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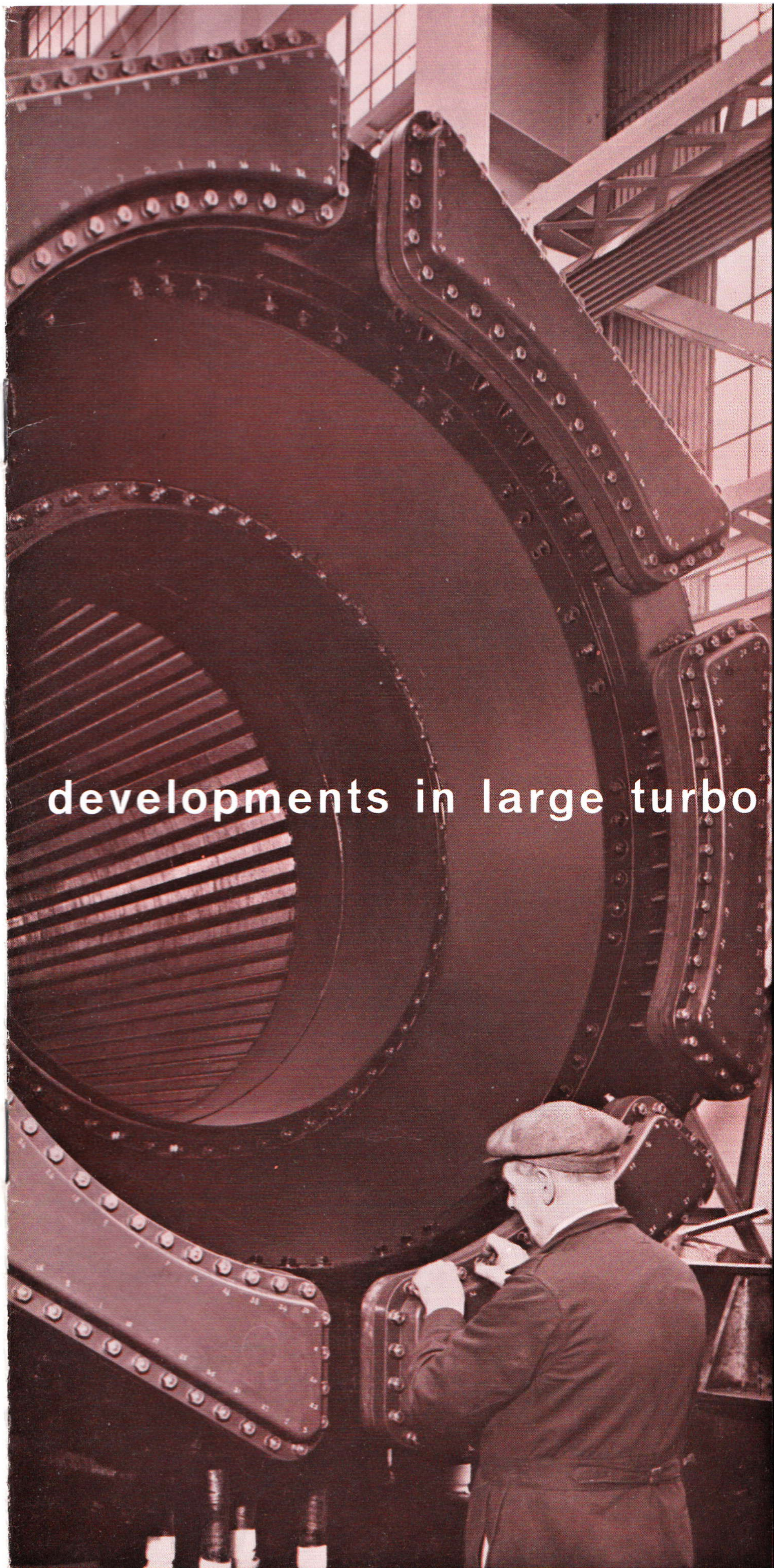

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Developments in Large Turbo Type Generators

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SUMMARY

THE modern large turbo generator has been made possible by developments in the manufacture of large forgings, techniques of construction and design progress — maintained by continued re-appraisal of known, and careful analysis of new, problems. The present paper reviews the progress leading to the direct liquid cooled generator and discusses a number of major problems which have been made prominent by the increase in maximum output. These include negative sequence, heating, asynchronous operation, current collection and short circuit torques.

INTRODUCTION

From the very earliest days the designer of steam turbine generating equipment has been urged to design larger and still larger units so that economics can be effected by an improvement in the overall efficiency of generation and by a reduction in the space required to accommodate the unit thus reducing the costs of building, cranes and personnel.

As the maximum size of rotor forgings has increased and the mechanical properties of such forgings have been improved, the size of generating units has been correspondingly increased to such an extent that the present day limitation is one of transport. The heaviest part of the unit is the generator stator and the only way in which the maximum output can be secured from a single unit is by development in design, and in particular, the methods adopted to remove the losses from the active material in the stator and rotor.

The enormous growth of the electrical industry has made large units necessary, but the rate of growth has in no small measure been due to the development of the large generating unit.

It seems a far cry from 1884 when Sir Charles A. Parsons secured his first patent covering the design and details of a high speed turbine driven direct current generator from which, based on an idea by Prof. George Forbes, in 1888 the first alternating current turbo generator was developed. Although slow speed alternating current generators had been built for some time previously, it was not long before the high speed a.c. generator made its impact.

The first four commercial units were built in 1889 being single phase units generating 75 kW at 1000 volts and running at 4800 R.P.M. corresponding to a frequency of 80 cycles. It was between 1892 and 1894 that a number of two-pole 150 kW units were built, these again running at 4800 R.P.M. but improved by the adoption of radial and axial ventilation ducts to give better cooling. One disadvantage of these early generators was the arrangement of the rotor winding in the form of a single layer winding lying on the smooth surface of a laminated rotor and restrained against centrifugal force by steel binding wire. In those days heavy and frequent short circuits were encountered and led to the loosening of the conductors and their support. By about 1900 tunnel slots were introduced and metallic armature end winding supports provided and while a number of units were built using this form of construction and arranged to generate two and three phase power at steadily increasing voltages it was soon found that difficulties were experienced with the insulation, the mechanical support and the reliability of such windings; this was mainly due to the overlapping of the two layers of the end windings. In the early 1900s

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the introduction of the cylindrical rotor, as we know it today, provided a significant advance in design.

It is of particular interest to note that in 1904 and 1905 water cooling was applied to the stators of two 500 kW generators in the form of 72, 0·875″ bore copper pipes expanded into slots in the outer periphery of the coreplate and terminating at each end in a cast iron water box which also formed part of the end covers. The copper tubes were expanded into the water boxes. In 1914 five 11,000 kW 2400 R.P.M. generators were built having rotors cooled by water flowing through a duct below each rotor slot, and this design was repeated in 1918 for three 15,000 kW 2400 R.P.M. generators (1). While the cooling was found to be quite effective, the tests indicated that the space occupied by the water duct would be more effectively used by deepening the rotor slot and filling with more copper. In 1922 the increased use of solid forgings and improved techniques had permitted an increase in generator rating to 20 MW at 3000 R.P.M. and up to the outbreak of the war in 1939 development was spasmodic but steady, most large generators being of the order of 30 to 50 MW at 3000 R.P.M. although there were a number of isolated large units rated at about 100 MW but operating at lower speed.

Also, although hydrogen cooling had been applied to synchronous condensers in the U.S.A. since 1928 and to generators since about 1937, British hydrogen cooled designs of generators were not commissioned until after 1945. Hydrogen cooling rapidly became a general feature of British designs and to catch up with the delayed programme of plant installation, due to the intervention of the war, a considerable number of 30 and 60 MW units were constructed. The changes in design at this period were relatively small; hydrogen was substituted for air and because of its better cooling properties the specific ratings of the generators were increased, particularly at the higher gas pressures. The main limitation to further increases in specific rating was the heating of the generator rotor. By 1952 the temperature gradients through the rotor slot insulation, along the rotor teeth and from the rotor surface to cooling air were eliminated by providing gas passages in the rotor copper. This direct cooling of generator rotors, while new in Great Britain, had been employed on the continent prior to 1939 on air cooled generators.

Direct cooling of the rotor conductors permitted an immediate increase in the specific rating of generators and it was not long before the rotor windings were cooled so adequately that the limit to machine development became the stator. Attention was concentrated on the direct cooling of stator windings and a number of generators have been commissioned having stator windings direct cooled with gas, oil or water (2, 3, 4). The largest single line unit on order in Great Britain is 500 MW at 3000 R.P.M.

Direct Cooled Generators

Before discussing some of the major problems which have been considered during the design of one particular make of liquid cooled generator and one in which the construction adopted for the stator presents a number of unusual features it would not be out of place to describe this design in a little detail.

The various arrangements which have been adopted for the direct cooling of rotor windings have been described elsewhere (5, 6), and a number of different types of direct gas cooled rotors have been developed and are operating satisfactorily. It is important to recognise that the maximum temperature of the rotor copper is largely determined by the temperature rise of the gas and in order to avoid large differences between the hot spot and the mean temperature rise as measured by resistance, care must be taken to keep the axial ducts as short as possible. In some designs where the hot spot temperature is likely to be excessive the mean copper temperature rise, which is the only reasonable method of measuring rotor temperature, must be reduced.

Development work on stator cooling was initiated into various schemes and in 1954 manufacture of two experimental conductors was commenced; one was to be a direct gas cooled conductor and the other a direct liquid cooled conductor using either oil or water. In parallel with this, heat transfer investigations were carried out and designs prepared, which indicated that direct gas cooling was unlikely to be more than an interim measure and that liquid cooling was the scheme to adopt.

Attention was focused initially on the use of oil as a cooling fluid, the heat transfer and heat capacity being very satisfactory while the insulation properties are well established. Despite the small volume of oil required for the cooling of the generator it was considered that it introduced an additional fire hazard in the event of a major breakdown, and that an appreciable leakage of oil could have a detrimental effect on the micanite insulation used for the stator windings. In order to overcome these difficulties various synthetic fluids were investigated each of which had its own peculiarities but none surpassing the qualities exhibited by water, which is an ideal fluid having a large heat capacity, fire resistance qualities coupled with low initial cost. Furthermore, the low viscosity reduces the duty of the circulating pump. Inherently water is a good insulator and with modern demineralisation plants it was considered that the purity of the water could be maintained at such a high level that the resistivity would be high and the electrical losses in the coolant kept to a minimum. While concern was expressed during the early stages of the development regarding the possible rate of dissolution of copper in the coolant, a comprehensive series of tests similar to those already published (7), was carried out, the conclusions being that water maintained at a reasonably high purity would provide a satisfactory coolant.

With the encouragement of the C.E.G.B. arrangements were made to apply direct water cooling to the stator windings of a 60 MW hydrogen cooled generator then partially constructed for the Tilbury

Generating Station. As the stator core had been built the system of gas ventilation was that for a conventional machine employing radial ventilation ducts.

It was decided that each individual strand of the conductor should be cooled since it was anticipated that the conductor would operate at a relatively high current density, thus leading to a shallow stator slot, giving minimum stator weight. The shallow slot also resulted in a lower natural reactance which is now becoming most valuable from the point of view of system stability. Furthermore, it was felt that an uncooled strand could overheat since although the individual strands of the conductor are maintained in good thermal contact within the slot, the conditions in the end windings are more doubtful and where the support of the end coils might no longer be continuous, the existence of small spaces between the strands could cause local hot spots.

While the use of water as a coolant introduced the need for resistance columns to prevent excessive leakage currents between phases and parts of the winding operating at different potentials, it was considered that there were disadvantages in feeding individual conductor ends through insulated pipes from a common manifold. Efforts were first directed to the devising of a common header at each end of the stator into which all the conductor ends could be fitted and supported as a solid structure. One of the early schemes was to cast the whole of the stator end windings into a solid cast resin mass with individual conductor (8) ends projecting to receive water from a common annulus. Naturally, this was criticised on the score of removal and replacement of conductors.

The scheme finally adopted was one in which each conductor end was arranged to terminate in a form of ferrule which would fit into a manifold water box, the latter being made of a cast filled resin material. The ferrules were fitted with "O" rings to make a watertight joint (9). There are six separate water boxes at each end of the stator (Fig. 1) corresponding to the six sections of a two-pole three phase winding. The electrical connections between the top and bottom layers of the windings are made by means of simple copper connections clamped onto an extension of the ferrule, as shown in Fig. 2. This clamped

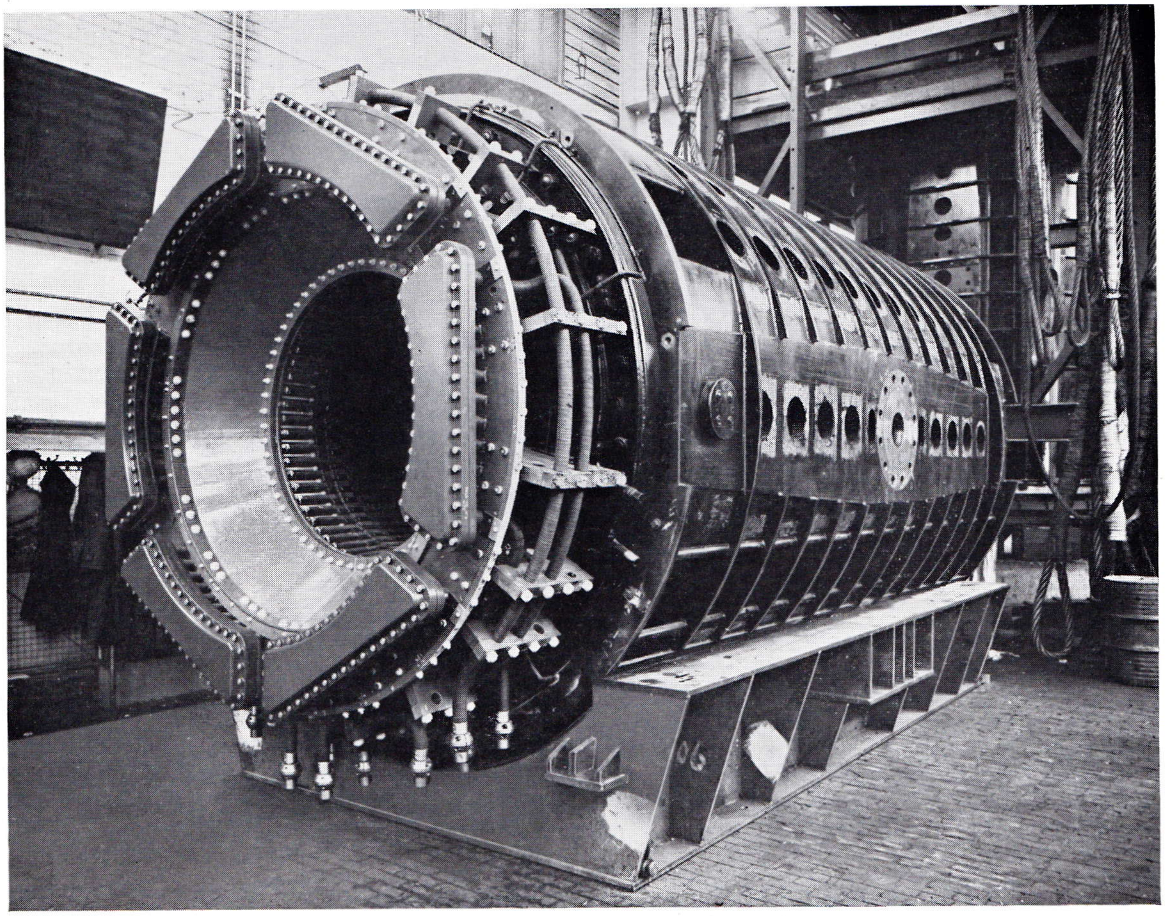

FIG. 1.—*The inner core and windings of a 200 MW water cooled turbine generator.*

connection, being within the water box, is well cooled.

The water boxes form the inlet and outlet headers for the coolant and are individually fed through plastic pipes from a water connection on the stator end walls. These pipes form the water resistance columns the shortest being about 2′ in length and the arrangement was found to be satisfactory on the prototype. On all later machines, however, this arrangement of plastic pipes has been modified, and the phase end connections leading to the winding are of copper tube so that in addition to providing the electrical connections from the stator terminals to the winding, they also carry the coolant to and from the water boxes. The water thus flows into the stator through the terminal bushings and these being water cooled can be made compact and facilitate the fitting of bushing type current transformers. The resistance columns are attached to the underside of the generator terminal bushings so that all plastic pipes become external to the stator. The bus bars to the generator transformer could also be included with the cooling system if required. The temperature rise of the water passing along the conductor is of the order of 12°C and as the temperature drop from the copper to the coolant is of the order of 2°C, the temperature rise of the hottest part of the stator conductor is only 14°C. It is interesting to note that the heat flow across the insulation may now be reversed and instead of the stator copper loss having to flow through the slot side insulation, part of the loss in the stator iron may tend to flow into the conductors.

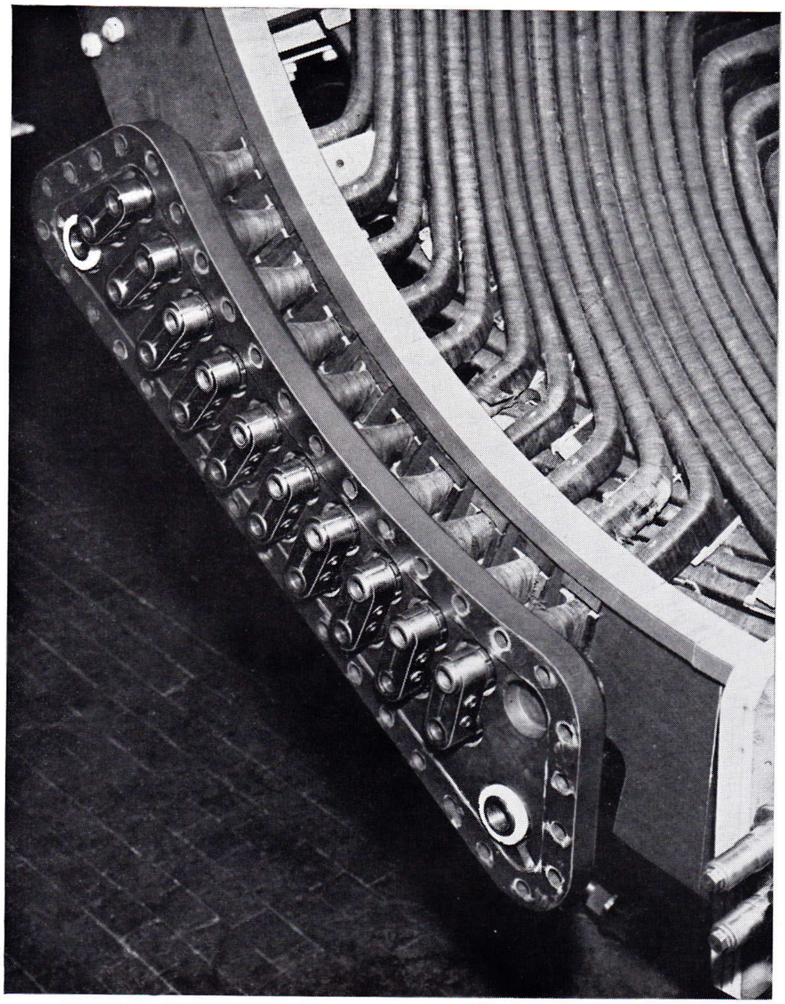

FIG. 2.—*The end windings of a 200 MW water cooled generator. The water box covers have been removed to show the connecting links between the top and bottom layers of the windings.*

As the stator conductors are cooled internally the stator ventilation system is modified from the normal radial axial system to an axial system, gas flowing axially inwards through holes in the stator core to a series of radial ducts at the centre of the stator and then to the air gap. The gas from the air gap is drawn out at each end by means of fans, which in addition to providing a high head for ventilating the stator, contribute materially to an increased gas flow through the rotor.

The prototype generator was first put on load in December 1957 and had completed 20,000 hours in service by April 1961. Throughout this period the water cooling system proved completely satisfactory, the only untoward event being a very short outage due to failure of the stator coolant conductivity meter. The water treatment plant on this generator consisted of a mixed bed demineralising plant treating a 10% bypass of the total coolant flow and a deoxygenerating plant treating 3% of the flow through the mixed bed. These treatment plants, although designed for regenerating, have not needed regeneration from one annual overhaul to the next and the contamination of the coolant appears to be slight.

Tests to ascertain the need for the water treatment plants were commenced in December 1960 and, in conjunction with the Generating Board, prolonged runs were carried out with the treatment plant out of service. The coolant make up changes, normally very small, were kept as low as possible by extracting only small volumes of coolant for sampling and during the test period the make up was not more than 10% of the coolant in the system. However, there had been some interchange of coolant between the head tank and the generator as there were 19 overnight or weekend off load periods during the test period which ended in March 1961. During this period the conductivity increased uniformly from 0·2 micromhos to 6·3 micromhos, the average rate being about 1·5 micromhos per month. This rate of increase is very much less than that measured shortly after the generator was commissioned, when the rate of increase of conductivity was about 0·5 micromhos per day. It is believed that oxide formation reduces the surface activity of the copper. In view of the low rate of increase in cooland conductivity, water treatment plant will be omitted on future water cooled generators. It is expected that a satisfactory level of conductivity can be maintained by bleeding off a small quantity of coolant at regular intervals replacing it with low conductivity water from the turbine condensate system or station demineralised water supply.

It is of interest to record that during the annual overhaul and inspection of the prototype liquid cooled stator a fine deposit was observed on the internal surfaces of the coolant pipework consisting of colloidal sized oxide particles. These particles, which will pass through any conventional type of strainer, have not caused any difficulty in the coolant circuit. Tests, however, are being continued in an effort to reduce oxidation of the stator conductors and pipework and contamination of the coolant. Two methods of approach are being tried, one by pH control and the other by metal deactivation. The former is being investigation by the addition of 0·25 ppm of ammonia, and neutralising amines, such as Morpholine and Cyclohexylamine, introduced into the system in appropriate quantities. Metal deactivation will be investigated by the addition of filming amines such as Octadecylamine and copper deactivators such as Benzotriazole.

Direct water cooled stators are an established form of construction and prototypes constructed by various manufacturers and differing appreciably in their method of construction, have operated satisfactorily for a number of years and demonstrated that the fundamental problems of the liquid cooled stator have been well considered and successfully solved. Direct water cooling has resulted in a significant increase in the maximum size of generator which can be constructed and transported to site.

The development of large units having a high specific rating has focused attention on a number of important problems, amongst which are those associated with the possibility of rotor damage when subject to negative sequence heating, the possibility of rotor heating and stator core end heating due to loss of excitation, the problem of current collection at sliprings and the possibility of excessive shaft and coupling stress due to the generator torques created under fault conditions.

Negative Sequence Heating

The actual mechanism of negative phase sequence heating leading to extrusion of slot and wedges and damage to the rotor slot end insulation has been described in a number of papers (10, 11). Results have been published, giving details of tests and calculations designed to determine the $I_2{}^2t$ capability of generator rotors.

There are three well defined problems.

1. The short time $I_2{}^2t$ capability having fault times restricted to less than 100 secs. This is the condition in which the temperature rise attained at the body end is a direct function of loss and thermal mass and is independent of local loss dissipation to the cooling medium.
2. The sustained $I_2{}^2t$ capability in which the fault is sustained for periods of minutes or hours. The temperature rise attained at the rotor forging end is now a function of loss dissipation to the cooling medium. The temperature distribution at the rotor body end is determined by the heat flow both from the surface to the cooling medium and from the surface to the general rotor mass. The limiting temperature levels are those which will have an adverse effect upon the rotor slot end insulation.

3. The effect of load on sustained I_2^2t capability. In any system, where the load is not completely balanced, due allowance must be made in the design of the generator. The normal temperature levels of a generator rotor, i.e. those due to the excitation power, are based upon the temperature classification of the rotor insulating materials and any superimposed heating due to a sustained negative sequence load will reduce the amount of excitation power permissible.

An analysis of the types of fault experienced has revealed few, if any, definite cases of rotor damage due to short time effects. Where a generator is feeding a system having a relatively high impedance, the fault current is such that the I_2^2t level does not approach the limit for the rotor. It is only when the generator is feeding into a system having a low impedance that the I_2^2t limit of the rotor can be attained. It would seem, however, that where such faults have occurred, the protective gear has operated rapidly and prevented overheating.

Most of the faults experienced have been, fortunately, on air cooled units and of a sustained nature. In one case, an air blast breaker closed on two phases only so that when the associated generator was synchronised and loaded up, overheating of the rotor occurred. Another case followed the closing of a 3-phase oil circuit breaker; one of the turbulator pots had not been correctly replaced after cleaning, so that on switching for synchronising, the cross arm fractured leaving one phase open. There are other types of fault which have resulted in rotor overheating but, in the cases quoted, the fault was detected because smoke emerged from around the generator shaft end.

Some years ago, recommended limits of negative phase sequence capability were established in Great Britain (12). These were based on knowledge accumulated from the analysis of a number of fault records, where details of the fault and extent of the rotor damage could be correlated. Fault records are not normally precise and the estimation of the equivalent I_2^2t level on any given rotor was subject to considerable error. In consequence, the safe levels selected were rather less than those specified in the relevant A.S.A. standard (13). While the latter relates only to conventionally cooled generators some attempt was made in the British table to allow for different methods of cooling.

The apparent variation in the I_2^2t capability of different rotors as shown in our analysis and details of tests published elsewhere, (10, 11), indicate that the determination of the I_2^2t level of a generator rotor is not yet precise. In some cases, it has been indicated that on small generators, the obvious damage due to negative sequence heating occurs from the loss of shrink fit of the end bell, leading to arcing whereas on larger units damage occurs due to extrusion of the end wedges before loss of shrink fit. It is to be expected that other variables such as the length of shrink face, end bell material, and alignment of rotor body end with the stator core end may have some effect.

Nevertheless, all other factors being equal, the I_2^2t rating of the modern, direct cooled, generator must be reduced below the level established for the conventionally cooled generator. The specific rating of the former is about three times that of the latter and as the rotor forging end is fundamentally similar in all types of design, it is to be expected that the I_2^2t level of the large generator will have to be reduced to about one third, i.e. in the case of the A.S.A. standard the I_2^2t rating will have to be reduced from 30 to 10.

The system engineer studies the capability of his system and estimates the I_2 levels which can be imposed on any given generator. His first inclination, no doubt, will be to ask for a generator to comply with his requirements. The generator designer, who is, numerically, very much in the minority, can express the I_2^2t capability of his unit with a fair degree of accuracy and within this limit of accuracy rotors built by different manufacturers will have a similar performance. The designer hopes that system engineers will appreciate the situation and design their systems to meet the generator characteristics.

Asynchronous Heating

It is well known that on loss of excitation a turbo-type generator operates as an induction generator running above synchronous speed with a small value of slip, continuing to generate active power but drawing the magnetising power from the system (14). The final load condition depends upon the effect of the speed rise upon the governor and stability is attained at the point where the governor speed-torque crosses the generator speed-torque characteristic. The distribution of heating in the rotor is very different to that due to negative sequence loading. At the low slip frequency the depth of flux penetration is great and heating of the rotor forging end is of a more general nature. C. A. Parsons records contain details of asynchronous operation on older type generators due to such causes as, for example, a broken exciter field lead. Even though such operation has been continued for some time overheating of the stator and rotor has not been recorded. There is little doubt that excitation has been lost and later restored on a number of generators without the occurrence being recorded and without overheating of the rotor.

Torque-slip characteristics under loss of excitation conditions have been published (14), and it is interesting to observe that the value of rotor loss calculated from the slip frequency is equivalent to a rotor loss similar in magnitude to the full load excitation loss, so that, provided the loss is more or less uniformly distributed, no overheating of the rotor would be experienced.

Additional tests were carried out recently (14), to investigate " coarse " synchronising and operation under " loss of field " conditions. The first relates to switching a generator onto its system before application of excitation, at or near to synchronous speed, and to cause it to pull into synchronism by application of excitation. The adoption of coarse synchronising is not new and while it has certain disadvantages it has the one main advantage that it can permit rapid synchronising under emergency conditions. During these tests operation under "loss of field" conditions was continued to permit observation of stator and rotor temperatures and to investigate the pulling into step on re-application of excitation. On the generators investigated, which were conventionally cooled, there was no overheating of the stator core end. The stator current was maintained at no more than rated value by reduction of load. The rotors did not suffer any overheating and the general conclusion from the tests was that on loss of excitation, the load should be reduced to restrict the stator current to rated value and at this level of load, say about 60%, the excitation could safely be applied to pull the generator back into step (14). It is important to ensure that conditions, when re-applying excitation, are such that pole slipping will not occur as this is considered harmful to the stator core end structure (15).

The torque-speed characteristic of a highly rated generator may be such that the generator is not capable of generating full load as an induction generator and the turbine governor speed torque characteristic will cross that of the generator on, say 50% load or less. The equivalent loss in the rotor body, calculated from the slip may be quite high, and the possibility of local heating of the rotor is increased. There is also some doubt regarding the extent of stator core end heating in these circumstances. There are two possible forms of action on loss of excitation. The first is to fit a "loss of excitation" relay and trip the unit after an interlock or reverse power relay has indicated that the steam valves are fully closed. Such interlocking devices are not yet fully proven and to trip a generator immediately on "loss of field", which could have been quickly restored, may seem rather unnecessary. The second alternative, that of reducing the load to some predetermined level on the turbine speeder gear while another unit is being "got away" requires a knowledge of rotor heating, stator core end heating, and the effect upon the turbine of a sudden load increase on synchronising. Such a scheme would also require an interlock to prevent re-application of excitation when the slip is beyond the minimum value for synchronising.

Underexcited Operation

The attention of engineers was drawn to the effect of underexcited operation of generators upon the stator core temperature a number of years ago, and curves were published (16), showing the characteristic variation of core end temperature with power factor. Tests in the underexcited region have been carried out in Great Britain (14), to study the effect of different types of automatic voltage regulators upon stability and to familiarise operating staff with conditions around the limit of stability. At the same time, heat runs were carried out at various power factors to secure information about core end temperature. Underexcited operation has been experienced on a number of generators supplied to the export market, fortunately without encountering restricting temperatures, and while underexcited operation is seldom experienced on our own system there is a possibility that it will develop with the extensions to the system.

There is a close similarity between the core end heating experienced during underexcited operation and that experienced during loss of excitation operation and, when a study was made of the asynchronous operation of generators a few years ago, a section of the paper was devoted to underexcited operation (14). The broad view was expressed that the end leakage field responsible for the eddy current losses, in and around the end winding structure, was the resultant of two fields, one being due to the stator ampere turns and the other to the rotor ampere turns expended upon the air gap. The application of this theory permitted the estimation of core end loss and temperature curves which bore a close similarity to those measured on various generators. It also provided an explanation for the difference of core end temperatures measured under conditions of no load short circuit and zero lagging power, both at rated current. Moreover, the theory applied equally well whether the rotor end rings were magnetic or non-magnetic. Of particular interest was a series of tests (14), carried out on a 60 MW hydrogen cooled generator on which a large number of thermocouples had been attached to the stator core end. Two sets of underexcited tests were carried out one with non-magnetic end rings and the other with magnetic end rings without in any way disturbing the thermocouples between tests. The same characteristic shape of power factor/core end temperature curve was secured in each case but the temperature levels with the magnetic end rings were just over twice those with the non-magnetic end rings.

The variation of the resultant end leakage field with power factor should be less with generators having a high short circuit ratio than with those having a low short circuit ratio and with the advent of the modern large generator, on which the short circuit ratio is maintained at the lowest possible level to obtain a minimum cost design, care must be taken to avoid excessive temperatures during underexcited operation.

Two companion papers (17, 18), were recently read which contained a detailed mathematical treatment of stator core end fluxes and it is interesting to observe that the curves therein expressed, again introduce the "two reaction" effect when determining the resultant end leakage field. The theoretical treatment described draws attention to the effect of winding core angle and the spacing between the winding core and core end, upon the magnitude of the end leakage fluxes and will no doubt lead to the development of useful investigation into large generator design and construction.

Excitation

The design of an exciter, direct driven at the same speed as the main generator, has always been a challenge to the designer and so successfully was this met that low speed exciters did not become necessary until excitation powers exceeded about 100 kW. The exciters for units rated at 60 MW and greater are usually geared down to approximately 750 or 1000 R.P.M. Despite the increased cost of gearing and a low speed exciter the reduced maintenance costs and improved reliability have well justified the adoption of the low speed exciter. More recently, the direct current exciter is becoming displaced by static excitation schemes consisting of an alternating current exciter feeding into static rectifiers usually of the silicon diode type. Preliminary running with prototype schemes has demonstrated their suitability for this duty and comprehensive tests including sudden short circuit tests have proved their capability of withstanding the onerous conditions thus imposed upon them. The largest single line generators to be built in Great Britain are to have static excitation.

Automatic Voltage Regulators

Tests (14), carried out with various types of automatic voltage regulators under underexcited conditions have effectively demonstrated that the modern zero dead band type of regulator is the most suitable and permits operation at load angles well in excess of that corresponding to the theoretical limit of stability. The results obtained tend to confirm that the most important factor in maintaining stability is the absence of the " dead band " and the actual response ultimately attained is only of secondary importance. Physically, this means that with the absence of a " dead band " the corrective change in excitation can be applied before the rotor has materially departed from its appropriate angular position, whereas, the presence of a dead band, in allowing the rotor to drift, means that additional excitation power is required to overcome the effect of the drift as well as that required to establish a new stable position. The general tendency is to adopt the use of magnetic amplifiers rather than rotating amplydines and the regulator schemes adopted for the direct current exciter seem well suited for use with static excitation schemes.

Current Collection on Slip Rings

Slip rings are a necessity for feeding the rotor winding, even with static excitation, and as long as field breakers are regarded as a necessity, slip rings will remain. Up till a few years ago the standard slip ring brush gear running on smooth slip rings up to 20 inches in diameter at 3000 R.P.M. and at currents up to about 600 amperes was adequate. With increase in excitation current, however, difficulties in current collection were experienced the result usually being characterised by fused " pigtails ", sparking, high and uneven brush wear, high ring temperatures and rough patchy skins on the ring surfaces. Very occasionally, damage was more severe such as scored rings, " fused " brush boxes and eroded or pulverised brushes.

These occurrences, though infrequent, coupled with the prospect of still higher excitation currents well justified a large scale investigation. Accordingly, a slip ring test rig was built with each individual brush current measured and monitored so that the various problems of brush life, current sharing, and brush grades could be investigated under laboratory conditions. At the same time the temperature of each brush and the slip rings was measured by means of thermocouples and radiation pyrometers respectively. The first test rig was designed for currents up to 1500 amperes, while a second test rig was later set up, suitable for currents up to 5000 amperes. Many interesting facts have come to light. Perhaps the first was that the current sharing between brushes varied periodically without any detectable reason for the change and that the effect of a grooved slip ring was to improve appreciably the stability of current sharing.

It was found that the normal brush material, a soft natural graphite impregnated with a small amount of oil, did not chip readily and resisted the formation of an insulating skip often caused by the presence of bearing oil or vapour in the vicinity of the slip rings. Examination of the brush material by X-ray diffraction showed that it possessed a preferred orientation, the brush being cut in such a manner that the basal plane was at right angles to the rubbing surface. While this ensured the best mechanical stability it was also found that the brushes possessed a grain structure in the plane normal to the basal plane and that chipping at the trailing edge of the brush was most likely to occur when the grain ran parallel to the trailing edge of the brush.

Those effects, which can lead to improved current sharing such as grooved slip rings and brush attitude, i.e. the larger dimension of brush arranged circumferentially, have been determined and adopted, but the fundamental question of current collection and brush wear is still being pursued. Brushes do not always wear evenly but there seems little doubt that the brushes which do not wear are those which do not carry current. Evidence indicates that when a brush is not conducting it is operating in a stable position with an air wedge separating, and electrically insulating it, from the slip ring. In the case of a good conducting brush the air wedge is very small or negligible. The current would appear to be carried by small grains of carbon which roll between the ring surface and the brush face. Evidence of this effect has been secured by drilling a small hole radially through the brush and collecting samples of these small carbon particles and comparing their size with the air wedge thickness. Once the air wedge becomes thicker than the available carbon particles, conduction ceases. One particularly convincing experiment was to set up a non-conducting brush and to inject fine carbon particles at the interface thus causing it to become conducting. When the supply of particles ceased the brush again became non-conducting. The research programme is still in progress but it is expected to materially assist in the problem of current collection.

Shaft Torques

As the rating of single line units has continued to increase so rapidly one obvious question arises. Is there some limiting output at which the coupling between turbine and generator can no longer transmit the torque? While it has been possible to provide adequate stiffness up till now, large diameter journals are in themselves a problem and the whole question of shaft torques merits examination.

The transmission of the steady power torque does not present a limit to design but the oscillating torques, which occur under fault conditions and may attain several times rated torque (19, 20), can cause high transient shaft stresses. These oscillating torques have been measured and are amenable to calculation but, roughly speaking, the maximum oscillating torque at the air gap is inversely proportional to the per unit subtransient reactance so that with $x''d=0{\cdot}2$ the maximum per unit air gap torque will be 5.

The estimation of the maximum stress in the coupling between the generator and turbine is complicated and well suited to the computer but it may not be inappropriate to enlarge on the physical effects to promote a more clear understanding. The generator rotor, on being subject to the oscillating torque, is made to oscillate, the amplitude of the oscillation being determined by the torque applied and the effective inertia of the rotor. If the turbine inertia was nil there would be no stress in the coupling between the generator and the turbine. But as the turbine possesses inertia a forced shaft stress is developed of an amplitude which increases with the turbine inertia. If the turbine inertia was infinite the coupling stress would depend only upon the angular twist and the stiffness or flexibility of the coupling. One means of reducing the coupling stress would be to incorporate a long lay shaft between the turbine and generator.

The coupling stress is also controlled by the natural torsional frequency of the system and if, for example, the natural torsional frequency was at the same frequency as the forced oscillations, a build up in stress could occur. As the natural torsional frequency departs from the oscillatory frequency the shaft stress becomes less. The results of a general computer study of this problem are interesting. The particular case shown is for a 500 MW single line turbo generator the prime mover consisting of one H.P., one I.P., and three L.P. turbines. The curves in Fig. 3 show the air gap torque and the shaft torques

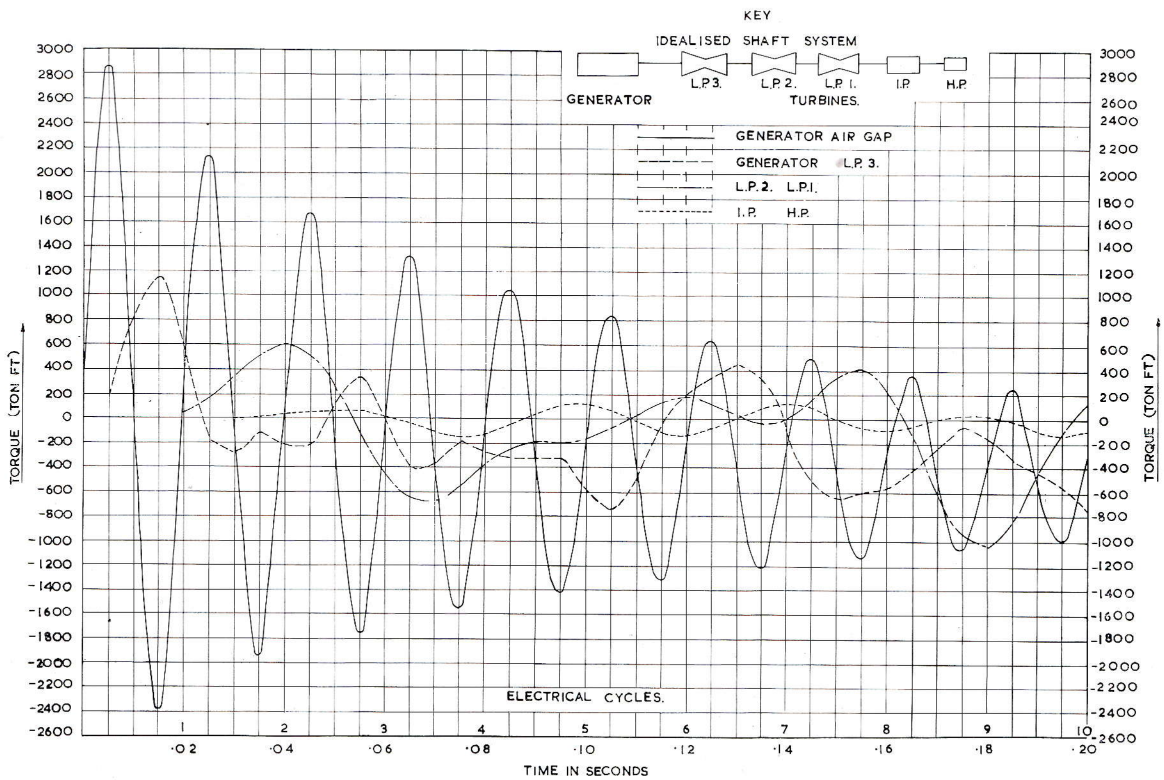

FIG. 3.—*Curves of short circuit torques in the shaft of a 500 MW single line turbine generator.*

developed at each of the couplings. The interesting points are, firstly, that the frequency of the coupling stress is at the natural torsional frequency of that part of the system, secondly, the maximum torque occurs in the generator/turbine coupling and is only 40% of generator air gap torque and thirdly, that it takes time, relatively speaking, for the peak stress to travel down the complete turbine shaft.

Following the computer calculations, a model, suitably scaled, was built to demonstrate these effects. This is illustrated in Fig. 4. It consisted of a pendulum which applied a fixed torsional oscillation to a vertically suspended wire carrying six heavy inertias corresponding to the generator rotor and the five turbine spindles. The rigidity of the wire was arranged to represent the various elastic couplings between spindles but, since the model was scaled down to a speed sixty times less than reality, the modes of vibration could be observed by eye. Oscillations of this model, recorded by means of a cine-camera, agreed closely with those obtained analytically with an electronic computer.

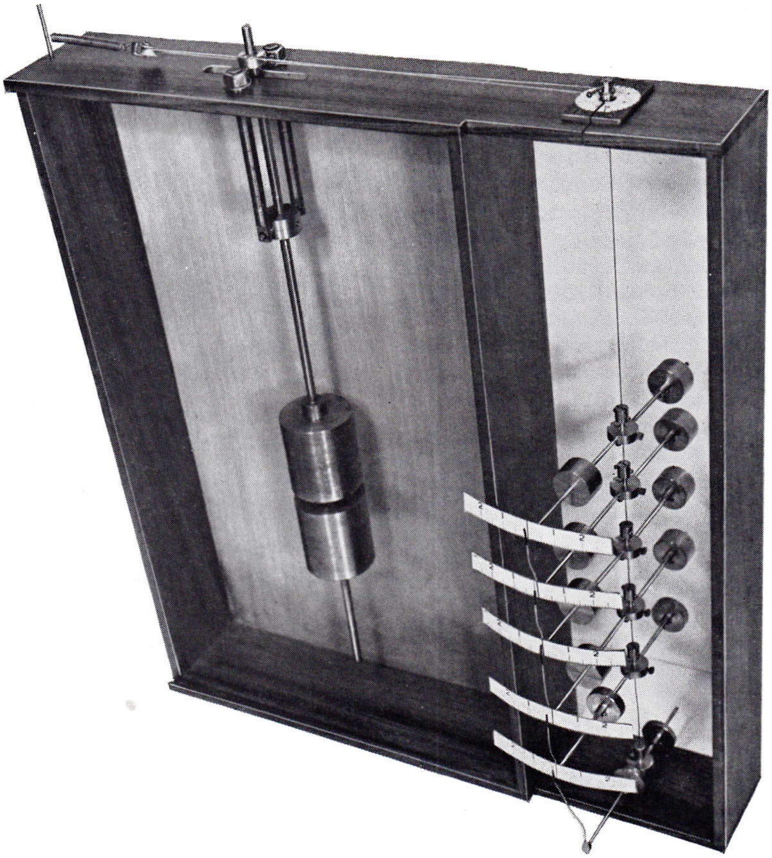

Fig. 4.—*Model to demonstrate the effect of torsional vibration in the shafts of turbine generators.*

An interesting scheme for reducing the maximum shaft torque was recently developed. As mentioned above the maximum coupling stress can be reduced by increasing the resilience of the turbine/generator coupling and with the advent of static excitation the alternating current exciter can be driven at the turbine speed. The opportunity is thus presented of incorporating the A.C. exciter between the turbine and generator. The overall length of such an arrangement is no more than that of a generator having a conventional geared direct current exciter. The consequent reduction in coupling stress due to the oscillatory forces is quite appreciable and this particular arrangement may be of assistance in the design of still larger single line units.

Conclusion

It has already been stated that the modern large turbo generator is the outcome of persistent development work in design and manufacture, and the author hopes that this review of one manufacturer's progress, especially regarding the liquid cooling of stators, may represent a worthwhile contribution to the advancement of the art. The particular problems dealt with, however, are only a proportion of those brought into prominence by increases in generator rating and system capacity.

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