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FUJI MARINE-USE EXCITING EQUIPMENT FOR SELF-EXCITED AC GENERATOR

Keisuke Teramoto
Kenzo Yamamoto
Kobe Factory

I. INTRODUCTION

It is now generally recognized that requirements for power supplies on ships include rational movement and savings in labor and economy, are increasing for more stable power than ever before, larger capacities and greater diversity. For such equipment, improved performance, greater simplicity and higher reliability are all needed.

Fuji Electric has already introduced its new standard series of self-excited AC generators for marine use which meet all of the above requirements. In this paper, we describe the exciting equipment for these generators.

II. FEATURES

In addition to the features of the self-excited AC generator itself, this new standard series boasts of the following:

1) Three types of control system are used so that the optimum system can be selected according to the application.
2) The top-mount type with air filter is standard. The components within the exciting equipment are all cooled effectively by clean air.
3) The equipment is both rational and compact.
4) Circuit construction is simple.
5) The voltage regulating accuracy is high and transient characteristics are excellent.
6) Temperature drift is low and voltage build-up characteristics are excellent.
7) Maintenance and inspection are easy.

III. STANDARD SPECIFICATIONS

This series is standardized over a wide range of generator capacities from 20 kVA to 2,250 kVA and from 4 to 14 poles. It satisfies all the various type of requirements needed for marine use.

1) Circuit system and application

The basic circuits are of the self-excited compound wound type. They consist of the following three types.

(1) SSW system

The basic circuit system is very simple since it is made up only of current components which compensate for the generator inner voltage drop due to the load current and of constant voltage components which have no relation to the load. It is used with generators for which the range of variation of the frequency and load power factor are small.

(2) SR system

The SR system is the basic SSW circuit containing a voltage control circuit operated by a saturable reactor. Therefore it can be widely used in general applications, although it is mainly employed with units of medium capacity or less.

(3) TR system

The TR system is the basic SSW circuit containing a voltage control circuit operated by a thyristor and AVR. It can be used with both common and special types of generators, although it is mainly employed with units of medium capacity or above.

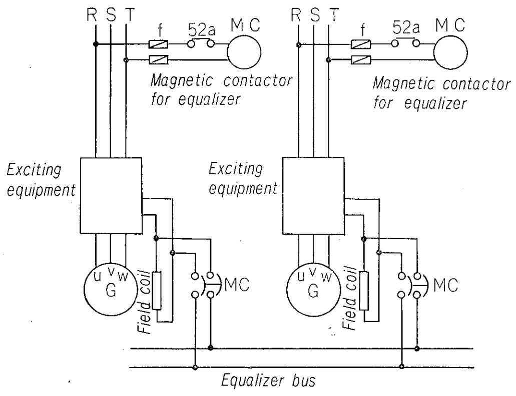
Table 1 shows the applications of each system.

Table 1 Application list for standard exciting system

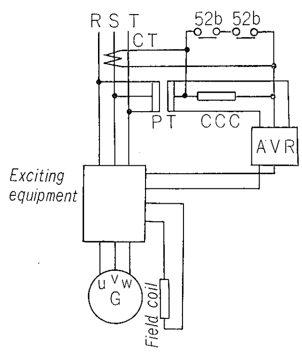
Application \ Standard exciting system	SSW	SR	TR
General applications where load power factor and frequency changes are small, medium capacity or less	○	○	
General applications, medium capacity or less		○	
General applications, medium capacity or over			○
Applications when changing over or normally parallel operation of different type and capacity generator			○
Applications where especially high accuracy of voltage regulation is required			○
Applications where load power factor and frequency changes are large			○
Other special applications			○

2) Standard construction

Type: top mount type with air filter, forced ventilated
Terminals: enclosed, solderless terminals
Cable lead-in: via water-proof gland on top or sides



(a) Equalizer system



(b) Cross-current compensation system

Fig. 1 Connection diagram for parallel operation

3) Applied standards
   (1) Nippon Kaiji Kyokai Kosen Kisoku (NK)
   (2) Lloyd's Registor of Shipping (LR)
   (3) American Bureau of Shipping (ABS)
   (4) Det Norske Veritas (NV)
   (5) Bureau Veritas (BV)
   (6) Standard specifications for Marine-Use AC Generators (JEM-R 2016) of the Japan electric Machine Industry Association.
4) Ratings: continuous
5) Application range: generator capacity 20 kVA to 2,250 kVA units with 4 to 14 poles
6) No. of phases: 3 phases
7) Frequency: 60 Hz
8) Applied generator voltage: AC 450 or 445 V (230 or 225 V is also possible in cases of small units)
9) Insulation class: Class B
10) Standard ambient temperature: 50°C
11) Temperature rise limit: transformer and reactor winding 70°C (resistance method)
12) Exciting capacity: Exciting capcity (2 minutes or more) at which the generator voltage can be maintained at 92.5% or more of the rated value when the generator has a lagging power factor delay of 0.5 and an over-current load of 150%.
13) Color of finish:
    Outer surface Munsell 7.5 BG 7/2
    Inner surface Munsell 2.5 Y 8/2
14) Pre-exciting device; accessory, attached inside main switchboard
15) Voltage setting device: accessory, attached inside main switchboard
16) Shunt: accessory shunt votage rating is 60mV
17) Parallel operation system: equalizer system (SSW and SR) and cross-current compensation system (TR)

IV. CHARACTERISTICS

The characteristics when the various systems are combined with generators are shown in *Table 2*. *Fig. 2* shows a typical oscillogram indicating the characteristics in this exciting system when the load of the self-excited AC generator is suddenly applied.

Table 2 **Characteristics of standard exciting systems**

Standard exciting system	SSW system	SR system	TR system
Voltage regulation (at rated power factor)	Within ±2.5%	Within ±2.5%	Within ±0.5%
Frequency characteristics (57~63 Hz)	∝Δf	∝Δf	Within 0.1%
Temperature characteristics	≈0%	≈0%	≈0%
Power factor characteristics	At times, tap changing necessary when 1.0 pf load	pf 0.7~1.0 are guaranteed	pf 0.7~1.0 are guaranteed
Instantaneous voltage change characteristics	JEM-R2016 Item No. 3	JEM-R2016 Item No. 3	JEM-R2016 Item No. 3
Voltage setting range	None	Within ±5% of rated voltage	Same as left

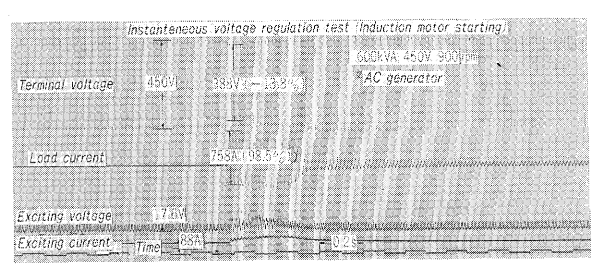


Fig. 2 Oscillogram of induction motor starting test

V. COMPONENTS AND OPERATION

Figs. 3, 4 and *5* show the standard connection diagrams for self-excited AC generators using the standard exciting systems.

1. Components

Table 3 lists the components of the standard exciting systems. The various systems consist of the components marked with a circle in their respective columns. In this table, components 1 to 4 are basic components and the rest differ according to the system. Component No. 12 is generally not needed but

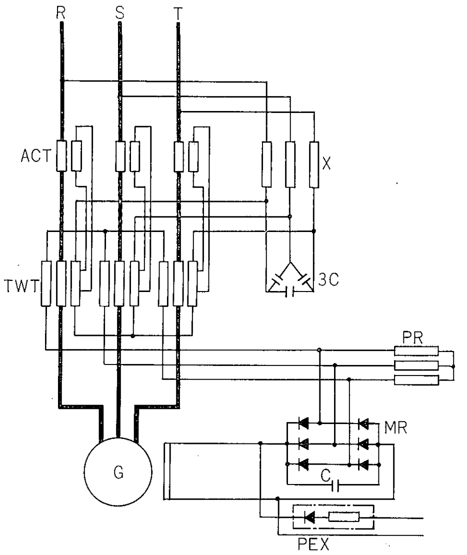


Fig. 3 Connection diagram of SSW self-excited AC generator

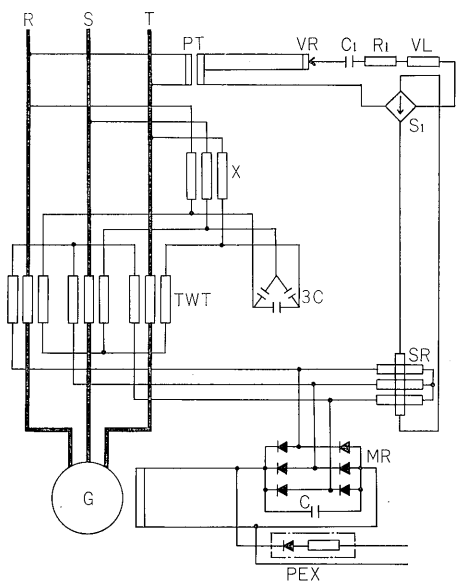


Fig. 4 Connection diagram of SR self-excited AC generator

it is given as a standard accessory for few residual generator voltage. Component No. 14 to 16 are for cross-current compensation during parallel operation.

2. Construction and Operation of Each Component

1) Three winding transformer

The exciting current necessary so that the generator can induce the rated no-load voltage (voltage component) and the exciting current necessary so that the rated voltage can be maintained and the generator inner voltage drop can be compensated for under load condition (current component) are combined vectorially. They are rectified by the main rectifier and this transformer supplies exciting current to the generator field. It is a 3-phase, 3-winding transformer consisting of a potential winding, a current winding and an output winding on a 3-legged iron core. An

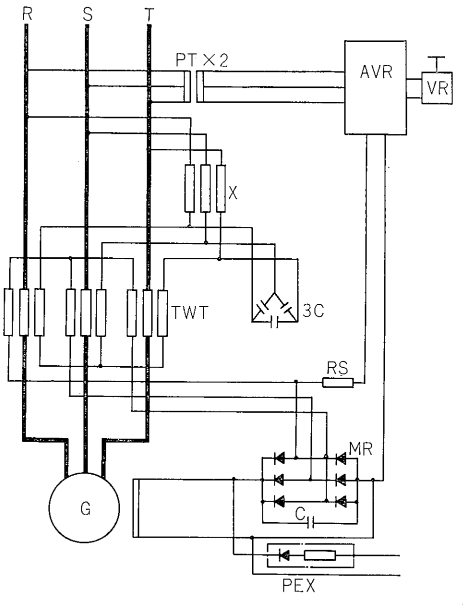


Fig. 5 Connection diagram of TR self-excited AC generator

Table 3 Components of standard exciting systems

No.	Name of component	Symbol	SSW system	SR system	TR system	Equipment location
1	Three winding transformer	TWT	○	○	○	In exciting equipment box of top-mount type
2	Main rectifier	MR	○	○	○	
3	AC reactor	X	○	○	○	
4	Capacitor	3C	○	○	○	
5	Aux. current transformer	ACT	○			
6	Protective reactor	PR	○			
7	Saturable reactor	SR		○		
8	Control device	IB		○		
9	Shunt resistor	RS			○	
10	TR type AVR	AVR			○	Attached outside or in main switchboard
11	Voltage setting device	VR		○	○	In main switch-board
12	Pre-exciting device	PEX	○	○	○	
13	PT	PT		○	○	
14	Magnetic contactor	MC	○	○		
15	Cross-current compensator	CCC			○	
16	CT	CT			○	

outer view of the transformer is shown in *Fig. 6.*

The core is of the cut core type so that the construction is both compact and simple. The winding construction is such that there is very little air included in the interior since the radiation effect must be good. The surface insulation is such that there is a large number of part exposed directly to the

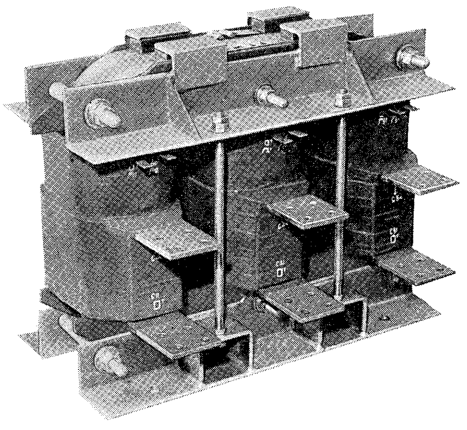


Fig. 6 Three winding transformer TWT

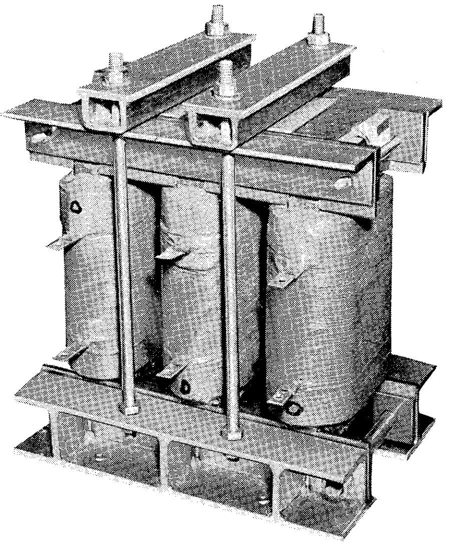


Fig. 7 AC reactor X

air and the surface insulation temperature gradient is very small. The reliability is therefore very high since there is no local overheating inside the windings.

2) Main rectifier

A silicon rectifier is used to rectify the 3-winding transformer output and supply exciting current to the generator field. Protection against surge voltage is achieved by capacity C for suppression of the hole storage recovery phenomena and the effect of capacitor $3C$ which will be described later.

3) AC reactor X

This reactor provides the combined phase relation between the current and voltage components and also supplies the required exciting voltage component to the TWT. It is a 3-phase 3-legged AC reactor with gaps arranged both above and below each legs. The gap length is easy to adjust so that the required reactance value is obtained. The tightening parts have been subjected to the heat cycle test and the construction is such that it can sufficiently absorb variation in the gap length caused by shrinkage of the insulation materials etc. The windings are wound directly around the iron core and the radiation effect to the core side is good. Since the same considerations are used in the insulation materials as for the TWT, it is compact and there is sufficient margin for the regulator. The overall unit employs a simple insertion construction in order to prevent alterations and play due to vibrations which are likely to occur in this type of equipment. The results of vibration tests show no changes and excellent characteristics are maintained. *Fig. 7* is an outer view of the AC reactor X.

4) Capacitor $3C$

This capacitor is chosen so as to provide resonance conditions between it and the AC reactor X. Because of this, the generator field current is not influenced by resistance value changes due to temperature rises in the field circuit, and the generator voltage has small temperature drift. The voltage build-up during generator starting is very good and even in generators where the residual magnetism is small, pre-exciting is not required and self voltage build-up is possible.

Generally, in rectifier circuits which have large inductance in the input and output circuits, there are discrepancies in the voltage waveform and control using thyristors is difficult. However, stable control is possible by shaping the waveform by means of this capacitor and stable control can be achieved.

This capacitor is small with little inner loss and the temperature rise is lower than usual capacitors by 10°C. The floor attachment and terminal constructions are such that they can resist the vibrations encountered in marine use.

5) Auxiliary current transformer

This is used only in the SSW system. It is auxiliary to the TWT current winding and is used for fine adjustment of the current component.

6) Protective reactor

As in the ACT, this is employed only in the SSW system. It suppresses the TWT output voltage due to PR saturation when there is a short circuit caused by the generator, suppresses the short circuit current and protects the main rectifier.

7) Saturable reactor

This is used only in the SR system and is a so-called 3-phase saturable reactor. In order to compensate for voltage change due to the influence of generator saturation, frequency changes, temperature variations etc., a part of TWT output is shunted by the shunt circuit. This shunted portion is controlled in accordance with changes in the generator voltage so that the rated voltage can be maintained.

The characteristics between the control current and output current are shown *Fig. 8*. The control current is controlled by the voltage regulation circuit.

The construction of the reactor is as shown in *Fig. 9*. There is no pressure applied to the windings and complete attachment can be made. Therefore, antivibration characteristics are good and the equipment is stable.

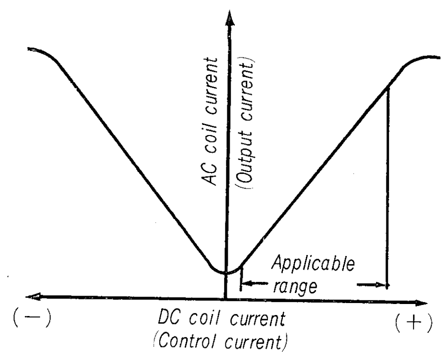


Fig. 8 Characteristic curve of 3ϕ saturable reactor

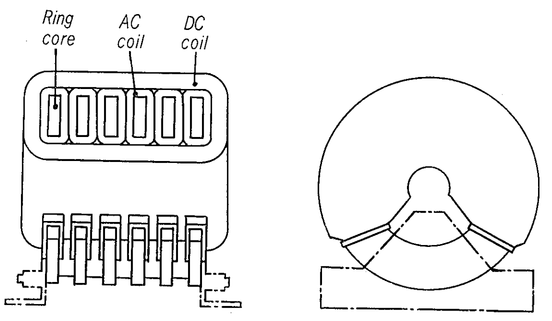


Fig. 9 3ϕ saturable reactor

8) Control device IB

This is used in combination with the SR system mentioned previously. It forms part of the voltage control circuit. The voltage control circuit detects changes in the generator voltage, controls the aforementioned SR current and maintains the generator voltage at a constant value. As shown in *Fig. 10*, it consists of saturated reactor *VL* selenium rectifier S_1, capacitor C_1 and resistor R_1.

The saturated reactor is a reactor with an iron core which has good saturation characteristics. It is a resonant made up of C_1 and R_1. The characteristic curves of this circuit are shown in *Fig. 11*. As is evident from this figure, operation is at points which are usually saturated in respect to the generator voltage. The circuit current changes sharply in respect to minute variations in the generator voltage.

9) Voltage setting device

This device is used to control the generator set voltage. The control range is generally ±5% of the rated value. In the SR system, the set voltage is controlled by controlling the input voltage of the voltage regulating circuit by using a slidac. In the TR system, a variable resistor is used and control is achieved through control of the AVR input voltage.

10) Series resistor

This is used only in the case of the TR system. The resistor is for control of the shunt factor of the shunt circuit using a thyristor which is located in the output circuit of the three winding transformer.

11) AVR

This is used in the TR system. The AVR consists of a thyristor and two printed circuit boards. One board consist of a PI regulator which provides a signal for the phase shifter by amplifying the difference between the generator voltage and its standard value: a phase shifter which receives the regulator output as input and provides a gate signal in the proper phase for the thyristor; and a pulse amplifier

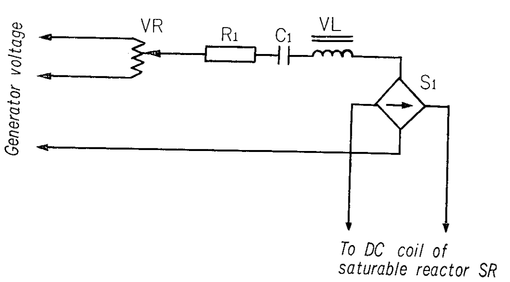


Fig. 10 Connection diagram of voltage control circuit

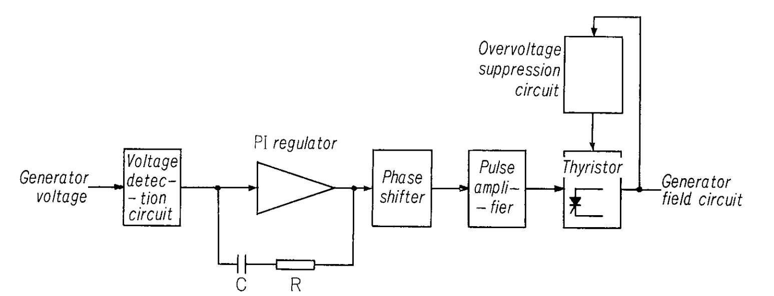


Fig. 12 Block diagram of Type TR AVR

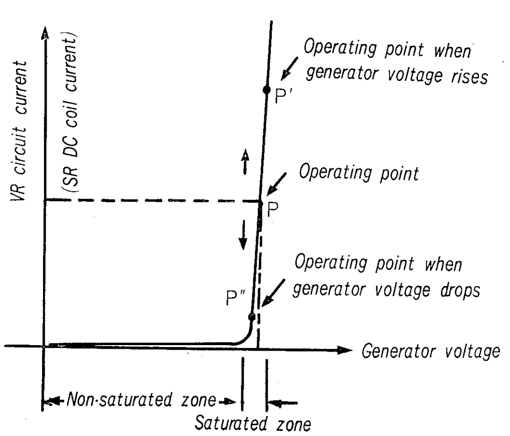


Fig. 11 Characteristic curve of voltage control circuit

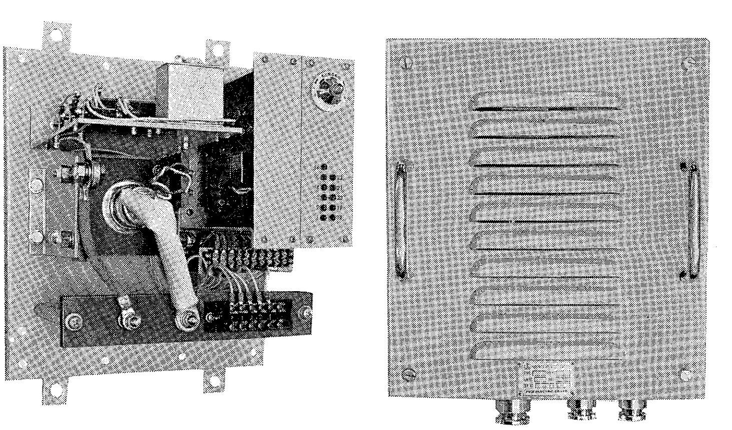


Fig. 13 Type TR AVR

which amplifies the output of the phase shifter. The other board contains a rectifier which rectifies the generator voltage and an overvoltage suppression circuit which suppresses the generator sustained short circuit current. *Fig. 12* is a block diagram of this AVR.

As can be seen from the connections for the TR system self-excited AC generator shown in *Fig. 5*, the output circuit of the three winding transformer contains a field circuit, and in parallel with it, a shunt circuit employing a thyristor. This shunt current is controlled by the AVR.

There are two types of attachment construction: the drip-proof type and panel attachment type. *Fig. 13* shows outer views of the drip-proof type AVR. The panel type is the same in construction as the drip-proof type; only the cable connection part differs.

The AVR employs a DC amplifier (MICRO PACK) consisting of an IC for DC amplification and an RC circuit for stabilization in the voltage control circuit. This means that the circuitry is simple and accurate, stable control is possible. Other features include compact and sturdy construction.

12) Pre-exciting device PEX

This device consists of a current limiting resistor and a selenium rectifier for preventing counter-currents. Generally it is not required and pre-exciting is performed by the DC power supply when there is a reduction in the residual voltage in the generator for some reason.

13) Potential transformer PT

This potential transformer is used for voltage detection in the SR and TR systems. The characteristics are well matched with those of the voltage regulation circuit and have been standardized.

14) Magnetic contactor for equalizer

When generators using the SSW or SR system are operated in parallel, these contactors connect the field circuits of each generator in parallel. They serve to stabilize the distribution of reactive cross-currents.

15) Cross-current compensator and current transformer

This system is for cross-current compensation when generators employing the TR system are operated in parallel. The cross-current compensator consists of the PT described in section 13) and reactor for cross-current compensation in a single unit. The connections are therefore simple and there is no need to worry about erroneous connections.

The current transformer is a generator current sensing CT. The sccondary current of this transformer is applied to the abovementioned reactor, and the cross-current is detected from the combined value of this reactor voltage and the generator voltage. The reactive cross-current is controlled by the AVR.

3. Operation

1) SSW system

The basic circuitry of the standard exciting system has been described before. Since an article concerning the system has already appeared in the Fuji Journal[1] only the outline required in explaining the other two systems will be given here.

Fundamentally, the system consists of the three winding transformer TWT, main rectifier MR, AC reacator X and capacitor $3C$. The exciting voltage component required to produce the rated no-load voltage is supplied from the generator voltage via the AC reactor to the voltage coil of the three winding transformer. The exciting current component which compensates for the voltage drop due to the load current when the load is applied from the current coil of the three winding transformer and is vectorially combined magnetically with the exciting component from the voltage coil. This is then rectified by the main rectifier and supplied to the generator field. The capacitor $3C$ is connected in parallel in the voltage coil of the three-winding transformer and since the reactance of this capacitor is selected so that it forms resonance conditions with the reactance of the AC reactor, the generator field current can be shown theorectically as in equation (1).

$$\dot{I}_f = \frac{\dfrac{\dot{V}}{jX} + \dot{I}_g}{1 + j\dfrac{R_f}{X}\left(\dfrac{X}{X_c} - 1\right)}$$

When $X_c = X$

$$I_f = \frac{\dot{V}}{jX} + \dot{I}_g \quad \cdots\cdots (1)$$

Fig. 14 shows the equivalent circuit of the SSW system. The first part of equation (1) shows the voltage component and the second the current component. As shown in equation (1), the generator field current is not affected by changes in the field resistance and there- fore there are very few changes in the generator voltage due to temperature changes.

When the generator is started, the first very small AC voltage induced in the generator at about 70% of the rated speed is amplified by the series resonance with the reactance of the AC reactor. This is induced in the secondary side of the three winding transformer which results in a rapid build-up of the generator voltage.

In addition, there are also an auxiliary CT, ACT for fine control of the current component, and a

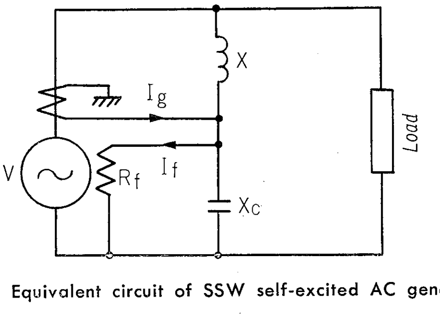


Fig. 14 Equivalent circuit of SSW self-excited AC generator

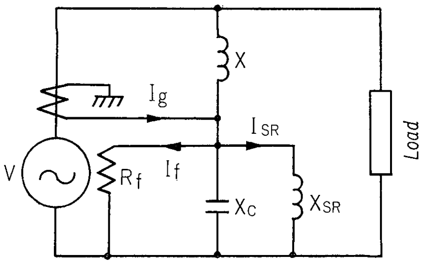


Fig. 15 Equivalent circuit of SR self-excited AC generator

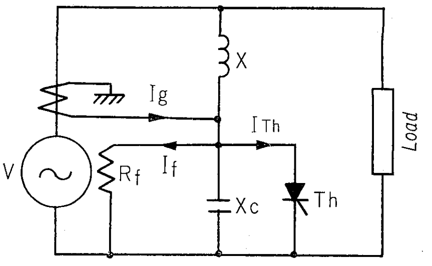


Fig. 16 Equivalent circuit of TR self-excited AC generator

protective reactor which suppresses the generator sustained short circuit current.

2) SR system

As was described previously, this system consist of the basic compound wound exciting circuit along with a branch circuit with a saturable reactor controlled by the voltage regulating circuit. Voltage changes caused unsuitable excitation are controlled by controllings the shunt current in this branch circuit. *Fig. 15* shows the equivalent circuit of the SR system and the field current I_f is as indicated in equation (2).

$$\dot{I}_f=\frac{\dfrac{\dot{V}}{jX}+\dot{I}_g-\dot{I}_{SR}}{1+j\dfrac{R_f}{X}\left(\dfrac{X}{X_c}-1\right)}$$

When $X_c=X$

$$\dot{I}_f=\frac{\dot{V}}{jX}+\dot{I}_g-\dot{I}_{SR} \quad \cdots\cdots (2)$$

The third part of equation (2) indicates the shunt circuit of the saturable reactor. This show the basic characteristics of the SSW system and also the characteristics due to the voltage control ability. As it is well known, the compound wound self-excited AC generator can supply excitation which can maintain the generator voltage constant in respect to any load or power factor. However, in practice, complete agreement is not possible because of such factors as the influence of generator saturation, temperature changes and frequency variations. There are also many cases where voltage control is required from the standpoints of the generator operating system or control. Therefore, a shunt circuit is placed in the field circuit and the current is divided beforehand. The shunt current is controlled in respect to any voltage variations and the generator voltage can be held constant. The contruction of this SR shunt circuit is as shown in *Fig. 4*. Since the output current of the three winding transformer has almost constant current characteristics, the field current can be controlled by controlling the SR shunt current. The SR DC current is finely controlled by a control device (voltage control circuit). In this voltage control circuit, the control accuracy is increased by iron resonance. The circuit is simple and has excellent voltage regulation characteristics.

3) TR system

This system is basically the compound wound exciting circuit with a shunt circuit employing a thyristor added. Voltage variations caused by unsuitable excitation are controlled by controlling the shunt current of this shunt circuit.

Fig. 16 shows an equivalent circuit of the TR system and the field current $\dot{I}_f$ is given by equation (3). In principle, this system is exactly the same as the SR system.

$$\dot{I}_f=\frac{\dfrac{\dot{V}}{jX}+\dot{I}_g-\dot{I}_{Th}}{1+j\dfrac{R_f}{X}\left(\dfrac{X}{X_c}-1\right)}$$

When $X_c=X$

$$\dot{I}_f=\frac{\dot{V}}{jX}+\dot{I}_g-\dot{I}_{Th} \quad \cdots\cdots (3)$$

The third part of equation (3) gives the thyristor shunt circuit current. The equation indicates basic SSW system characteristics and the voltage control ability.

The necessity of voltage control has been discussed previously but since voltage regulation in this system is carried out by means of a thyristor shunt circuit which is controlled by an AVR containing a PI regulator, the voltage control is both highly accurate and very stable.

The thyristor shunt circuits consists of a thyristor and a series resistor as shown in *Fig. 5*. The output current of the three winding transformer has almost constant current characteristics and therefore the field current can be controlled by controlling the thyristor shunt current. The series resistor controls the amount of current division.

In general control circuit which have high reactance in the input and output circuits, the input and output voltage waveform is distorted and control is adversely affected. However, in this system, the waveform is refined completely by means of the effect of capacitor 3C and stable control is achieved[(2)]. A future article is planned to give a detailed explanation of the AVR.

VI. CONSTRUCTION

1. Model Types

*Top mount type—*with air filter and forced ventilation
Self-standing panel type—natural ventilation
Panel insertion type—natural ventilation and parts insertion

2. Standard Systems

The type with the asterisks (*) in section 1 is Fuji's standard type. The inner construction is as shown in *Fig. 17*. The generator air intake passes through the air filter attached to the frame of the exciting equipment. The air cools all components of the exciting equipment and is transmitted to the generator. *Fig. 18* shows an outer view.

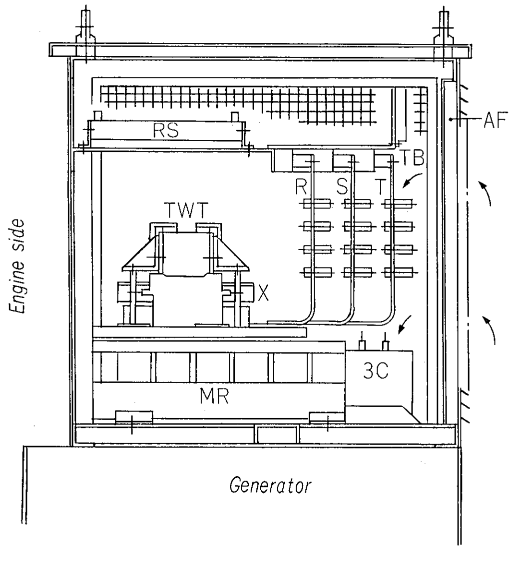


Fig. 17 Mounted type exciting apparatus

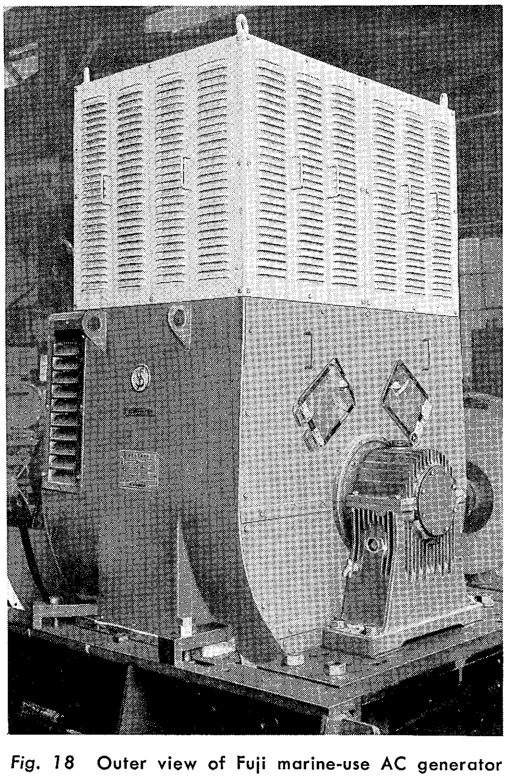


Fig. 18 Outer view of Fuji marine-use AC generator

3. Construction Features

In addition to the general features, the exciting equipment top mounted has the following features:
1) Since the air intake is purified by the air filter, there is much less dirt than usual inside the generator, which facilitates maintenance.
2) The air within the exciting equipment is continuously replaced by purified air and there is no need to worry about adverse temperature rises in the vicinity of the components which often occur in natural ventilation system when circulation is bad. Thus, the cooling effect is excellent.
3) The generator loss within the exciting equipment is very small and the pressure loss is only several mmAq. Therefore it is not necessary to have a large fan inside the equipment.

4. Terminals and Wire Conduits

The fixtures for cable lead-in are arranged on the top as a standard for small capacity units and for medium or larger capacity units they are arranged on the top or either side of the equipment.

The terminals with solderless terminal for external cable connection are bolt-type terminals with solderless terminal as a standard. Their features include simple cable connection, few accidents due to tightening defects or breaks since steel bolts are used, and the elimination of faults casued by bad connections or shrinkage of insulation material since there is direct connection between outer and inner wires.

VII. EXTERNAL DIMENSIONS

The generator of the new standard series cover of wide range of 85 types from 20 kVA to 2,500 kVA and from 4 to 14 poles. *Table 4* gives the external dimensions of this equipment.

VIII. CONCLUSION

This article has introduced the new series of exciting equipment for self-excited AC generators for marine use. This series is the result of the company's long years of experience and also through practical investigations. It is hoped that it will meet all customer requirements. In the furture, efforts will be made to develop even more relaible and stable power supplies.

References

(1) Shimizu, Nakata: Fuji-Siemens type 240 kVA self-excited AC generator, Fuji Electric Journal **31**, No. 3 (1958)
(2) Ihara, Moriyasu: Thyristor type automatic voltage regulator for marine-use AC generators, Fuji Electric Journal **40** No. 2 (1967)

Table 4 Dimension list of mounted type exciting apparatus

Dimensions \ Type number	1	2	3	4	5	6	7	8	9	10
A	550	600	700	800	930	1,200	1,300	1,150	1,250	1,350
B	635	660	760	800	880	780	780	800	850	950
C	610	660	760	860	990	1,260	1,360	1,210	1,310	1,410
D	695	720	820	860	940	840	840	860	910	1,010
E	30	30	30	30	30	30	30	30	30	30
h	550	550	600	600	600	600	600	850	850	900
H	580	580	630	630	630	630	630	880	880	930