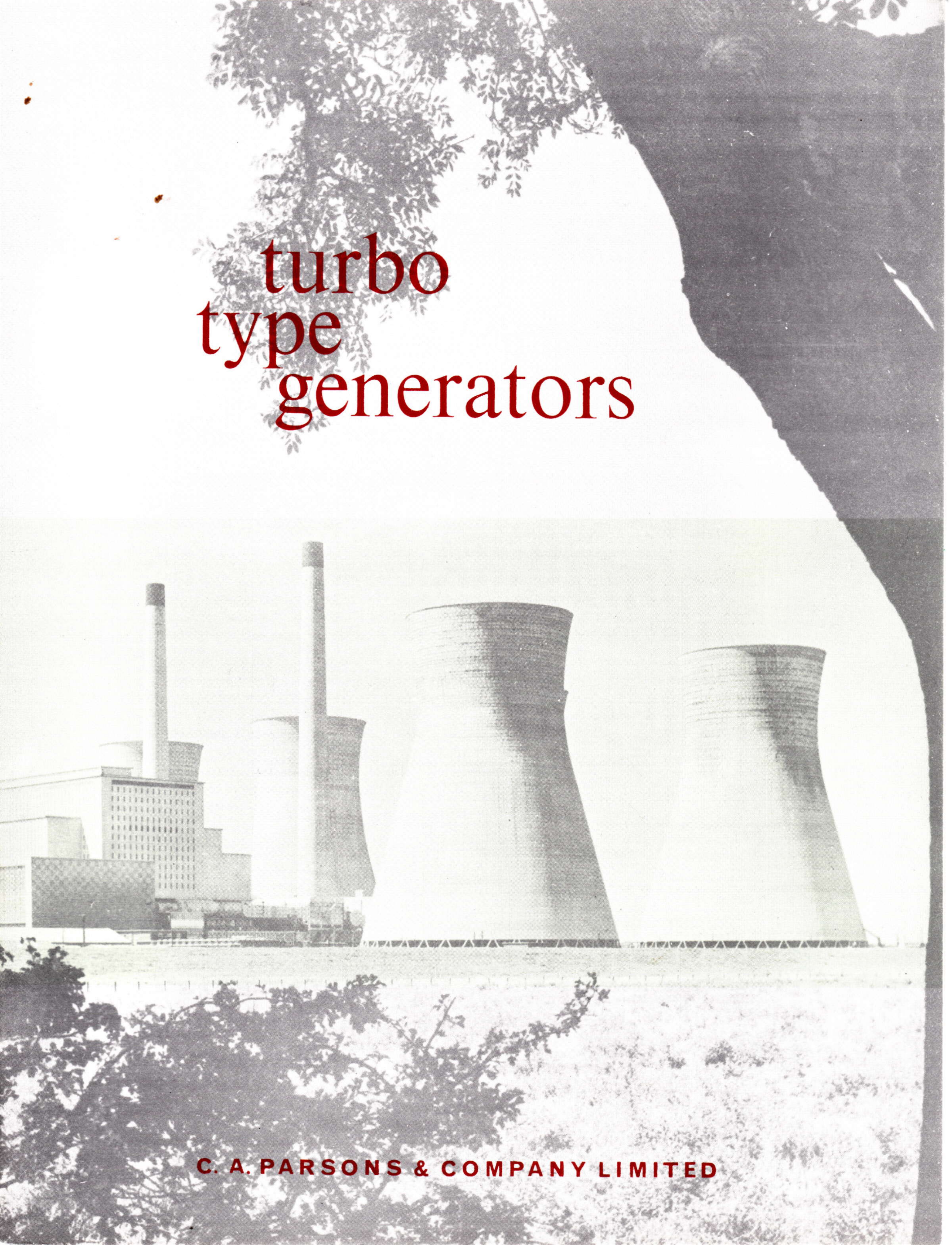
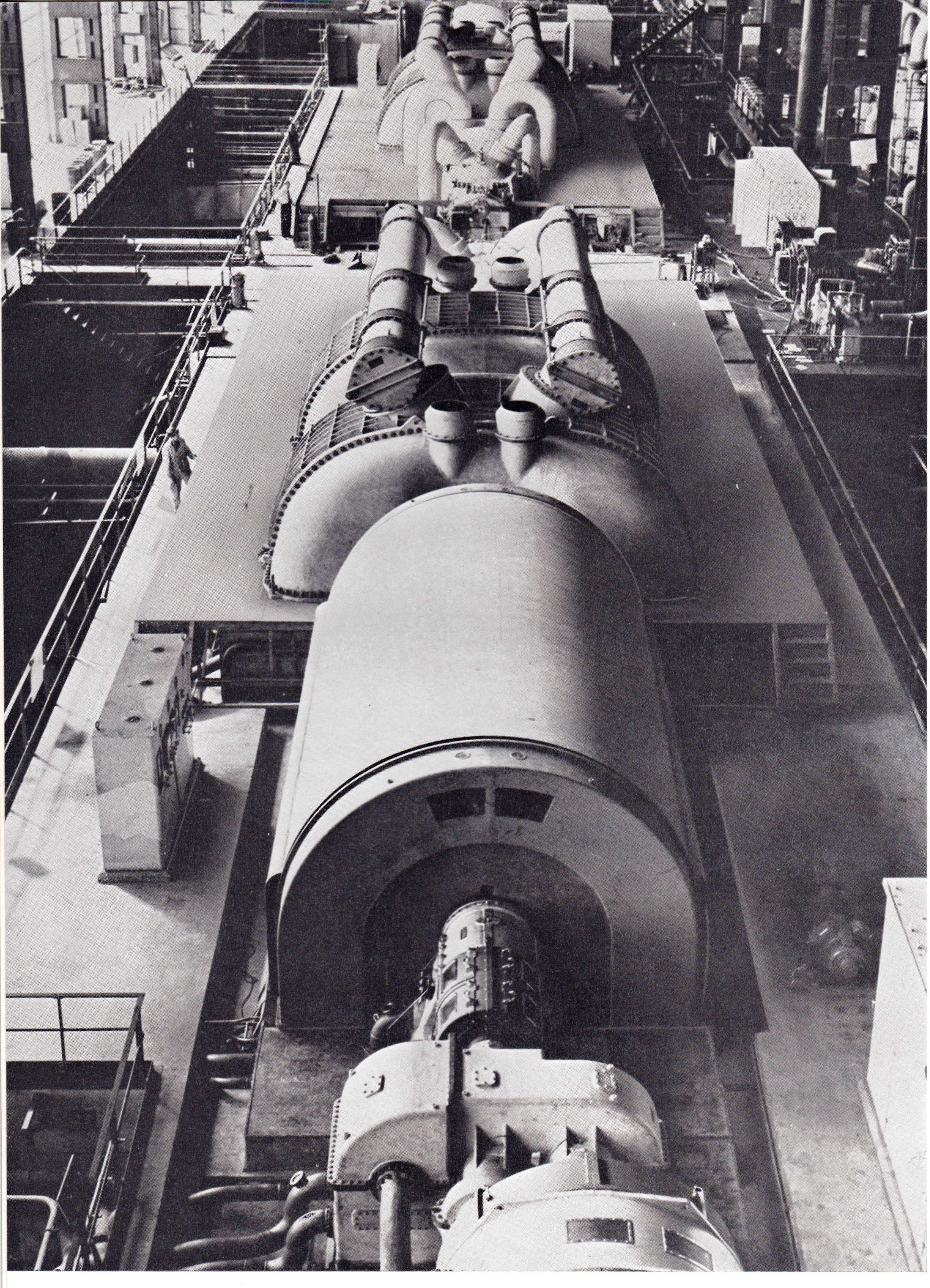
turbo type generators



C. A. PARSONS & COMPANY LIMITED

turbo type generators

BY W. D. HORSLEY, M.I.E.E., Director and Chief Electrical Engineer



Britain's first 550 MW turbo generator, Thorpe Marsh power station, England.

Reprint of the Progress Review on Turbo Type Generators published by the Institution of Electrical Engineers in their Proceedings 1963

1. Introduction

THE decade which has passed since the last progress review on turbo generators was published in 1952 has witnessed remarkable advances in their design and construction.

The demand for electrical power has increased at a steady pace throughout the world with a corresponding growth in the size of interconnected electrical supply systems and in the output of generating stations and individual generating units. For example, the installed capacity of plant in Great Britain has increased from about 17,700 MW in 1952 to over 37,000 MW in 1962, and a similar rate of growth is being experienced in many other countries.

One of the main objectives in the development of electricity supply systems is the economical production of electrical energy and consequently much emphasis is placed upon lower capital and operating costs. A greater economy in material and manufacture is obtained with units of large output resulting in a lower cost per kW and also a saving in space which gives lower building and foundation costs. In addition a higher efficiency is obtained by using high output machines, because this enables full advantage to be taken of higher steam conditions with reheating of the steam.

The siting of power stations in Great Britain is becoming an increasingly difficult problem and the installation of larger sets in fewer stations of high output is a step towards its solution.

For large supply systems the above considerations lead to a demand for generators of the maximum output that can be built.

During the beginning of the period under review a large number of 60 MW 3000 RPM hydrogen cooled sets were in operation or being commissioned. The first 100 MW 3000 RPM generator was installed in 1953, a 120 MW unit in 1958 and the first 200 MW single line two-pole generator in October 1959. The CEGB placed an order in 1958 for a 550 MW cross compound unit with both lines running at 3000 RPM for commissioning in 1962 or 1963. Finally a number of single line 500 MW 3000 RPM units were ordered in 1961 for commissioning in 1965. The increase in output of single units during this period is remarkable.

In the United States single generators of over 300 MW at 3600 RPM are running and cross compound sets of 800 MW and 1000 MW have been ordered. In the Soviet Union 325 MW generators have been built and 600-750 MW 3000 RPM single generators are contemplated.

Up to the present the preferred practice for both economic and technical reasons is to build and test the complete generator in the maker's works. The physical size of these very large units is restricted by a number of factors, such as the maximum size of one-piece forgings, and the weight and dimensions of the generator stator which is the heaviest single part and is limited by available transport facilities. Over some routes in this country at the present time the maximum nett transportable weight is 200 to 220 tons. The problem is constantly under review and depending upon the location of power station sites the limit may be raised in the future.

The stator weight of the first 60 MW 3000 RPM generators which were supplied for the British CEGB system was of the order of 125 tons and for a 120 MW set, 140 tons while the 500 MW single unit generators will have a heaviest lift of under 200 tons. These figures demonstrate the spectacular advance in the utilisation of materials and in the design of generators. The improvement has been achieved to some extent by higher quality steels for forgings and coreplate but primarily by developments in the cooling of stator and rotor windings.

The siting of modern power stations in Great Britain near coal-fields involves the transmission of large blocks of power to the distant load centres.

The capacitance of the transmission system permits a higher generator power factor to be adopted and units of larger output are now specified to operate at 0·85 or 0·9 P.F. instead of 0·8 P.F. as in the past. At the higher power factor a generator of increased rating in MW may be designed within the same transport limits.

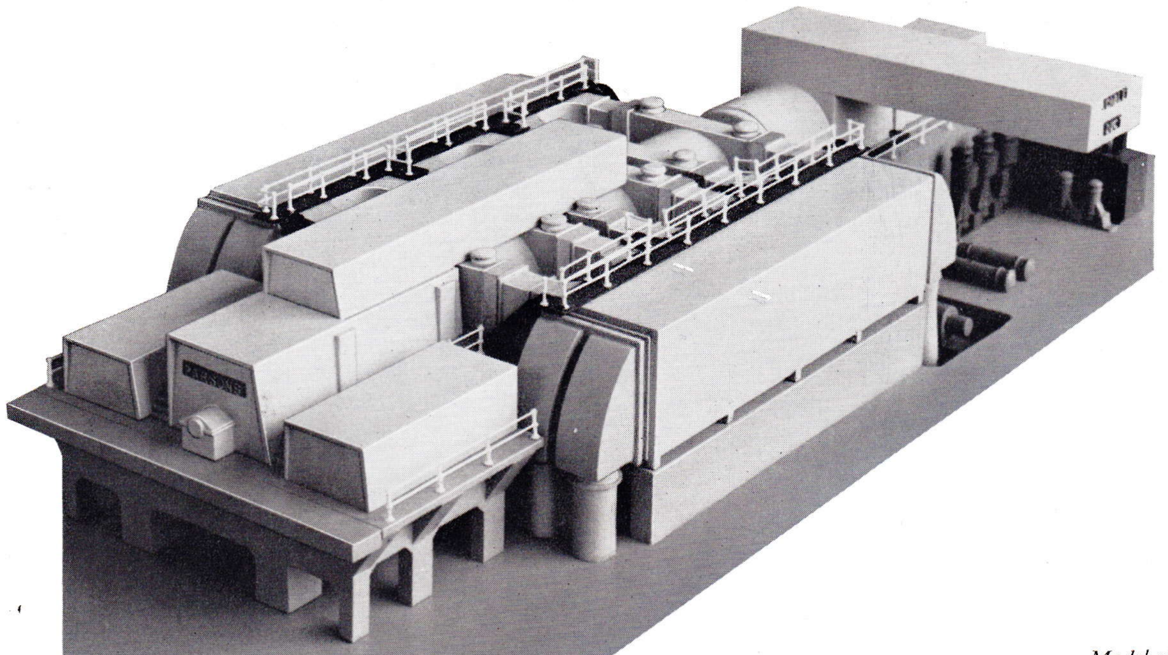
Another design characteristic, the short circuit ratio also has an effect on output as well as an important bearing on the operating stability of the generator and system. For some time values of 0·5 for 0·8 P.F. generators connected to the 132 kV system and later 0·6 for generators of higher power factors connected to the 275 kV lines have been adopted. Similar values or lower have been in use on the Continent while in America they normally have been much higher. With lower short circuit ratios the performance of automatic voltage regulators becomes of greater importance in maintaining stability. In recent years static forms of voltage regulators have been developed that are quick acting and have a negligible zone of insensitivity or " dead band ". The CEGB have made a number of extensive tests on machines connected to the " grid " system in normal and fault conditions using different types of voltage regulators.

These investigations indicated that with use of latest forms of voltage regulation in conjunction with adequate excitation response, satisfactory operation would be obtained with generators working over a range of power factor from 0·9 lagging to 0·9 leading with a short circuit ratio as low as 0·3. There are design limits which may set a lower limit to this ratio. A low short circuit ratio has the advantage that a greater output can be obtained without exceeding transport limits and the capital cost of a generator so designed is reduced. The CEGB have now adopted a short circuit ratio of 0·4 which makes a 3000 RPM generator of 500 MW output or more at 0·85 P.F. practicable.

These changes, together with the outstanding improvements in cooling, have resulted in highly rated designs for these large sets. The electrical loading of the generator and consequently the stator transient reactance have been appreciably increased. The latter has an important effect upon system stability and may impose another limit to be overcome in the future. The relatively lower inertia constant of these advanced units also has an adverse effect upon system stability.

The high reactance of generators of large output has the advantage that the electro-magnetic forces in the stator windings under fault conditions are reduced. On the other hand eddy current heating in a solid rotor during abnormal conditions of operation is accentuated in more highly rated machines. The negative phase sequence heating in rotors of large generators is another problem which is engaging the serious attention of designers.

The mechanical stresses in the shaft ends and couplings of machines of high output arising from normal full load torque are becoming higher and the ability of these parts to withstand the additional oscillatory forces during sudden short circuits have



Model of 500 MW single line turbo-generator 3000 RPM.

been studied. A thorough investigation involving detailed calculations, which have been greatly assisted by the use of computers and experiments with scale models, has gone far in elucidating the problem and the evolution of satisfactory designs.

As generators become larger and more complex they are designed to closer limits and in more detail. The characteristics which affect their behaviour and performance particularly in large systems have become of increasing importance and involve a considerable amount of work in their determination. The digital computer is employed increasingly for such calculations and its application has also been extended to include basic design as well as routine computations.

More extensive research facilities in general have contributed to the design and development of the present day large turbo type generator.

The experience which manufacturers have gained in the design, manufacture and operation of units of high output in Great Britain has been of invaluable assistance in meeting competition in the export market. A number of British made turbo generators of 200 and 300 MW are operating in Canada and there is a 500 MW set in the United States.

2. Developments in Cooling

2.1. *General*

During the period under review development has been concentrated in the use of hydrogen for cooling turbo generators of 20 MW and upwards. Air cooling is still adopted for sets up to 30 MW and for some high voltage machines of 50 MW, but hydrogen at increased pressures is employed exclusively for very large sets with the addition of liquid cooling for the stator windings.

Before 1952 the hydrogen pressure chosen was usually about $\frac{1}{2}$ lb per sq. inch gauge and advantage has since been taken of the more effective cooling to be obtained at higher hydrogen pressures. A number of machines are operating at 15 and 30 lb per sq. inch gauge and larger generators now under construction are designed for operation at 45-60 lb per sq. inch. The greatest gain has been obtained by the development of systems of cooling in which channels are provided in the active conductors and either a gas or liquid coolant is brought into direct contact with the copper. Temperature gradients through the insulation are thereby avoided.

Direct gas cooling has been used for both rotor and stator windings but the larger heat capacity and higher heat transfer of liquids quickly led to their application to the direct cooling of stator windings.

2.2. *Direct Gas Cooling*

2.2.1. *Rotor Windings*

A number of different forms of direct gas cooled rotors have been devised and are in successful operation throughout the world.

The first direct hydrogen cooled rotor in this country was commissioned in 1952 and the application of this technique extended rapidly.

There are three main types of construction of which there are many variants in the design of the cooling passages in the copper and they are associated with a variety of ventilating systems. In the first, axial ducts of suitable shape are provided in the copper which are formed during the drawing process or by building up the conductor with channel or similar sections. The gas may be forced or drawn through the rotor conductors from one end to the other in a single pass. In other designs the gas is drawn in at both ends and discharged into the gap between the rotor and the stator through holes provided in the copper, insulation and slot wedges in the centre portion of the rotor.

In a second type radial ducts in the copper coils which are distributed over the full length of the rotor body are formed by punching or machining individual strips. At each end of the rotor the gas enters subslots which are machined in the rotor body beneath the winding slots. The gas flows from these ducts into the radial slots in parallel and is discharged at the rotor surface through holes in the winding retaining wedges. Extensive research into the configuration and proportions of the ducts and channels has resulted in further gains in heat transfer.

A combination of radial and axial cooling ducts arranged to form a number of circuits in parallel fed from a subslot has given a high performance.

Where radial cooling is used in the body of the rotors the end windings are usually axially cooled.

The third main type termed the "air gap pick-up" method is used in America. In the windings in the rotor body, a number of parallel gas paths through the copper are provided in which the gas both enters and leaves through ducts leading to the surface of the rotor. The orifices of the inlet and outlet holes emerging at the rotor surface are shaped so that the peripheral motion of the rotor surface induces a flow of gas in the appropriate direction. With this arrangement the end windings and part of the embedded copper are axially cooled.

Improved methods of direct cooling are continually being explored and new forms may be developed. It seems likely that many years of running experience will elapse before a basic construction evolves.

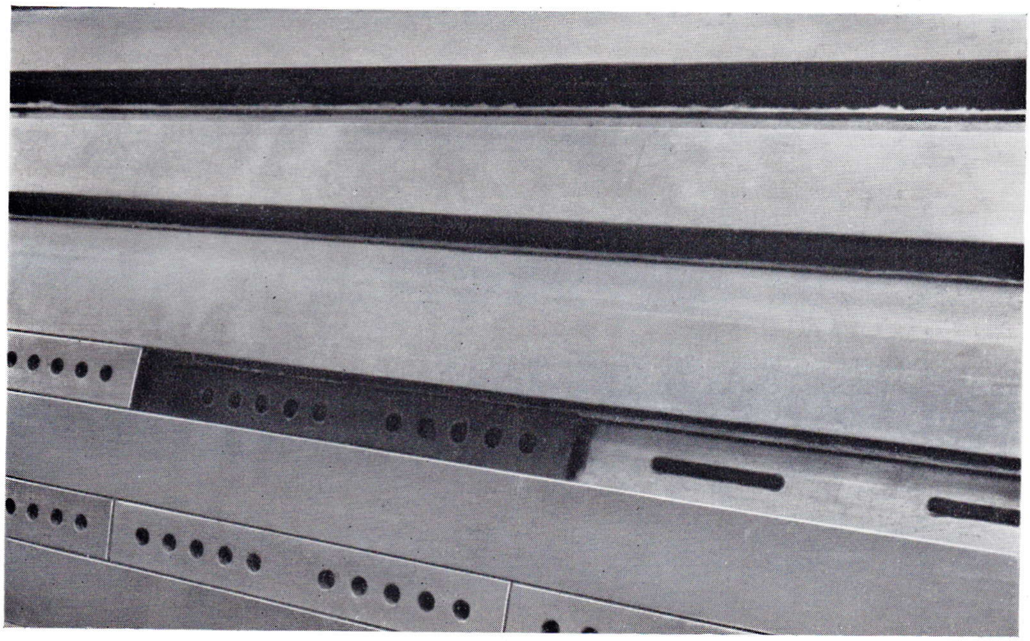
The greatly improved heat transfer gained by direct cooling of rotor conductors, as described in the previous Section, has enabled a much higher m.m.f. rating of the rotor to be obtained.

2.2.2. *Stator Windings*

The increase in stator m.m.f. and therefore in the output of a generator which is made possible by direct rotor cooling has in turn led to the application of direct cooling of stator windings for large generators.

A number of designs using direct gas cooling have been developed by several manufacturers and are in service. Direct gas cooling for stator windings was applied to a 125 MVA generator in America in

1953 and later to 111, 222 and 324 MVA generators in Great Britain. The gas ducts are generally in the form of thin walled rectangular tubes of high resistance material built into the stator bars and lightly insulated from the copper strips forming the conductor. In order to avoid the practical difficulty of providing gas channels through the walls of the main insulating tubes with adequate leakage surfaces the gas is admitted at one end of the conductors and discharged at the other. The mass flow and therefore the thermal capacity of the gas must be sufficient to ensure that the temperature rise of the gas over the length of the conductor is reasonable. The gas is supplied from the generator ventilation system and multi-stage fans mounted on the rotor shaft or a high speed blower may be used for its circulation.



Enlarged detail of rotor showing radial slots in coil, insulation and holding wedge.

2.3. *Direct Liquid Cooling*

Direct gas cooling for the windings of large generators is a considerable advance but as previously mentioned in section 2.1. liquids have many advantages for this application, and are being used by the majority of makers.

2.3.1. *Stator Windings*

An oil cooled stator winding was commissioned in America in March 1956, and the first direct cooled stator winding using water was installed in this country in the same year.

Oil has excellent insulating properties but it may increase the fire hazard and even a small leakage might have a harmful effect upon the insulation normally used for the stator windings. Water is free from those objections while its heat transfer properties are superior to those of oil and the power required for the circulation is less. Pure water is a good insulator and there is no practical difficulty in maintaining its electrical resistance at a reasonably high level. A comparatively short water column will withstand a high potential without difficulty and the loss due to the small leakage currents, even with moderately pure water, is not significant. With water the area of passage required is small and the stator conductors may conveniently be built up of rectangular tubes and transposed in accordance with accepted practice. These tubes are readily produced by the copper suppliers. The main problem in applying liquid cooling lies in the water connections to the conductor ends which must be liquid tight and able to withstand the specified electrical pressure tests. A number of designs using water have been evolved by many manufacturers. The majority use conductors in which all the strips are hollow and the water flows from one end of the winding to the other through all conductors in parallel.

In some designs the water connections to the conductor ends are made of a flexible plastic material (usually p.t.f.e. in extruded form). The other end of these pipes is connected to circumferential manifolds, usually made of stainless steel, surrounding the windings inside the stator casing.

The manifolds are insulated to enable winding insulation resistance measurements to be made but are connected to earth during normal operation. Several machines up to 325 MVA with this form of construction are in operation in the United States using either water or oil as the coolant.

Another design has been developed in this country in which the use of a large number of individual water connections to the winding is avoided. The conductors, which are built up of hollow strips transposed along the length of the slot, terminate in hollow ferrules. Each group of conductors forming a half phase have their ferrule ends fitted into a common water box moulded in cast epoxy resin. There are thus six of these water boxes at each end of the stator, one for each half phase section, and they are spaced to allow ample clearance between phases. The coil to coil connections between top and bottom layers of the windings are made by simple clamps inside the water boxes. The water supply to the boxes is taken through the main leads and the terminal bushings which are thus also water cooled. The water connections to the main leads outside the casing pass through tubes of insulating material to provide resistance columns. A 60 MW hydrogen generator using the box construction has now been in satisfactory operation in Britain for about 5 years, and 200 MW sets have now been commissioned.

In order to reduce the number of water connections to the stator winding one manufacturer has adopted a slightly different approach to the problem. The conductor is built up from groups of three copper strands consisting of a rectangular copper tube between two solid strips which are transposed in the normal manner. The water is fed to the winding through hollow terminal bushings at both the phase and neutral terminals and discharged from tappings at the centre of the phases through insulated copper pipes and small insulating bushings. Resistance columns are provided outside the stator. With this arrangement there are only twelve water paths in parallel and the coolant flows through a number of conductors in series.

The cooling water system for stator windings is simple; turbine condensate or demineralised water having a low electrical conductivity is used although the value is not critical, as the losses from electrical leakage currents in pipes, boxes and resistance columns are small. The windings form part of a closed circuit which may also include a heat exchanger, pumps, filters, gas detraining chamber and make up tank. The heat exchanger may be connected in shunt with the main hydrogen coolers using distilled water so that there is no danger of contamination should a leak occur. A small demineralising plant may be included in the system as a precaution.

On the Continent liquid cooling has been used for the stator core and the core end support plates in addition to the stator windings and the design contains some unusual features. Oil was selected for the coolant and has the advantage that the possibility of rusting of the passages in the stator core is avoided. The rotor is cooled by hydrogen under pressure and is separated from the stator by a cylinder of insulating material in the stator bore. The space in the stator is filled with nitrogen at the same pressure as the hydrogen. The gas to the direct cooled rotor is supplied by an external blower through suitable ducts and external coolers. As all parts of the stator are liquid cooled internal fans and coolers are not required.

2.3.2. *Rotor Windings*

Indirect water cooling of turbo generator rotors has been employed successfully in the past, notably in Britain, but is is relatively ineffective and has the drawback that intensification of cooling in this way increases the temperature differential between the copper and iron. Operating experience indicates that the reliability of insulation may be affected as much or more by temperature gradients as by the temperature level.

The direct liquid cooling of rotors is receiving the attention of many manufacturers but the problems of centrifugal force and of feeding the liquid in and out of the windings are difficult. It does not appear likely that direct liquid cooling of rotor windings would lead to an immediate increase in the output of generators or better utilisation of material as there are other limitations in the design. For example, it is not practicable to take full advantage of direct cooling of either stator or rotor windings as the increase in copper losses and therefore loss in efficiency would be too great. Direct liquid cooling of the rotor would, however, enable the hydrogen pressure to be reduced with a saving in windage losses and in the weight of the stator casing.

2.3.3. *Stator Core*

The stator core in the majority of modern high speed generators is cooled by some form of the well established multiple radial axial system of ventilation in which radial ducts are spaced every few inches along the length of the core. The introduction of direct cooling of the stator conductors reduces the amount of heat to be dissipated from these ducts and simplifies the problem of cooling the core. There are advantages in using axial instead of radial ducts and axial cooling of stator cores is being used increasingly for large units. Internal fans mounted on the rotor either at one or both ends, are generally favoured though some variety is shown in the arrangement of the gas circuits. The gas coolers are also usually fitted within the generator casing and, again, some diversity is shown in the shape and location of these components.

3. Materials and Construction

3.1. *Stator Casings*

The continued increase in unit output, the use of hydrogen at higher pressures and the development of a variety of cooling systems has led to many changes in the design and construction of stator casings.

The fabrication of stator casings with welded steel plate is universal and well adapted to the more complicated structure of hydrogen cooled machines. Heavier plates are now required for the higher hydrogen pressure, particularly for the end walls which may be 3-4 inches thick.

Although the possibility of a hydrogen explosion is remote, casings for large hydrogen cooled generators have been made from a notch ductile steel instead of the low carbon steel commonly used for air cooled machines. The end doors or brackets for the former may be of cast steel but the tendency is towards an increasing use of fabrication for these parts. The bearings may be located in these brackets, a practice which is frequently adopted for large sets. It is usual to apply a hydraulic proof test of 1·5 times the maximum working pressure. Test pressures up to 90 lb per sq. inch have been applied and little difficulty is experienced with leakage through the welded structure. Some care is needed in the design and making of joints, particularly those of the end doors and a variety of means has been developed by different manufacturers to ensure effective sealing against gas leakage.

The gas coolers are generally situated inside the casing and may be arranged longitudinally, vertically or horizontally across the axis. There are obvious advantages in making the casing as nearly cylindrical as possible and this object is best achieved with the longitudinal type of cooler. This construction may also have some advantage in meeting transport restrictions.

Transport limitations may make it necessary to subdivide the stator units of high output into two or more parts. A large number have now been manufactured with the core and windings assembled in a compact fabricated frame which is then mounted in or attached to separate hydrogen tight casings. A variety of designs have been produced which have been influenced to some extent by the different cooling systems in use.

In one form the frame carrying the core and windings is a skeleton construction sliding into an outer cylindrical casing. The gas coolers which may be either longitudinal or vertical and, usually four to six in number, are mounted in the outer casing.

The separate outer casings are comparatively light but their dimensions may cause difficulty in transport in some parts of the world and they may therefore be further subdivided into two or more sections bolted together or welded permanently on site.

In another form of construction the outer casing is divided on the horizontal centre line which has the advantage that during assembly the inner frame is lowered directly into the bottom half of the outer.

In yet other designs the core and windings are built into an enclosed cylindrical casing of minimum dimensions to reduce the weight of the heaviest lift. The gas coolers are vertical and enclosed in separate box-shaped compartments which are fitted to either one or both ends of the main casing.

The stator cores of two-pole generators are deflected by the magnetic forces due to the air gap flux and a double frequency vibration is caused which though small may cause difficulties if transmitted through the bedplate and foundations. By suitable design the amplitude of the deflection may be limited to a reasonable value. This requirement imposes a limitation in the design of more highly rated machines and in the use of higher quality coreplate, and in many of the larger machines some form of flexible mounting is interposed between the core and the frames or casings or beneath the stator feet to allow a higher core deflection without harmful external effects. The avoidance of natural resonance in any parts of the stator or surrounding structure at the double frequency is of particular importance.

3.1.2. *Coreplate*

Grain-oriented cold-rolled silicon steel which has a lower loss and a higher permeability in the direction of rolling has been in use for many years for transformers. This material has been used extensively in America for turbo generators but it has not been readily available in this country until recently and the majority of machines installed in the period under review have cores built with ordinary hot-rolled plates. Further experience with grain-oriented plate may lead to its greater use for turbo generator cores in Britain.

The core of a turbo generator is a more complicated structure than that of a transformer and for several reasons full advantage cannot be taken of the better qualities of grain-oriented plate. Some manufacturers in recent years have been using a cold-rolled non-directional plate which has similar magnetic properties to hot-rolled material of equivalent grade and is comparable in price.

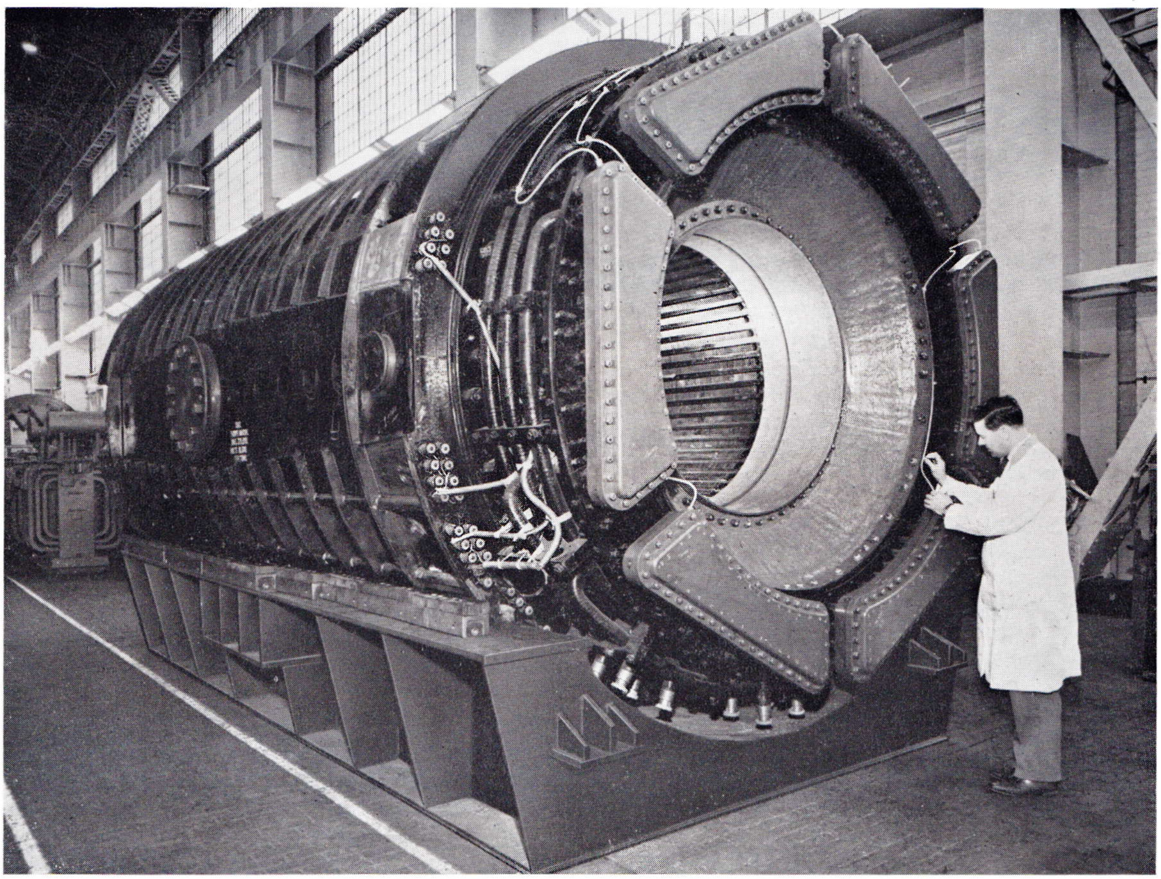
A more detailed review of coreplate materials including a reference to the development of a new material which is grain-oriented in two directions at right angles, is given in the current progress review on alternating machines.

3.1.3. *Insulation*

For many years the main insulation of stator conductor bars has been built up of mica splittings bonded with an insulating varnish on a suitable backing and applied in the form of either sheet or tape. A varnish with a bituminous or similar base has been most commonly used. This type of insulating tube has proved to be most reliable in service and it is still being used in most modern machines in Britain. A variety of materials is used for the insulation of the individual strips forming the conductors. These include mica strip and tape, varnished glass tapes or impregnated braids, and asbestos tape. The conductors are vacuum dried and impregnated under pressure with suitable varnishes and for some generators the end windings of the finished stator are similarly treated in large autoclaves.

The end winding supports, packings and other parts are made from impregnated fabrics, hardwood or compressed laminated plywoods. Glass cord, tapes and synthetic fibre materials are used for binding, securing packings and similar purposes. In America, and to some extent in Europe, synthetic polyester resins have been developed and used extensively for the bonding of mica for the main insulation on stator conductor bars. More recently epoxy type resins, modified to give some degree of flexibility, have been employed.

Yet another form of insulation has been developed in recent years using mica as the chief constituent. Mica splittings are treated to produce very small flakes of mica which are then built up into a sheet with a thin glass or other suitable backing. The process is similar to that used in paper making and a synthetic resin is employed as a bond. Glass fibre may be incorporated to give mechanical strength. This material has been used in tape form for stator conductors. With direct liquid cooled stator windings the thermal charcateristics of the main insulation become of less importance and in future it is possible that materials other than mica may offer advantages.



275 MW hydrogen and water cooled generator stator.

3.2. *Rotors*

3.2.1. *Forgings*

During the last decade, the maximum capacity of steel makers for the production of large forgings has not increased greatly but nevertheless has kept pace with the requirements of manufacturers of large generators. Advances in technology have resulted in improved qualities of forgings and large alloy steel shafts with better physical properties made to the stringent specification necessary for generator rotors are now available.

Further developments have been made in inspection and testing and, in particular, in more sensitive ultra sonic equipment for internal examination of steel forgings which, in addition to raising acceptance standards have assisted the steel maker in improving his manufacturing methods and thus in producing sounder and more reliable forgings free from significant internal defects.

In recent years there has been an extended use of vacuum stream degassing process in the casting of ingots for steel forgings in this country as well as in America and on the Continent. This method was designed primarily to reduce the hydrogen content of the steel to a safe level to prevent the occurrence of "hair line" cracks or "flakes" which were a major hazard in large basic steel forgings ten years ago. The vacuum degassing process enables basic electric steel to be used safely in place of the traditional acid open hearth process which has been used for all large forgings in Britain until recently. Whilst equally sound forgings have been produced by a proper use of the latter method, a process which includes vacuum degassing has economic advantages which no doubt will lead to its eventual adoption by all steel makers.

In Britain before the war plain carbon steel generator shafts were made weighing 70 tons while today forgings approaching 100 tons in weight are available. The weight of the forging is determined by the size of the ingot and as a larger discard is necessary with alloy steels, the maximum available weight would be about 10% less than the above figure. In America a generator shaft forging weighing 125 tons has been made recently from a 240 ton ingot.

At the beginning of the period under review carbon steels having a 0·02% proof stress of 22 tons per sq. inch and alloy steels of 33 tons per sq. inch were in use. The highest current British specification is 37 tons per sq. inch proof stress with either a 3% Cr.Mo. or a $2\frac{1}{2}$% Ni.Cr.Mo.V. composition. In America Ni.Cr.Mo.V. steels having a proof stress of 38 tons per sq. inch and which have a high permeability are in use. In Britain the chrome alloy steel has been widely used on account of its low transition temperature though it has a lower permeability compared with the nickel steel alloy. Both in Britain and on the Continent interest is being taken in steels for generator shafts having comparatively high nickel content to obtain higher tensile properties whilst retaining good permeability and impact properties.

3.2.2. *End Bells*

The end bells which support the end windings of the rotor against centrifugal forces continue to be a major limiting factor in the design of generator rotors for the highest performance. For 3600 r.p.m. rotors it is common practice, particularly in America, to use high tensile forged (magnetic) steels having a yield point of 75 tons per sq. inch. The permeability of the material used for these end bells has a marked effect upon the leakage fields at the ends of the core and upon the stray losses in these regions. Non-magnetic austenitic steels of high strength have been available for many years and are almost universally used for end bells in Britain and on the Continent for 3000 r.p.m. generators and to a less extent here and in America for 3600 r.p.m. rotors. A typical composition of this steel is 8 to 9% each of manganese and chromium and 4% nickel but alloys having 18% manganese and 3% Cr. have also been used. The material is cold worked to give an ultimate tensile strength up to about 65 tons per sq. inch. These steels are susceptible to stress corrosion and minor surface cracks may develop. There have been a few exceptional experiences of severe cracking developing in end bells during manufacture or on the rotor while in storage before going into service. A few serious failures have also been experienced under running conditions without evidence of stress corrosion or any other obvious defects.

These experiences led primarily to improvements in manufacturing methods and this material is now generally accepted as being sound and reliable. Amongst other precautions which have been adopted end bells may be coated with a special protecting varnish and care is taken in storage to avoid harmful conditions. It is also the practice of many manufacturers to subject the rings to a hydraulic or equivalent test before fitting to the rotor.

These austenitic steels are being produced with 0·2% proof stress of 55-60 tons per sq. inch and an ultimate strength of the order of 65 tons per sq. inch. Non-magnetic steels of a different composition having a higher tensile strength are being investigated at the present time.

Titanium alloys which have a high tensile strength and a specific weight a little more than half that of steel would offer considerable advantages if their suitability for end bells is established. Unfortunately the "notched bar" toughness of titanium is less than that of steels at present used for end bells and its properties show greater variation with temperature. These characteristics and other aspects are receiving attention.

3.2.3. *Windings*

Hard drawn silver bearing copper has been used successfully for many years for rotor conductors and there is no difficulty in obtaining this material in the various sections which may be required for direct cooled windings. Aluminium alloys have been employed for the windings of a few large rotors in recent years in America but its use does not appear to have become extensive.

Bonded mica sheet for the main slot liners and the interturn insulation also has been long established and it is still used for indirectly cooled windings by many makers. With direct cooled windings there is a danger of loose mica obstructing ventilating passages and slot liners made of glass fabric bonded with an epoxy resin has been widely adopted. Of the various insulations used for the interturn insulation an asbestos based material which has good mechanical properties is probably the most common.

4. Excitation

4.1. *Exciters and Sliprings*

During the past ten years generator excitation requirements have increased appreciably; typical exciter ratings are 275 kW for a 100 MW generator built in 1951 and 2200 kW for a 500 MW generator designed in 1961. The nominal voltage of large exciters is usually in the range 375 to 500 volts with current ratings of up to 4500 amperes and the many brushes required to collect this current from the commutators of d.c. exciters increase the task of maintenance. A frequent requirement is that generators shall operate, without shutting down, for periods of at least twelve months and this has led to a search for increased brush life and facilities for " on load " brush changing.

For many years a considerable amount of research has been devoted to the problem of current collection from sliprings as well as from commutators. These investigations have included research into the fundamental properties and behaviour of brushes and collecter surfaces, and in the detail design of brushholders, springs, brushgear arrangements and ventilation. A number of constructions have been devised to enable brushes or complete brush box assemblies to be changed safely with the set on load. Great progress has already been made and further advances on current collection may be expected in the near future.

Because of the high excitation powers required for modern large turbo-generators d.c. exciters are almost invariably gear driven at a reduced speed from the generator rotor or by separate motors. At the lower speeds their reliability is of a high order and maintenance is reduced.

The use of a.c. generators having lower short circuit ratios has placed increased emphasis on excitation system performance and exciter response ratios of one per unit or greater are often specified. Exciter field frames of laminated construction may be used to reduce the exciter field power requirements and, consequently, the size and cost of the voltage regulating equipment.

4.2. *Static Rectifiers*

To reduce maintenance to a minimum increasing attention is being paid to schemes in which a.c. exciters in conjunction with static rectifiers are used instead of d.c. exciters. Germanium rectifiers have been used for this purpose but development in recent years in silicon-diode rectifiers has greatly accelerated progress in the design of rectifier excitation systems for large powers. By using a static rectifier speed reducing gearing is not required and the exciter brushgear is practically eliminated. The rectifier is usually sectionalised so that any one section can be isolated on load for the replacement or maintenance of the diodes. The silicon diode cell, while being of small size, possesses the characteristics that current overloads must only be of short duration and overvoltages, however transient must be avoided entirely. The choice of diode rating is therefore important and protective devices are usually incorporated to isolate the rectifier in the event of a fault across the rectifier.

The a.c. exciter may be excited from an a.c. pilot exciter and rectifiers, which, in turn, can be excited from a permanent magnet generator and rectifiers. Modern voltage regulators employing magnetic amplifiers are used for automatic operation and in addition saturable reactors or induction regulators are provided for manual control. The a.c. exciter is capable of high rates of voltage response but the associated voltage regulating equipment may be larger and more expensive than is required for a d.c. exciter.

In the United Kingdom prototype rectifier excitation systems are in operation on 30 MW, 60 MW and 120 MW sets and more than 20 generators of 300 MW and 500 MW capacity which will have a.c. exciters with static rectifiers are under construction.

A rotating a.c. exciter has been selected as the power supply to the rectifiers in all the above installations as it is a well tried arrangement and known to be reliable. Alternative systems in which the rectifier is fed from special windings in the stator or, from voltage and current transformers have also been used and may find wider application, in the future.

While the a.c. exciter, together with a static rectifier, requires only a small number of brushes it does not solve the problems of current collection at the rotor sliprings. Attention is therefore being directed towards the use of rectifier assemblies mounted on the rotor shaft and supplied from a.c. exciters of rotaing armature pattern. The rectified current is then fed directly into the rotor winding without the need for sliprings. This form of excitation has been used commercially for a number of small alternators in the United Kingdom but larger units are being made or are on test. In the United States a 180 kW rotating rectifier set was put into service on a 50 MVA unit in 1960 and a 1350 kW unit is to be commissioned on a larger set in the near future.

Silicon-diode rectifiers and also controlled rectifiers are developing rapidly and full advantage will be taken of both in the development of more advanced excitation systems for the largest generators.

5. Automatic Voltage Regulators

System stability tests on an extensive scale have demonstrated that automatic voltage regulators of the quick-acting, negligible dead-band pattern possess considerable advantages over earlier electromechanical regulators and their use is becoming widespread.

In such regulators the voltage sensitive element takes the form of a completely static network and produces an output signal which may be subsequently amplified in a rotating or a static amplifier, and then used to control the exciter voltage. The latter type having no rotating parts or brushes is coming into increasing favour. This type of regulator is in service on generators of all ratings up to the largest size.

6. Auxiliary Equipment

6.1. *Shaft Seals*

Two main types of construction are used for the gas seals on the rotating shaft at each end of the stator, and their construction and characteristics have been fully described in earlier literature.

In the United Kingdom in particular the thrust type of shaft seal has come into much wider use and is now used by most manufacturers.

Various changes have been necessary to keep pace with the increase in hydrogen pressures and the latest types of thrust seal are suitable for large generators operating at hydrogen pressures up to 60 p.s.i.g. In the United States machines are being designed for 75 p.s.i.g. hydrogen pressure.

In some designs, particularly for operation at hydrogen pressures in excess of 45 p.s.i.g., two oil supplies are used. One is to provide the sealing oil, the pressure of which is fixed by the hydrogen pressure and the other to exert a thrust. By suitably proportioning the areas on the seal ring on which the two oil supplies are effective and by adjustment of the pressure of the thrust supply, which is independent of the hydrogen pressure, the seal face loading can be kept at a satisfactory value over a wide range of gas pressures.

The seal oil supply system is similar for all manufacturers and there have been no major changes in its arrangement.

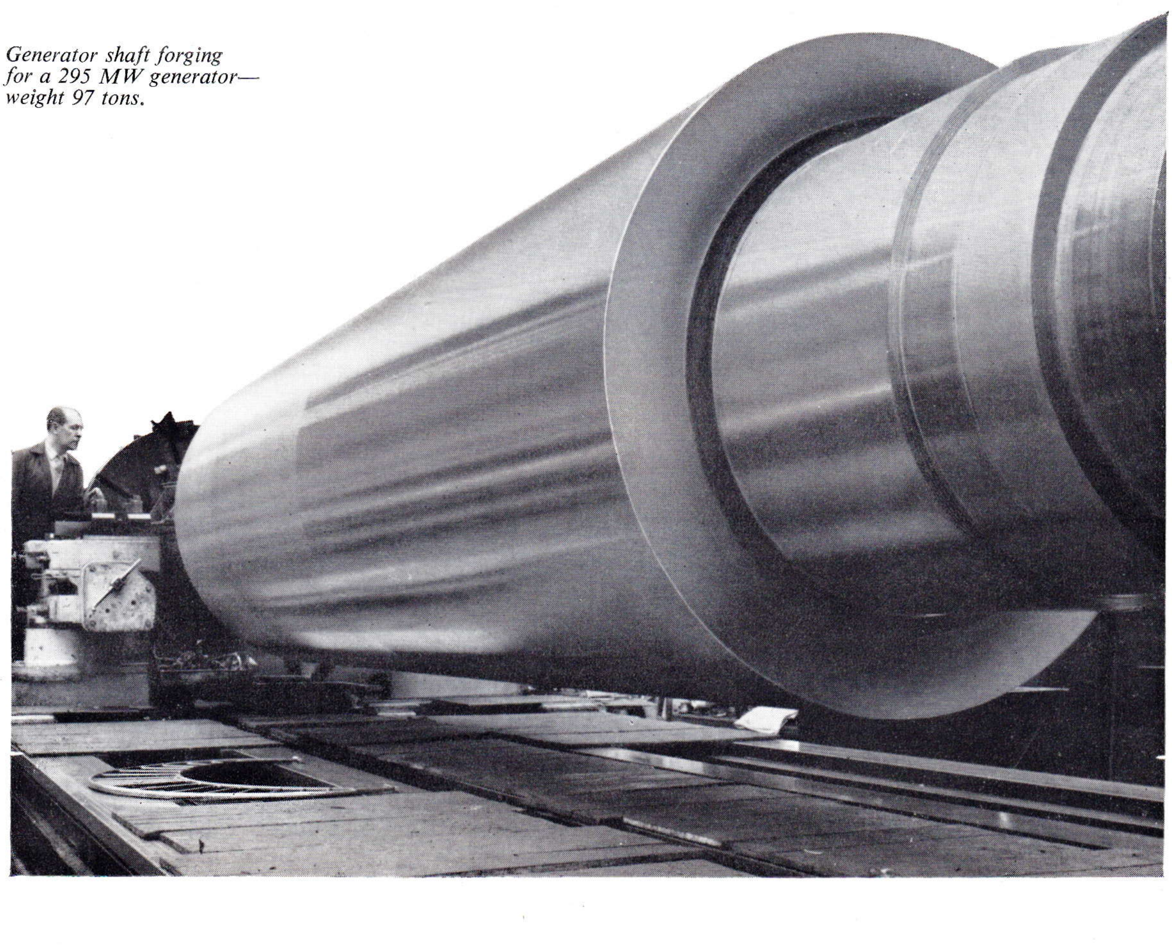
The bearing oil system was a convenient source of supply for generators operating at low hydrogen pressures and for the higher pressures in modern units it is general practice to use the higher-pressure supply provided for the turbine governor and servo mechanisms.

Improvements have been made in component details and arrangement. An addition has been made to the higher pressure hydrogen cooled generators in the form of "traps" or "loop seals" with vents to atmosphere which are frequently incorporated in the bearing oil drain lines. The object is to confine any hydrogen which may escape past the shaft seals, due to failure of the oil supply or other causes, to the generator bearing enclosures and prevent it spreading throughout the oil system.

6.2. *Hydrogen and Carbon Dioxide Supplies*

On early hydrogen cooled generators the hydrogen and carbon dioxide bottles required for make

Generator shaft forging for a 295 MW generator—weight 97 tons.



up, filling and scavenging were usually connected to manifolds near each generator where the space was usually insufficient to accommodate sufficient bottles for a complete scavenging and filling operation.

In modern stations hydrogen and carbon dioxide are stored at central points from which they are piped to each generator. The hydrogen storage depot is usually located in a separate, well-ventilated building. The detailed arrangements of the control panels and piping for the hydrogen may vary considerably in practice.

Hydrogen is usually stored in large bottles each containing 2000 cubic feet of gas at N.T.P. whereas a bus main is almost always used for carbon dioxide distribution.

Syphon tube bottles are invariably used for carbon dioxide storage to obtain a high discharge rate without loss due to freezing. In some stations the carbon dioxide is admitted to the generators as a liquid, the change in state taking place inside the stator casing. In others a vaporizer may be provided in the distribution system and the carbon dioxide admitted to the generator as a gas.

Bulk storage of carbon dioxide is to be used in at least one station now under construction. With this system two or three tons of carbon dioxide are stored in a special tank which is refrigerated to reduce the vapour pressure. The storage tank is replenished directly from a tank wagon.

6.3. *Instrumentation and Automatic Controls*

Generator stator temperatures have long been measured by thermocouples or by resistance thermometers, and for larger generators the tendency has been to increase their number and distribution. For example, with advance in specific loading and the greater possibility of operation at leading power factor an increasing number of temperature measuring points are made in core and sections and supports.

More use is being made of multi-point potentiometric type temperature recorders and in remote and semi-remote operated stations data "loggers" are being introduced and are also used to monitor stator temperatures. The data "loggers" operate as high speed temperature scanners and alarm systems.

For the measurement of the generator rotor temperature continued use is made of the dynamometer type of indicator. If an excess temperature alarm is also required it is usually operated from a combined indicator and recorder.

It has become common practice to operate the generator with its cooling medium controlled within set limits and for this purpose it is usual to employ a temperature sensitive device in the gas circuit to control automatically the cooling water quantity to maintain a set gas temperature throughout the load and cooling water temperature range.

The increase in charging capacity due to the growth of high voltage transmission systems has created a need for instrumentation giving an indication of the margin of generator stability under leading power factor conditions. For this purpose a vector meter or an instrument giving an indication of the machine load angle is used. In one arrangement a rotor angle limiting device has been incorporated with the voltage regulator, the generator excitation being automatically raised whenever a pre-selected load angle is reached. Visual indication of the load angle is also provided.

The control system for all hydrogen cooled generators now employs intrinsically safe circuits for all electrical control initiating devices associated with hydrogen equipment. This feature was at one time only fitted to generators for the United Kingdom but it is now more widely specified.

Automatic hydrogen purity correction equipment was fitted to early hydrogen cooled generators, but it was found that the comparatively infrequent functioning of this gear did not justify its inclusion. The normal admission of fresh hydrogen to restore the loss due to leakage was sufficient to maintain the required purity.

The rate of fall of purity may be accelerated for the large generators now being installed because of larger seals and oil flow. Purity correction by means of leakage may not be adequate and its re-adoption for automatically controlled generating stations is contemplated.

Generator bearing pedestal vibration is continuously measured, and recorded together with the turbine vibration measurements on a multi-point potentiometric recorder. Alarms may be operated by this recorder or by the vibration detector amplifier. Other equipment may include rotor earth fault and loss of excitation alarms.

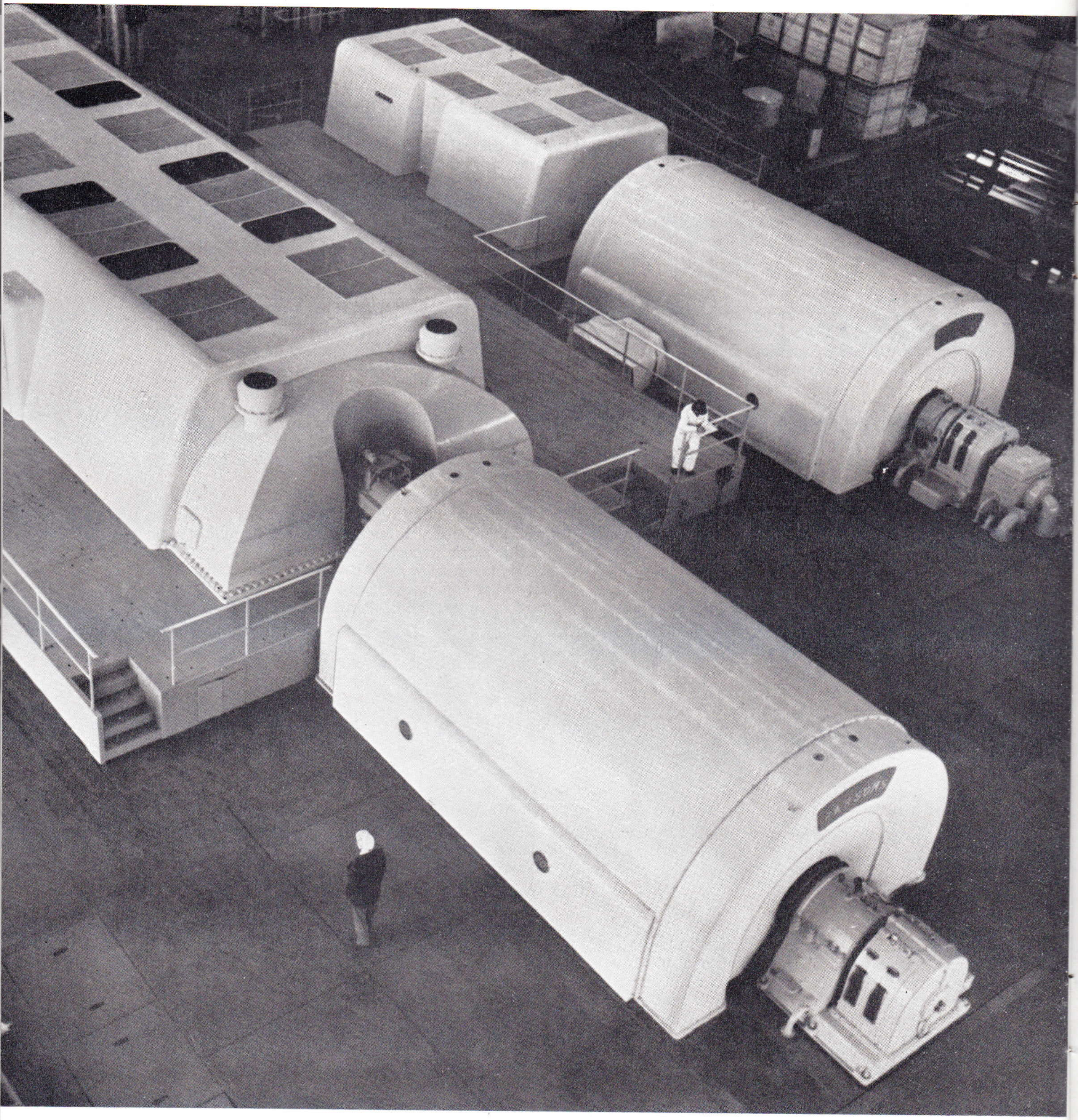
7. Conclusion

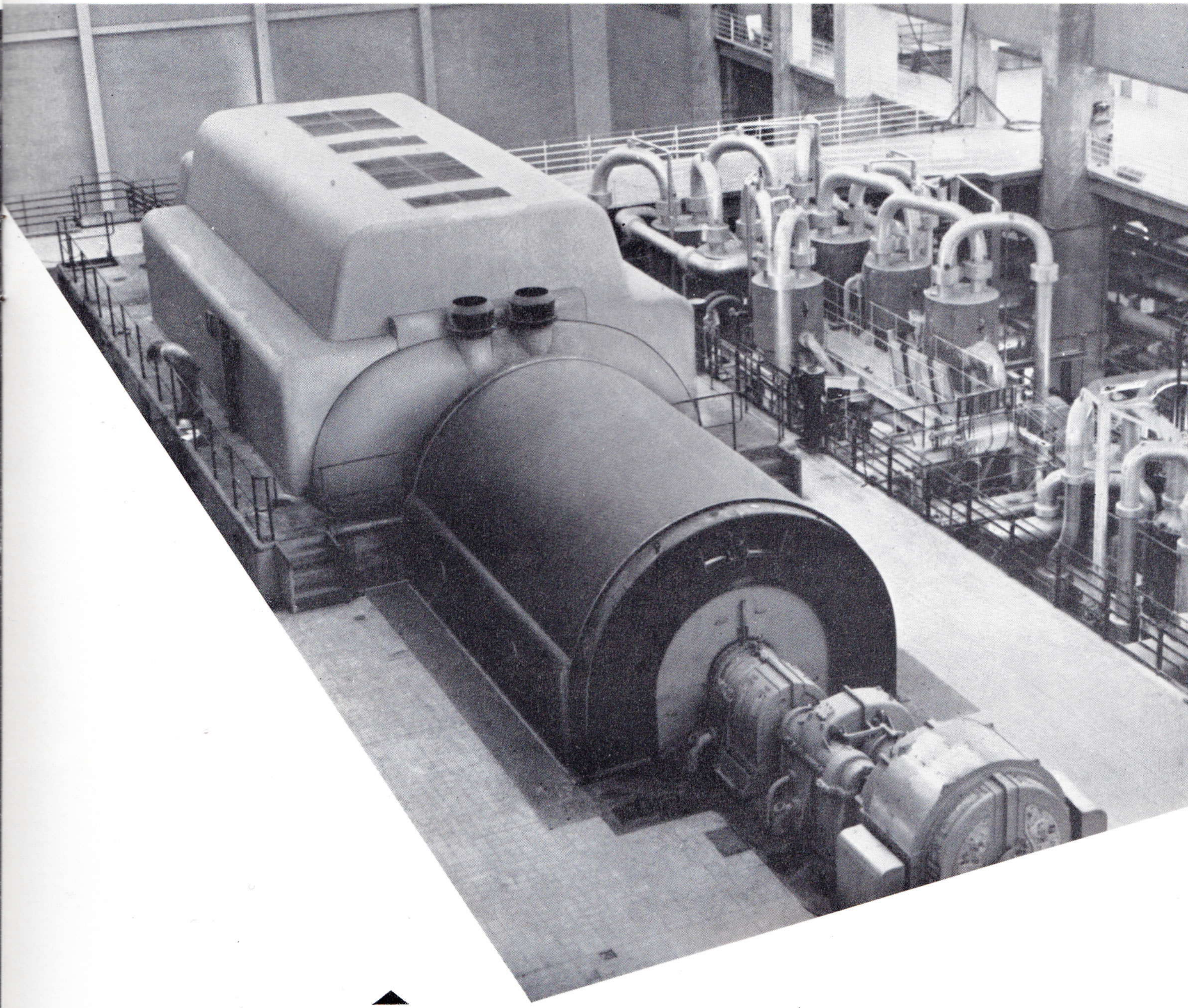
The history of the development of the high speed generator since 1884 when Sir Charles Parsons designed and made a $7\frac{1}{2}$ kW d.c. generator running at a speed of 18,000 r.p.m. has been marked by rapid and at times outstanding progress. The greatest achievement of the last decade has been the marked reduction in size, weight and unit cost of turbo generators of high output which can be attributed to the successful application of both gas and liquid to the direct cooling of rotor and stator windings. At the same time the many improvements in details of design, construction and methods of manufacture, to which it has been possible to refer only briefly in this review, have contributed to the traditional high reliability of large turbo generators.

In view of the continued expansion of the Electrical Supply Industry coupled with the ever increasing availability of new knowledge and new techniques in so many scientific and engineering fields there seems little doubt that the present trend in the production of high speed a.c. generators will continue in the next decade.

8. Acknowledgement

The writer is indebted to many colleagues for assistance in the preparation of this review.





One of two 200 MW turbo generators, West Thurrock power station, England.

First 300 MW turbo generator, Ontario Hydro Lakeview power station, Canada.