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A.c.-d.c. Converter Plant

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A.c.–d.c. converter plant

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[Plates 21 and 22]

An 'ideal' converter would accept the power flow of a 3-phase a.c. system operating with sinusoidal voltage and current, and, without energy storage and by a continuous process, convert to or from d.c. Present-day converters rely, however, on repetitive circuit switching operations, more than 12 per cycle being generally uneconomic despite the cost of the energy storage components required in damping circuits and in the filters to maintain acceptable waveforms.

Analysis of the operation of such converters is based on the mathematics of repetitive transients (Laplace and Fourier) and on the use of a d.c. transmission simulator, an extensive model at 10^{-7} scale in power, which is also necessary in the development of complex electronic control circuits.

There exists a great background of experience contributing to the design of most components of the power circuit. In contrast, the development of the switching device, whether thyristor stack or mercury arc valve, calls for advances in the state of art, both in scientific appreciation and in technology, which must be supported by full scale tests.

There is little immediate prospect of the theoretical 'ideal' converter, but this is unimportant, provided that development leads to enhanced overall reliability.

1. Introduction

It is universally understood that in an ideal d.c. system on steady load, not only the mean but also the instantaneous power flow is truly constant. It is less widely appreciated that for as long as the load impedance and supply voltage are constant in a sinusoidal balanced 3-phase a.c. system, the same is true. Individual phases carry varying power, which even reverses momentarily in the case of reactive loads, but the total net instantaneous power flow of the three phases is constant and equal to the mean transmitted power. Thus an ideal converter need store no energy if a continuous process of conversion can be found. Mathematically an ideal inertia-less synchronous machine coupled to an ideal inertia-less homopolar machine meets the requirement.

It is uneconomic to use two machines where one will do. The combined a.c./d.c. machine known as the rotary converter was therefore developed and was applied for many years at powers up to a few megawatts.

The transverter developed by J. E. Calverley, father of Dr T. E. Calverley, whose paper precedes this, set out to apply the same basic ideas to h.v.d.c. Though it was before its time, it was the forerunner of all modern converters in that it relied upon cyclically repeated switching operations to connect the d.c. line to whichever a.c. phase had the most appropriate e.m.f. at any instant. The practical development of h.v.d.c. stems however from the availability of static switching elements – first the mercury valve and latterly the thyristor.

Accepted terminology in d.c. transmission now uses the word valve to mean any single branch of the power circuit having the property of unidirectional conduction, the start of which can be inhibited by a control signal. The word valve thus embraces both the mercury arc device and the equivalent single phase assembly of thyristors.

2. The basis of conversion by cyclic switching

In any system for a.c.–d.c. conversion by cyclic switching, symmetrical treatment of the three phases suggests a multiple of three valves, and symmetrical treatment of positive and negative half cycles suggests a multiple of two valves. The '6-pulse' converter bridge, as shown in figure 1,

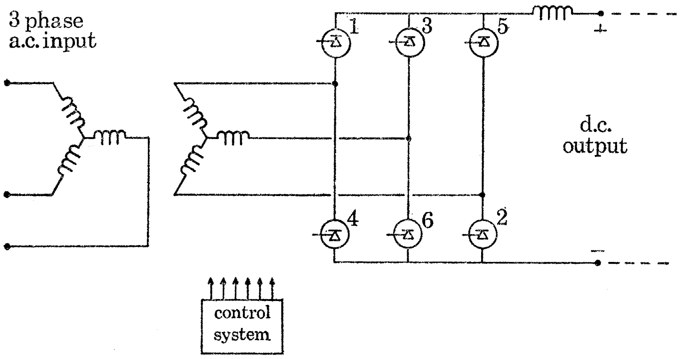

Figure 1. Basic 6-pulse converter circuit.

is thus the simplest arrangement to be considered, from which others may be derived. In addition to the valves, a converter transformer is needed to provide isolation between a.c. and d.c. systems. This also adjusts the voltage ratio to the required nominal value and provides slow adjustment of voltage ratio by tapchanger. The action of this circuit is most easily understood in terms of a constant voltage a.c. system and constant d.c. current. This is emphasized in the diagram by the inclusion of the d.c. reactor.

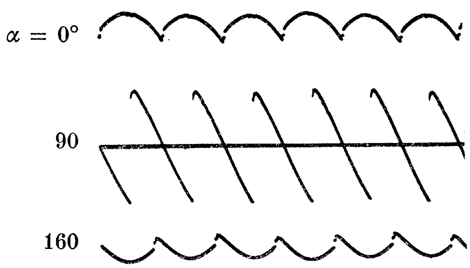

Figure 2. D.c. bridge voltage (6-pulse).

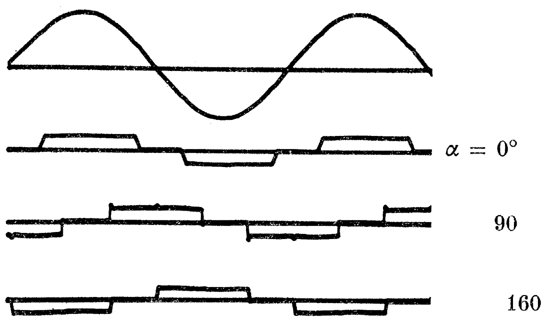

Figure 3. A.c. voltage and current (6-pulse).

The output voltage to the d.c. reactor from an uncontrolled diode rectifier of this type is well known (figure 2), and is shown in the upper trace of this oscillogram. The a.c. phase having the highest voltage in either polarity is connected by the appropriate diodes to the d.c. terminals; in any one period of the a.c. system there are thus six peaks of output voltage and the mean d.c. voltage approaches the a.c. peak.

The valve used in practice is not a diode, but is capable of delaying the start of conduction beyond the point at which positive volts first appear across it. Each valve thus starts to conduct only when a control signal is given. If this control signal is delayed, the next valve in sequence does not take over conduction as in the diode rectifier; the phase which is already conducting continues to determine the output voltage which, therefore, follows a sine wave until the delayed firing of the incoming valve. If this firing delay angle, α, is 90 electrical degrees for all valves, successive commutations from valve to valve select corresponding portions from each of the six a.c. sine waves, and thus generate a saw tooth output waveform of approximately zero mean value. Further retarding the valve firing times (to about $\alpha = 160°$) takes us right down the sine wave to negative voltage, of which the lower trace shows almost the limiting case, beyond which any further delay would cause the incoming valve to lose the positive voltage it needs if it is to conduct. We can thus control the ratio of mean d.c. to a.c. volts from a positive value smoothly through zero to negative by adjustment of the firing angle of the valves. The corresponding power flow for the upper trace is from a.c. to d.c. system (rectification). For the centre trace the mean d.c. voltage is zero, and power transfer is thus also zero; for high valve firing angles (lower trace), the current direction is unchanged although e.m.f. has reversed, and power flow is, therefore, from the d.c. to the a.c. system.

Alternating current

Consider now the current flowing in the a.c. system (figure 3). In rectification this is almost in phase with the a.c. voltage – power flow is thus from the a.c. system to the d.c. system. For the valve firing delay (about $\alpha = 90°$) which gives zero d.c. volts, the current is in quadrature with voltage, thus giving zero power, although the magnitude of a.c. current is unchanged. For inversion (at firing delay around $\alpha = 160°$) the current is almost in anti-phase with voltage; thus power flow is reversed. Note particularly that throughout the whole range of control there is an inductive lagging component of current. This is a direct result of the need for forward voltage to start conduction in the incoming valve.

Thus we have control of the d.c. to a.c. voltage ratio but not of current ratio. Current on the a.c. side is always proportional to d.c. current, though we can control its phase through a range approaching 180° in elementary theory or 160° on more detailed analysis.

Harmonics

In any practical cyclic switching system, waveforms are non-sinusoidal and harmonics must exist.

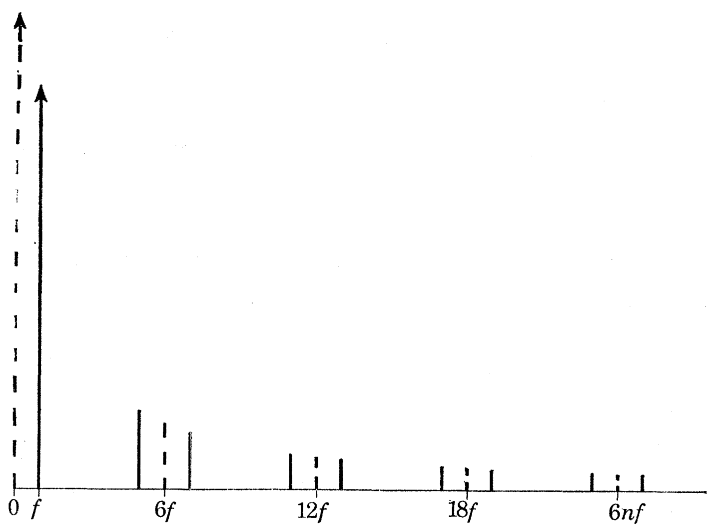

FIGURE 4. Harmonics generated. f, supply frequency; – – –, d.c. side voltage; ——, a.c. side current.

The d.c. voltage and a.c. current both have substantial harmonic content (figure 4). Fourier analysis shows that on the d.c. side we have ideally 6th, 12th, 18th, 6*n*th orders, and on the a.c. side corresponding harmonic pairs, 5th and 7th, 11th and 13th, 17th and 19th, ... $(6n \pm 1)$th. In practice, imperfect symmetry of a.c. e.m.f., components and valve firing times leads to generation of a complete line spectrum of all harmonic orders including relatively small but appreciable values of the intermediate 'non-theoretical' harmonics 2nd, 3rd, 4th, etc.

3. Practical circuit

Figure 5 illustrates various additions to the basic circuit which unfortunately are necessary in practical exploitation of the cyclic switching principle. To avoid needless complexity of diagram, the surge divertors, such as are used to limit overvoltages in any power system, are not shown.

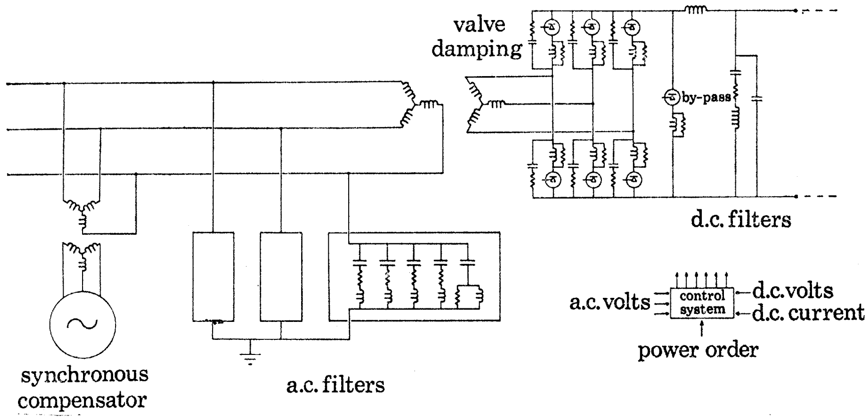

Figure 5. A practical converter.

(a) *Damping*

Resistance-inductance and capacitance-resistance damping components are added to control the transient oscillations excited in the main power circuit at instants of switching. Design of these circuits is a straightforward engineering compromise based on Laplace analysis of the circuit, and the use of components of essentially standard design.

(b) *Bypass*

A bypass valve or vacuum circuit breaker may be added to divert current when the group is shut down.

(c) *Filters*

A.c. and possibly d.c. harmonic filters are added to attenuate currents which would otherwise flow in the a.c. and d.c. power systems, leading to undue losses and to interference with telecommunication systems. A.c. filters (normally shunt-connected) typically comprise 5th, 7th, 11th and 13th harmonic series resonant acceptor circuits, with a damped bandpass section for higher harmonics.

Design of filters for steady-state performance is again an engineering compromise, complicated by uncertainty as to the harmonic impedance of the a.c. system, which varies with operating conditions and is liable to tune the entire filter to the undesirable high impedance resulting from parallel resonance, particularly if system frequency is abnormal. Components are again

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essentially of established basic design, except in one recent innovation in which variable inductors are controlled by phase error detectors to keep the filter arms in tune.

(d) *MVAr control*

The capacitance of the filter partially compensates for the inductive load which the converter throws on to the a.c. system, but further MVAr generation, and its fast control, are needed to prevent undue variation of a.c. voltage. At the generating station this can usually be provided by the alternators, but additional rotating machines (synchronous compensators) must often be provided at receiving terminals.

(e) *Control and protection*

Control circuits determine valve-firing instants in response to ordered power and to feedback of information on d.c. voltage and current and on a.c. system conditions. Practical control equipment employs semiconductor circuits, both discrete components and integrated circuits. Reliable operation of complex circuits is achieved by attention to detail design and by application of redundancy. Very great flexibility of operation can thus be obtained, and the converter is unrivalled in power transmission in its speed of response to control action.

Control design is a typical complex engineering compromise, which can be illustrated by one design requirement. At the non-theoretical harmonic frequencies already discussed, the a.c. system and its harmonic filters may, by parallel resonance, present a high impedance to the converter. If slight unbalance generates non-theoretical harmonic currents, these create non-theoretical harmonic voltages which may cause further unbalance of control action. One of the earlier applications of the phase-locked loop which is so prevalent in today's electronic world was to produce accurately timed firing of converter valves in a manner which opens this unwanted feed-back loop and thus avoids harmonic magnification or even instability.

The analysis of control and power circuit operation can in part be carried out by conventional analytical techniques, but the example above illustrates the complexity of the circuit to be analysed. Interaction of so many parameters, particularly those governing transient distortion of power circuit waveforms following shock excitation by any disturbance, forces the designer to support his analysis by practical test of actual control equipment with extensive models of the a.c. and d.c. networks and converter circuits. Figure 6, plate 21, shows about half of a 'simulator' which is a flexible model used in the basic evolution and development of controls, in proving the final saleable equipment,and in the design and 'trouble shooting' of the power circuits.

4. Valves of today

Valves, unlike the other high-power circuit elements, are of recent origin and require both fundamental scientific technique and most extensive testing in their development.

Both mercury valve and thyristor are limited in voltage withstand of an individual element – in the plasma device by 'vacuum' breakdown and by the consequences of Paschen's Law, and in the semiconductor by avalanche breakdown.

(a) *The mercury valve*

In this the mercury pool cathode is the established source of high electron currents. It requires auxiliary supplies and it is uneconomic to employ too many individual cathodes. Valves have therefore evolved in which voltage subdivision is obtained by many grading grids within a single structure.

A typical 150 kV 1800 A valve (figure 7, plate 21) employs 27 such grids within each main anode insulator. Proper design of the intergrid insulation demands that each grid be supported by a steel 'bucket' which is required to shield the porcelain from grid metal sputtered by the plasma. This dictates the great size of the porcelain. Six anodes share a common cathode and local control system. This permits use of a 'current divider', a group of transformers seen above the valve, to force current sharing over the electrode faces despite the tendency of the plasma to local concentrations, particularly as current falls to zero.

Plasma initiation and deionization both propagate at finite speed, initiation from cathode to anode, deionization from anode to cathode. This leads to poor voltage distribution at start and finish of conduction during which the intergrid gaps nearest the anode sustain most of the voltage. This limits the rating of such valves to around the present voltage level.

This phenomenon, and the need to prove current sharing, show clearly that tests at full-rated current and full-rated voltage are essential in valve development. The high cost of such testing is illustrated by the equipment shown in figure 8, plate 22, which is a small part of the total required in the testing of valves, which are in themselves expensive to produce in small numbers for development.

Overcurrent and overvoltage tests are also needed, to study the 'series arc' mode of conduction which results when high fault currents lead to failure of space charge neutralization by mercury ions. In this mode individual 'vacuum arcs' (more accurately iron vapour arcs) form between individual grids. Many detail models are needed to permit the application of diagnostic methods to study of this phenomenon and others such as ion migration in porcelain, non-uniform plasma distribution, and residual gas transients in normal and overload conditions.

(*b*) *The thyristor valve*

The thyristor has relatively simple auxiliary circuits and is therefore employed in series connected stacks, with voltage grading enforced by tapping the individual thyristors across a capacitor and resistor divider formed from the damping circuits (figure 9, plate 22).

As series connected elements are thus identical, this avoids the basic problem of poor voltage division during propagation of the conducting phase of the medium, at the cost of circuit complexity. Many auxiliary components are required with each thyristor – these include inductors, capacitors, resistors, heat sink, and electronic control circuits.

Complete valves of any rating can be built by using adequate numbers of series/parallel thyristors; the rating of the individual thyristor is thus important only in minimizing cost, which is excessive if undue subdivision of the auxiliary circuits is necessary.

For each thyristor of today's rating that incorporated in an h.v.d.c. valve, the converter can be rated at about 1 kV, 1 kA d.c., these limits being set by the need to withstand transient overvoltage and currents rather than by conditions at normal full load. Foreseeable thyristor developments are likely to raise both these limits by a factor of two or more. Thus large numbers of thyristors, are and will be, needed in practical valves, which are viable only because redundancy is readily built in, to permit continuing operation following failure of a few thyristor modules.

Although in theory one module of a thyristor valve is representative of the whole valve, practical engineering demands testing of complete valves of rating near that required in service.

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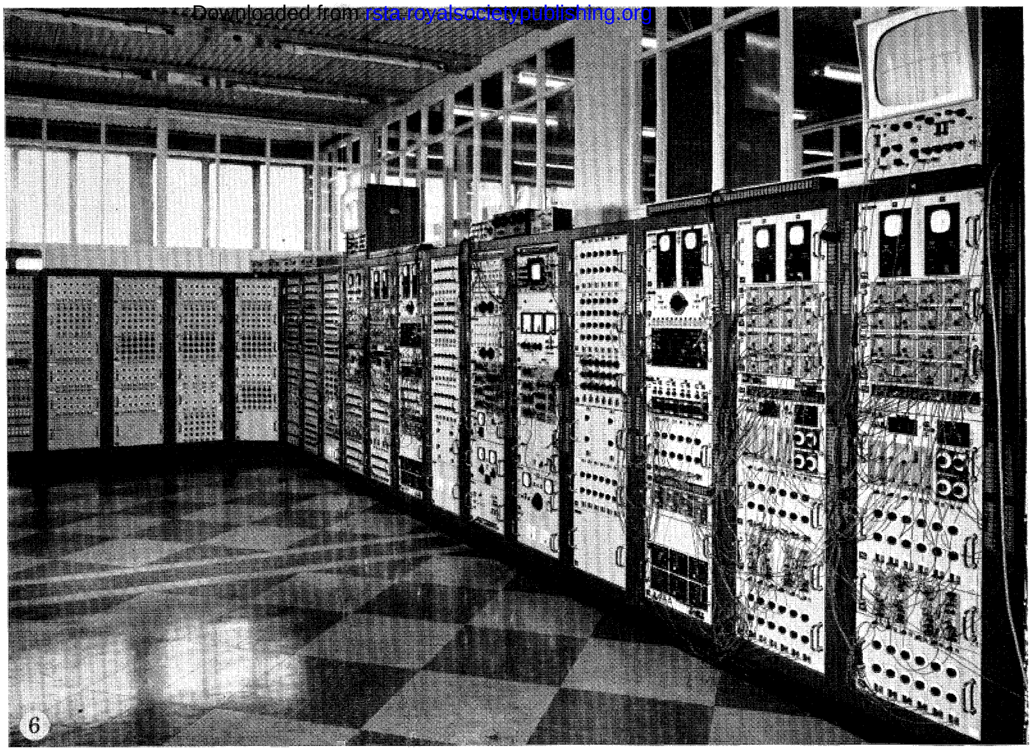

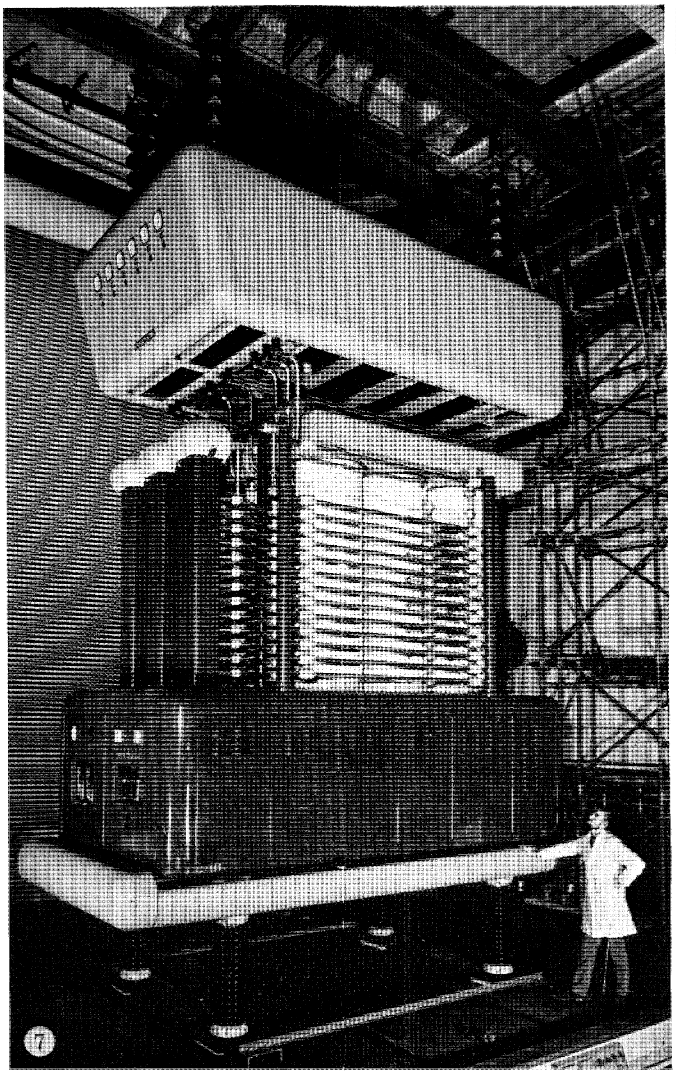

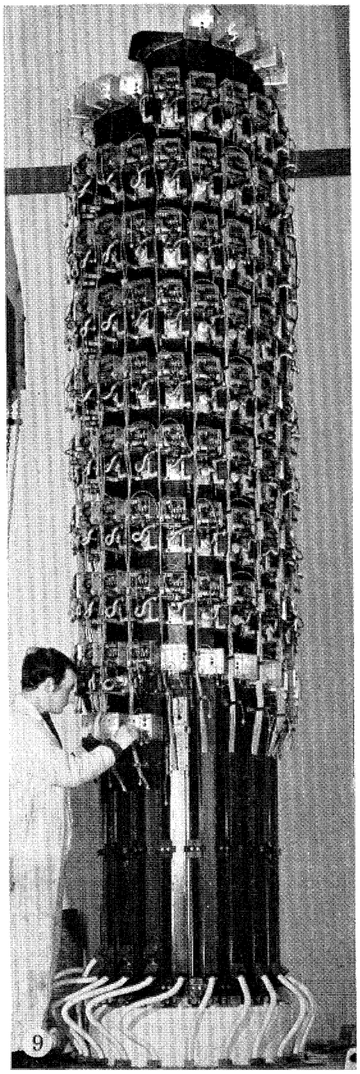

FIGURE 6. High voltage d.c. simulator.

FIGURE 7. 150 kV 1800 A (bridge rating) high voltage d.c. mercury arc converter valve.

FIGURE 9. 100 kV 320 A (bridge rating) assembly for outdoor oil-cooled thyristor valve.

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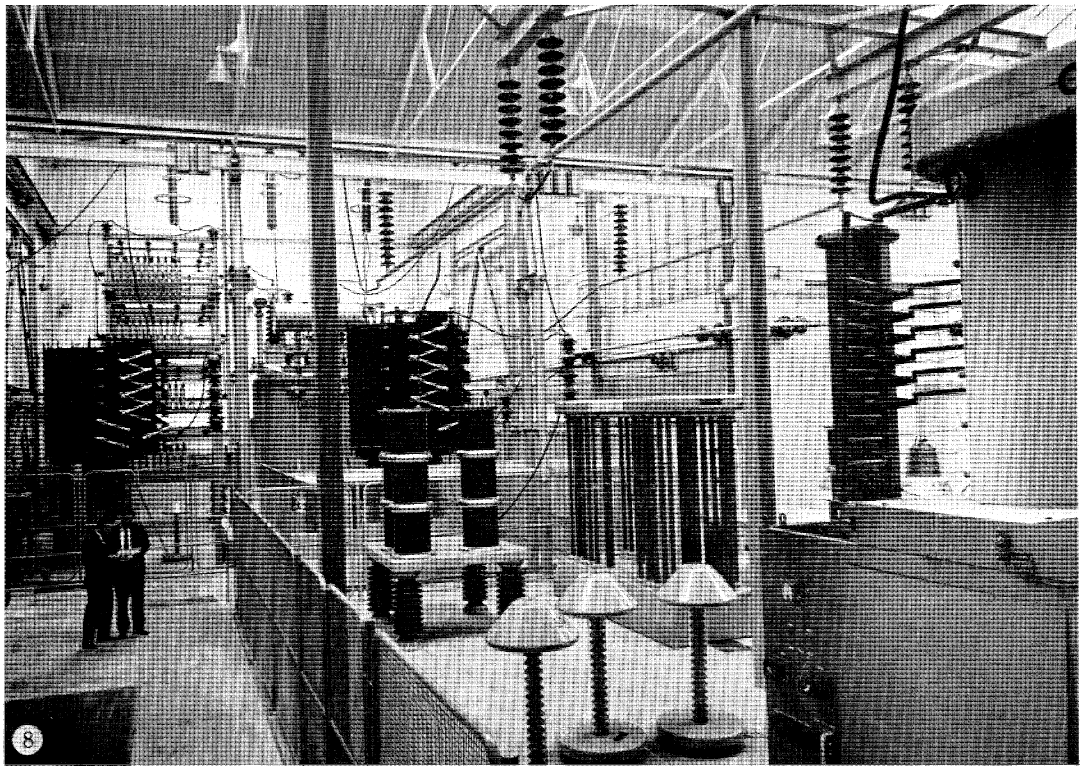

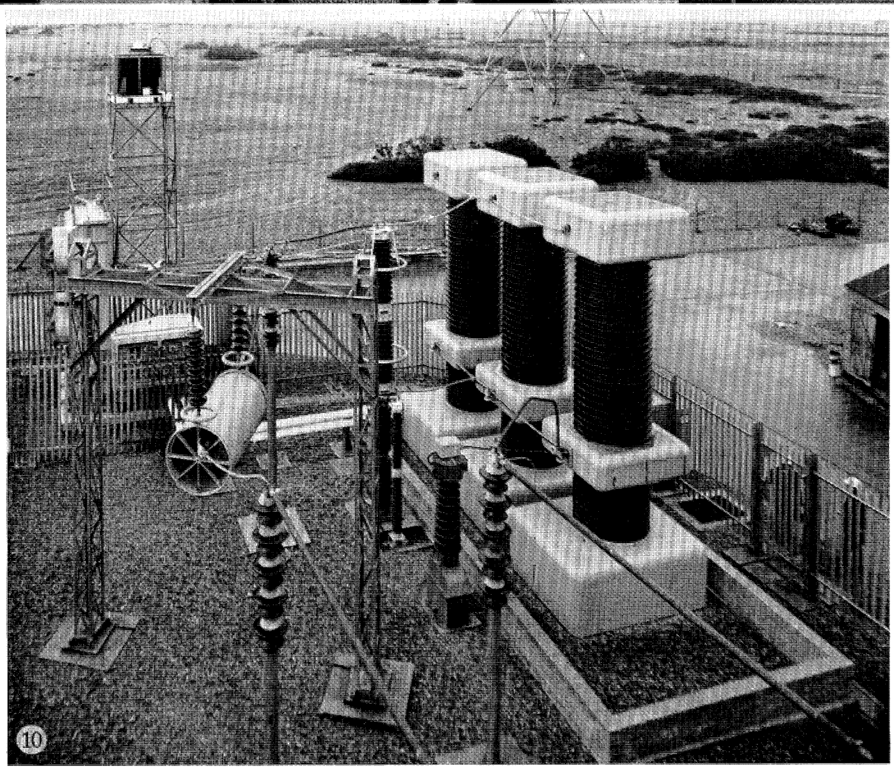

FIGURE 8. High voltage d.c. testing laboratory.
FIGURE 10. 100 kV 960 A (bridge rating) thyristor valve.

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Development costs are thus substantial, though typically less than for plasma devices because the individual thyristor is smaller and has much of its development cost met from industrial applications.

5. The converter station

In combining individual converter bridges, such as already described, a useful saving in harmonic filter costs can be achieved if half of the individual converters are supplied with a.c. voltages phase shifted through 30° by star/delta transformers. This shifts the phase of 5th, 6th and 7th harmonics by 180°, so that they cancel the corresponding harmonics from the other converters, though of course 11th, 12th and 13th harmonics are shifted 360° and still, therefore, add. Note that no extra equipment is needed to achieve this saving.

To help to explain the importance of this, the relative costs and power losses of various parts of a converter station are shown in table 1, which indicates orders of magnitude only, because there are great variations from scheme to scheme. For example, the capitalized cost of the converter loss may be as low as the 15 % of total capital shown here, but is likely to be over 30% in many cases where energy is expensive.

Table 1. Capital cost and losses

equipment	cost %	loss %
valves	25	10
transformer	30	60
damping	5	20
a.c. filter	10	5
control	2	—
other	13	5
total loss†	15	100
total cost	100	—
synchronous compensator	30	25

† 1.5 % of transmitted power.

The table illustrates the fact that costs are spread over the whole range of items and that no major advance can come from reduction of one component only of the cost.

In the example of harmonic cancellation discussed above, a small percentage of the total cost of the converters was saved in the filters at the expense of a very minor change in the transformers. In low-power systems it is possible to use groups of 24 valves to give cancellation o 12th, 18th and 24th order harmonics on the d.c. side and the corresponding orders on the a.c. side. In h.v.d.c. transmission it is not practicable to combine four converters of present-day rating in this way, because the resulting loss of transmission in event of a single fault would generally be too large for the a.c. system. If we subdivide each present-day converter, then the extra costs of transformers and more complex other circuits will swamp the saving in filter cost.

Much the same applies to most of the complex circuits proposed from time to time to give 'forced commutation' and thus eliminate synchronous compensators. Any circuit which requires extra components rather than re-arrangement of existing ones, or demands subdivision into smaller units, tends to be uneconomic in high power applications. This applies particularly if the extra components, auxiliary thyristors for example, must be rated not for a relatively easy normal duty, but for possible transient overload comparable with that of the main components.

6. Possible future trends

(a) *Mercury arc valves*

The existing mercury arc valve is economically difficult to beat and with detail development could be economic for a considerable time. Mercury arc developments in the U.S.A. seek to apply technology developed for aero-space (ion propulsion) to vary vapour pressure through the cycle in accordance with the demands of load current. This is theoretically attractive, but demands most advanced technology to control surface conditions in the critical plasma region of the valve.

(b) *Other plasma devices*

Valves need not necessarily employ mercury plasma, but the vast cost of development, and the fact that any plasma device suffers problems of surface degradation in service, combine to render basically new plasma devices unlikely.

(c) *Thyristors*

The silicon thyristor is capable of considerable development, though both voltage and current ratings are possibly subject to fundamental limits. It has the theoretical advantage over the plasma device that surfaces are relegated to low stress non-active parts of the device, which is likely, therefore to be of superior life. Thyristor development may soon lead to incorporation of much, if not all, of the gate drive circuity in the main silicon slice. If this reduces external gate circuits to simple light guides from a common source, this will substantially reduce the high costs of subdivision of auxiliary circuits. Further materials research may also help in this by producing new thyristors of higher voltage rating, or more effective voltage limiters (e.g. metal oxide) which will permit thyristors to operate continuously at near their breakdown voltage.

(d) *Other solid state devices*

The transistor is more difficult to manufacture in high ratings than is the thyristor, but offers the apparent advantage of controlled turn off. In theory this could be used at any point in the cycle to generate the e.m.f. needed to force commutation of current to the next valve in sequence, thus removing the restriction on valve firing angles which leads to undesirable inductive loading of the a.c. system by any present-day converter.

Unfortunately controlled turn off of current is not only difficult to achieve at high device ratings – it is also difficult to use, because circuit inductance resists turn off and leads to unacceptable dissipation in the semiconductor device unless more complex circuits are used. We have already seen that this is usually expensive.

(e) *MVAr control*

The need for synchronous machines for MVAr control is likely to be avoided in future by the use of polyphase saturated reactors, which have the advantages of faster response and no moving parts. Polyphase saturated reactors of over 50 MVA rating are already in service for control of system voltage, and at busbars where severely fluctuating loads are imposed by arc furnaces of converters feeding rolling mills.

The same basic concept of cyclic switching which is applied in the converter is applied in the saturated reactor for MVAr control. Cyclic saturation of iron-cored reactors interconnecting the a.c. phases automatically maintains near constant a.c. voltage. Polyphase interconnexions minimizes harmonic generation, substantial cancellation of all harmonics below the 35th being economic in this case. Saturated reactors unfortunately share another feature with converters – they present only inductive loads to the a.c. system. When they are used for voltage regulation in conjunction with converters, large static capacitor banks may be necessary to establish an initial net capacitive current for the saturated reactor to control.

(*f*) *Saturated capacitors for MVAr control?*

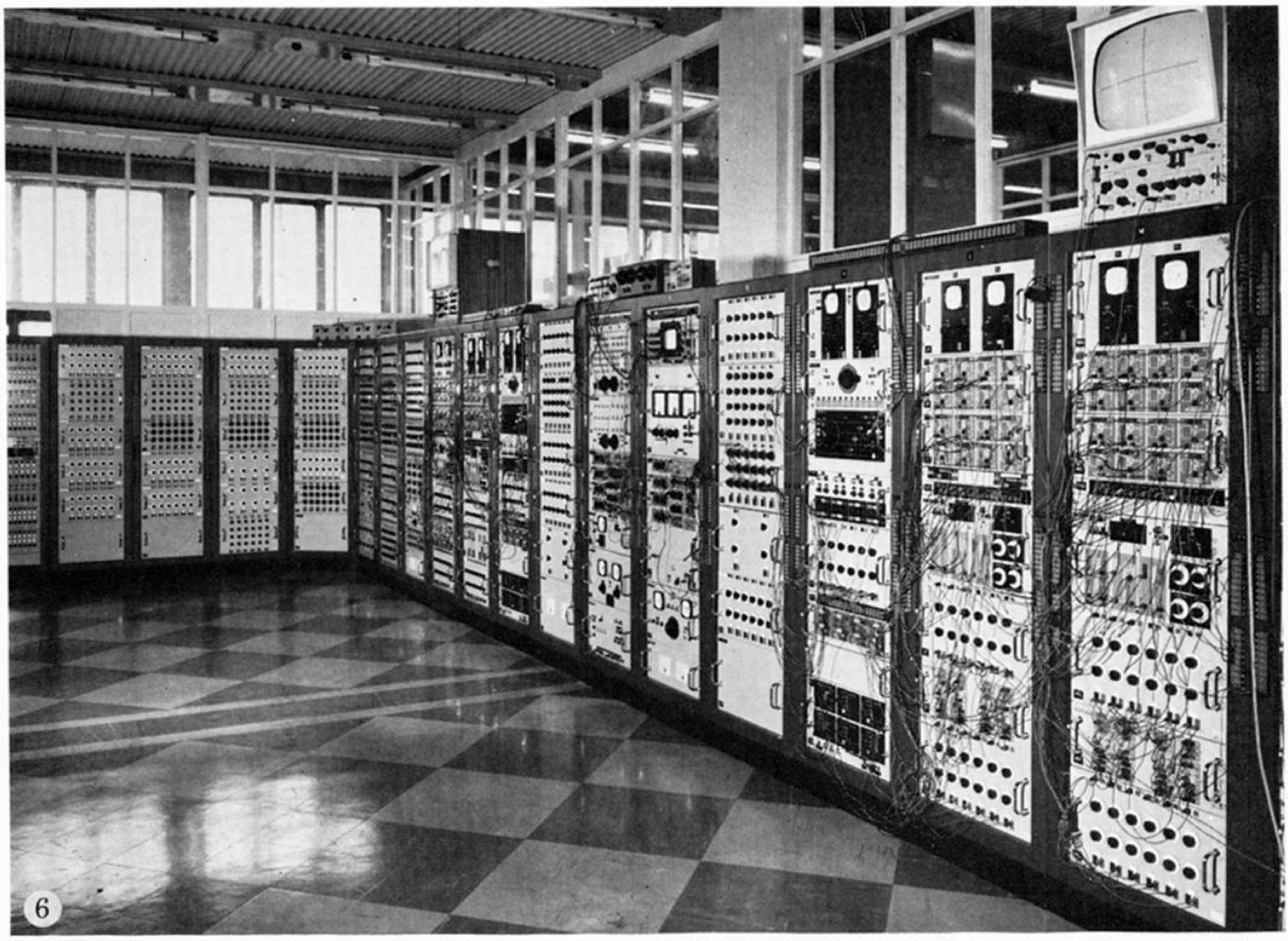
A poly-phase saturated capacitor possessing the same low harmonic generation and voltage control characteristic over a range of leading currents that the iron-cored polyphase saturated reactor exhibits for lagging currents would be valuable. Is it theoretically possible and is there any hope of a practical technology for its construction at high power level?

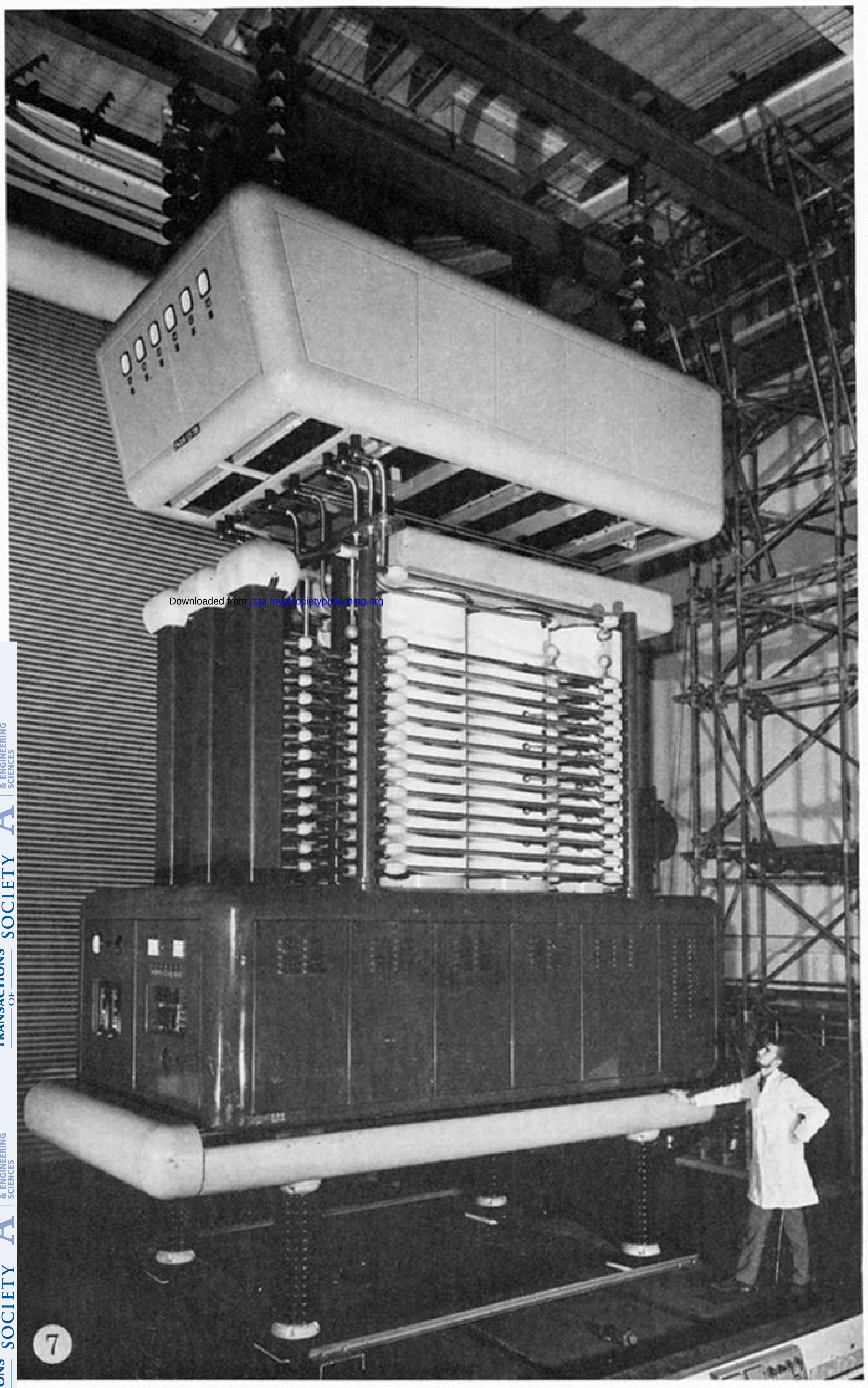
(*g*) *The 'ideal' converter*

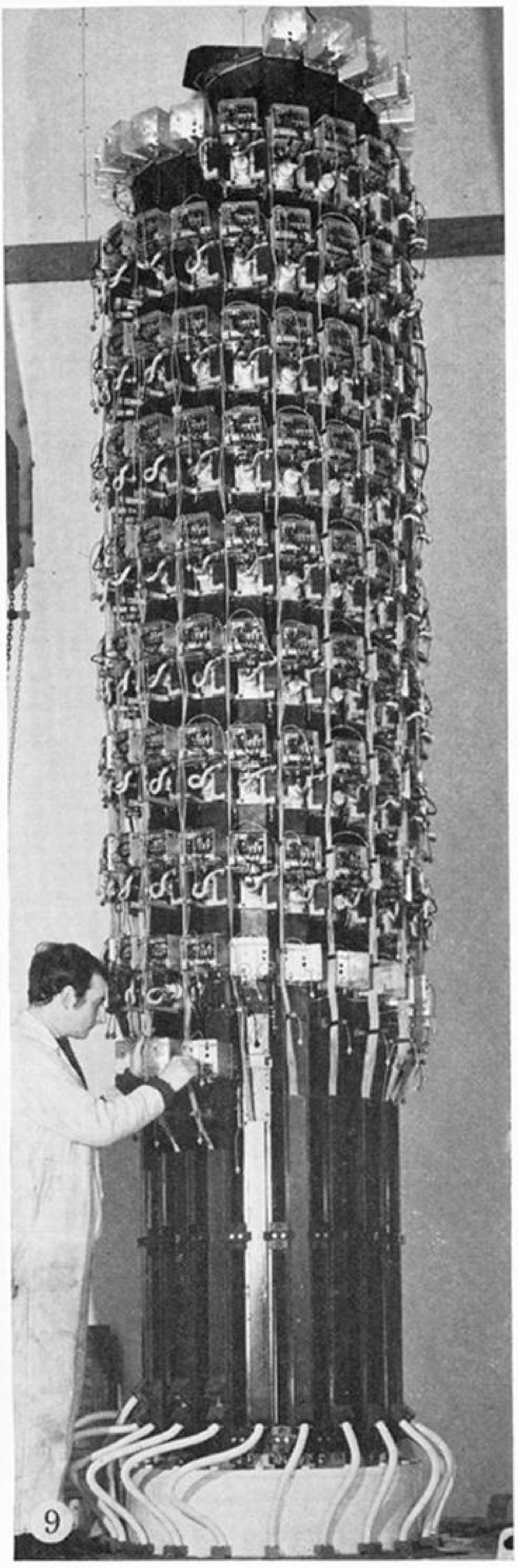
The 'ideal' converter that operates by a continuous process, generating no harmonics and no reactive current flow has not yet been realized. What new principles should we look for? Clearly we wish to couple individual a.c. phases to the d.c. system by ideal transformers of continuously variable ratio. The idea of distributed solid state circuits controlling flux linkages to achieve this appears to lie in the field of science fiction. If there were any overwhelming advantage to be expected of an 'ideal' converter this would no doubt soon change, but it seems that scientific advance and new technology will permit the 'cyclic switching' converter to meet the immediate needs of our growing power systems.

7. Conclusions

There are thus many possible applications of science to the creation of more economic converters. As in much of power engineering, however, the most immediately useful outcome of technological advance and the application of scientific technique is likely to be enhanced reliability of equipment. It should be our aim to achieve from all components, from contactors and oil pumps upwards, reliability comparable with that attained in modern electronics. If this can be achieved, despite adverse economic trends, by funding adequate and properly, directed scientific development, then we will be making effective use of our scientists and engineers.







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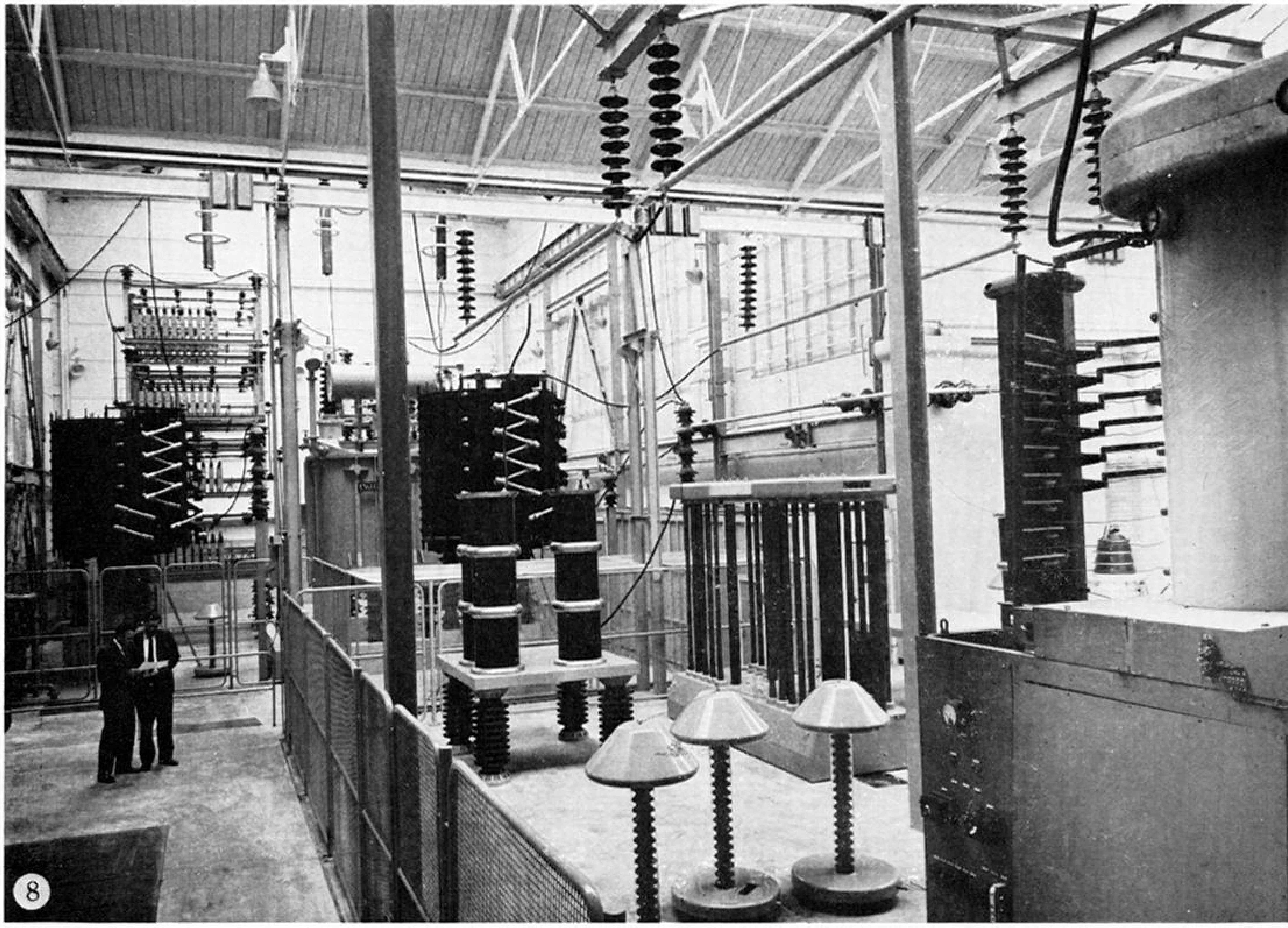

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