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BRUSHLESS A-C GENERATOR

By Mitsuru Takahashi

Design Dep't., Kawasaki Factory

Isamu Suzuki

Central Technical Dep't.

I. FOREWORD

Synchronous generators have long been excited by d-c exciters. However, the emergence of a self-excited compound a-c generator several years ago provided occasion to examine the self-exciting system from various angles. It has been discovered that the self-exciting system has superior characteristics not only for medium size equipment in vessels but for electric generators as well. What has made this possible is, among other things, the advance made in the field of control systems including magnetic amplifiers as well as dry type rectifiers, notably silicon rectifiers. However, the fact that this has eliminated troubles and painstaking supervision of commutators and brushes which were the weakest parts of d-c exciters through the employment of static exciters is little recognized.

Even if a static exciting system is adopted, both slip rings and brushes are still necessary to provide field winding of a generator with d-c current and, although improvements are being made as a result of studies on its sliding characteristics and material, problems yet continue to pose themselves. Consequently, where there is oil vapour in ships in paricular, or where there is much inert gas, or again where a high speed machine is concerned such as a turbine generator, a strong demand is felt for elimination of slip rings and brushes.

To meet such demand, our company has developed a slip ringless and brushless generator of an entirely new exciting system with SCR used in its voltage control. It has been proven as a result of tests, that this generator exhibits highly excellent performance in static and dynamic characteristics. We consider that because of these favorable findings plus its economy there is a great possibility for this exciting system to be used in vessels and electric generators in the future and we offer this article to all interested parties showing the construction of various parts of this system, function, characteristic analysis and test results.

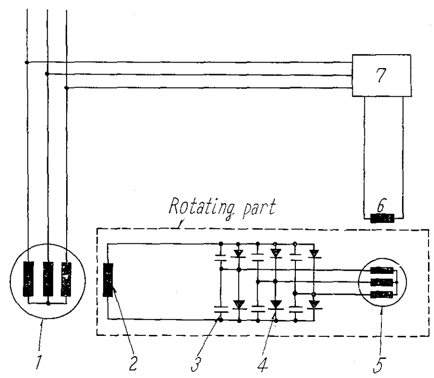
II. BRUSHLESS GENERATOR

1. Outline

This is not to say that there were no synchronous generators without slip rings and brushes.

There were, for example, permanent magnet generators and high frequency generators having an inductor type rotor but the former were limited in capacity, while the latter have a low utilization factor and neither can be economically used for medium machines upward as a service frequency power source. And if one tries to design a synchronous generator of over medium capacity in a most ideal manner, one always arrives at a revolving field type construction and so one has to provide field current to the rotating field. In the past, this was done through slip rings. The brushless a-c generator is one which replaces them by a d-c rectifying apparatus consisting of a silicon rectifier and a-c exciter arranged on the common rotating shaft, doing completely away with all sliding contact parts such as slip rings.

In *Fig. 1* the connection diagram, field winding *2* of the generator *1* gets field current from armature winding *5* of the a-c exciter and the rectifying device



1. Main generator
2. Field winding
3. Protective condenser
4. Silicon rectifier
5. Armature winding of a-c exciter
6. Field winding of a-c exciter
7. AVR control circuit

Fig. 1 Schematic of exciting device of brushless a-c generator of silicon rectifier *4*. Voltage control is carried out by controlling field current of field winding *6* of the a-c exciter by AVR circuit composed of a voltage detecting device and SCR.

Respective constituent elements are broken down as follows.

2. A-c Exciter

The a-c exciter is as an important element in the characteristics of the brushless generator as the silicon rectifier and there are several problems with regard to design which were fully examined by testing and analysis.

The construction of the a-c exciter is that of a synchronous generator of a revolving armature type. Polyphase winding of the rotor gives rise to polyphase a-c voltage by exciting the field winding of the stator.

Let us examine the points in designing the a-c exciter such as phase, frequency, capacity selection and performance characteristics.

1) Selection of phase and frequency, and armature reaction

m: Number of phases
I: Effective value of a-c current
I_d: D-c current
I_{1a}: Fundamental effective value of a-c current
W_1: Number of series windings per phase
Z: Total number of series conductors
p: Number of pair of poles
K_p: Short pitch factor
K_d: Distribution factor
A_1: Ampere conductors per cm $(IZ/\pi D_i)$
D_i: Outer diameter of armature

Generally, when a rectifier is connected to m phase exciter as load, the following formula is satisfied.

$$I_d=\sqrt{\frac{m}{2}}\cdot I \quad \cdots\cdots(1)$$

$$I_{1a}\frac{1}{\sqrt{2}}\cdot\frac{4}{\pi}\cdot I_d\cdot\sin\frac{\pi}{m}$$
$$=\frac{2}{\pi}\cdot\sqrt{m}\cdot I\cdot\sin\frac{\pi}{m} \quad \cdots\cdots(2)$$

The *mmf* of armature reaction F per pair of poles arising out of fundamental current I_{1a} applied to armature winding is:

$$F=0.9\,m\cdot\frac{W_1}{p}\cdot K_p\cdot K_d\cdot I_{1a} \quad \cdots\cdots(3)$$

Assuming that the number of slots per pole per phase is large, $K_d\simeq\frac{2m}{\pi}\cdot\sin\frac{\pi}{2m}$ and $Z=2m\cdot W_1$, so that formula (3) may be transformed into formula (4).

$$F=\frac{1.8}{\pi}\cdot\frac{K_p\cdot D_i}{p}A_1\cdot m\cdot\sqrt{m}\cdot\sin\frac{\pi}{2m}$$
$$\cdot\sin\frac{\pi}{m} \quad \cdots\cdots(4)$$

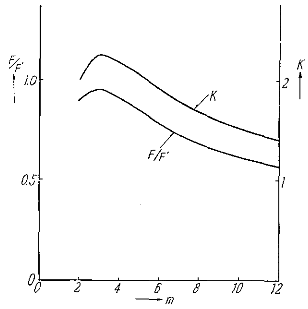


Fig. 2 Relation between number of phases and armature reaction

When K is set for $K=m\sqrt{m}\cdot\sin\frac{\pi}{2m}\cdot\sin\frac{\pi}{m}$, the relation between m and K is as shown in *Fig. 2*. In other words, it may be seen that armature reaction is maximum when $m=3$ and with the increase of m, it decreases.

If we define *mmf* of the armature reaction at normal load which is not rectifier load as F', formula (5) holds for the same a-c effective value current.

$$F'=0.9\cdot\frac{K_p\cdot D_i}{p}\cdot A_1\cdot m\cdot\sin\frac{\pi}{2m} \quad \cdots\cdots(5)$$

Consequently, F/F' is maximum at 0.955 with $m=3$ as illustrated in *Fig. 2* in which F/F' expresses the ratio of the *mmf* of armature reaction when a-c exciter is connected with inductive load through a rectifier to the *mmf* at normal load, and it decreases with the increase of m and when $m=12$, it becomes 0.571. This must be taken into consideration in calculating field current to be discussed later.

From *Fig. 1* it may be seen that when the number of phases increases, armature reaction becomes small which is desirable from the point of view of design but when one thinks of the arrangement of the rectifier and the manufacture of the armature winding, $m=6$ may be the limit. Generally, it is advisable to use three phase double way connection (Graetz connection) by dint of its favorable utility rate and simplicity in connection and arrangement, in which case m becomes 3. This means the greatest armature reaction but if the number of turns of field winding of stator is selected to meet it, it may be compensated for, so there will be no problem.

The higher the frequency, the greater the response, which is a good thing, but core loss increases and the number of poles increases in direct proportion to the frequency so that there is a limit from the viewpoint of structure and economy. When one considers a recent tendency toward high response of the control circuit, it may be seen that when if a commercial frequency is selected the full capacity of a brushless generator can be displayed. The prototype uses 4 poles 33.3 c/s and has displayed characteristics as anticipated.

2) Voltage, current, power factor and field current at rectifier load.

Fig. 3 shows an example in which an a-c exciter

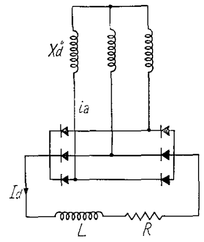


Fig. 3 Rectifier circuit

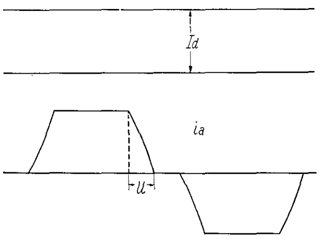


Fig. 4 Wave form of a-c and d-c current

is connected to the rectifier with a great inductive load in the Graetz connection. A-c current of each phase develops an overlap angle u by internal impedance of the power source and if the condition of $i_u + i_v + i_w = 0$ is met, it shows a wave shape as illustrated in *Fig. 4*. The overlap angle u is shown as in formula (6).

$$u = \cos^{-1}\left(1 - \frac{p \cdot x_d'' \cdot I_d}{\pi \cdot E_{d0}}\right) \quad \text{..............(6)}$$

x_d'': Subtransient impedance of a-c exciter
E_{d0}: No load d-c voltage

When each harmonic component of a-c current as in *Fig. 4* is analyzed by Fourier analysis, *Table 1* (a) is obtained.

Table 1 Harmonic Component of *i* & *v*

Order of harmonics ν	1	3	5	7	9	11	13
(a) Caluculation i_{ao} (%)	100	2.2	15.5	7.96	2.5	1.3	1.61
(b) Actual measurement i_{ao}(%)	100	1.9	16.8	8.57	1.9	2.2	4.48
(c) Actual measurement v(%)	100	0.5	13.4	7.06	0.8	2.5	1.59

Fig. 5 shows an oscillogram of actual tests made with a 15 kva generator. The phase current wave shape is almost the same as in *Fig. 4* and the result of Fourier analysis is shown in *Table 1* (b). The value of each harmonic component is almost identical with the calculated one. It may be seen from this that harmonic components over No. 5 and No. 7 may be disregarded because of their low rate of content.

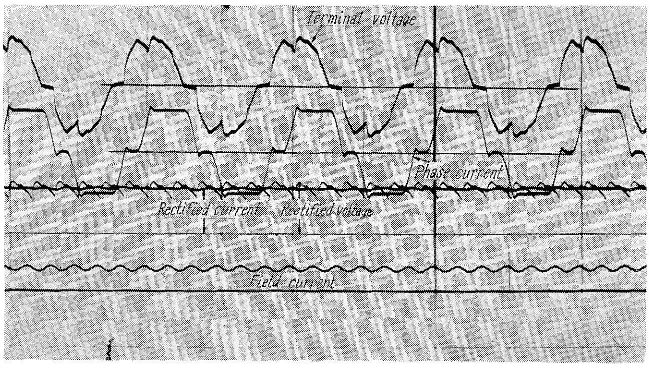


Fig. 5 Oscillogram of each component on inductive rectifier load

When harmonic currents of Nos. 5 and 7 flow to armature winding, they form themselves *mmf* of time harmonics and it turns 5 times and 7 times as fast as the synchronous speed in the reverse direction and in the same direction of rotation, and respectively, of the main revolving field, so that in the field circuit is induced No. 6 harmonic as may be known from the oscillogram in *Fig. 5*. This harmonics gives rise to *mmf* of time harmonics that cancels the previously stated *mmf* of time hamonics, but flux quantity corresponding to negative sequence impedance remains uncanceled, so that in the armature winding is induced harmonic voltage of $E_\nu = k \cdot f_\nu \cdot \Phi_\nu$ and affects voltage shape. Therefore, the voltage wave is

$$e \cong \sqrt{2}\cdot E_1 \sin\theta + \sqrt{2}\cdot E_5 \cdot \sin(5\theta + \varphi_5) + \sqrt{2}\cdot E_7 \cdot \sin(7\theta + \varphi_7)$$

Consequently, the wave shape of terminal voltage is as shown in the oscillogram in *Fig. 5* and the result of its wave shape analysis is in proportion to the value of each harmonics of current as is exhibited in *Table 1* (c).

Losses will increase as will be stated in the next paragraph as a result of these harmonic components, but the ratio of fundamental wave of voltage and current as against effective value including total harmonic wave is

$$\frac{V_1}{\sqrt{\sum V_\nu^2}} \simeq 0.985, \qquad \frac{I_1}{\sqrt{\sum I_\nu^2}} \simeq 0.98$$

so that these may be thought of as having no big difference.

D-c reduction factor of voltage and current will be obtained next.

D-c no load voltage is set as E_{d0} and effective value of a-c voltage is set as E, and, in Graetz connection,

$$E_{d0} = 1.35 \cdot E \quad \text{....................................(7)}$$

When load current flows, reactance drop and forward voltage drop e_s of rectifier occur. When E_d is set as d-c voltage at load, then formula (8) is obtained.

$$E_d = E_{d0} - \frac{m \cdot x_d'' \cdot I_d}{2\pi} - e_s \quad \text{.......................(8)}$$

In the case of silicon rectifier, e_s is relatively small but depending upon the value of X_d'' it (E_d) may become small more than 20% of E_{d0} so that to obtain on-load saturation curve of a-c exciter, it is necessary to insert the relationship of formula (8) to the load saturation curve of a usual ordinary synchronous machine. And the necessary field current should be calculated from it.

Relationship between a-c current I_a and d-c current I_d is as per formula (9).

$$I_a = \sqrt{\frac{2}{3}} \cdot I_d \cdot \sqrt{1 - 3\phi(u)} \quad \text{....................(9)}$$

Reduction factor varies according to overlap angle u but with the usual value of X_d'', $I_a \simeq 0.76 \sim 0.81 I_d$

about. What is interesting here is that with the d-c voltage when X_d'' is great the voltage drop at load increases, whereas d-c current increases when X_d'' increases.

Power factor at load varies according to load current and is expressed as per formula (10)

$$\cos\varphi = 0.955 \times \frac{\cos^2 \frac{u}{2}}{\sqrt{1-3\phi(u)}} \quad \text{.....................(10)}$$

When formula (10) is calculated with measured value put in u of formula (6), $\cos\varphi \simeq 0.92 \sim 0.94$ at full load. In other words, it is sufficient to select 0.9 as the rated power factor of a-c exciter.

In order to calculate required field current, it is sufficient to consider three phase short-circuit curve taking into account the decrease in armature reaction as in *Fig. 2* and formula (8) (9) (10). Results actually measured very closely correspond to those calculated values.

From the foregoing relationship among valtage, current and power factor all the necessary values on the a-c side that are necessary for field of main generator may be determined so that it is possible to decide specifications of output at rating, voltage, and current of a-c exciter.

3) Loss and ceiling voltage

As far as brushless a-c generators are concerned, it is generally not easy to measure losses of main generator. It is because an a-c exciter enters in-between and its loss is included. Therefore, it is very important to calculate loss of the a-c exciter. As stated previously, since even if the voltage wave is distorted it is induced secondarily by harmonic current, iron loss is different, of itself, from the calculation when a harmonic component exists in main flux. As *mmf* of time harmonics revolves, negative sequence resistance loss has to be added. Since a fixed impedance load is always connected to an a-c exciter, iron loss and copper loss coexist and with the increase of output both increase and it is very difficult to separate one from the other precisely but in actual measurements there is about 10% increase of loss as compared with the aggregate iron loss, copper loss and stray load loss calculated by fundamental flux and fundamental current. Even though this is only a minor loss to the main generator, it must be carefully examined in respect to separation of loss from the main machine and the a-c exciter as well as in determining the constitution of the a-c exciter.

With a machine for ships, there is the starting of an induction motor and with generators for power generation there is ceiling voltage so that it is nesessary to think about transient characteristics.

In *Fig. 6*, E_0 represents no load saturation curve of the a-c exciter while curve E stands for load saturation curve obtained in *2*). The operating point of the a-c exciter, either in static or dynamic state,

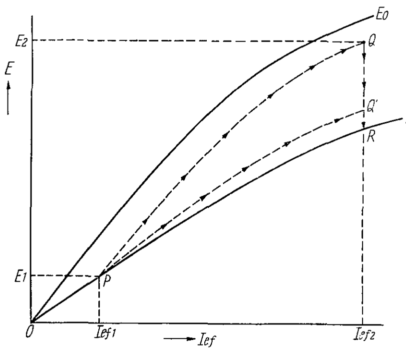


Fig. 6 Transient performance on load curves

is situated within the territory bordered by curves E_0 and E. If a big load is suddenly applied to the main generator at E_1 voltage in operation at point P, field current of the a-c exciter would quickly become from I_{ef1} to I_{ef2} if SCR or a similar high response material should be used but the field current of the main generator increases due to a field time constant, and voltage goes up from E_1 to E_2 and P to Q, and as current flows to the field of the main generator by E_2, point Q goes to point R. However, if a control device not so responsive should be used, the rise of I_{ef} of field current is not fast and the ability to intensify the field of the main generator would decrease such as P-Q'-R and response goes down. This makes a big difference as compared with a d-c exciter with relatively less effect of armature reaction and so in determining the constitution of an a-c exciter it is necessary to carefully study no load and load saturation characteristics, field time constant, control system and response.

3. Silicon Rectifier

1) Construction

It is because silicon rectifying elements of high reliability have been developed in recent years that brushless generators have come to be easily realized. However, in order to satisfy all the requirements of the rotating parts, its fixing method presents the biggest problem. Mechanically, the centrifugal force it is subjected to during high speed rotation, and with diesel-driven machine pulsating torque, vibration of engine must be considered; electrically, cooling, condenser, resistance and fuse, and connections must be simplified.

Our company fitted each rectifying element and condenser to an independent supporter and there are six groups in which the supporter itself is utilized for current passage and heat dispersion which are connected in the Graetz way (patent applied).

Through this, electrical as well as mechanical stability is ensured to a very satisfactory degree and also exchange of groups with ease has become possible. *Fig. 7* shows exterior views of field pole of the main generator, armature of the a-c exciter and a silicon rectifier situated between them. Each group of silicon rectifiers is fitted under the fan and it may

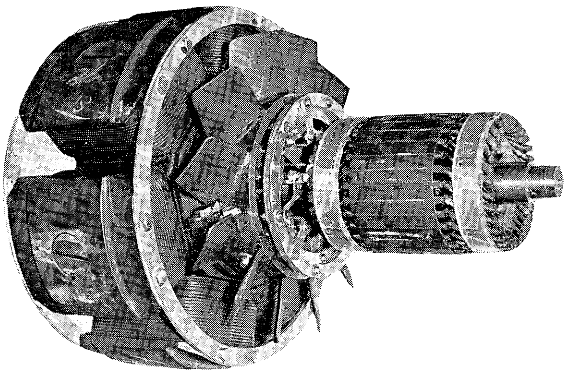


Fig. 7 Complete rotor of brushless generator

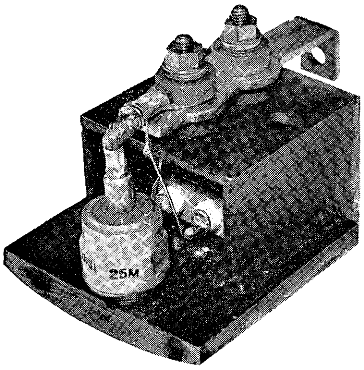


Fig. 8 One group of silicon rectifiers

be seen that even with brushless generators the total shaft length does not differ from that of the conventional machine. Each group, as shown in *Fig. 8*, may be fitted with silicon elements, condenser, etc. as well as the function of fan.

2) Setting of capacity

In determining capacity of a silicon rectifier, the following operating conditions should generally be considered :

(1) Overload operation for a short time.
(2) Voltage by excitation push up from the a-c exciter.
(3) Surge voltage that enters by electromagnetic induction from the rotor winding of main generator.
(4) Excessive current induced in the field circuit at the time of abrupt short-circuit.

(1) and (2) naturally limit the selection of voltage and current but (3) is such that through sufficient investigation during the developmental stage of self-excited a-c machine that there is no abnormal voltage in the field circuit, which is already ascertained. As for (4), electric current greater than the rating may flow at abrupt short-circuit but is the normal direction current for a rectifier and if endurance for excessive current is taken into account to begin with, there will not be any problem.

When a silicon rectifier is connected to an inductive load as a field circuit, for instance, it is necessary to connect the condenser in parallel with each silicon element. This is to preclude abnormal voltage that may arise out of a time difference between recovery of reverse blocking characteristics of the element and disappearance of the stored carrier. Condenser capacity should be increased by the increase in subtransient reactance X_d'' of a-c exciter.

4. Measuring Method of Field Current

With the brushless a-c generator, field circuit of the main generator is separated electrically from the stator side. The question is, therefore, how to calculate field current. One of the methods to enable this may be a measuring system which indirectly uses voltage that may be induced to winding provided on stator side by introducing field current by furnishing a small generator to the rotor. Still, there is a calibration problem between the two and various characteristics belonging only to the generator cannot be measured, such as temperature rise of field winding, no load saturation curve, three phase short-circuit curve, losses, etc. Comparison between design value and test value can only be approximate because the a-c exciter must be used as a mean.

With these facts in mind, our company thought it best to provide measuring slip rings on which brushes may be manually pushed only for measuring, and has adopted it for the prototype.

In this may, various characteristics of the main generator may be obtained as before but, in addition, the load saturation curve of the a-c exciter may be measured and compared against design values.

5. Automatic Voltage Regulator

As an automatic voltage regulator (AVR) of the main generator, SCR is used as a main amplifier as in *Fig. 9*. This AVR consists of the following parts :

(1) Primary means
(2) Amplifier (regulator)
(3) Pulse generator
(4) SCR power amplifier

1) Explanation of function of each part

(1) Primary means

The primary circuit is furnished with an auxiliary transformer (△/人-△) to keep control system delay as little as possible, the full wave of which is rectified to obtain primary voltage with an extremely small ripple.

By comparing this with zener diode for fundamental voltage connected to *B* power circuit consisting of a rectifying device, difference voltage is obtained. For zener diode, the temperature coefficient employed is close to zero to keep voltage setting fluctuation by temperature to a minimum. Voltage setting may be effected by a variable resistance connected in series to the primary circuit. As for voltage setting, the function will be the same if terminal voltage of zener diode is so connected as to match the primary circuit.

(2) Amplifier (regulator)

A transistorized differential amplifier in two stages is assembled in cascade and by adding a damping

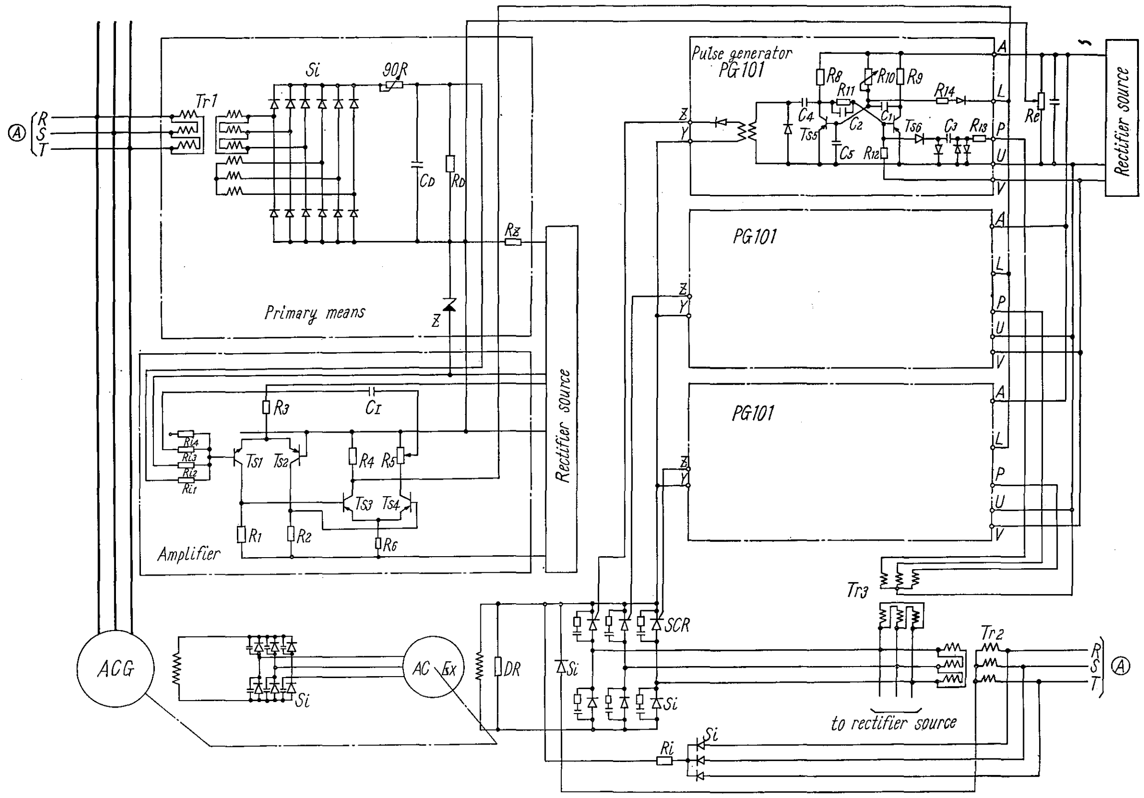


Fig. 9 **Connection diagram of AVR circuit**

circuit of C, R from the output side PI damping circuit is made.

If the primary circuit voltage is lower than zener terminal voltage, T_{s1} collector current is smaller than T_{s2} collector current, and for this reason T_{s4} is almost in a saturated condition, while T_{s3} is in a cut off situation. As terminal voltage increases and zener terminal voltage and primary voltage balance out, T_{s1} current increases and T_{s2} conversely decreases and, as a result, T_{s3} gets collector current and T_{s4} collector current decreases.

Damping circuit gets voltage from R_5 terminal and by C_1 conversely adds against polarity of differential input the variation of terminal voltage, to effect damping action.

(3) Pulse generator

To terninals P-U is given a synchronous signal in synchronization with power voltage. On the other hand, between terminal L and resistance R_e is added output of the amplifier. When amplifier output voltage is greater, T_{s5} is on and C_1 is charged with voltage of the power source.

When a synchronous signal is given, T_{s6} changes from off to on, and an electric charge is instantly discharged through channel R_{10}-R_4-R_e-T_{s5}-C_1, and at this time R_4 terminal voltage also is discharged and is limited by D_1. After that, charge of C_1 is discharged through route C_1-R_{10}-R_9-C_1 and as soon as T_{s5} base becomes minus, T_{s5} comes through.

At this time C_4 charge gets discharged and pulse generates by a pulse transformer and SCR gate added.

Therefore, when voltage between terminals of R_4 is great, trigger pulse is not given during period in which SCR voltage of power is added and SCR does not fire. When R_4 terminal voltage becomes small, trigger pulse is given while regular direction voltage is applied and SCR fires.

(4) SCR power amplifier

When SCR is used as in the connection illustrated, the relationship between firing angle and d-c output voltage is

$$E_a = 0.675\ E\ (1 + \cos\alpha)$$

E_a: D-c average voltage (v)

E: A-c line voltage (v) (effective value)

α: Firing angle (degree)

In the section of the rectifier connected to minus side in the plan SCR is also used, and when control is made by three phase double way system inverter operation may be done by increasing firing angle. By reversing the polarity of the exciter field voltage, rapid demagnetizing action takes place and this will insure rapid demagnetizing when trouble occurs or even in normal operation response may be increased.

2) Comprehensive action

At the time of initial operation, residual voltage occurs with the rise in rotating speeds. This voltage acts on a self-exciting circuit to gradually increase voltage. When B power source is established by this voltage, zener terminal voltage is held at a constant value. On the other hand, if generating voltage does not reach a set value, T_{s1} base potential is higher than emitter potential and T_{s3} is cut off and gives voltage increase instructions.

As voltage increases and the difference is smaller, T_{s3} cut-off condition is released and T_{s3} collector current increases.

On the other hand, T_{s4} collector current decreases. This variation is taken from R_5 terminal and is added to T_{s1} base in the direction of checking the voltage increasing instructions. Thus, excess in increase of voltage is avoided and rapid voltage establishment carried out.

Since in normal operation zener terminal is held at a constant value, if there is any change in generator terminal voltage, this is detected to retain terminal voltage at a prescribed value.

This circuit is merely a circuit designed for automatic voltage regulation but with the addition of cross current compensating circuit parallel operation may be possible. It may also be provided easily with a constant power factor operation device, kva limiting device and other control capacities.

These devices employ a transistor as an amplifier so that its output may be very small. Consequently, it is possible to make the entire equipment about 1/10 or less than the static type automatic voltage regulator such as the conventional magnetic amplifier. Control efficiencies are much better also.

III. PROTOTYPE AND TEST RESULTS

1. Specifications of Prototype

Specifications of generator, a-c exciter and rectifier of our prototype are as follows:

Generator:

Three phase 125/150 kva, 50/60 c/s, 200/220 v 1000/1200 rpm, 6 pole, 0.8 pf, exciting voltage 70 v

A-c exciter:

Three phase 4.5 kva, 33.3/40 c/s, 70/84 v 1000/1200 rpm 4 pole, 0.9 pf, exciting voltage 110 v

Silicon rectifier:

Three phase double way rectification Si25, 60 amp with parallel condenser

2. Test Results

1) Various characteristics and static characteristics of the machine

Measuring of the no load saturation curve, three phase short-circuit characteristics, iron loss and copper loss of the main generator was done with the use of small slip rings. *Fig. 10* represents a combined characteristic curve with no load saturation curve of the main generator in the first quadrant and load saturation curve of the a-c exciter in the third in the truly measured value. The second quadrant shows characteristics of AVR circuit and the fourth

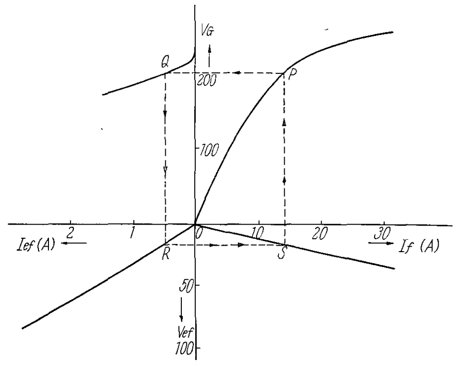


Fig. 10 Combined characteristic curves

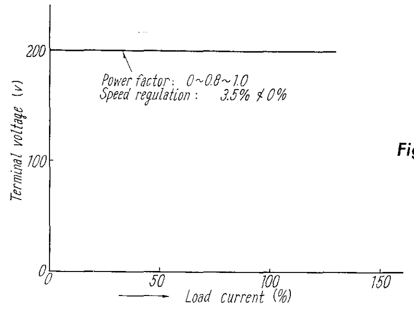


Fig. 11 Load characteristic curve

field resistance characteristics of the main generator. Since, as already referred to, the AVR circuit has SCR and zener diode with its sharp voltage detecting characteristics, load characteristics without any voltage differentiation may be obtained.

Fig. 11 represents a load characteristic curve measured. From no load to 125% load, the setting voltage comes within the range of 200 ± 0.5 v both when the speed regulation is 3.5% or 0% and when the power factor is anywhere from 0 to 1.0. This amounts to an accuracy of $\pm 0.25\%$ and 1/10 the accuracy of a self-excited a-c machine for marine vessel use. It is natural that this accuracy should be available regardless of the power factor and speed regulation when one thinks of control circuits utilizing electronics such as the zener diode and SCR.

2) Transient characteristics

Foremost concern was shown over the response of the exciting system when it comes to performance of brushless a-c generator. The self-exciting compound a-c generator has been able to extend its use to marine machines and power generation machines due to its high response. When CT action is made use of, the time constant in a field circuit is almost disregarded; such as the rapid and big change in input voltage. But with the brushless generator, as there is an a-c exciter in between, lag in the time constant in the field circuit of the main generator necessarily exists. Therefore, increase of response depends entirely upon the control circuit and it is for this reason that the SCR control circuit is adopted.

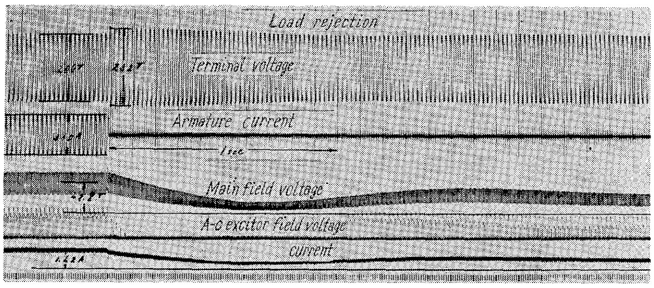


Fig. 12 Oscillogram of 100% load rejection at 0.8 pf

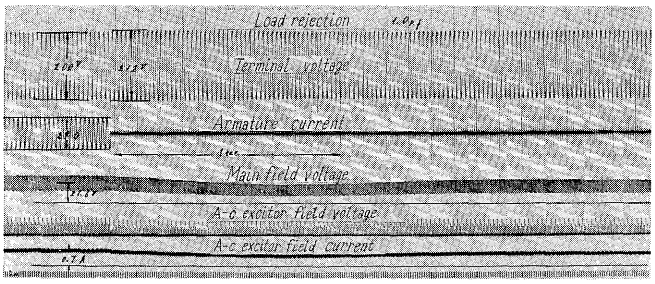


Fig. 13 Oscillogram of 100% load rejection at 1.0 pf

A load rejection test was taken as one of the transient characteristics. *Fig. 12* shows an oscillogram of 100% load rejection at 0.8 pf, while *Fig. 13* shows that of 100% load rejection at 1.0 pf. Voltage regulation is maximum at the moment of load rejection, which is about 16% and 6% respectivelly and is recovered at rated voltage in about 0.6 sec. Immediately after rejection, SCR output or field voltage of the a-c exciter decreases and, after a little delay, its field current and main field voltage follow.

Voltage regulation value at the time of rejection depends upon transient reactance of the machine and when it is compared with that of a self-excited compound system the value is the same but the time it takes before the setting is twice or about 0.6 sec. as against about 0.3 sec. with the self-excited compound system. It must be said, however, that without the utilization of CT action this must be an extremely high response.

Fig. 14 then shows an oscillogram of an induction motor start. Like load rejection, voltage drop at the moment of start is maximum and at load application of 110% it shows 15% voltage drop. Field voltage of the a-c exciter immediately goes up, and the main field voltage also goes up with only a little delay and terminal voltage is recovered. In other words, with a brushless generator induction motor start is possible as with a self-excited compound system.

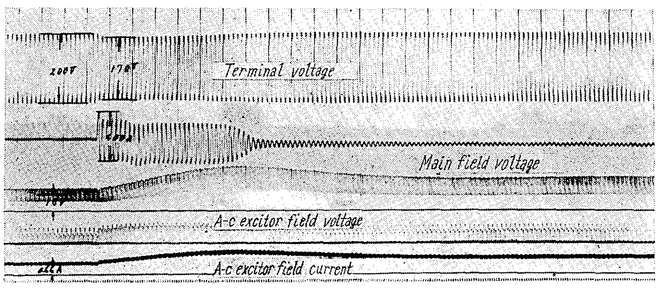


Fig. 14 Oscillogram of motor start

A setting voltage modification was carried out to check indicial response of the closed loop of the field system and the main machine. When voltage is varied ±20%, it takes 0.6 sec to arrive first at the setting volues of complete response. Field time constant of the a-c exciter is 0.47 sec and that of the main generator is 1.4 sec. so that this response must be described as fast.

Voltage build-up may be realized in a few seconds by merely supplying electricity of kick current for a brief moment to the field winding of the a-c exciter. Self-excited operation commences then, including control circuit and a closed loop will be formed.

As a means to test excessive transient characteristics, a full voltage three phase abrupt short-circuit test was conducted. This was designed to ascertain the condition of transiency upon the rectifier as well as to check if the exciting system, at the time of short-circuit, can withstand short-circuit current or not. The result is that sustained short-circuit current about four times as much as the rated current of the main generator could be applied with no undesirable effect upon the silicon rectifier.

IV. FEATURES OF BRUSHLESS A-C GENERATOR

1. Dependable Operation

Such sliding parts of the a-c generator as slip ring, commutator and brush are usually the most sensitive parts for operation and maintenance, thus trouble ascribable to those is the most frequent of all. Therefore, the fact that they are no longer required utterly removes the possibility of trouble and also renders the past maintenance and cleaning almost unnecessary.

2. Economy

The possibility of having the exciter and the rectifier on the same shaft as the main generator makes it possible to make this generator in almost the same space area as the past d-c exciting type machine. The use of the SCR exciting system with high response and stability for the control circuit gives it response characteristics against sudden load change almost like those of the self-excited compound type machine.

Due to the SCR control circuit requiring little space, it may be built in the frame of the generator. In any case, the past switchboard can be greatly diminished, so that viewed from the standpoint of the generator set as a whole, great economy is achieved.

V. CONCLUSION

We have so far studied problems including performance characteristics of the newly completed brushless generator with SCR control. We have made many careful tests prior to manufacturing the prototype and we have been able to obtain results as anticipated. Advantages of being brushless can best be utilized in unfavorable circumstances where there is much vapour or oil vapour, for instance, and the employment of the present generator will doubtless go a long way toward reducing total cost.

As for the SCR control circuit and rectifier, we tested perfectly a three phase short-circuit over and over again in order to be sure of the strength and safety of every part. As for its ability to withstand vibration, our system is such that a diesel engine will be directly fitted to the stator of the main generator. When subjected to high vibration on the order of 20μ for a long time, it stood up without a problem.

Brushless generators are being used for turbine generators of the class of 100 Mva abroad but in our country they have only just begun to be used. It may be a fair assumption, however, that thanks to their many superior characteristics they will be in demand more and more and we have been able to reconfirm the confidence that we can definitely satisfy the requirements of users fully.

References

(1) A. W. Ford; Brushless generators for aircraft, TIEE p 437 Jan. 1962

(2) P. Juen; Schleifring-und kommutatorlose Erreger-anordnung für Generatoren, Siemens Zeitschrift p 234 April 1962