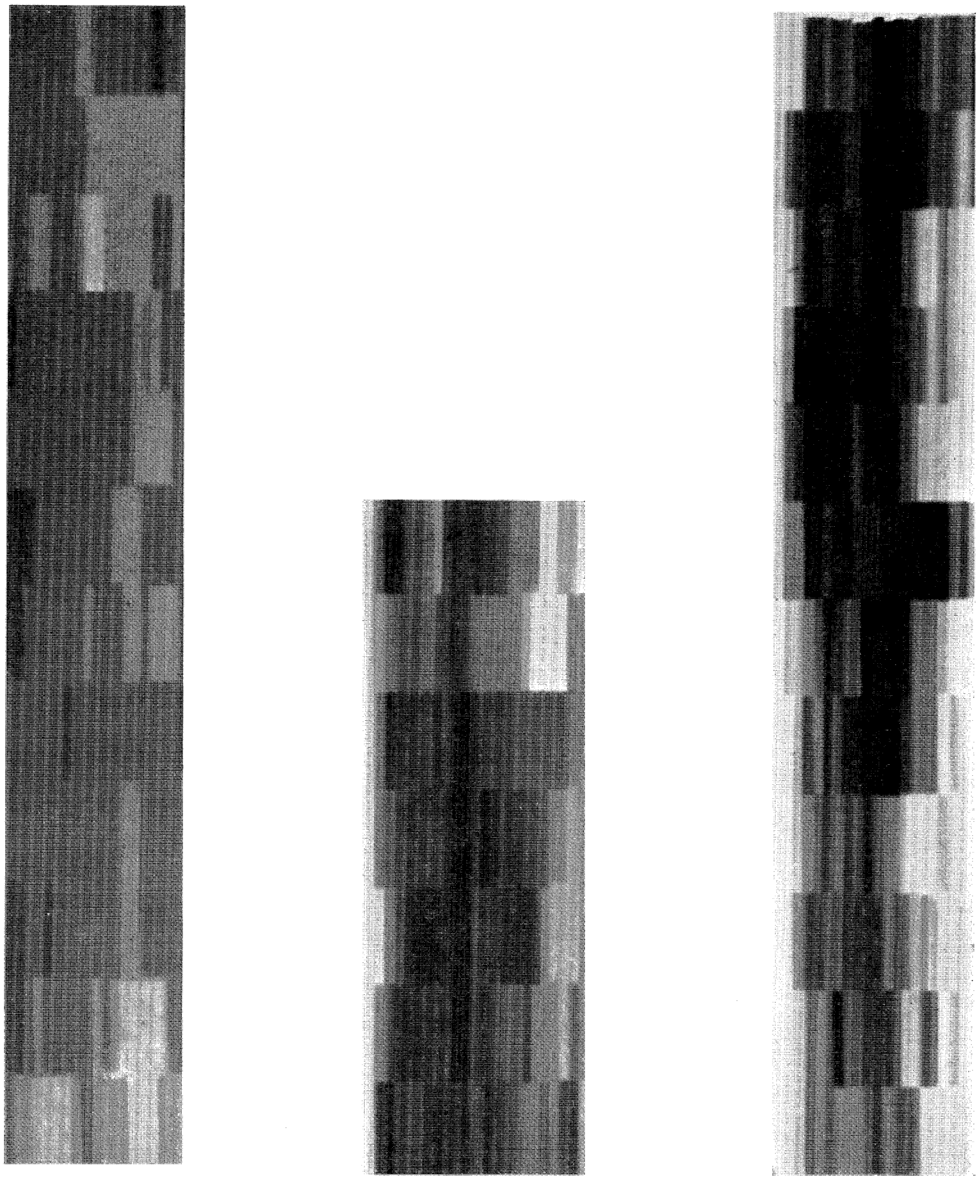
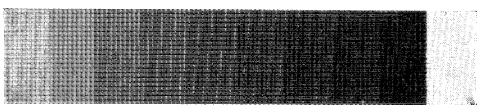


(*a*) (*b*) (*c*)

shade key



| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| sample 1 | 0.4 to 0 | 0 to −0.4 | −0.4 to −0.8 | −0.8 to −1.2 | | | | | | |
| sample 2 and 3 | −0.4 to 0 | 0 to 0.4 | 0.4 to 0.8 | 0.8 to 1.2 | 1.2 to 1.6 | 1.6 to 2.0 | 2.0 to 2.4 | 2.4 to 2.0 | 2.8 to 3.3 | 3.3 to 4.0 |

parts/$10^6$

FIGURE 6. Magneto striction distribution in sheets of core iron. (*a*) Sample 1, 3.35 m × 0.574 m; (*b*) sample 2, 1.98 m × 0.695 m; (*c*) sample 3, 3.35 m × 0.66 m.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Special core constructions have been adopted to reduce transport height which in the U.K. is often limited to 5 m.

Figure 3 shows how, in the case of a 3-phase transformer the transport height can be reduced. Instead of using a 3-limb core, a 5-limb core is used. The yoke cross-sectional area is reduced to 50 % and this gives a considerable saving in height. The transport length is increased, but this is not usually a limitation.

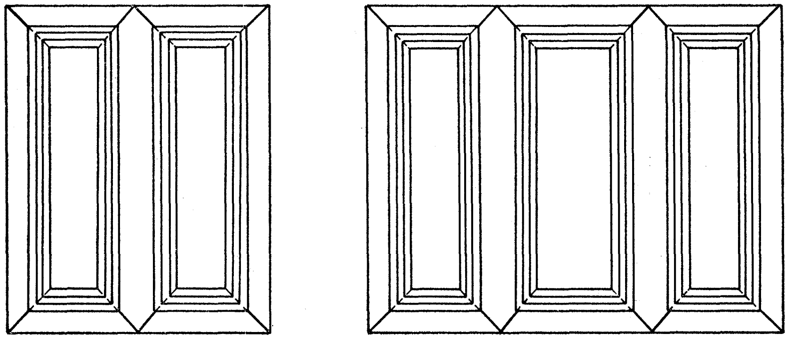

FIGURE 4. Arrangement of single-phase cores: left, 3-leg and right, 4-leg core.

A similar situation applies to single-phase cores. In figure 4, the diagram on the left illustrates a core for a single phase transformer having one wound limb. The diagram on the right illustrates the core for a transformer having two wound limbs. In both cases a saving in height is achieved because the yoke depth is reduced to 50 %. If the rating of transformers results in transport weights of the order of 500 tonnes or more the solution adopted will almost certainly be either the use of smaller transformers in parallel or erection on site.

## 3. Core and excitation flux

When the primary is energized magnetic flux is induced in the core circuit. In order to achieve minimum weight and cost, the magnetic characteristics of transformer cores are worked to permissible high limits. Design restraints on excitation flux are imposed by the following factors:

(1) Saturation at overvoltages.

(2) Iron loss at normal voltage and frequency which is usually capitalized.

(3) Maximum permitted noise level.

(4) The core surface temperature which must be limited to a value that will not injure the core itself or adjacent materials.

(5) Mechanical design of the core.

The design has to be such that the core can be lifted during manufacture and that it is adequately supported to withstand transport stresses and the mechanical stresses resulting from a short circuit. High clamping pressures have to be avoided to ensure that noise is minimized. Furthermore, the insulation between different parts of the core and its support structure must be adequate to limit undesirable circulating currents.

Figure 5 illustrates how the watts loss in grain oriented steel varies with the induction density. The two curves show how the loss is sensitive to the direction of rolling. The core has to be designed so that the direction of magnetization is always parallel to the rolling direction – hence the need for mitred joints.

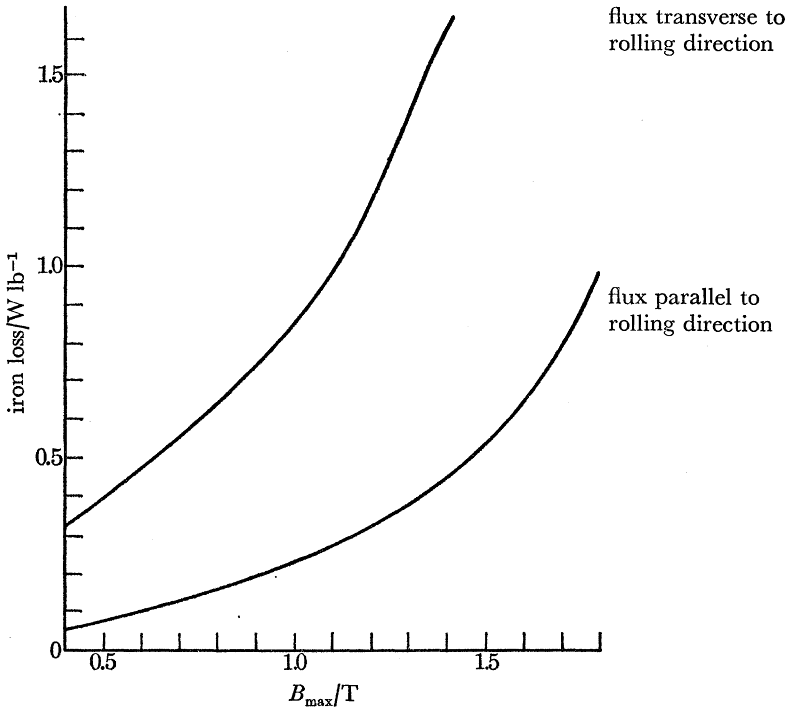


FIGURE 5. Typical curves of iron losses (1 lb ≈ 454 g).

Figure 6, plate 11, illustrates how magneto-striction varies in sheets of core iron. Three sheets of core iron are shown. Each sheet was cut up into rectangular samples for test purposes. The degree of shading illustrates the degree of magneto-striction recorded for each sample. The darker the shading – the bigger is the magneto-striction. It can be seen that the variation from point to point is very marked and this influences the core noise.

## 4. LEAKAGE FLUX

One of the important parameters is the impedance of a transformer. The impedance restricts the flow of short-circuit currents in power networks. This desirable characteristic is offset to some extent by the voltage regulation which occurs particularly at lagging power factors. Furthermore, in the case of primary generator networks the stability of the system is influenced by the value of the short-circuit impedance.

These factors set limits to the impedance of transformers and this has a substantial effect on design. The impedance of a transformer is caused by the fact that all the flux generated by the primary winding does not link with the secondary winding or vice versa, and the designer must ensure that the correct value is obtained. At the same time he must arrange that sufficient space is available between the two or more windings to achieve the required dielectric strength.

The total leakage flux is proportional to the product of the main flux and the percentage leakage reactance. In design terms, the leakage flux is proportional to the square root of the product of the kVA per leg, the percentage leakage reactance and a geometry factor dependent on the physical dimensions of the windings.

Once the actual magnitude of leakage flux in a transformer has been determined it is necessary to ensure that it can be accommodated without producing excessive overall losses and without producing local hot spots which may cause the evolution of gas. These factors have received considerable attention in recent years.

Core constructions which allow the entry of leakage flux perpendicular to the plane of wide core laminations should be avoided. Vertical magnetic shunts consisting of packets of core iron may be used to shield the core leg. The leakage flux is then diverted away from the main core leg and allowed to pass down these leg shunts; the shunt is designed so that the leakage flux enters the thin edge of the shunt laminations. Magnetic shunts may also be used to shield the yoke clamping structure or to shield the tank side from the effect of leakage flux.

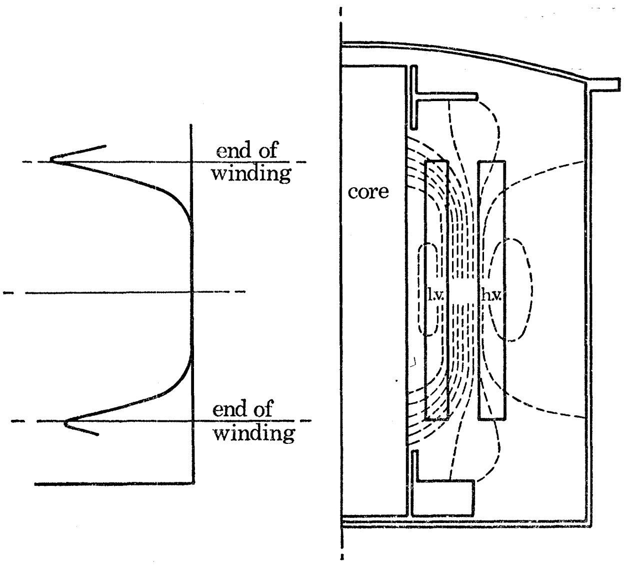


FIGURE 7. Typical magnetic flux plot.

Figure 7 shows a typical leakage flux pattern. The leakage flux is produced by the ampere turns of the l.v. and h.v. windings which oppose each other. The flux emerges from the h. to l. space near to the ends of the windings. It then enters either the core structure, the clamps or the tank and thus completes the magnetic circuit. A critical region occurs in the core, near to the ends of the windings. At this point the flux density is a maximum and local overheating may occur.

Figure 8 is similar except that horizontal magnetic shunts are shown at the top and bottom – near to the ends of the windings. The shunts collect a considerable proportion of the leakage flux with a corresponding benefit to the value of the flux which enters the core. The plot on the left indicates that the radial density is approximately halved.

In the case of 3-phase transformers, the top and bottom horizontal shunts do not have to be linked magnetically – they are completely separate. The fluxes from the top (or bottom) of the three legs will sum to zero.

Figure 9, plate 10, illustrates the core and coils of a large single-phase transformer fitted with horizontal shunts. In this case, the flux that emerges from the top of the single winding has to

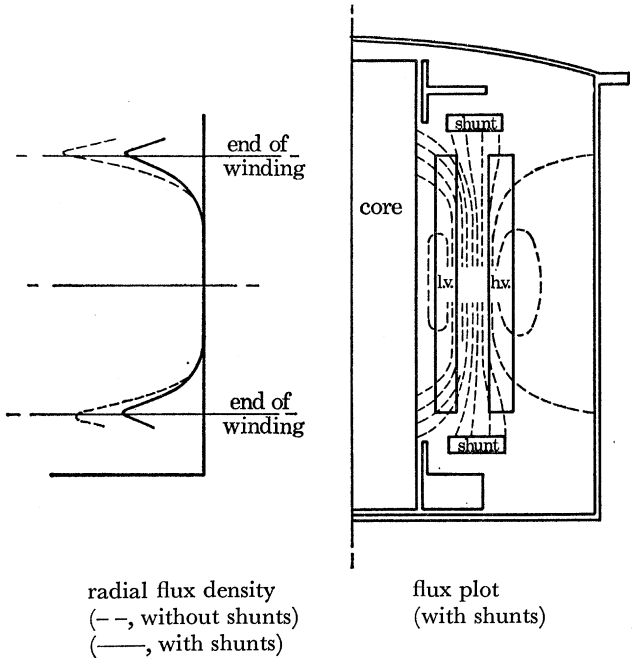


FIGURE 8. Typical magnetic flux plot.

be returned to the bottom via the vertical members of the shunts. More and more attention is being paid to leakage flux patterns, and sophisticated calculations using computers are being developed which allow for much better accuracy in prediction than was possible in the past.

The leakage flux problem will continue to escalate as transformers increase in rating, and further development work is needed to ensure satisfactory operation in service. The temperature rises obtained during factory tests when the transformer is energized in such a way that leakage flux only is involved may well not apply under service conditions when the core flux is superimposed on the leakage flux. This problem is being investigated.

## 5. LOSSES IN WINDINGS

In addition to providing sufficient conducting material to carry the load current in transformer windings, provision must also be made for dealing with eddy and circulating currents in the conductors due to the non-uniform flux pattern. Eddy currents are controlled by minimizing the area of conductors at right angles to the leakage flux direction at every position in the pattern. This is achieved by stranding and insulating the various strands from one another. However, when the strands are paralleled at the terminals, circulating currents may result due to unequal induced voltages. The circulating currents cause additional loss and risk of overheating. On smaller transformers transpositions are usually made to equalize strand voltages, and on large transformers continuously transposed conductor is used. When groups of continuously transposed cables are needed, for example in the case of low voltage windings of generator transformers, transposition of the cables is needed for the same reasons.

With careful design, it is possible to restrict the eddy current losses in the windings to a value of less than 20 % of the $I^2r$ losses.

An analysis of the component losses in two transformers is given in table 1. In both cases the total stray losses have been limited to a value less than 15 %.

The active losses are the $I^2r$ losses in the l.v., the h.v. and the h.v. taps.

Stray losses are caused by eddies in the windings (l.v., h.v. and taps) and also losses in the core, clamping structure, magnetic shunts and the tank.

The eddies in the windings of the 67 MVA units are approximately 10 %. The eddies in the l.v. winding of the 400 MVA transformer are 18 %. However, in both cases the total stray losses are less than 15 %.

Table 1. Analysis of load loss

| component losses | 67 MVA single-phase transformer, losses in kW at 75 °C | | 400 MVA single-phase transformer, losses in kW at 75 °C | |
|---|---|---|---|---|
| l.v. $I^2r$ | 56.5 | — | 257 | — |
| l.v. eddies | — | 4.9 | — | 46 |
| h.v. $I^2r$ | 58.5 | — | 400 | — |
| h.v. eddies | — | 5.7 | — | 26 |
| taps $I^2r$ | 13.4 | — | 8.5 | — |
| taps eddies | — | 0.8 | — | 0.8 |
| core, clamping structure, magnetic shunts, etc. | — | 8.4 | — | 23 |
| tank | negligible | | negligible | |
| total | 148.2 | — | 761.3 | — |
| total strays | | 19.8 (13.3 %) | | 95.8 (12.6 %) |

## 6. Short-circuit strength

### 6.1. *Short-circuit forces*

The flux pattern inherently affects short-circuit forces in windings. At each conductor position, the flux density is determined by the location of the conductor and the current flowing in each of the other conductors in the windings. These flux densities are influenced by the presence of boundary conditions imposed by the core. Boundary conditions are usually satisfied by assuming mirror images of the windings in the iron path, with good results in practice. The forces on each conductor can be evaluated. Care must be taken in defining the winding sections if accurate results are to be obtained.

Figure 10 indicates the use of the image technique and it also shows the direction of the magnetic field and the direction of the resultant forces exerted on the conductors. The forces can be resolved into radial and axial components which permits us to consider two systems of loading without serious loss of accuracy.

### 6.2. *Radial forces*

In the simple case of a two-winding transformer the radial forces act outwards on the outer windings and are reacted by hoop tension in the copper conductors. The forces act inwards on inner windings which must be adequately supported by the insulation and core if instability failures are to be avoided.

### 6.3. *Axial forces*

A theoretically balanced winding will have equal and opposite forces about the horizontal centre line, resulting in a compression–relaxation motion during the short circuit. Such a condition is rarely achieved in practice because some out of balance occurs. In this event there are resultant pulsating electromagnetic driving forces towards one end of the coil. The insulation materials are elastic but they support compressive forces only. Substantial movements of the winding can take place making it necessary to recalculate the electromagnetic driving forces during the movement. A mathematical analysis of this problem is complicated and calculations must be carried out with the aid of a digital computer.

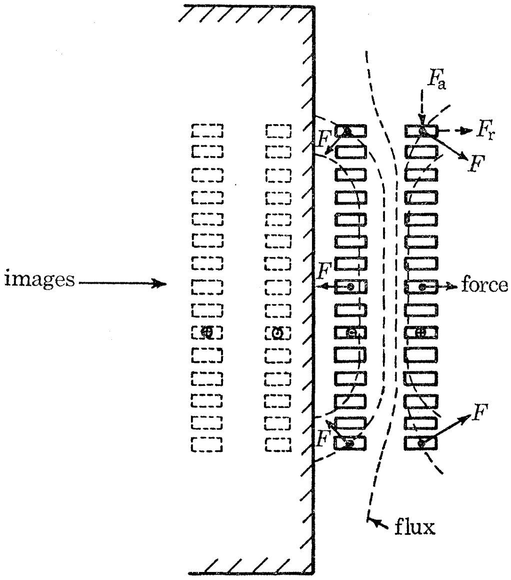


FIGURE 10. Electromagnetic forces.

### 6.4. *Tests*

Due to lack of sufficient plant capacity it is not possible to carry out full-scale short-circuit tests on large power transformers at a testing station. Full-scale models can be used to determine failure stress levels for particular modes of failure. The results of such tests must be correlated with the theoretical analysis.

## 7. Dielectric strength

### 7.1. *Test levels*

In the 1930s, despite inadequate information about network transients and necessary safety margins, a scale of test voltages for transformers was agreed. The principal test was to induce, at power frequency, a level of three times working voltage on each winding line terminal to ground. Subsequent development work and experience have shown that the level was shrewdly chosen.

Impulse testing was introduced in the late 1940s and a good deal of attention was given to the distribution of internal transient voltages and the disposition of dielectric materials. As transmission voltages increased there was some reduction of the ratio of induced test to working voltage, but before the introduction of lightning arresters the limit was about 2.7 to 1.

Table 2 shows typical present-day test levels and indicates how the introduction of lightning arresters has resulted in a reduction of basic test levels at the higher transmission voltages.

Circuit breakers capable of keeping switching transients to twice the peak of the power frequency voltage to earth (i.e. 2 per unit) have been developed thus reducing the switching surge level. This has brought about the need to introduce a more realistic induced test at a lower voltage level for a longer duration. This lower level is under discussion at the present time. The actual values have not yet been decided.

Table 2 shows one set of test values which have been suggested. Coincident with the move to lower test levels has been the introduction of partial discharge tests and it is becoming universal to link the induced test of long duration with a partial discharge test.

Table 2

(*a*) Existing typical test levels

| nominal voltage kV | induced test kV r.m.s. (p.u.) | | impulse test kV peak (p.u.) | | switching surge test kV peak (p.u.) | |
|---|---|---|---|---|---|---|
| 132 | 230 | (3) | 550 | (5.1) | 460 | (4.3) |
| 275 | 460 | (2.9) | 1050 | (4.7) | 870 | (3.9) |
| 400 | 630 | (2.7) | 1425 | (4.4) | 1180 | (3.6) |
| 500 | 750 | (2.6) | 1675 | (4.1) | 1390 | (3.4) |
| 700 | 960 | (2.4) | 2050 | (3.6) | 1700 | (3.0) |

(*b*) Possible future test levels

| nominal voltage kV | 1 h induced test at 1.5 times working volts kV r.m.s. | impulse test kV peak (p.u.) | | switching surge test kV peak (p.u.) | |
|---|---|---|---|---|---|
| 275 | 238 | 850–1050 | (3.8–4.7) | 750–850 | (3.3–3.8) |
| 400 | 346 | 1175–1425 | (3.6–4.3) | 950–1050 | (2.9–3.2) |
| 500 | 432 | 1300–1550 | (3.2–3.8) | 1050–1175 | (2.6–2.9) |
| 700 | 606 | 1550–1950 | (2.7–3.4) | 1425–1550 | (2.5–2.7) |

### 7.2. *Partial discharge*

The prime object of all tests on transformers is to ensure satisfactory operation in service. In the case of dielectric performance we have to ensure that the insulation will not deteriorate at an unacceptable rate. Oil and paper form the principal insulation media for large transformers and from a knowledge of the strength of various types of structure, designers arrange their material in such a way as to withstand the working and test voltages which are estimated to exist in elemental components.

Insulation withstand characteristics are functions of electric stress level, area surface stress, etc., and before breakdown actually occurs, partial discharge will usually occur. Partial discharge is an electrical discharge that only partially bridges the insulation between the main electrodes.

Partial discharge on sample elements can readily be measured as a high-frequency current or voltage. Figures 11 to 13 show a few examples of insulation samples which have been tested to obtain a statistical analysis of insulation behaviour. High discharge levels on transformers are unacceptable. In the case of transient voltages they may manifest themselves as low-energy sparks with gas evolution which can impair the strength of an insulation structure. Power frequency discharge leads to burning of the solid insulation and the decomposition of the insulating oil.

Work on insulation samples has indicated that a wide variety of partial discharge pulses can be produced even on the same type of sample. Some of these pulses have high rates of rise and

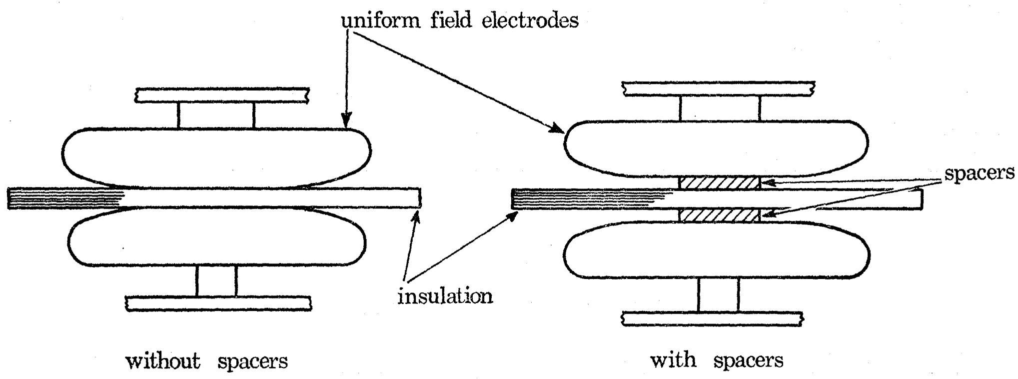


FIGURE 11. Insulation models using uniform field electrodes.

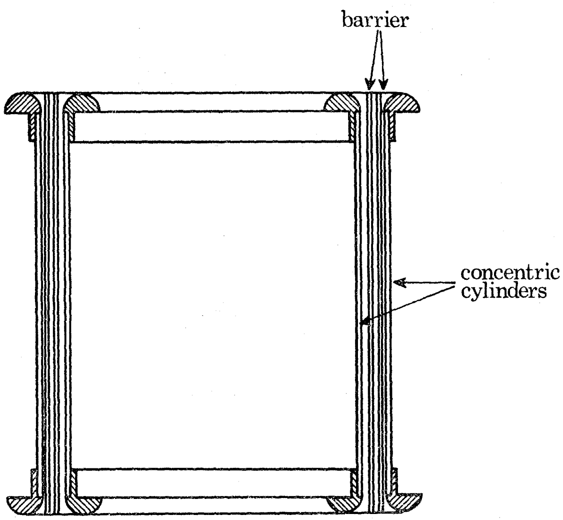


FIGURE 12. Insulation model using concentric cylinders and barrier insulation typical of that used between h.v. and l.v. windings.

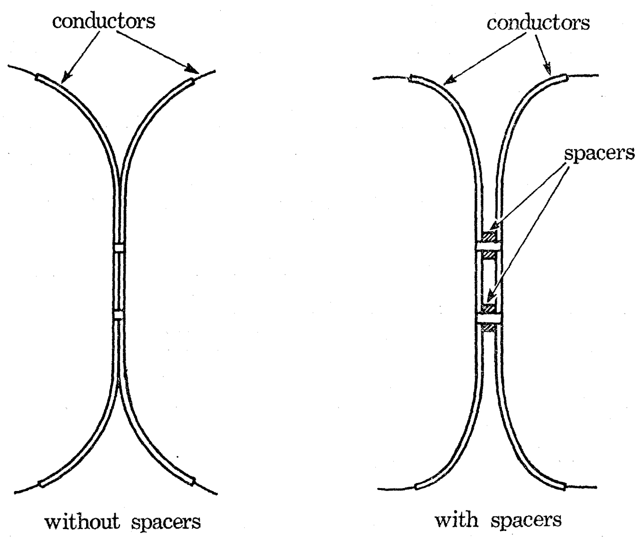


FIGURE 13. Insulation models of conductor samples.



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fall, others are relatively broad in shape having a pulse width of about 10 μs. Considerable attention is being devoted to analysing these characteristics in terms of damage.

The information obtained from tests on samples and models has to be related to the measurements made on full-size transformers. Measurements on production transformers can only be made at the winding terminals. A measurement of partial discharge at the terminals does not indicate the site of the discharge. The pulse waveshape and amplitude will be modified before reaching the terminal. Furthermore, there is no certainty that the measured discharge is associated with a particular winding; it may have originated in a major insulation area – the partial discharge signal being passed to the measuring terminal through capacitance coupling.

The h.v. terminal of a large transformer could be 6 m above ground level and the measuring problems introduced are difficult or even impossible to solve. The frequency spectrum of partial discharge covers a band of approximately 10 kHz to 10 MHz and interference from broadcasting stations and other sources become a serious limitation unless a fully screened test room is available. Large u.h.v. transformers would require screened test areas having dimensions of about 45 m and the costs would be correspondingly high.

An overall assessment of the electrical measurement of partial discharge indicates that we are unlikely ever to reach a completely satisfactory measuring standard for large transformers.

## 8. Gas in oil

The measurement of gas in oil is another method of testing for deterioration of insulation caused either by partial discharge or by overheating of insulation and metal parts. During factory tests, atmospheric gases are present in transformer oil in proportion to their solubility and the time for which they are in contact at particular pressures during the processing cycle. Damage is indicated by the presence of other gases produced by decomposition of oil or paper, etc., and these gases (which are referred to perhaps a little inaccurately as combustible gases) ideally ought not to be present in samples of oil taken from a transformer.

In practice many difficulties have occurred which have prevented full exploitation of this method. Measurement of 'combustible' gases at very low concentrations is difficult to do accurately. It is certain that for some types of discharge a sensitivity of measurement of about 0.1 part/$10^6$ of gas in oil is needed and at present this does not appear to be practicable. For this type of discharge we are unable to estimate accurately the rate of gas production inside a transformer.

## 9. U.h.v. transformers

As soon as new levels for dielectric tests referred to earlier have been established, the production of u.h.v. power transformers in the 1100 to 1200 kV voltage class could become a reality.

The test levels for this class will exceed the established levels for 700 kV by only a small margin. Table 3 indicates a comparison of test levels. The induced test level is the same but for a longer time. The full wave impulse test level is increased, but no chopped wave test is required. The switching surge level is increased only slightly.

The method of carrying out impulse and switching surge tests is well established and methods for detection of failure are both sensitive and adequate. Whether or not the present procedure for carrying out partial discharge tests is adequate has still to be resolved.

Preliminary designs for u.h.v. transformers have already been done. The Swedish Company A.S.E.A. and the German Company Transformatoren Union have built prototype transformers. Details of these have been released in the technical press.

If u.h.v. transformers are used in the U.K. they would be required to either link with the 400 kV system or to connect direct to a generator.

We have prepared a number of preliminary designs in accordance with these requirements but we will illustrate one only (figure 14). This is a 1000 MVA single-phase auto transformer

Table 3. Probable test levels for 1100 kV

| | induced test/kV | impulse test/kV | switching surge test/kV |
|---|---|---|---|
| present day 700 kV test level | 960 for 1 min discharge test at 465 | 2050 Full wave<br>2350 chopped wave | 1700 |
| probable test levels for 1100 kV | 960 (1.5 p.u.) for 1 h accompanied by discharge test | 2250 full wave<br>no chopped wave | 1800 |

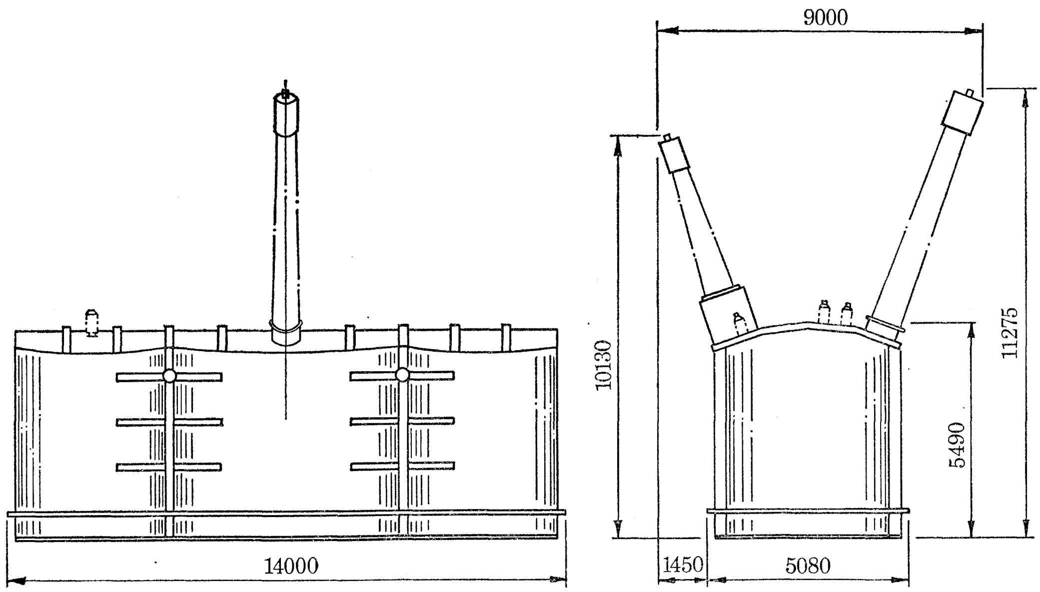


Figure 14. Outline arrangement of 1000 MVA $(1100/\surd 3)/(400/\surd 3)/33$ kV single-phase auto transformer. Transport weight 420 t; total weight 600 t.

Table 4. 1100 kV transmission and generator transformer test voltages

| | h.v. winding/kV | l.v. winding/kV |
|---|---|---|
| nominal system voltage | 1100 | 400 |
| 1 min power frequency test voltage | 960 | 350 |
| rated lightning impulse withstand voltage | 2250 | 1425 |

for a 3000 MVA star/star bank of ratio 1100/400 kV having an impedance of 17%. The overall dimensions are given in mm. The transport dimensions are length 14 m, height 5.03 m, width 5.08 m, and the transport weight is 420 tonnes. These figures are within the expected transport limits.

The test levels for which the transformer has been designed are shown in table 4. These levels correspond to those shown in tables 2 and 3.

Figure 15, plate 10, shows a single-phase transformer which is part of a 3-phase bank rated at 510 MVA. It is part of the Quebec Hydro transmission network operating at 700 kV. This is the highest commercial a.c. transmission voltage in operation today.

## Conclusions

In this paper, we have tried to cover a very wide field. Detailed technical discussion of the many facets of transformer engineering has not been possible. We have tried to show that by using modern design and by taking advantage of reduced test levels consequent upon the use of lightning arresters and improved circuit-breakers, it will be possible to design and build the largest units envisaged operating at voltages up to 1100 kV.



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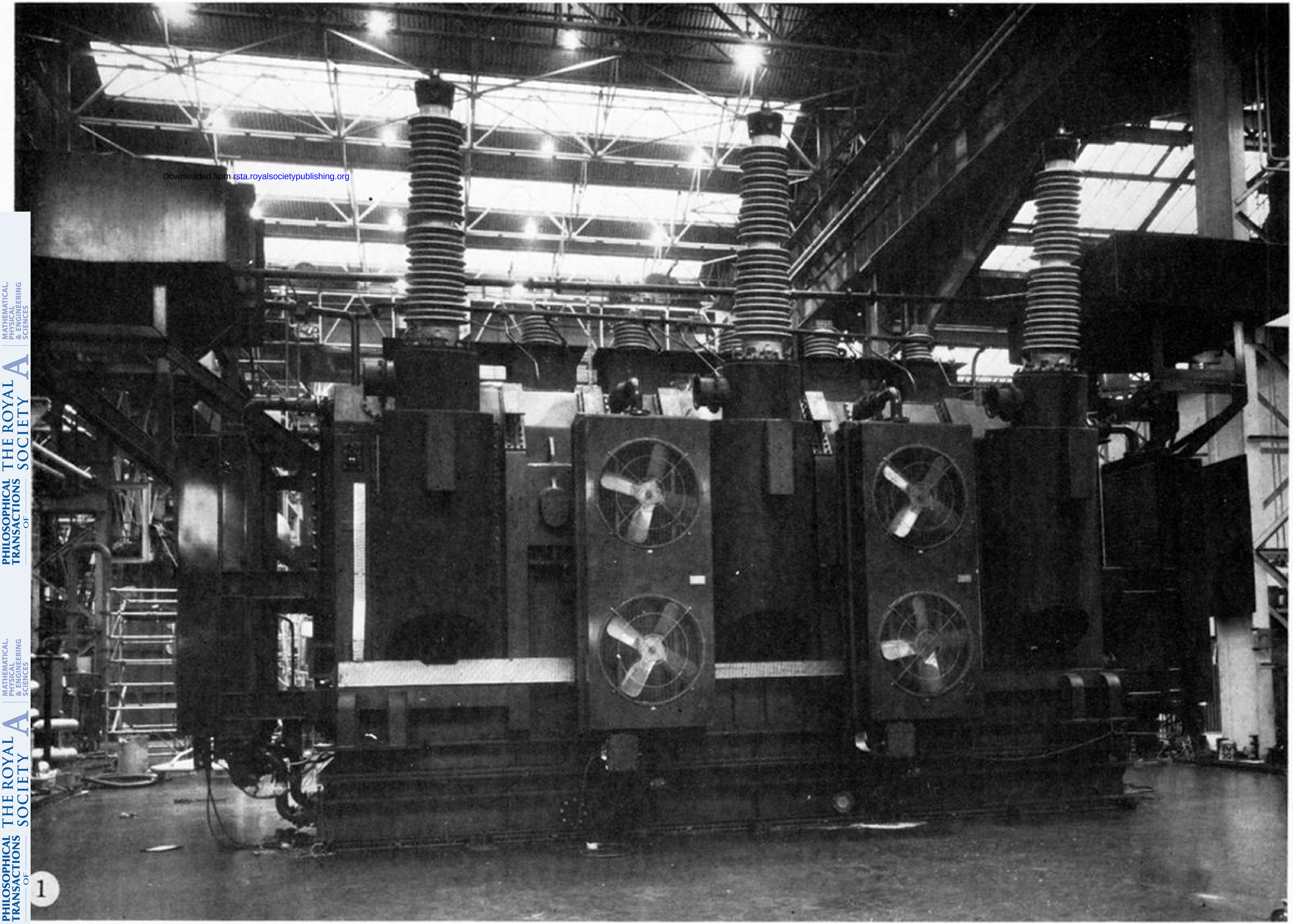





FIGURE 1. 710 MVA, 3-phase generator transformer. Delta/Star connected. Ratio 21/345 kV.

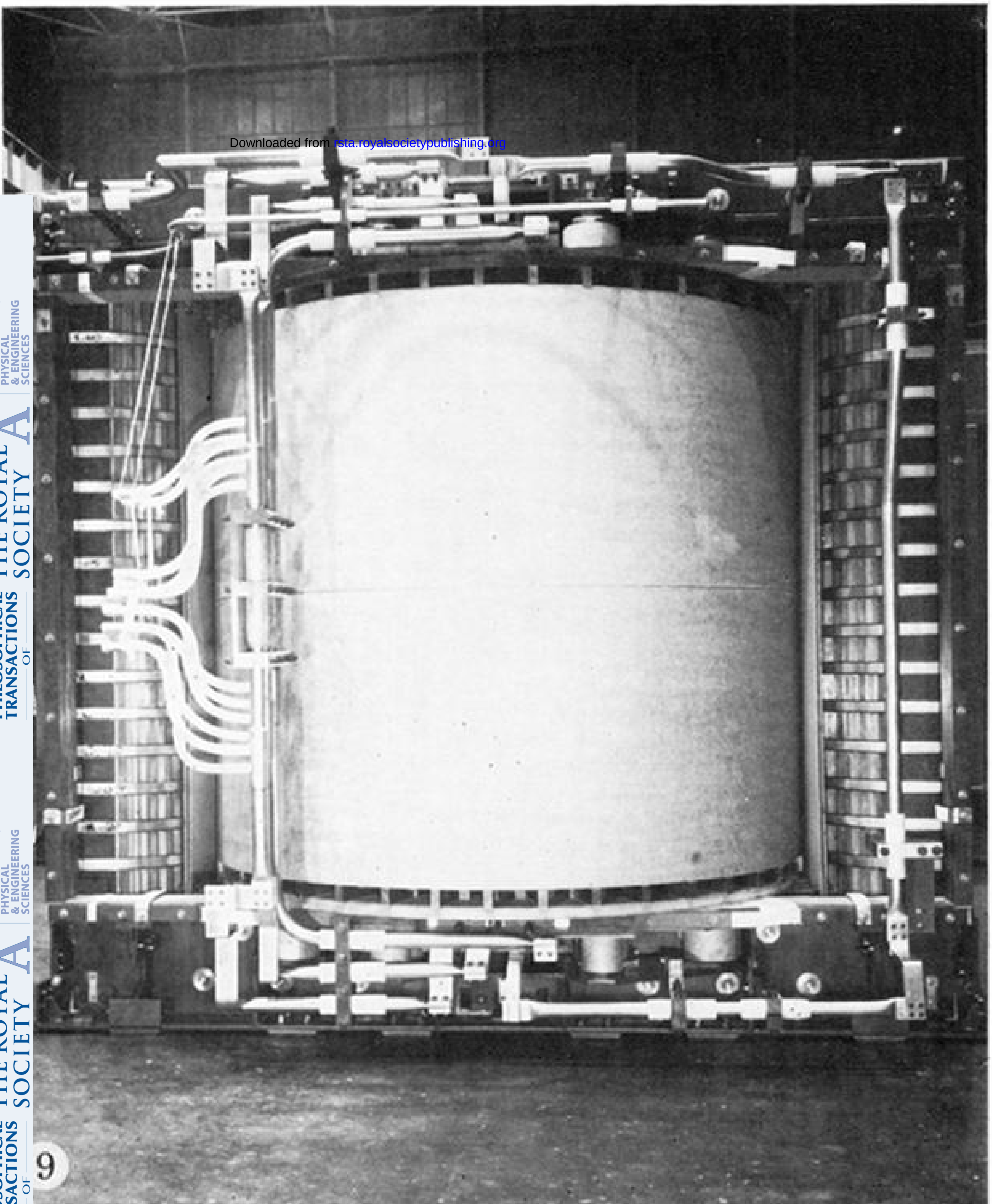

FIGURE 9. Core and coils of single-phase transformer fitted with horizontal magnetic shunts.

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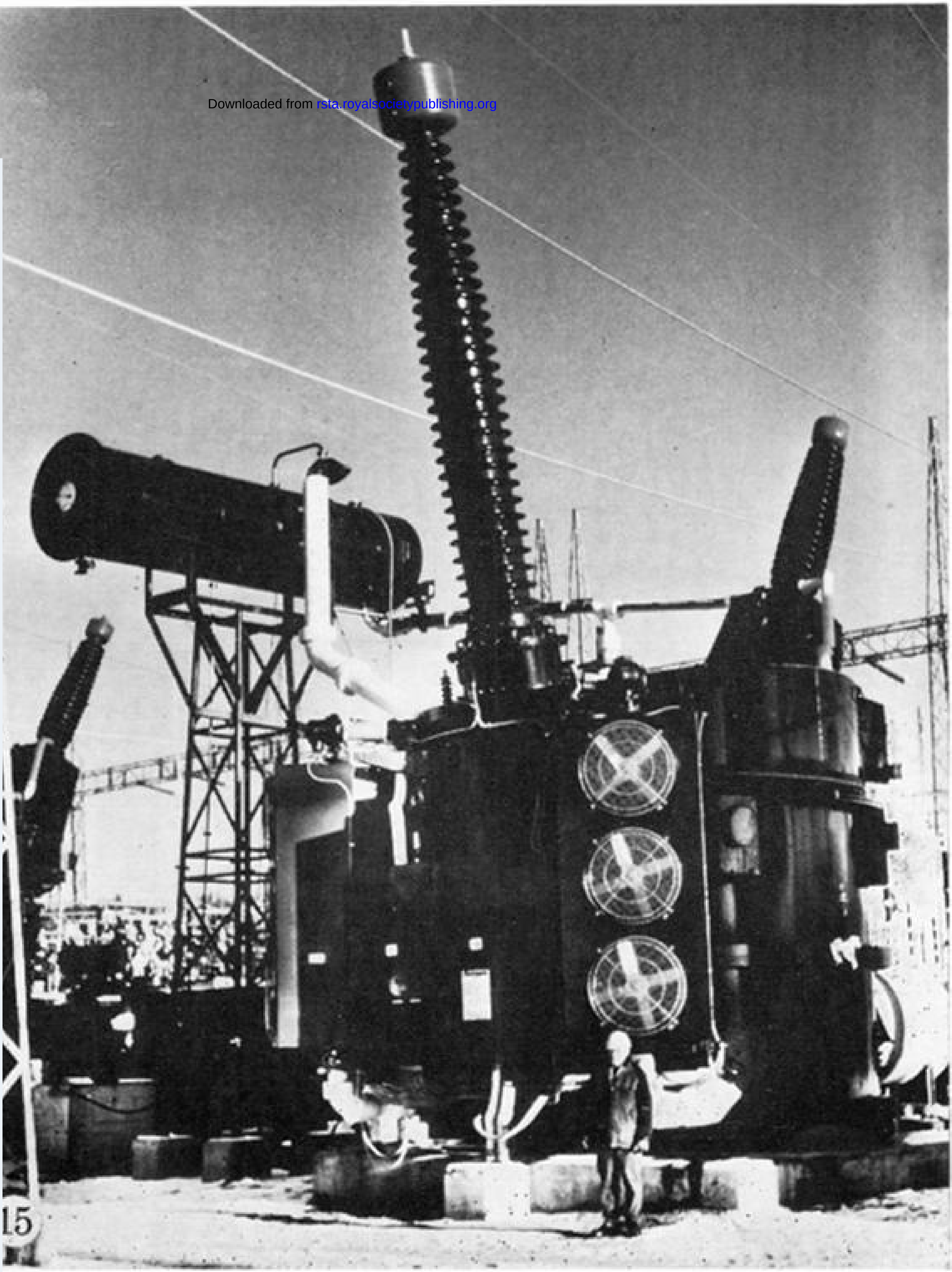
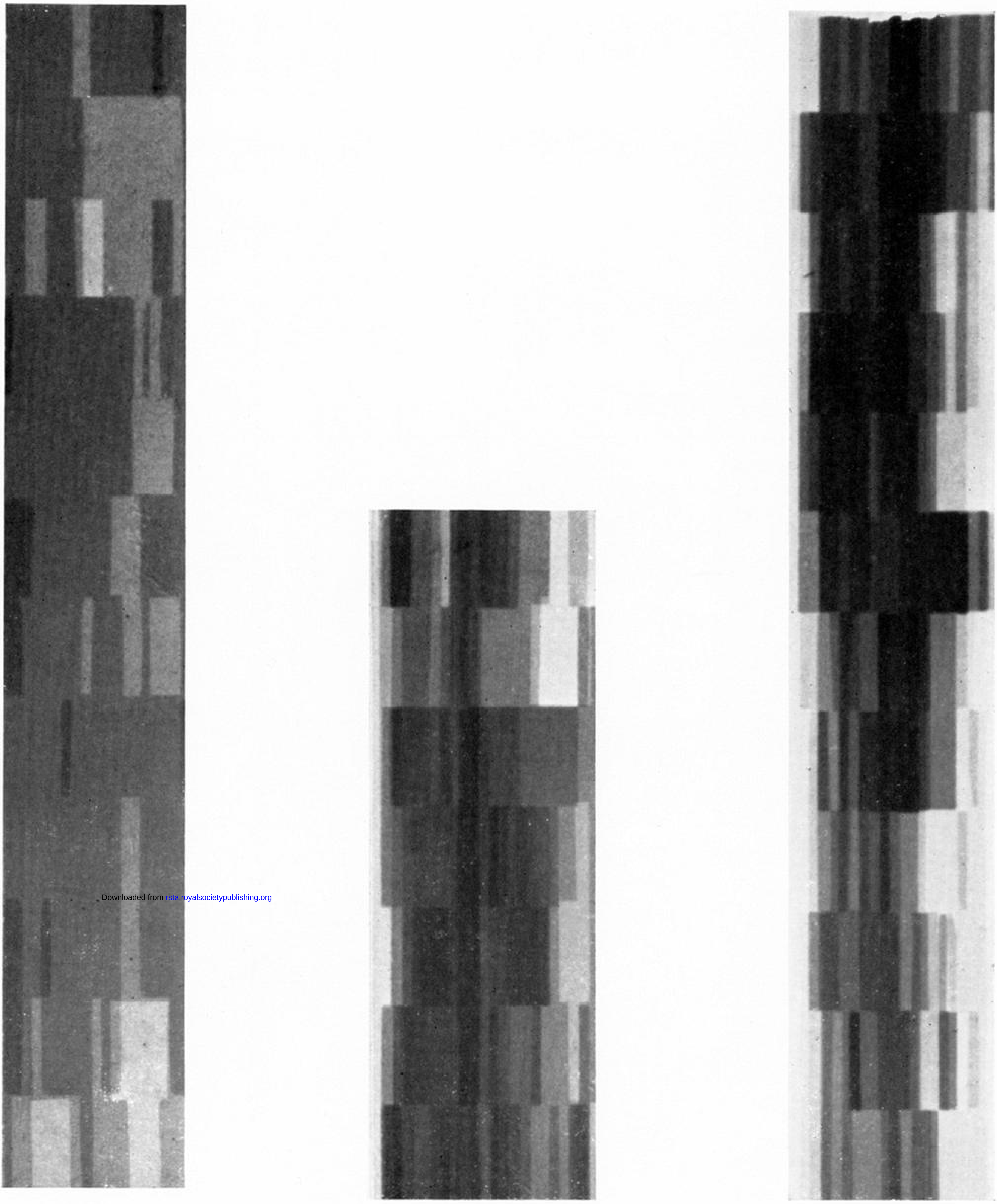
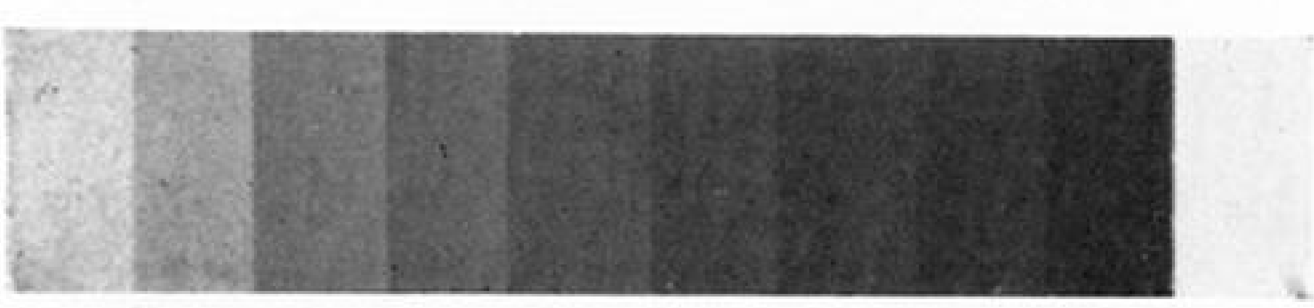



FIGURE 15. 700 kV single-phase auto transformer.



(a) (b) (c)

hade key



| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ample 1 | 0.4 to 0 | 0 to −0.4 | −0.4 to −0.8 | −0.8 to −1.2 | | | | | | |
| ample 2 and 3 | −0.4 to 0 | 0 to 0.4 | 0.4 to 0.8 | 0.8 to 1.2 | 1.2 to 1.6 | 1.6 to 2.0 | 2.0 to 2.4 | 2.4 to 2.0 | 2.8 to 3.3 | 3.3 to 4.0 |

parts/$10^6$

FIGURE 6. Magneto striction distribution in sheets of core iron. (a) Sample 1, 3.35 m × 0.574 m; (b) sample 2, 1.98 m × 0.695 m; (c) sample 3, 3.35 m × 0.66 m.