the design of VERY LARGE turbo-type generators

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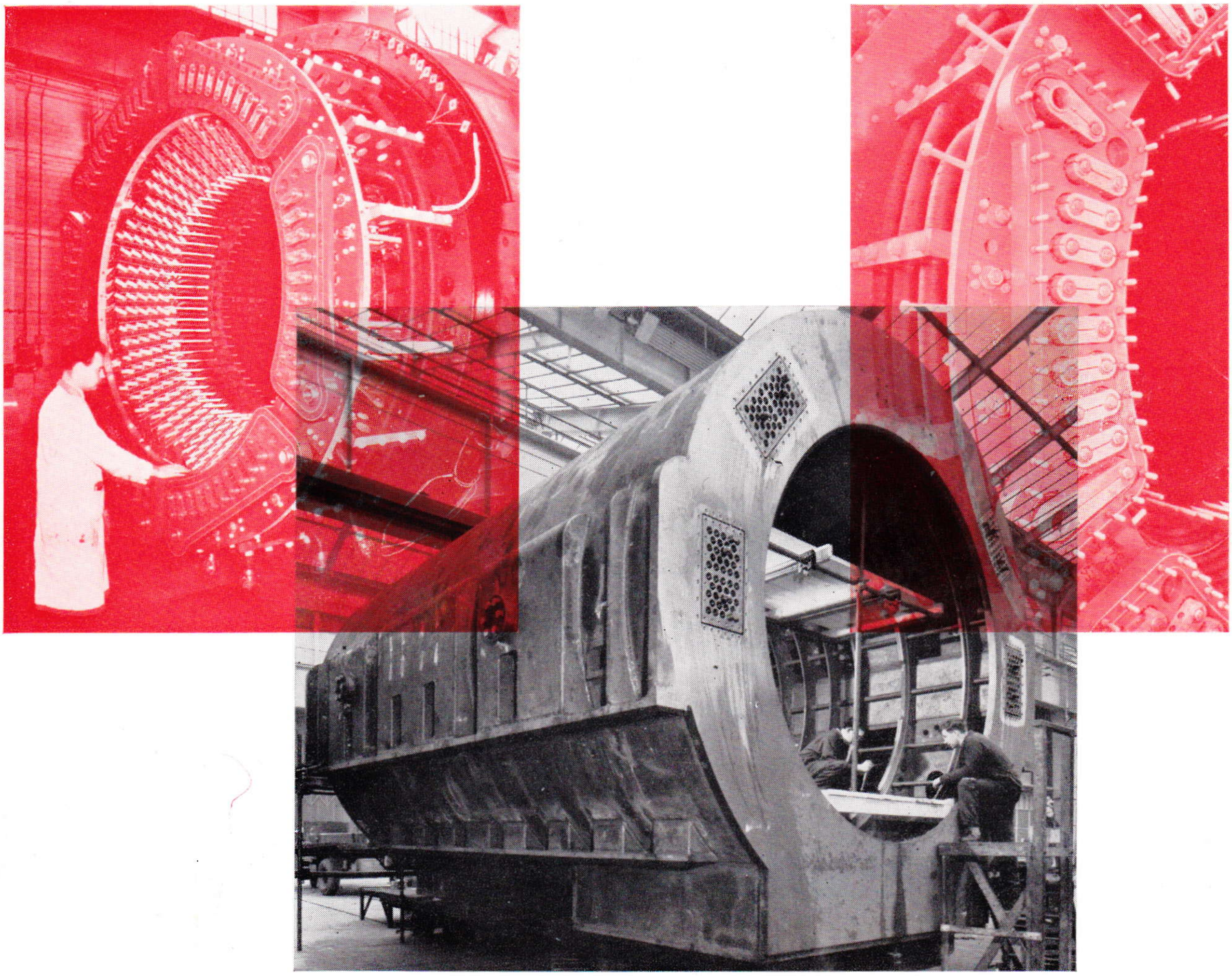

The Design of VERY LARGE Turbo-Type Generators

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Introduction

DUE to increases in population and in standards of living there is an ever rising world-wide demand for electrical power. One overriding factor in the development of systems to supply this power is the initial economical production of the electrical energy. Thus in highly developed countries much emphasis is now placed on obtaining lower capital and operating costs for turbo-generators.

It can be shown that the larger the output of a turbo-generator set the greater the economy in material and manufacturing costs per megawatt of power generated. In addition a better overall efficiency is obtained for the present day sets of large output because these enable full advantage to be taken of refinements in the feed-heating cycle and in the turbine blading itself. The siting of power stations, particularly those using nuclear fuel, in densely populated countries is also an increasingly difficult problem and the installation of larger turbo-generator sets in fewer power stations is of assistance in solving this problem. Larger sets also mean that there is, in addition, an overall saving in physical space required per megawatt generated and this in turn gives rise to relatively lower overall building and foundation costs.

The startling increases in the output of turbo-type generators obtained over the last decade have been made possible by the use of improved materials, cooling methods and design techniques and so the rate of increase in output has been far greater than the rates of increase in both weight and volume of such generators. In Great Britain improvements in generator power factors and decreases in the acceptable short circuit ratios have also assisted greatly in enabling generators of higher output to be designed within given transport weight limits.

An impression can be gained of the current size of generators from the fact that at present Parsons have recently built or are building at their Heaton and Witton Works twenty-six of the forty-seven 500 MW and the first two 660 MW single line turbo-generator sets so far ordered by the CEGB (Table 1). This is in addition to two 313 MW and two 350 MW sets for the CEGB, two 300 MW and two 540 MW sets for Canada and fourteen 200 MW sets for Australia and South Africa.

The world's first 500 MW single line generator was synchronised by Parsons on 27th February, 1966 at Ferrybridge "C" power station (Fig. 1i). One such set will supply the needs of a city with a population of about one million people. Ferrybridge "C" power station will contain four 500 MW sets and it is of interest to note that the combined output from the "A" and "B" stations on the same site is 445 MW of which 300 MW is made up from three Parsons 100 MW machines commissioned in 1959.

There have already been several review papers [1–4] detailing the design and constructional techniques necessary to build the generators up to 275 MW rating produced by Parsons. Therefore this article will concentrate on giving a broad description of the construction of the 500 MW generators now being put into service and the 660 MW generators at present under construction at Heaton Works.

General Design and Construction

The 500 MW generators are designed to run at 3000 rpm and give a three phase 50 c/s output of 15,437 amps at 22 kV when operating at a power factor of 0·85 lag. The short circuit ratio of these machines is not less than 0·4. For transport convenience the stator is divided concentrically into two parts—the inner frame carrying the core and windings, and an outer casing which carries the gas coolers and contains passages for the cooling gas (Fig. 2). The outer casing is

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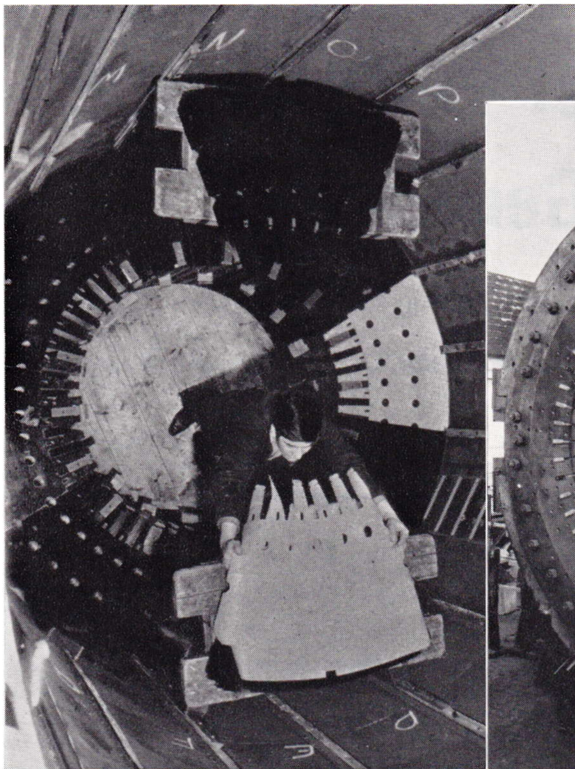

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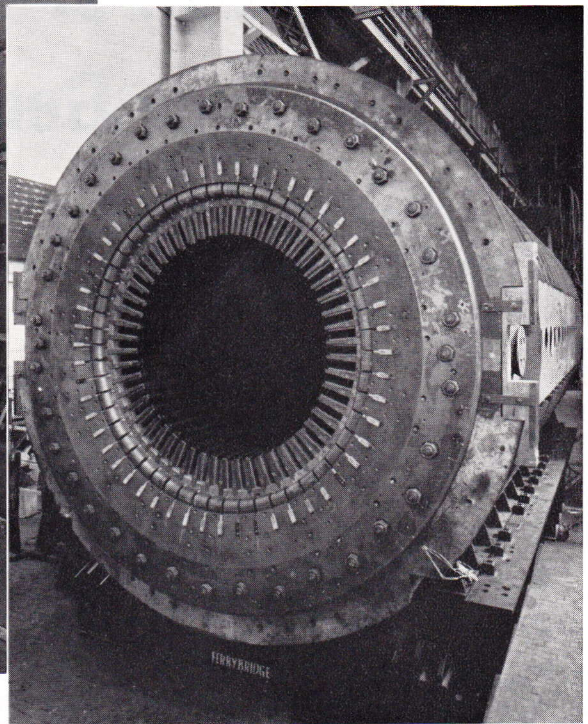

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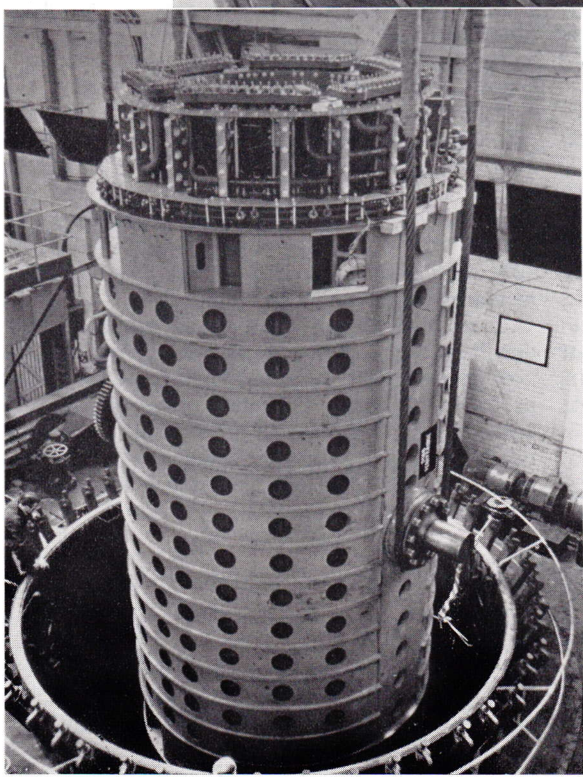

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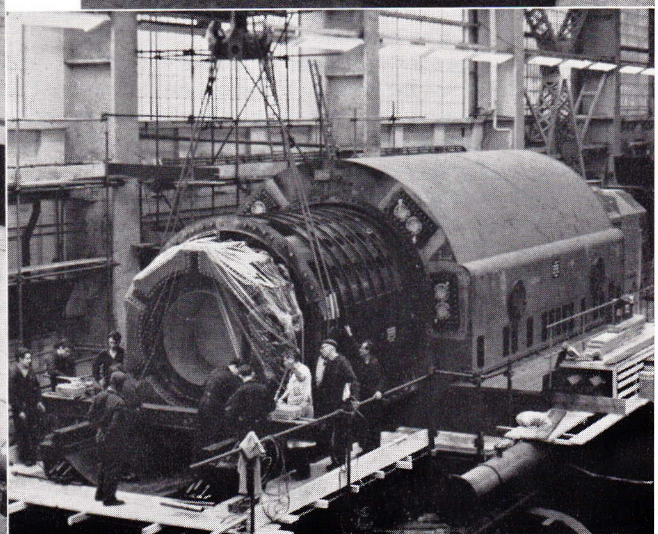
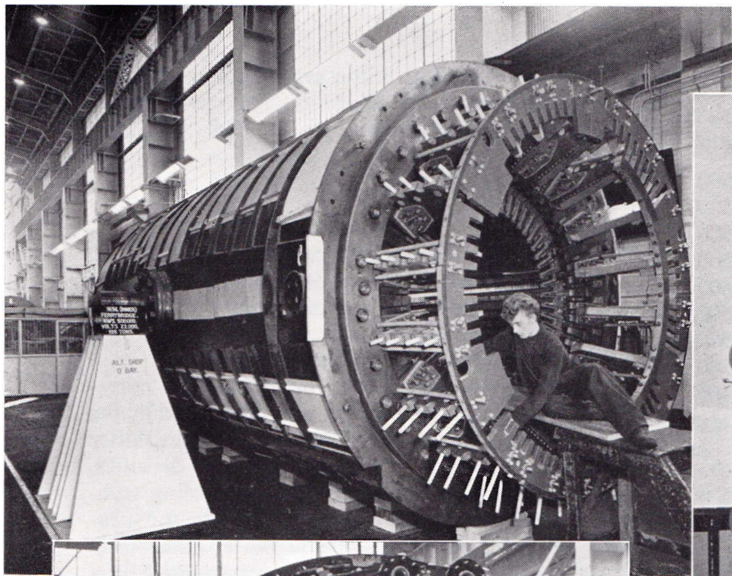


(g)

Fig. 1.—The construction of a 500 MW generator.

(a) *Assembly of core.*
(b) *Completed core showing core end plate.*
(c) *End winding supports.*
(d) *End winding.*
(e) *Completed inner frame.*
(f) *Lowering the inner frame into the impregnator.*

(c)



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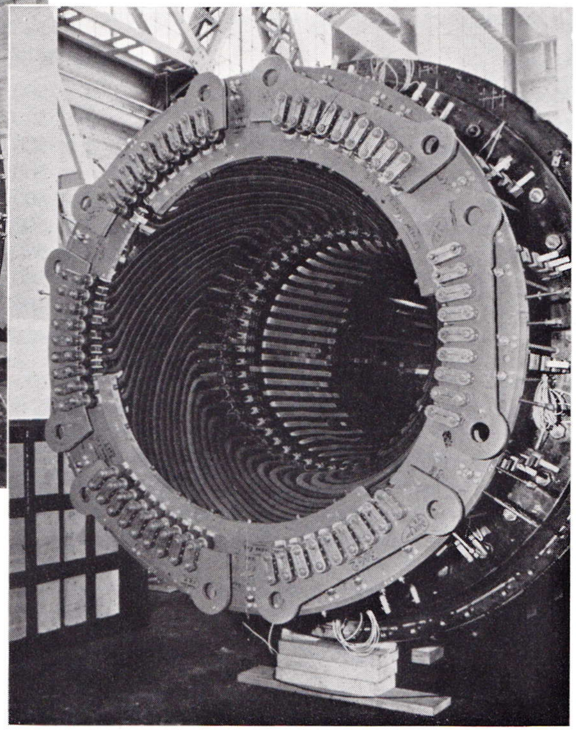

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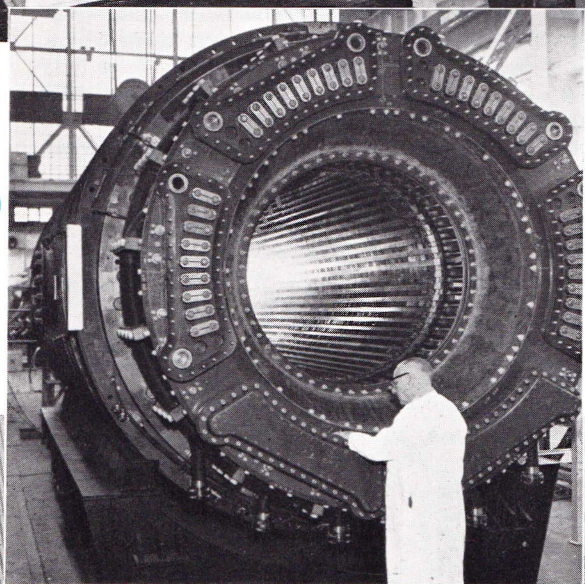
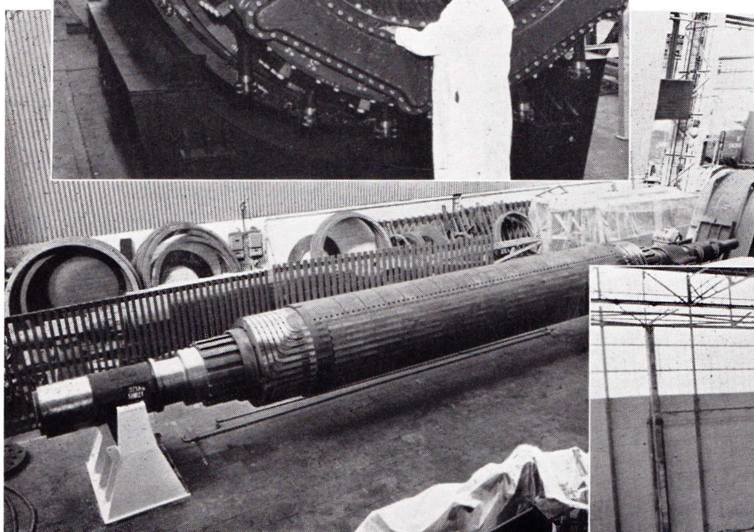
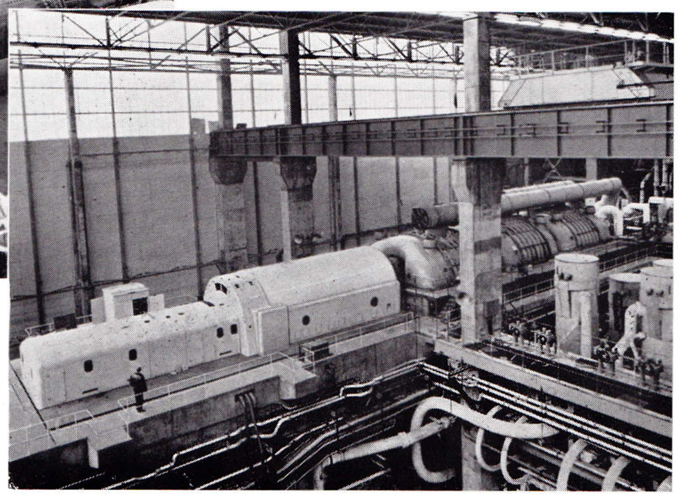




(h)

(i)



(g) Inserting the inner frame into the outer casing on the test bed.

(h) Rotor without fans and retaining caps.

(i) 500 MW machine at Ferrybridge "C" Power Station.

TABLE 1.—*Single-line turbo-generator sets of 500 MW and over, under construction by Parsons.*

Station	*Rating MW*
Didcot	4 × 500
Fawley	4 × 500
Ferrybridge "C"	4 × 500
Kingsnorth	4 × 500
Pembroke	4 × 500
Ratcliffe-on-Soar	4 × 500
Rugely "B"	2 × 500
Pickering, Canada	2 × 540
Dungeness "B"	2 × 660

fabricated from steel plates and is designed to withstand an internal explosion. The stator winding is directly cooled by demineralised water and the rotor and core by hydrogen at 45 lb/in^2. Excitation is obtained from a three phase 100 c/s a.c. exciter whose output is rectified in a static silicon diode rectifier.

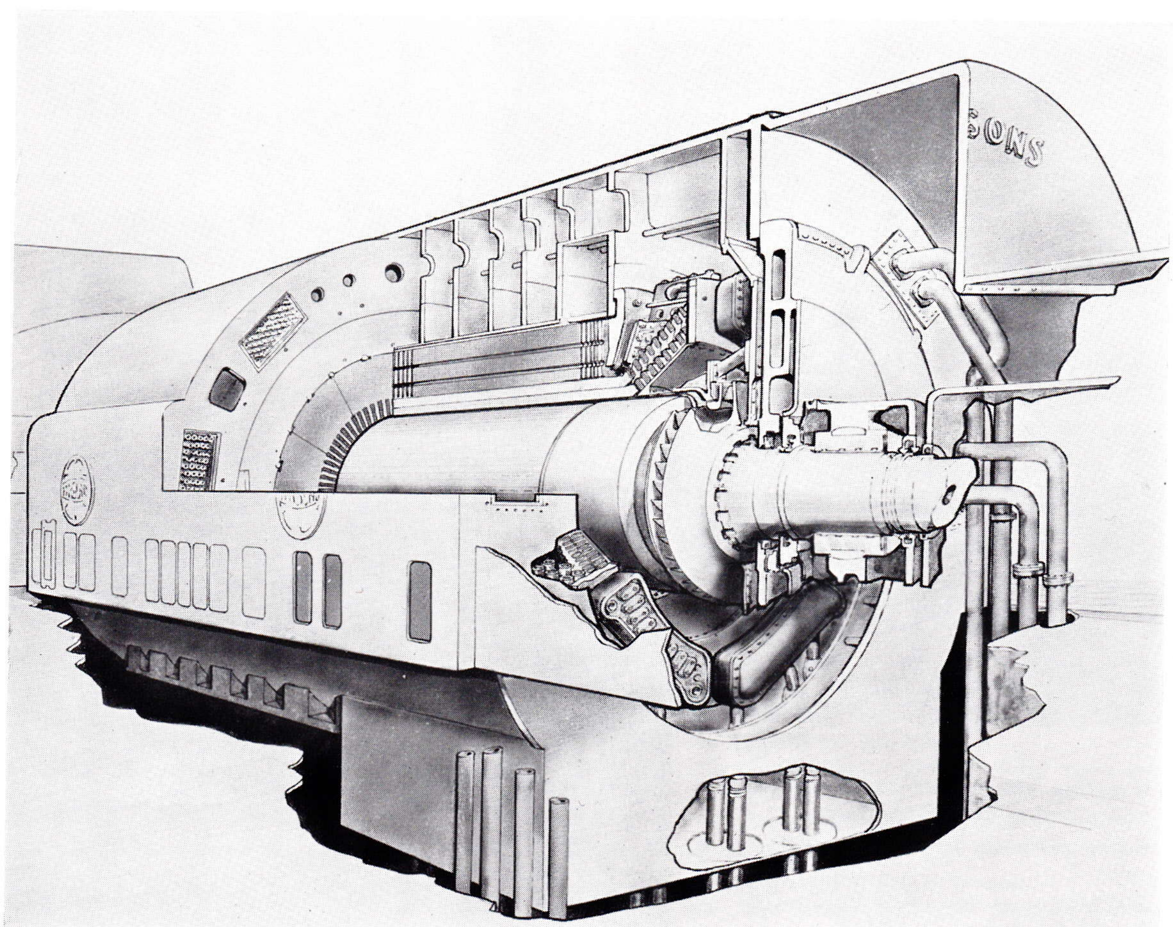
The 660 MW generators are similar in construction but rather longer with an output of 19,076 amps at 23·5 kV also at a power factor of 0·85 lag. In this case however the short circuit ratio is greater than 0·5 whilst the hydrogen pressure is 60 lb/in^2. The excitation is obtained in a similar manner to the 500 MW generators.

ROTORS

The general physical appearance of the rotors used for the present day large turbo-type generators (Fig. 1h) is no different to that of those for generators of much smaller output. Due to the greater lengths the use of transverse slots to equalise the stiffness on the two axes has now however become more important.

The increase in output has necessitated a corresponding increase in the ampere turns produced by the rotor winding. Whilst the main gain in this latter quantity has been due to increased current densities, made possible by improvements in the cooling techniques employed for the rotor conductors, the proportion of active copper in the rotor has also been slightly increased. The amount of copper carried by a rotor is limited by the high rotational stresses and thus by the mechanical properties of the steel forging used for the rotor. 500 MW generators running at 3000 rpm employ steel forgings with a specified minimum yield

FIG. 2.—*Cutaway view of a Parsons 500 MW hydrogen/water cooled generator.*



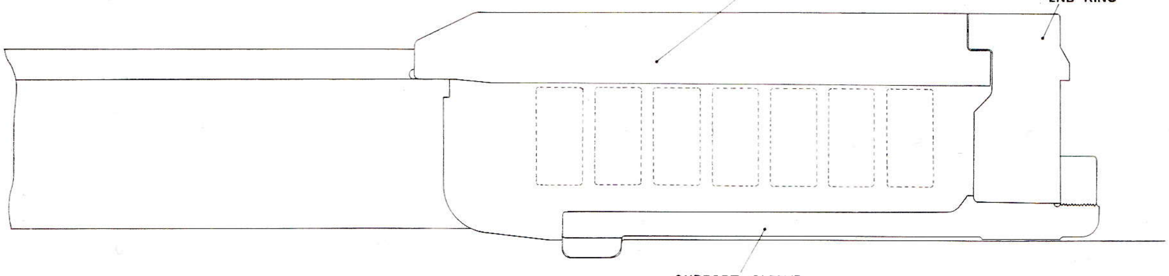


FIG. 3.—*Retaining cap fixing method.*

of 36 tons/in². Advances have been made also in the inspection and non-destructive testing of forgings, using boroscope and ultrasonic techniques, thus allowing more confidence to be placed initially in the mechanical quality of the forging.

Much investigation is at present being carried out to determine the best composition of a rotor from the point of view of impact strength (at the centre of the shaft), low transition temperature and relative permeability. The trend is towards the use of nickel chrome molybdenum vanadium steels. Very large rotors which have nickel contents between 2 and 3½% have been tested for their mechanical and magnetic properties. Such tests have clearly shown that the higher the nickel content, the better the relative permeability and the 3½% nickel steel, with special heat treatment, shows a marked improvement in impact strength.

The major advance however has been in the production of extremely large single piece rotors. As examples of the limits to which steel-making technology has now been extended the finished length, diameter and weight of a complete rotor for a high speed 660 MW generator are 666 inches, 45 inches and 85 tons respectively from an initial ingot weighing about 170 tons. For a 540 MW generator running at 1800 rpm the comparable dimensions are 507 inches, 64 inches and 123 tons from an ingot weighing 280 tons.

There are various ways of fixing the retaining caps, which support the rotor end windings against centrifugal forces, onto the main rotor shaft. One method adopted by Parsons which has given completely satisfactory service, is shown in Fig. 3. The nose of the cap is a shrink fit onto a spigot at the end of the rotor body. An end ring, which supports the other end of the cap, is shrunk onto a support sleeve which itself is fastened to the rotor body by a bayonet type fitting followed by a final shrink fit. Supporting both the end ring and the support sleeve, and therefore the retaining cap, at roughly the same axial position along the shaft eliminates deflection forces. This form of construction also means that the retaining cap is a plain ring containing no holes or keyways or other stress raising points. The material used for the retaining cap is a non-magnetic high-tensile austenitic steel with a yield strength of 57 tons/in². The use of a non-magnetic material here assists in reducing the stray losses in the end regions of a generator by reducing the leakage fields. For a 660 MW high speed generator the end cap has an outer diameter of 48 inches and is 32·5 inches long, the caps being subjected to ultrasonic examinations, crack detection and hydraulic tests before final machining.

The rotor windings are accurately formed from hard-drawn silver bearing copper strip which has an annealing temperature well over the maximum working temperature of the winding. The end windings are carefully packed with accurately moulded pieces of epoxy glass laminates to give mechanical support and to prevent movement of the windings. The rotor slot insulation consists of synthetic resin bonded glass laminate slot liners with rubberised asbestos strips between turns. The end windings are insulated from the retaining ring by several layers of a polyester material.

Due to the inherent high damping characteristics of solid rotors, damper windings are not fitted thus allowing more active copper to be used in the rotor slots.

Rotor and Core Cooling

The rotor windings are directly cooled with hydrogen. The operating pressure in the 500 MW generators is 45 lb/in² and in the 660 MW generators 60 lb/in². Fig. 4 shows a schematic diagram of the cooling channels in a 500 MW rotor. A number of narrow radial ducts are formed in the rotor coils along the complete length of the embedded portion of the windings by punching slots in the solid copper strip and the interturn insulation. The sides of these radial ducts are staggered (Fig. 5) to produce turbulence in the gas flow within them which results in improved heat transfer. The radial ducts are fed with gas from both ends of the rotor through longitudinal sub-slots machined beneath the main winding slots which in turn are fed from slots under the end ring support sleeve. The gas is discharged at the surface of the rotor through holes in the coil retaining wedges. Cold gas is thus supplied to each radial duct so that uniform cooling is obtained over the full length of the rotor.

The end windings are made up from hollow copper, containing two cooling ducts and, although partly cooled by the gas in contact with the external copper

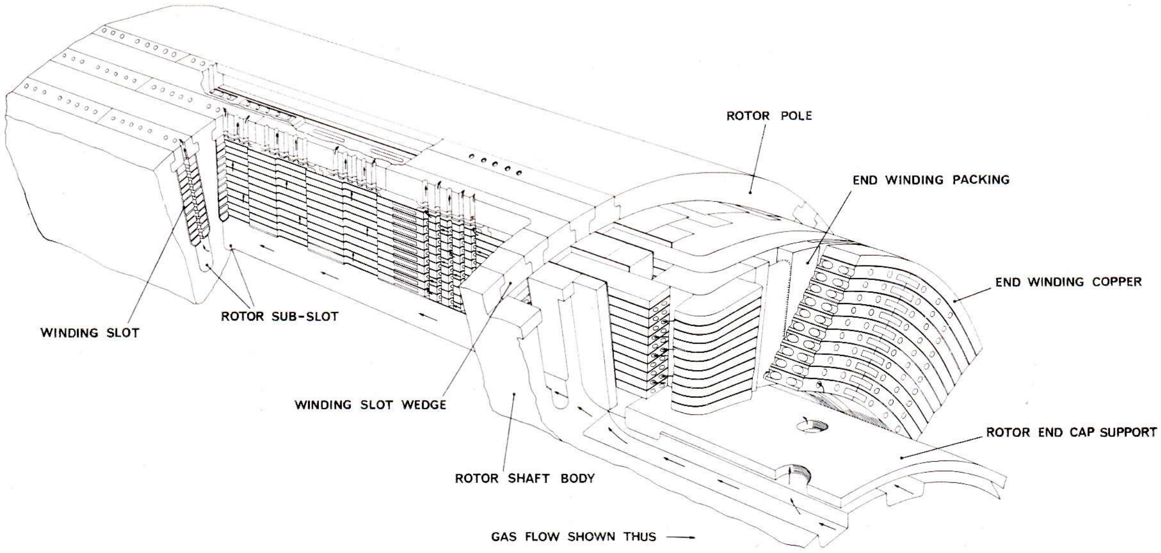


FIG. 4.—*Rotor cooling circuits.*

surfaces, are mainly axially cooled. The hydrogen, having flowed from the slots under the support sleeve through holes in the support sleeve, is picked up by holes in the end faces of the strips. After passing through the end winding strips the gas is discharged into the gap through radial ducts. After these particular radial ducts the hollow copper is terminated and joined to the solid slot copper. The hydrogen gas is circulated through the windings by the natural head produced by the rotor supplemented by high-pressure fans mounted at each end of the rotor body.

The warm gas from both the rotor and the stator, after being extracted from the gap, is passed through four longitudinal gas coolers, that utilise condensate, and are mounted in the upper half of the stator casing. The tubes in the hydrogen coolers are of integral finned copper expanded into tube plates at each end. Support plates are fitted at intervals along the tubes and whilst one end of the cooler is rigidly fixed to the stator casing the other is provided with a flexible joint to allow for differential expansion.

The main cooling of the stator core is axial, there being two axial ducts behind each stator slot. On discharging from the coolers the cool gas divides into two paths, part being directed into the annulus feeding the rotor ends, the rest being directed into a number of ducts in and behind the stator core. At the centre of the stator core are a number of radial ducts, some of which allow gas, after cooling the stator core, to re-enter the gap whilst the remainder feed gas directly from the coolers thereby reducing the average temperature of the gas in the gap. Relatively more heat is generated in the end regions of the core, especially under conditions of leading power factors, so there are also several radial ducts at both ends of the core to

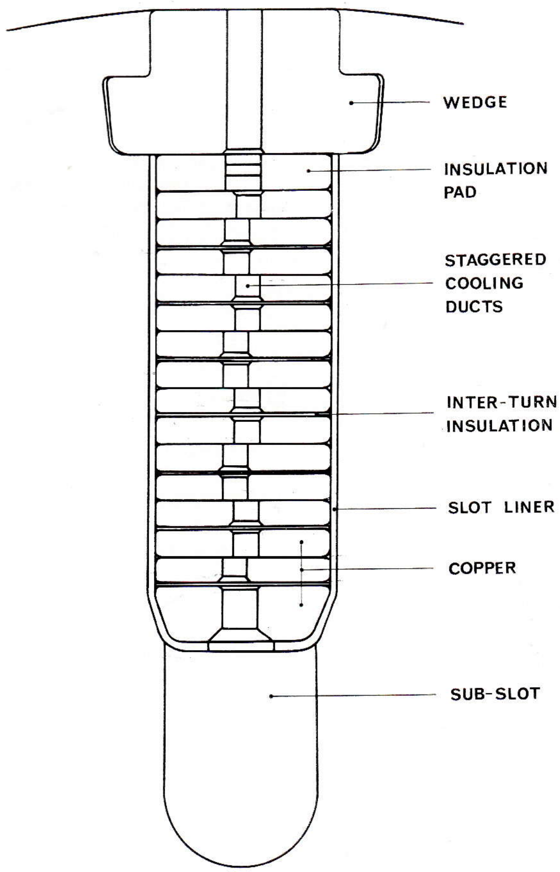


FIG. 5.—*Cross-section through a rotor slot.*

provide extra cooling. In addition the heat produced in the core end plate is reduced by means of a water cooled copper screen mounted between the core end plate and the stator end windings. When the stray magnetic fields generated in the end winding region impinge on a metallic object, such as the core end plate, they cause eddy currents to be set up with the resultant production of resistive losses and temperature rises. The copper screen prevents these fields from reaching the core end plate and the heat which is therefore now produced in the screen is easily removed by the cooling water.

Liquid Cooled Rotors

The development of a direct liquid cooled rotor is at present receiving much attention. Because the coolant holes within the copper are smaller for a liquid cooled rotor, in comparison to a gas cooled rotor, more active copper can be used in the rotor slots so that a larger output can be obtained for a given frame size. Particular design aspects of interest are the methods of feeding the liquid in and out of the windings, of limiting the liquid velocity within the windings to a value below that which causes erosion, and of preventing galvanic corrosion. The former aspects are well covered by various design and test rig investigations whilst the latter is being studied in the laboratory to determine the fundamental mechanisms that take place.

In this context it is interesting to note that early in the century Sir Charles Parsons designed and built five 11 MW and three 15 MW generators using water to cool the rotor windings indirectly. These successfully operated for a number of years and no difficulties were experienced in getting the water either in or out of the rotor.

Stators

Core construction

For transport convenience the stator is divided concentrically into two parts. The inner frame, carrying the core and winding, is as compact as possible, consistent with adequate strength and rigidity. The outer casing carries the gas coolers and contains passages arranged to direct the flow of cooling gas to and from circulating fans on the rotor shaft. The outside diameter of the inner core frame and the bore of the outer casing are correspondingly stepped at their ends to simplify assembly. Although the total weight of the combined unit is slightly greater than that of the equivalent single piece stator the heaviest lift is appreciably reduced.

The stator core laminations are, as is usual practice, in the form of stampings 0·013—0·014 inches thick. The sectors of core plate are punched in one operation with a compound punch and die, so that the slots and keyways are accurately pitched, scrubbed to remove burrs and then stove-enamelled on both sides to obtain a heat resisting and durable insulating layer between the laminations. A layer of adhesive is finally placed on one side of each lamination.

The laminations are assembled with the joints staggered and are held in position by dove-tail keys in the inner frame (Fig. 1a). Radial spacing pieces are used between sections of laminations to provide radial ducts where required. At frequent intervals during assembly the core is pressed tight using a predetermined pressure before the core is finally contained longitudinally by non-magnetic end clamping plates. The core teeth are supported by manganese steel fingers fitted into the clamping plates (Fig. 1b). After the core is complete it is heated to a sufficient temperature to completely cure the adhesive and thus give a bonded core. This type of core ensures continuous mechanical contact over the whole diametral core depth and so minimises double frequency vibration.

The magnetic pull between the rotor and the inner surface along the bore of the stator, due to the presence of the gap flux, distorts the stator core from a circular to an elliptical form, the minor axis of the resultant ellipse being in line with the poles. Thus as the rotor moves through a complete revolution any individual part of the stator moves through two cycles of displacement which gives rise to vibration with a frequency double that of the generator frequency. Whilst such double frequency vibration is inherent in the stator of a two pole generator, its amplitude can be reduced to a harmless level by correct proportioning of the electrical and mechanical design parameters. There can also be set up in addition, longitudinal modes of vibration. Such vibration, besides producing noise, can cause mechanical damage to the stator bar insulation and wedges, and other difficulties if transmitted through the bedplate and foundations. The use of a bonded core is also of great help in reducing this type of vibration.

The magnitude of the overall vibration can be reduced to a limited extent by keeping the flux density in the gap to a moderate figure and by increasing the depth of the core to increase the stiffness; the latter is in turn controlled by economics and transport limits. To prevent propagation of the double frequency vibration through to the bedplate a flexible mounting, in the form of a neoprene strip, is interposed between the inner and the outer casing. It is also necessary to avoid natural resonance in any parts of the stator or surrounding structure at the frequency of the vibration.

Stator Conductors

The stator winding is of the usual double layer diamond coil type, the half coils being formed and insulated before insertion in the slots. The conductors are built up from a number of hollow water cooled rectangular copper strips enabling the use of high current densities and therefore giving shallow slots, minimum core weight and a low reactance. The individual strips, which are insulated from each other by means of silicone varnish and impregnated glass braid, are of such a width and thickness, and are so arranged in two stacks, to permit suitable transpositions of the strips along the slot portion, to reduce to a minimum additional losses due to eddy and circulating currents.

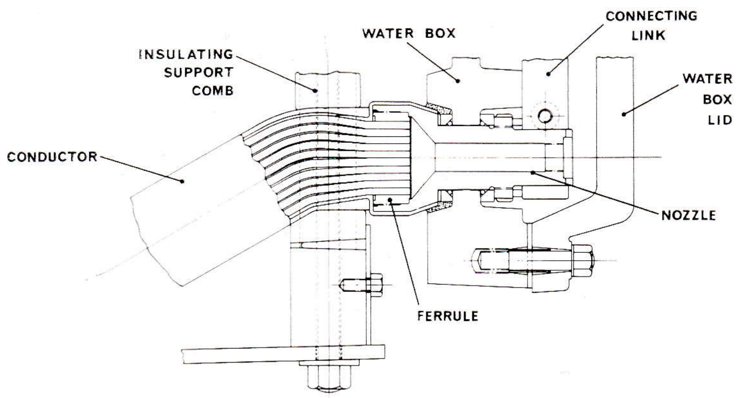


FIG. 6.—*Stator conductor end arrangement.*

The main insulation used on the stator conductor bars is built up of mica splittings bonded with an insulating varnish onto a suitable backing. The straight embedded parts of the conductor are insulated by a full length sheet of this material which eliminates the possibility of any tape migration. The end windings are insulated with the same material in tape form. Great care is taken with the joint between the sheet wrapped part of the conductor and the tape wrapped end winding. The slot insulation is wrapped tightly and moulded under high pressure and temperature forming an insulating tube of substantial thickness. This gives a tube of insulation that whilst being homogeneous and firm, retains some flexibility to enable it to withstand the resultant forces occurring due to system faults or faulty synchronising. Finally a semi-conducting layer is wrapped around the conductor to prevent corona formation in the slot.

End Windings

The finished stator end windings are vacuum impregnated by drying out the whole stator in a large autoclave under a vacuum, within 2 mm Hg of absolute vacuum (Fig. 1f). During the final impregnation a pressure of 30 p.s.i.g. is applied to ensure complete penetration of the varnish into the end windings.

The conductors in the end winding region are packed tightly against one another, so that there is no gas space left between the conductors (Fig. 1d). The end winding supports, packings and other parts are made from impregnated fabrics and compressed laminates which being non-metallic eliminate problems due to voltage stressing and eddy losses. Glass and synthetic fibre cords and tapes are used for binding and securing purposes. The end winding packings are corded into position, from supports attached to the end clamping plates, in such a way to obtain an arch-bound construction adjacent to the core. This construction, particularly with the water box arrangement discussed in the next section, results in an extremely strong arrangement well able to withstand the forces produced by system faults. Additional strength is obtained by an insulating comb which supports every conductor immediately behind each water box. This completely arch-binds the conductors at this position and an insulating core lying along the top of the conductors.

Special precautions are taken where the conductors emerge from the core to provide voltage stress relieving conditions to prevent corona and tracking discharges.

Stator Cooling

The individual hollow strips in the stator conductors are directly cooled using demineralised water, the water flowing through all the strips in parallel from one end of the conductor to the other. At the end of each conductor the strips terminate in ferrules (Fig. 6). Each group of conductors forming a half phase have their ferrule ends fitted, using "O" rings to make a water tight joint, into a common water box moulded in cast filled epoxy resin. This arrangement eliminates the need for a large number of individual water connections being made to the winding. In a two pole machine there are six water boxes at each end of the stator, one for each half phase section, spaced to allow ample clearance between phases. The coil to coil connections between top and bottom layers of the winding are made by simple clamps which are water cooled as they are inside the water boxes. Removal of the water box covers enables the boxes to be thoroughly cleaned and, what is more important, gives access to each individual strip in the conductors, which can then be flushed out and checked to ensure they are not restricted. The water supply to the boxes is taken through the main leads and the gas-tight terminal bushings (which pass through the stator casing) which are thus also water cooled.

Resistance columns, comprising tubes of epoxy resin bonded glass tape, whose function it is to separate the water circuit from the electric circuit, are attached to the underside of the terminal bushings and so are external to the casing. They are thus easily accessible for examination and replacement if necessary. Replacement can be carried out without removing hydrogen from the stator.

Demineralised water having a low electrical conductivity is used although the value of conductivity is not critical, the losses from electrical leakage currents in the water being very small. The stator windings form part of a closed circuit which includes a heat exchanger, pumps, fine mesh strainers or filters, gas detraining chamber and make-up tank. Make-up for the coolant system is supplied through the header tank from the turbine condensate system. The coolant system is designed so that the maximum water pressure in the generator is less than the normal hydrogen pressure. In the unlikely event of any slight leakage occurring this will then be gas to water so that the risk of water leakage into the generator is extremely small. The inlet to outlet temperature rise of the coolant is about 20°C and as the temperature difference between the copper and the coolant is only 5°C the maximum temperature rise of a conductor at rated load is only about 25°C. The low temperature gradient across the stator conductor insulation and the low temperature rise of the copper virtually eliminates any harmful effect arising from differential in thermal expansion. The coolant temperature at the inlet to the generator is maintained at about 5°C above the hydrogen temperature at the outlet from the gas coolers. This is to avoid any possible risk of any water in the hydrogen condensing out onto the surface of the conductor insulation. Condensate is also used as the cooling medium in the heat exchanger.

A portable demineralising unit, which can be connected into the generator circuit, is provided for use in the event of it being desired to improve the condition of the coolant without make-up. When the demineraliser is in service about 5% of the total coolant quantity is passed through it.

The stator core is hydrogen cooled by means of the system of radial and axial ducts described earlier.

Stator Casings

The stator casing is fabricated from mild steel plates and bars, sub-divided into suitable compartments to produce uniform ventilation, and is designed to be able to withstand an internal explosion. The risk of such an explosion is negligible, intrinsically safe electrical circuits being used wherever hydrogen is likely to be present.

The ends of the stator casing are closed by substantial end covers. The joints between the end covers and the stator casing are metal to metal containing grooves filled with a sealing compound. The stator casing and end covers are subjected to a hydraulic pressure test of $1\frac{1}{2} \times$ the maximum working pressure to ensure mechanical soundness.

In cases of transport difficulty the stator casing can be sub-divided into two or more sections, for example it can be split on the vertical centre line, the parts being bolted together or welded permanently on site.

Shaft Seals

The shaft seals are the thrust collar type, collars being provided for this purpose on the rotor shaft on the generator side of each main generator bearing. The seal ring, which is free to move axially in the seal housing, has a white metal face maintained in contact with the collar by spring, oil and gas pressure.

The white metal face is divided into two parts by an annular groove. The portion of the face radially outward from the annular groove is itself divided into a number of sections by radial grooves whilst the portion of the face radially inward from the annular groove is plain.

Oil under pressure, is supplied to an oil chamber behind the seal ring from where it flows through a number of ports into the annular groove in the seal ring face. Whilst the majority of the oil flows radially outward past the grooved face without coming into contact with the hydrogen, the rest of the oil flows radially inwards, past the continuous face, forming the required seal and is then drained off to a hydrogen detraining tank. The oil is obtained directly from the turbine governor oil system. When the generator is running the oil is supplied via a shaft driven pump; whilst the generator is at rest or on turning gear the oil is supplied via an a.c. motor driven pump. There is also a d.c. standby pump in case of failure of the a.c. auxiliary oil supply.

Excitation

Rotor Sliprings and Brushgear

The sliprings are placed together at the exciter end of the rotor, outside the main bearing centres, in a separate and rigid brushgear pedestal. The complete brushgear is totally enclosed and ventilated from a separate rotor driven fan, the cooling medium being filtered air. Hinged windows are fitted to the brushgear covers to permit observations of the sliprings and brushgear and to enable any necessary adjustments to be made during running conditions. The connections between the rotor winding and the slip ring are made through heavy copper conductors, running axially along the bore of the rotor shafts, and cast in epoxy resin. The radial connections from the sliprings and the windings to these leads are through seals to prevent gas leakage along the bore of the shaft.

The rotor sliprings contain a helical groove, this feature being very effective in maintaining good contact between the brushes and the ring. In addition the current sharing between brushes is improved as is the generator reliability and brush life. A graphite grade of brush is used which has good lubrication properties and a low coefficient of friction.

The brush holder is a quick release type. In this type a complete unit made up of brush-box, springs and current carrying connectors together with six brushes, can be detached with the aid of an insulated key. Thus new brushes can be fitted into the holder away from the generator. The action of placing a fresh brush holder in position on the generator automatically completes the electrical connection to the holder and releases the brushes so they become free to move into contact with the ring. Pressure is applied to the brushes by means of constant tension springs which eliminates regular re-setting of pressures and also results in more even wear rates.

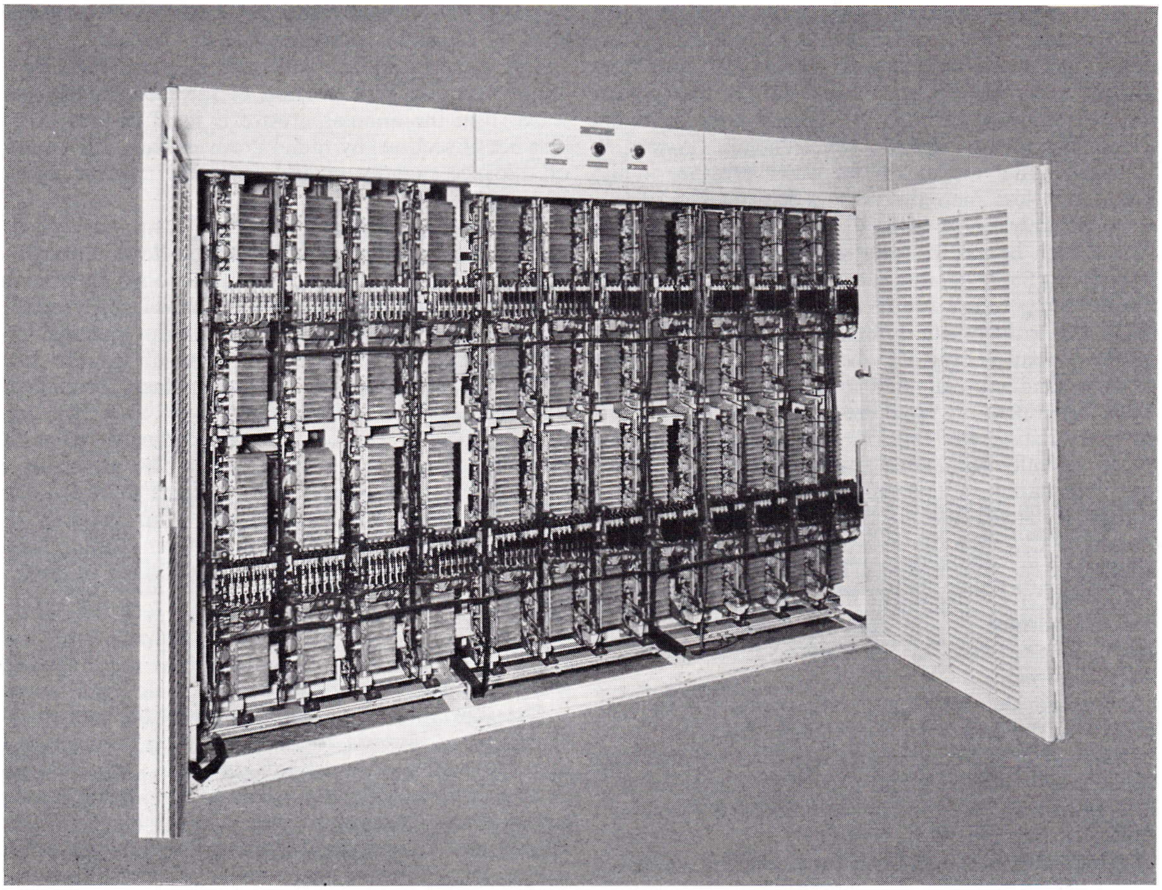


FIG. 7.—*Rectifier section.*

EXCITATION SUPPLY

Because the equivalent d.c. generator would be of large physical dimensions, resulting in awkward maintenance problems, the excitation supply is obtained from a three phase 100 c/s a.c. exciter whose output is rectified in a static silicon diode rectifier. The main exciter consists of a revolving field system and stationary armature and is direct-driven from the main generator rotor. The rotor of the main exciter is separately excited by an a.c. pilot exciter directly coupled to the main exciter. The stator casing of the main exciter is totally enclosed and the stator core is laminated. As in the main generator the stator conductors are in diamond coil form, laminated and transposed to reduce losses. The complete stator is dried under vacuum and the end windings impregnated. The main exciter rotor is of the laminated cylindrical type. The sliprings are weldless steel forgings, shrunk directly onto the shaft over mica bushes. Here again the complete brush holders are detachable by means of an insulated key.

The pilot exciter is of the rotating armature type and has two distinct field windings. One is fed at constant current from a small permanent magnet a.c. generator, through a rectifier, whilst the other is supplied with the rectified pilot exciter output current to provide a measure of compounding. Thus the pilot exciter voltage is always constant irrespective of load.

The rectifier unit consists of four self-contained, three-phase full wave rectifier sections, each connected in a conventional six armed bridge network (Fig. 7). The sections are paralleled to form the complete rectifier unit. The diodes, used for the excitation system for the 660 MW generators, are of the alloyed junction high grade silicon type and have a maximum peak transient reverse voltage rating of 1600 volts and a maximum mean forward current rating of 300 amperes. The inverse voltage rating of the diodes has been chosen so that an appreciable margin exists above the highest voltage which could occur in operation. The number of diodes per section is such that the rectifier can still supply full machine excitation continuously with one section out of commission. The whole rectifier is cooled by natural air a special cooling fin being incorporated on each diode.

Each section of the rectifier contains a.c. and d.c. isolators. Interlocks ensure that only one section at a time can be isolated and that access to the diodes cannot be obtained until they have been disconnected completely from the excitation circuit.

The complete equipment is rated to accept fault conditions in excess of the field forcing current rating. The increased current which flows in the rotor circuit, and consequently through the diodes, immediately following a three-phase fault at the generator terminals is well within the diode capability. The most severe current loading on the diodes would occur in the event of a short circuit on the d.c. side of the rectifier, for instance at the main generator sliprings. Protection is provided by the operation of the main field breaker. The breaker is tripped by the action of an over-current relay. In the event of the field circuit breaker failing to operate under fault conditions ultimate protection to the rectifier diodes is provided by high speed fuses. The fuses, which also ensure removal from the circuit of any failed diode, are mounted in an accessible position on the diode cooling structure.

Each fuse is shunted by a low capacity striker pin fuse. In the event of diode failure the striker pin fuse immediately operates a mechanical trigger system and this in turn initiates operation of a visual warning system. This comprises a set of warning lamps mounted towards the top of each rectifier section cubicle. To obtain quick identification of a faulty group within a section, each indicator assembly incorporates an indicator lamp which lights in the event of a fuse failure.

The rectifier arrangement is so rated that three parallel paths in the arm of a section bridge can be lost before replacement becomes urgent. To assist in voltage sharing, diode resistors and capacitors are fitted. These take the form of potted modules and are mounted adjacent to each diode. A capacitor-resistor voltage surge suppression network is connected between the d.c. connections of each rectifier section. The initial application of this form of excitation system was on a 60 MW generator. The unit has now been in continuous operation for over four years. During this time there has been no replacement of diodes or fuses.

Rotating Rectifiers

Considerable experience has also been gained with the use of full scale rotating rectifier test rigs. The ultimate aim is to use completely self-contained excitation systems with rectifiers mounted directly on the generator shaft so as to eliminate the need for brushes. The reliability of shaft-mounted rectifiers has already been proved by trouble-free operation on a number of smaller generators mainly running at speeds up to 1,800 rpm.

Investigations have been completed to determine the most suitable arrangements of lead connections and base mountings to withstand the acceleration forces associated with high speed rotors running at 3,000 and 3,600 rpm. The rectifier assembly has the most simple mechanical arrangement to provide reliability and individual diodes are mounted so that the junctions are under compression under centrifugal loading. The diodes are connected in a conventional six arm bridge with each arm containing diode paths in parallel. Each diode has in series a fused link. The fused links prevent any connected circuit from feeding into a shorted diode. The fuse links are each complete with an indicating device which is normally held in a fixed position by the fuse element. Should the fuse element open, then the indicating device is released and is forced out of its normal position by centrifugal force. The released indicating device is conveniently detected under stroboscopic light while the machine is in operation so that a shutdown can be planned well in advance after a given number of fuses have opened. This type of excitation system will shortly be commissioned both on a 60 MW and a 350 MW generator.

Automatic Voltage Regulators

The automatic voltage regulating equipment is of a magnetic amplifier type having a negligible dead band and a high speed of response. A three phase voltage transformer is connected to the generator terminals. This feeds a full wave rectifier bridge which therefore produces a direct voltage proportional to the voltages produced by the generator. The resultant direct voltage is compared with a reference to produce an error signal. Using this error signal voltage control of the generator is provided by means of a voltage setting rheostat which is in circuit between the rectifier and the reference bridge. The polarity of the output of the reference bridge is dependent on the magnitude of the rectifier voltage relative to the setting. This output feeds the signal windings of a two-stage magnetic amplifier. As the regulator output is not of sufficient magnitude to control the field excitation it is therefore subjected to two further stages of amplification before being fed to the exciter field windings. The power supply for the final stage transductors is provided by the a.c. pilot exciter. Variation of the final stage magnetic amplifier control winding current determines the exciter field current and consequently the generator rotor current and generator MVAr.

Automatic Control

The advantages to be gained from the use of automatic start-up equipment for a turbo-generator are that precisely controlled, pre-defined acceleration and loading rates and therefore heat input rates are guaranteed for every start. Turbine stresses are thus kept within safe limits and the fastest possible start-up is achieved.

Experience of the control of a synchronous generator, a 60 MW generator and a 200 MW generator has now been obtained. In the latter case control of the boiler, generator and turbine auxiliaries is carried out by a digital computer whilst the run-up, loading and flange heating is covered by an analogue controller. The analogue controller is a special purpose digital computer being ideally suited to the purpose of operating under a fixed programme for start-up and shutdown conditions (Fig. 8). It is characterised by each of its components having one specific function, so that all inputs and outputs are available simultaneously. Thus no scanning or data storage facilities are required and the programme, that is the list of operations to be performed and the order in which they are carried out, is determined by the way the components are wired together. At present the functions of the equipment fall under three classifications: (*a*) pre-start checks (*b*) running-up from turning gear to synchronous speed, and (*c*) loading. The operation and constructional details of the equipment have been given in full elsewhere [5]. Such a system is currently being designed for a 660 MW unit.

Conclusions

With the successful operation of the 500 MW generators it is interesting to consider what size of generator can be built in the future without making radical design or constructional changes.

The now well proven technique of direct cooling of the stator winding with water and the rotor winding with high pressure hydrogen will enable the production of a factory built generator with outputs up to at least 900 MW.

Introduction of rotating rectifiers will eliminate problems associated with the brushgear that could arise due to the higher excitation powers required.

The increasing use of sophisticated automatic control equipment coupled with development in the field of electrical governing will ensure the safe start-up and operation of the very large units to be built in the near future.

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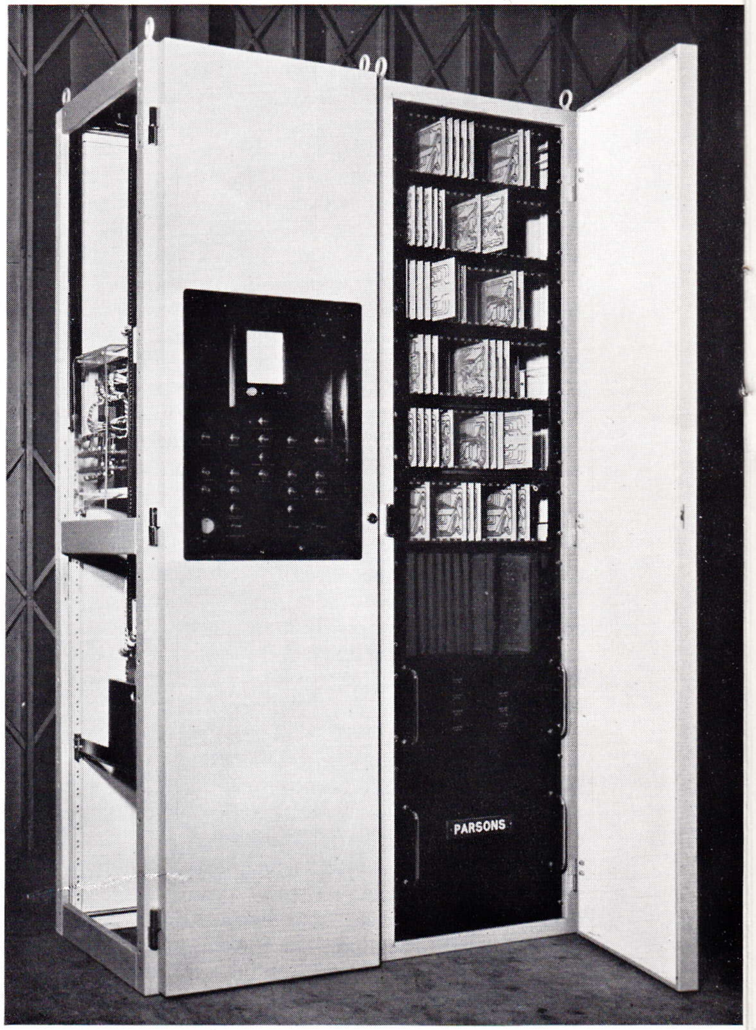

Fig. 8.—*Cubicle housing turbine automatic run-up equipment.*

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