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BRUSHLESS TURBINE GENERATORS

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I. FOREWORD

With the trend toward construction of large capacity turbine generators, a new brushless turbine generator system is attracting a great deal of attention. The current collector, indispensable but causing numerous problems in conventional synchronous generators, has been entirely eliminated in the new turbine generators. It is well recognized that with the increased demand for electric power, construction of highly efficient thermal power plants has become a matter of utmost importance in almost every country of the world, and the capacity of individual turbine generators has gradually increased year after year. In the United States and Europe, large capacity generators with outputs of 500,000 to 700,000 kw are being produced and operated on a practical basis. There is also a trend in this country toward the use of higher capacity turbine generators, 400,000 kw turbine generators are already in use and larger capacity turbine generators are now under development. One of the major problems arising from increased turbine generator capacity lies in the requirement for extremely high excitation power. Generator output is proportional to the product of rotor volume and ampere loading. In large capacity generators, however, the volume of the rotor is restricted due to limitations on the amount of steel that can be used in rotors. Thus, high output must be obtained through increased ampere loading. Improved cooling methods have made it possible to increase ampere loading, resulting in the inevitable increase in excitation power.

Fig. 1 shows the relationship between turbine generator output and excitation power. As can be readily seen, the excitation power required for a 400 Mva generator is approximately 1250 kw, and it reaches as high as 2500 to 3200 kw in 800 Mva turbine generators. It is obvious that excitation current for such generators will eventually reach as high as 4000 to 5000 amp and that numerous problems will be encountered in trying to collect such high current.

However, with recent extensive improvements made in semiconductor elements, production of brushless excitation systems having sufficient reliability has become possible. As a result the problems in collecting current, described above, have been basically solved and it has become possible to develop new turbine generators, one after another.

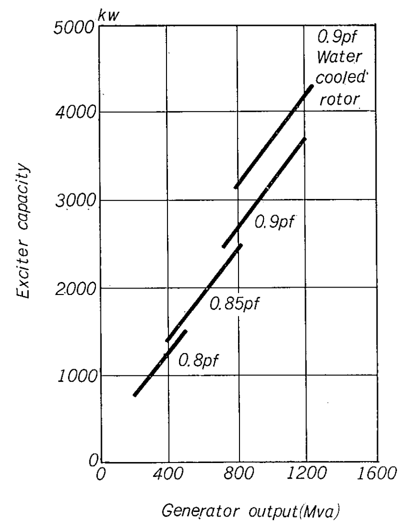


Fig. 1 Exciter capacity of large turbine generators

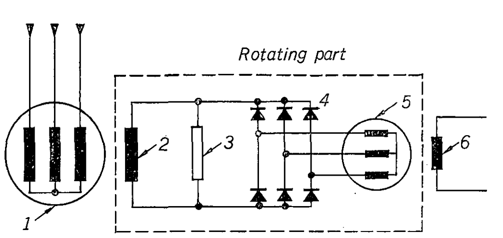
Let's review the history of the brushless turbine generators. The first 50 Mva brushless turbine generator was made by the Westinghouse Electric Corporation in 1960. Westinghouse also produced a 352 Mva turbine generator in 1963. Reportedly, a considerable number of large capacity brushless turbine generators have been produced and actually operated since these first two. The Siemens Company of Germany, which shares a technical exchange agreement with the Fuji Electric Company, has produced a 100 Mva brushless turbine generator, and is now producing a 200 Mva and a 400 Mva brushless turbine generator. A great deal of time and effort has also been applied to study and research on brushless turbine generators in both France and England.

From the above, it can be readily seen that the position of brushless turbine generators is steadily becoming more important in the field of large capacity power generators. Considering the fact that this excitation system was developed to eliminate brush trouble in generators used in aircraft flown at extremely high altitudes, it is only natural that this system would be applied to turbine generators used under adverse environmental conditions. It is a well known fact that numerous problems are encountered in maintenance of medium and small capacity turbine generators used for power sources in chemical plants due to corrosion of the slip rings and brushes resulting from adverse environmental conditions. This new brushless excitation system is expected to go a long way toward solving these problems also.

Fuji Electric early recognized the advantages of brushless ac generators, and has conducted extensive research directed toward the development of such generators. Fuji Electric has supplied a variety of diesel driven generators to various customers, including 3250 kva equipment. A 22,500 kva, 3000 rpm, brushless turbine generator has been recently produced in the Kawasaki Factory. This generator is the largest generator of this type in this country. Using this generator as an example, various problems concerning brushless turbine generators are described herein for the purpose of providing reference information to those who might be interested.

II. BASIC CONSTRUCTION AND PRINCIPAL FEATURES OF BRUSHLESS TURBINE GENERATORS

A basic connection diagram of a brushless turbine generator is shown in *Fig. 2*. As can be clearly seen in this diagram, the principal components of a brushless generator are the main power generator, the rotary rectifier and the ac exciter. The ac exciter, which has a rotating armature, is connected directly to the main generator. Its output current is rectified by a silicon rectifier installed on a common shaft with the ac exciter, and is applied as exciting current to the field winding of the main generator. In some brushless turbine generators, a permanent magnet generator is added as a direct connection to the above described system, as a power source for excitation of the ac exciter. Discharge resistor and other protective devices are also provided in the rotary rectifier, as shown in the figure. The discharge resistor is permanently connected to the terminal of the field winding and protects the silicon rectifier from high field winding induction voltage resulting from failure and shorting of the main generator. Details on the individual components are explained in the following paragraphs:



1. Main generator stator winding
2. Main generator field winding
3. Discharge resistor
4. Silicon rectifier
5. Ac exciter armature winding
6. Ac exciter field winding

Fig. 2 Brushless excitation system

Principal features of brushless turbine generator are as follows:

1) Maintenance is simplified, since there are no brushes or slip rings.

Difficulties encountered in design and manufacture of brush equipment required for collection of large current have been eliminated. Maintenance of slip rings and related components, such as cleaning around the current collector, replacement of brushes, repair or replacement of corroded or damaged slip rings, etc., is no longer necessary. As a result, overall maintenance costs have been appreciably reduced. Moreover, damage of the windings from deposited brush carbon dust has been completely eliminated and the service life of the insulation has been extended.

2) Suitable for use under adverse environmental conditions.

Maintaining slip rings and brushes used under adverse environmental conditions, such as those found in chemical plants where they are subjected to oil, steam, and corrosive gasses, is an extremely difficult task. However, these conditions have little affect on brushless generators, which can be used effectively under such adverse environmental conditions.

3) Direct connection of the exciter provides improved operational stability.

In turbine generators excited by a separate motor-generator, numerous special provisions must be made for excitation current, since the power supply of motor-generators is also affected when there is a disturbance in the system. On the other hand, excitation current in brushless generators is obtained directly from the main generator shaft and effective excitation is provided even when the system is disrupted. Reliable excitation is provided for the main generator and the operation is stabilized.

III. CONSTRUCTION OF PRINCIPAL BRUSHLESS GENERATOR COMPONENTS

1. Ac Exciter

As previously mentioned, the ac exciter is a rotating armature type synchronous generator in which load is applied from the field winding of the main generator through the rectifier. Thus, there are several differences between the ac exciter and conventional synchronous generator. These differences are not explained in this presentation, since they have been explained in detail in various published papers.

When maximum main generator excitation current and voltage are given and the rectifier circuit connection system has been determined, it is possible to compute the rated output, voltage, current, and power factor. In designing an ac exciter, its frequency can be set at any desired level. However, in most cases, intermediate frequencies are selected in the range of 150 to 300 cps, so as to reduce the time constant and increase response.

Ceiling voltage of the ac exciter should be 150% or more of ac exciter voltage corresponding to main generator rated excitation voltage. It is identical in this respect to conventional dc exciters. Excitation system response ratio should be within 0.5 to 2.0, applying the same definition as applied to dc exciters. The exciter system will not provide excitation quick enough if voltage response ratio is less than 0.5. On the other hand, if response ratio is higher than 2.0, the capacity of the automatic voltage regulator will be unnecessarily high and uneconomical. Normally a response ratio of approximately 1.0 is considered adequate for turbine generators. This value can be easily provided in a brushless turbine generator excitation system.

2. Rotating Rectifier

Usually, either a 3-phase, full-wave circuit or a 3-phase, haef-wave circuit is used in rotating rectifier wiring connections. A 3-phase, full-wave circuit contains many leads and has high reverse withstand voltage and a high utilization factor. Conversely, a 3-phase, haef-wave circuit has a low reverse withstand voltage and a limited number of leads. A 3-phase, haef-wave circuit is employed when excitation capacity is small and excitation voltage is low, and a 3-phase, full-wave circuit is employed when excitation capacity is higher.

The most important component in a brushless excitation system is the silicon rectifier comprising the aforementioned rectification circuit. Extremely gratifying results have been obtained ever since silicon elements were first introduced as an excitation source for synchronous equipment. This element has shown proven reliability in stationary applications. However, in brushless generators, the element must be applied to a rotating unit and is exposed to an extremely powerful centrifugal force. Consequently, extensive research has been made and numerous tests conducted to make this an extremely efficient and reliable element.

Fuji Electric employs two types of pressure contact silicon elements in the rotating rectifier. They are called Si 250·3 and Si 250·3 R. In Si 250·3, the direction of normal current is from the base to the lead. Conversely, in Si 250·3R, the normal current flow direction is from the lead to the base. Conventional silicon elements, referred to as soft-brazed elements, are constructed by applying a silicon plate on a base plate having an expansion coefficient rearly identical to that of silicon crystal, such as molybdenum, tungsten, etc., and by brazing the base plate onto a copper base. However, these softly brazed elements are mechnically weak and do not stand up when used in rotating units. In contrast to these conventional silicon elements, new pressure-contact silicon elements have been developed to eliminate the mechanical weaknesses found in the brazed type. In these new elements, a silicon plate is applied to a thin base plate, and pressure-contact is provided between the element lead wire and the base. The element will withstand extremely high pressure in the direction perpendicular to the base plate. The use of unsuitable brazed elements has, therefore, been eliminated. A simplified construction diagram of this pressure-contact silicon element is shown in *Fig. 3*. Its characteristics are shown in *Table 1*. This element has the following outstanding features:

1) The silicon plate is firmly secured to a thin base plate and can withstand extremely high pressure applied at right angles to the base plate. Thus, far superior mechanical strength is provided under the pressure-contact system. Furthermore, there are no mechanical weak points such as those found in soft-brazed elements.
2) The copper electrode applied on top of the silicon plate contacts the single silicon crystal through a

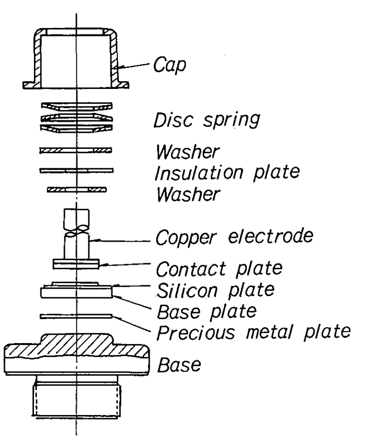


Fig. 3 Pressure contact silicon element

Table 1 **Specifications of Pressure Contact Type Silicon Element**

Item	Unit	Condition	Si 250·3	Si 250·3R
Normal Rated Current	Amp (mean)	Air cooling 6 m/s 50°C	280	240
Peak Reverse Withstand Voltage	v peak	Commercial frequency half-wave continuous	1200	1200
Maximum Ac Input Voltage	v rms	—	430	430
Allowable Continuous Temperature of Connected Units	°C	—	160	160

contact plate which has an expansion coefficient almost equal to that of the single silicon crystal. Thus, it is balanced with the thermal expansion of the single silicon crystal plate. A precious metal plate is applied between the base plate and the base. With this construction, the base plate can freely expand and contract on the precious metal plate as a result of temperature variations, and no stress will be applied to the silicon plate, even when there is a temperature change.

3) High precision electrodes are provided with precise contacts so as to prevent localized overcurrent.
4) The element is filled with an inert gas, and, therefore, the silicon connection does not become corroded or degenerated, even when it is used under extremely high temperatures for long periods of time.

Fig. 4 shows the pressure-contact silicon element and the rotating rectifier cooling unit in which the silicon element is installed. As previously described, two different current flow directions are provided in Fuji Electric's pressure-contact element. Thus, a bridge can be formed with a simple lead connection using the same cooling unit. This is an extremely advantageous feature. In addition, a new flat silicon element has been developed under the pressure contact system. This new flat silicon element is under study for application to brushless generators.

The rated continuous current of the rotating rectifier used in brushless turbine generators is approximately 150% of rated excitation current used in conventional generators. With this rating, the rotary rectifier will sufficiently withstand increased excitation current resulting from rapid excitation due to system disturbances, and even against overcurrent induced in the field circuit as a result of the generator being quickly shorted out. Insofar as the voltage rating is concerned, consideration must be given to excitation voltage during quick excitation, abnormal voltage during short-circuiting, abnormal voltage during improper synchronous closing, field induction voltage when slipping out of synchronous operation, and other significant factors. An unusually high voltage is generated when excitation current flows in a reverse direction. This is a typical characteristic of non-synchronous operation of generators. Except in isolated cases, voltage induced in the field winding of conventional turbine generators when shifted to non-synchronous operation will not normally exceed four times the rated excitation voltage. *Fig 5.* is a sample oscillogram of a turbine generator charged with rated load under non-synchronous operation. This figure shows both rotor current and voltage. In this example, peak voltage is approximately 3.5 times the rated excitation voltage. Abnormal voltage generated during non-synchronous operation is one type of condition that cannot be avoided in a silicon rectifier circuit. However, no problems will be encountered as long as the rating is established through careful study of rotating rectifiers used in brushless excitation systems, since these matters have been thoroughly investigated in stationary systems using silicon rectifiers and satisfactory results have been obtained.

3. Protection Element

A strong reverse current flows through the silicon rectifier element for a short period of time during commutation, due to the so-called " carrier storage effect ". In the case illustrated in *Fig. 6*, in which rectifiers are connected to the power supply of internal inductance L, excessive reverse current flows through the element " *1* " when commutating from phase a to phase b. Reverse voltage block characteristics are quickly recovered, preventing this flow of current. As a result, the energy $2\times\frac{1}{2}Li^2$ accumulated in L

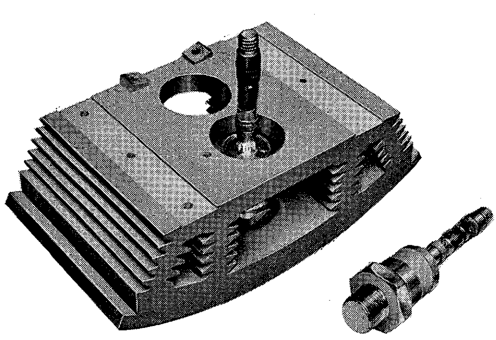


Fig. 4 Silicon element and cooling unit

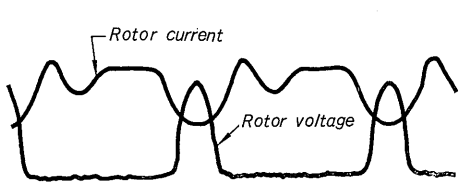


Fig. 5 Rotor voltage and current during asynchronous operation

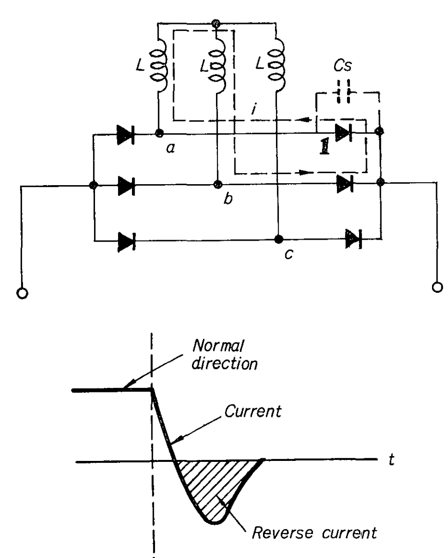


Fig. 6 Carrier storage effect

is stored in element stray capacitance *Cs*. However, since *Cs* is too small in silicon elements, high oscillation voltage is generated. If excessively high voltage results from this carrier storage effect over a period of time, the reverse current characteristics of the element will be destroyed. Therefore, excessive voltage is suppressed by inserting braking resistance *r* to increase the attenuation of the oscillation, and capacitor *C* is inserted in parallel for protection.

When abnormal voltage is observed on a synchroscope, an excessively high voltage appears when no protective capacitor is provided. However, when a 2μF capacitor is inserted, almost no peak voltage is observed. Such a protective device is provided in the rotating rectifier. The components must also be capable of withstanding powerful centrifugal force.

Silicon rectifiers must be connected in parallel for generators having large excitation current. Under this type of connection, if one of the paralle lelements is broken and rectification is not properly provided, the bridge is shorted. To avoid this, a fuse must be provided. It goes without saying that the fuse must have circuit breaking characteristics which are balanced with the overcurrent characteristics of the element. However, these characteristics must also be assured even under powerful centrifugal force. Therefore, a special fuse is employed which differs from those used in conventional stationary silicon elements. In most cases these fuses have an operational indicator and can be observed through a stroboscope during operation.

IV. 22,500 KVA BRUSHLESS TURBINE GENERATOR FOR DELIVEREY TO ASAHI CHEMICAL INDUSTRY CO., LTD.

Having provided a general description of brushless turbine generators, a more detailed description is furnished in this chapter on the 22,500kva brushless turbine generator for deliverey to the Asahi Chemical Industry Co., Ltd. This brushless turbine generator is the largest capacity turbine generator ever produced in Japan. Its specifications are as follows:

1. Component Specifications

1) Generator
   Type: Horizontal shaft, cylindrical, rotating field, synchronous generator
   Output: 22,500 kva
   Voltage: 11,000 v
   Current: 1175 amp
   Frequency: 50 cps
   Speed: 3000 rpm
   Power factor: 0.8 (lagging)
   Number of poles: 2
2) Ac exciter
   Type: Horizontal, rotating armature, synchronous generator
   Output: 70 kva

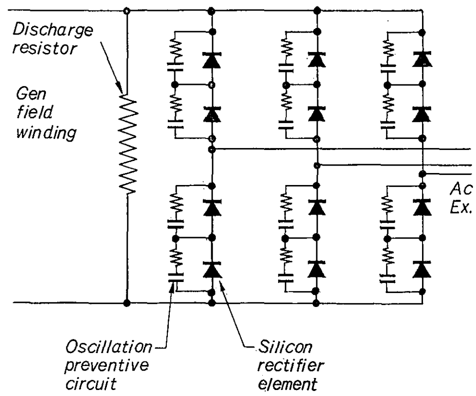


Fig. 7 Rotating rectifier connection

   Voltage: 110 v
   Current: 367 amp
   Frequency: 150 cps
   Speed: 3000 rpm
   Power factor: 0.9 (lagging)
   Number of poles: 6
3) Rotating rectifier
   Type: 3-phase, Graetz connection, silicon rectifier
   Output: 70 kva
   Voltage: 140 v
   Current: 450 amp
   Element: Refer to *Fig. 7*
4) Permanent magnet generator
   Type: Horizontal shaft, rotating field, permanent magnet generator
   Output: 2 kva
   Voltage: 110 v
5) Automatic voltage regulator (AVR)

2. Construction

Fig. 8 shows a sectional view of the exciter used in this generator. The rotating rectifier, ac exciter, and permanent magnet generator are assembled on a common shaft, and are directly connected to the end of the main generator shaft. The permanent mag-

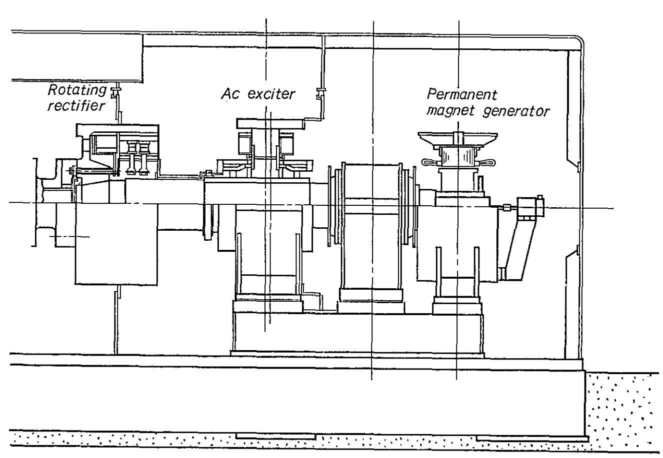


Fig. 8 Cross-section of brushless excitation system

net generator, which serves as the power source for the ac exciter, retains its stability regardless of conditions of the external power source. Therefore, even when disturbance occurs in the system in which the main generator is connected, the permanent magnetic generator provides constant excitation, thereby stabilizing the system and making it entirely free from the influence of disturbances in the main system. These exciters are isolated from the outer section by covers. They are fully enclosed and are cooled by cooling air branched from the cooling system of the main generator.

A 6-pole, 150 cps, ac exciter has been designed which uses a salient pole stator and a damper winding. The coil end portion of the armature winding is firmly secured to withstand high-speed rotation of the armature. The rotating rectifier consists of a silicon commutator, its cooler, capacitor resistance, protective resistance, and retaining ring which holds these components when they are subjected to centrifugal force. *Fig. 7* is a connection diagram of this equipment. Two series-connected silicon elements are provided on each arm. The reason these silicon elements are not connected in parallel is due to the fact that the pressure contact type silicon elements use a 3-phase Graetz connection which has a continuous current capacity of up to 720 amp, while rated excitation current of the turbine generator is only 400 amp. As an alternate, a rectifier circuit of prescribed output can be devised from a parallel connection of several silicon elements which are much lower in rating. It appears that this alternate method of connection would be highly reliable since it would be possible to minimize the drop in overall output, even if one of the parallel branched silicon elements is defective. However, in actual usage, a fuse is applied to keep output drop to a minimum. Use of additional parts (fuses) is a negative factor in improvement of rectifier circuit reliability. Hence, desired effects are not always obtained under the alternate method. Furthermore, use of additional parts results in increased dimensions complicates construction of the rotating rectifier, and is uneconomical. Therefore, when the rating of the silicon elements is higher than the rated exciting current of the turbine generator, a parallel connection should not be used. Since the exciting voltage of this rotary rectifier is 140 v, one silicon element connected in series is adequate. However, two elements connected in series are used for assurance against the danger of the silicon element becoming defective. The most common failure in the elements is loss of rectification. The rectifier circuit is always closed. When two silicon elements are connected in series, the rectifier circuit will operate normally at all times, even if one of these elements does not function properly. The rotary rectifier is, therefore, extremely reliable.

The silicon elements are applied to the cooling unit.

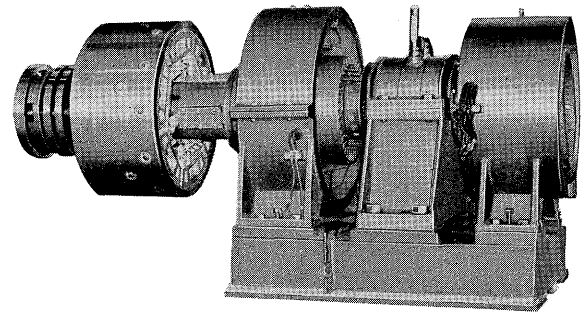


Fig. 9 Rotating rectifier for 22,500 kva generator

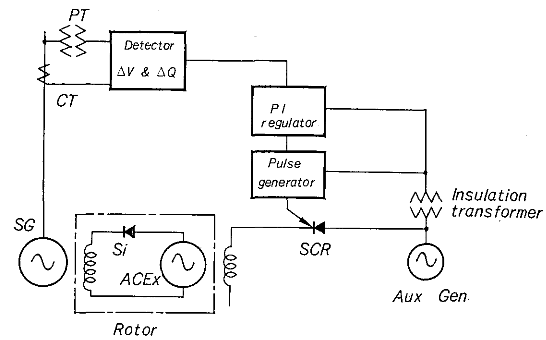


Fig. 10 AVR system

The cooling unit has a cooling fin and is designed to provide a suitable ventilating passage. The cooling also serves as a part of the conductor lead between elements. It is fastened to the inside of the retaining ring through an insulator with bolts.

The oscillation-preventing circuit consists of a capacitor and resistance contained in molded epoxide resin in a single unit construction. The capacitor used in this circuit is also impregnated with epoxide resin. It is a special type finally selected for usage after experimental tests. The rotating rectifier unit also has a built-in discharge resistor used to reduce abnormal voltage applied to the rectifier circuit when the exciting current is reversed. *Fig. 9* shows a photo of the rotating rectifier. Shown from left to right in this photo are the rotating rectifier, ac exciter, and permanent magnet generator. A provisional slip ring is installed on the rectifier for testing purposes.

The AVR circuit is shown in *Fig. 10*. A transistorized adjustor (TRANSIDINE) is used as the amplifier control element. It has a far shorter delay than the magnetic type amplifiers, but still has greater amplification. The main amplifier contains a thyristor which is simple in construction and easily adapted. Therefore, accuracy and adaptability are assured. AVR control power is fed from the directly connected permanent magnet generator referred to above. Thyristor AVR has been selected over magnetic amplifier type AVR after careful comparison. Results of reliability analysis show that this type of AVR is equal to or better than conventional type AVR systems. The input section leading to the AVR has an arrester and isolation transformer to eliminate improper operation that may result from noise interference. An arc suppressing coil is used in the AVR panel where contact arcing is normally a problem. Thus, every possible feature has been incorporated in the design of the AVR circuit.

3. Generator Experiments on Trial Basis

Sufficient preliminary tests were performed to unquestionably conclude that the brushless excitation system must not be applied except in cases where the turbine generator has high speed and large capacity, making sure that each component of the brushless rotating rectifier is properly adaptable, as explained in Chapter III.

Furthermore, through tests on individual components, it has been assured that the silicon elements are not adversely affected when subjected to a pressure of 1000 kg (testing for ability to withstand centrifugal force). The elements were subjected to an impact strength test in which shock was applied twenty times using 50 g, and five times with 100 g. These shocks were applied in both horizontal and vertical directions. In vibration resistance tests, 50 cps, 1.5 g (unilateral amplitude of 150) oscillation was applied over an extended period of time with the elements repeatedly connected and disconnected. (Repeated heat cycle test). Test conditions were far more severe than those encountered under actual operation. However, results of the tests prove that there was no drop in element characteristics or loss of air tightness. These tests confirmed that these elements were suitable for use in rotating rectifiers.

Similar pressure tests (centrifugal force tests) were applied to the oscillation prevention circuit. Test results proved that use of pressure increases the capacitance of oil capacitors available on the open market to an appreciable extent. This indicates that electrode intervals are reduced by applying pressure to the capacitor element, and capacitors sold on the open market cannot be safely used under centrifugal force. Therefore, we decided to develop a special epoxide resin-impregnated capacitor for use in brushless exciters. This new special capacitor has far less change in capacitance than conventional oil condensers.

The capacitor is installed in the rectifier together with oscillation damping resistance in a molded, single unit construction.

We produced a test model rotating rectifier with the same output as an actual rectifier using components selected on the basis of these tests. We then performed a series of tests on the rectifier. The rectifier has output current of 600 amp and output voltage of 550 v. Various tests were performed on this rectifier, including the acceleration test (4320 rpm), temperature rise test, and long-duration continuous operation test, etc. During the tests every component was carefully checked for characteristics and variations. The results of these tests clearly show that the elements, capacitors, and resistances can readily withstand actual operating conditions. *Fig. 11* is a photo showing the test model rotating rectifier under test. For testing purposes, load and power source were connected through slip rings. In view of these test results, we have utmost confidence in the reliability and performance of our 22,500 kva brushless turbine generator.

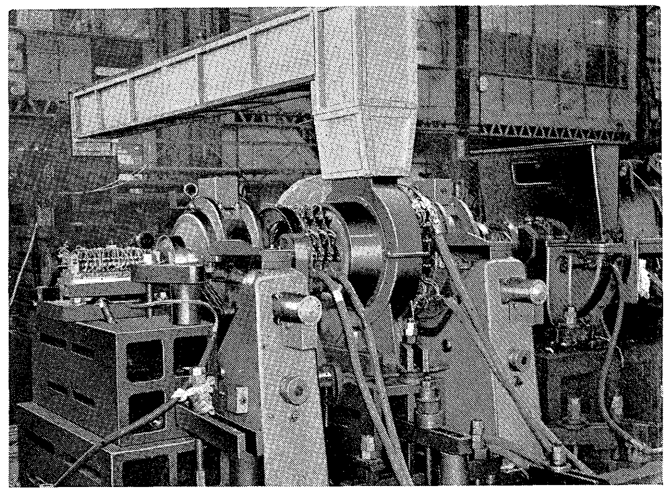


Fig. 11 Trial rotating rectifier

V. CONCLUSION

We have provided an explanation and discussion of the brushless generator from the standpoint of its components and application of sample components to the 22,500 kva Turbine Generator. As mentioned in the beginning of this report, more and more brushless turbine generators will be produced and supplied with the trend toward larger capacity generators, and with the increased demand for generators that can withstand adverse environmental conditions. We hope that this paper will be of some assistance in future development and improvement of this type of equipment.