UDC 621. 313. 322-181. 4 : 629. 123

NEW SERIES MARINE USE SELF-EXCITED AC GENERATORS

By Shoji Moriyasu
Hirosaku Watanabe
Kawasaki Factory

I. PREFACE

Due to the technological progress of the shipbuilding industry in Japan, the number of ships built in this country in recent years has so rapidly increased that it may be called a wonder of the world. It is also a remarkable feature that electrical systems in ships have been changing from dc to ac, and the demand for ac generators which are the new source of electric power in ships is steadily increasing. As the size of ships to be built increases, it is quite natural that generators for these ships should have a large capacity. With the increase of speed of diesel engines, both the speed and capacity of marine use ac generators are increasing yearly. On the other hand, because of the requirements of space control in ships, compactness of these generators is demanded by customers.

In view of the above tendencies, Fuji Electric, combining the latest technology with its experience and using newly-developed materials, have completed a new standardized series of marine use self-excited ac generators, which are compact and of high performance. We wish to present some of the outstanding features of these new series generators for the benefit of our customers.

II. OUTLINE OF NEW SERIES OF MARINE USE AC GENERATORS

The new series marine use ac generators are classified into 9 types by their standard outputs, which range from 200 kva to 1250 kva. The number of poles, which determines the rpm, is from 4 to 14. The generators in this range are most favored by general customers.

1. Standards Conformed to and Standard Specifications

The new series generators have been designed to conform to all standards of marine use equipment. Therefore, they meet any of these standards. Some of the main standards are as follows:

1) Japan Marine Association's Steel Ship Codes
2) Lloyd's Register of Shipping
3) American Bureau of Shipping
4) Norske Veritas
5) JEM-R

The standard specifications are as follows:

1) Horizontal shaft, salient poles, rotating field, enclosed ventilated drip-proof machine
2) Ratings:
   (1) Rated operation: Continuous
   (2) Rating output: 200 kva～1250 kva
   (3) Terminal voltage: 450 v
   (4) Number of phases: 3 phases
   (5) Frequency: 60 cps
   (6) Speed: 514 rpm～1800 rpm
   (7) Power factor: 0.8 lag
3) Insulating materials: B class
4) Ambient temperature limits: 50°C
5) Temperature rise limits:
   Stator windings 70 deg (by resistance method)
   Rotor windings 70 deg (by resistance method), multilayer windings
   80 deg (by resistance method), single layer winding with exposed bare surfaces
6) Excitation system: Static type excitation device

2. Cooling System

The driving side of the generator has an internal fan, which draws in by suction cooling air from the opposite side and exhausts it at the driving side. This is the so-called one-side suction system. To distribute cooling air to all sections where thermal loss may occur, the cooling air circuit inside a generator is designed to cool the generator very effectively, with the proper cooling dimensions determined. *Fig. 1* is a schematic diagram of the cooling system.

With the one-side suction system, an uneven rise of temperature can occur along the longitudinal axis of the iron core of the stator. However, with the cooling system of this generator, by properly arranging the constrictions in the air duct, an almost uniform distribution of temperature rise is obtained. *Fig. 2* is a diagram of the temperature rise distribution measured by thermocouple.

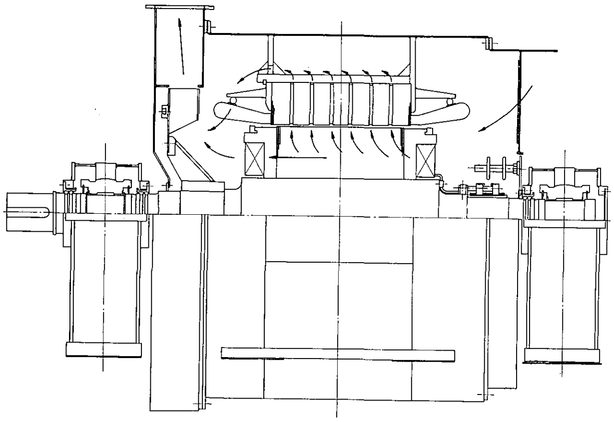


Fig. 1 Cooling system of high speed marine use ac generator

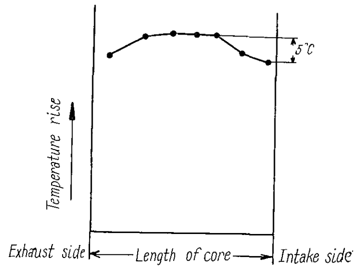


Fig. 2 Axial temperature rise distribution of stator winding

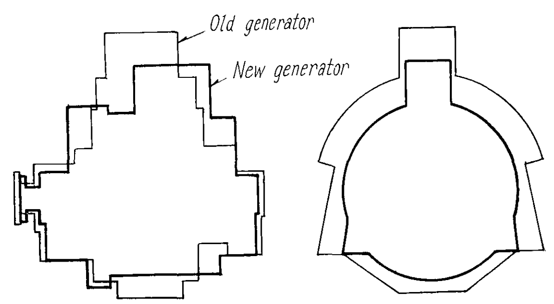


Fig. 3 Comparison of dimensions between old and new generator

3. Standard Classifications and External Dimensions

Fifty classes of the new series of marine use ac generators, ranging from 200 kva to 1250 kva and from 4 poles to 14 poles, were grouped into 14 types. As a result of this grouping, more parts were standardized, designing and manufacturing were accelerated, and cost was decreased.

As described above, excellent newly-developed materials are used for the new series of marine use ac generators. Their cooling systems are more effective, and they are more compact. Moreover, their new steel plate structure reduces their weight. The overall weight has been decreased by approximately 25%, compared to conventional marine use ac generators. *Fig. 3* shows a comparison of the new and conventional generators of the same output and speed. The external dimensions of the new series of generators are shown in *Fig. 4* and *Table 1*.

III. EXCITATION DEVICE AND CHARACTERISTICS OF NEW SERIES OF MARINE USE AC GENERATORS

The new series of generators employs a static type excitation device which has a silicon rectifier. The excitation current component which is proportional to the voltage from the reactor and the excitation current component which is proportional to the load current from the current transformer are combined vectorially and supplied to the field windings.

As these generators have compound-wound characteristics, they can follow sudden changes of load and maintain the voltage. Accordingly, they can be directly applied to cage-type induction motors. So it is quite practicable to employ a pole change-type induction motor in the winch system of a ship, greatly improving loading and unloading efficiency.

There are two types of standard excitation systems; the Fuji-type (without AVR) and the CL type (with AVR). The Fuji-type excitation system is sufficient to satisfy the requirements of the voltage regulation. Accordingly, we consider the Fuji-type to be more suitable for marine use generators, because it is simpler in construction, does not need adjustment, and is easier in maintenance. However, if there is a requirement, due to a special application of the generator, to precisely determine the voltage within a narrow range, an AVR which is best suited for the specific purpose can be attached to this excitation device.

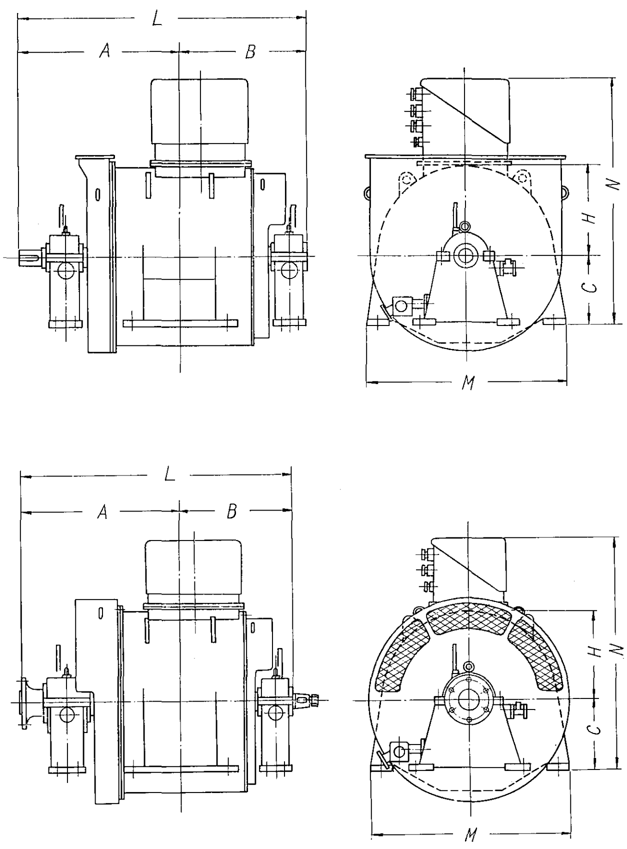


Fig. 4 Outline of new series marine use ac generator

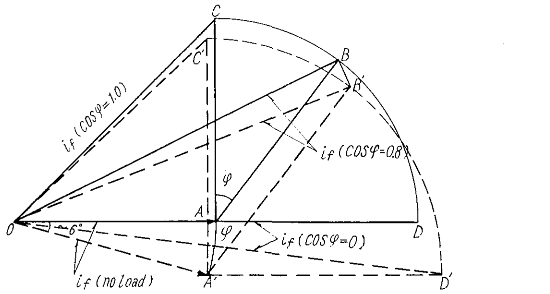
Table 1 **Dimensions List of New Serines Marine Use Ac Generators**

No. of Poles	Output (kva)	Model	L	A	B	C	H	N	M
						Outside Dimension (mm)			
	250	266/19	1685	920	765		500	1305	1150
	320	266/21	1725	940	785		500	1305	1150
	400	266/26	1835	995	840		500	1305	1150
4	500	296/20	1725	960	765	450	575	1480	1300
	625	296/23	1785	990	795		575	1580	1300
	800	296/26	1855	1025	830		575	1580	1300
	1000	296/30	1965	1080	885		575	1580	1300
	1250	326/27	2005	1130	875		650	1755	1450
	250	266/21	1665	920	745		500	1305	1150
	320	266/26	1775	975	800		500	1305	1150
	400	296/20	1655	925	730		575	1380	1300
6	500	296/23	1715	955	760	450	575	1480	1300
	625	296/26	1785	990	795		575	1580	1300
	800	296/30	1895	1045	850		575	1580	1300
	1000	326/27	1965	1110	855		650	1655	1450
	1250	326/31	2095	1175	920		650	1755	1450
	250	266/26	1735	985	750		500	1305	1150
	320	296/20	1640	960	680		575	1380	1300
	400	296/23	1700	990	710		575	1380	1300
8	500	296/26	1770	1025	745	450	575	1480	1300
	625	296/30	1880	1080	800		575	1580	1300
	800	326/27	1940	1135	805		650	1655	1450
	1000	326/31	2070	1200	870		650	1655	1450
	1250	386/25	1875	1090	785		700	1805	1550
	200	266/26	1735	985	750		500	1305	1150
	250	296/20	1640	960	680		575	1380	1300
	320	296/23	1700	990	710		575	1380	1300
	400	296/26	1770	1025	745		575	1380	1300
10	500	296/30	1880	1080	800	450	575	1480	1300
	625	326/27	1915	1110	805		650	1655	1450
	800	386/25	1795	1060	735		700	1705	1550
	1000	386/29	1905	1115	790		700	1705	1550
	1250	386/32	2015	1170	845		700	1805	1550
	200	296/20	1640	960	680		575	1380	1300
	250	296/23	1700	990	710		575	1380	1300
	320	296/26	1770	1025	745		575	1380	1300
	400	326/23	1815	1055	760		650	1455	1450
12	500	326/27	1905	1100	805	450	650	1555	1450
	625	386/25	1795	1060	735		700	1705	1550
	800	386/29	1905	1115	790		700	1705	1550
	1000	386/32	2015	1170	845		700	1705	1550
	1250	406/31	2015	1150	865		750	1855	1650
	200	296/23	1700	990	710		575	1380	1300
	250	296/26	1770	1025	745		575	1380	1300
	320	326/23	1815	1055	760		650	1455	1450
14	400	326/27	1905	1100	805	450	650	1455	1450
	500	386/25	1795	1060	735		700	1605	1550
	625	386/29	1905	1115	790		700	1705	1550
	800	386/32	2015	1170	845		700	1705	1550
	1000	406/31	2015	1150	865		750	1755	1650

1. Steady State Voltage Regulation Characteristics

In principle, all self-excited ac generators have the characteristics of maintaining constant voltage for all power factor and all load. However, due to the magnetic saturation of iron and the saliency of the rotor, the voltage tends to rise at high power factor load, and tends to drop at low power factor load.

Generally speaking, these tendencies are more outstanding with low speed, high capacity generators. To overcome these tendencies, the new series generators have employed the zig zag connection system



OA OA′ (Terminal voltage component of exciting current)
$AB=AC=AD$ $A'B'=A'C'=A'D'$ (Load current component of exciting current)
$AB<A'B'$ $\because$ $OB=OB'$
$OC>OC'$....cos $\varphi=1.0$ $OD<OD'$....cos $\varphi=0$
(——without zig zag connection - - - with zig zag connection)

Fig. 5 Zig zag connection's effect

in the voltage coil of the three windings-transformer, by which the proper phase lag of the exciting current component proportional to the voltage is obtained, as shown in *Fig. 5*.

Fig. 5 shows that the zig zag connection decreases the exciting current when the power factor increase, increases the current when the power factor decrease, and can have the preferable voltage regulation, preventing the voltage rise at $\cos\varphi=1$ and the voltage drop at $\cos\varphi=0$. With the CL system, this connection method has the advantage of narrowing the range of adjustments.

2. Instantaneous Voltage Regulation Characteristics

If a load is suddenly applied to a generator which is supplied with a constant excitation voltage from its source, instantly the voltage drops by a certain amount, then the voltage goes gradually to a lower voltage.

The vector diagram of *Fig. 6* shows that the air gap flux OC ($=X_{ad}I_f$, where X_{ad} is the mutual reactance) is generated by the field current I_f, decreases, due to the armature reaction (I), by the amount CG on the direct axis and by the amount GJ on the quadrature axis; the amount which corresponds to OJ remains in the air gap.

On the other hand, in the field circuit, a flux leakage OE occurs which is proportional to the field current I_f, so the flux linkage of the field windings

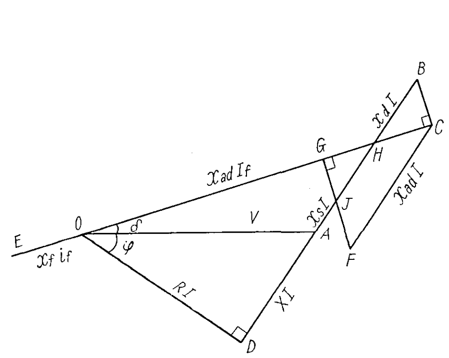


Fig. 6 Vector diagram for generator

is EG. This EG cannot change in accordance with the sudden changes of load. The terminal voltage V and the current I is maintained so as to hold EG at a certain level.

Let us consider the case of a generator operating without load, to which a pure reactance load is suddenly applied.

Before the application of load:

$$OA = OG = OC = V_o = X_{ad} I_{fo}$$
$$OE = X_f OC / X_{ad}$$

After the application of load:

$$OA = V = XI$$
$$OC = (X_d + X) I = X_{ad} I_f$$
$$GC = X_{ad} I$$
$$OE = X_f OC / X_{ad}$$

In the above:

- X: Load reactance
- X_f: Leakage reactance of field
- X_s: Leakage reactance of stator
- X_d: Direct axis synchronous reactance
- V_o, I_{fo}: Terminal voltage and field current during no-load operation
- V, I, I_f: Terminal voltage, armature current, and field current during load operation

In the condition that the flux linkage EG of the field does not change by the application of the load, we have the following equations.

$$V = \frac{X}{X + X'_d} V_o \qquad I = \frac{V_o}{X + X'_d}$$

$$\Delta V = \frac{X'}{X + X'_d} V_o \qquad I_f = \frac{X + X_d}{X + X'_d} I_{fo}$$

In the above equations:

- ΔV: Instantaneous voltage drop
- X_d: Direct axis transient reactance;

$$X'_d = X_s + \frac{X_{ad} \cdot X_f}{X_{ad} + X_f}$$

After that the field current decreases in accordance with the field time constant, the operation finally arriving at the state which can be expressed by the following equations:

$$I_f = I_{fo} \qquad \Delta V' = X / (X + X_d)$$

With a load of $\cos\varphi = 0$, the instantaneous voltage drop ΔV is determined solely by X'_d, being completely unrelated to X_q; however, with a general load, the instantaneous voltage drop ΔV depends upon X'_d and X_q.

With the conventional automatic voltage regulator, the signal for increasing the voltage is issued after the voltage drop due to the change of load, so there invariably occurs a delay in voltage recovery. Therefore, in this case, the voltage drop is larger than that indicated in the above equation by ΔV.

With the excitation device employed in the new series of generators, the voltage recovery is accomplished very rapidly. The voltage changes at the start of an induction motor are clearly shown in *Fig. 7*. It is seen from this chart that the voltage begins its recovery as soon as at the next cycle of load application, the maximum voltage drop occurring at the moment of load application.

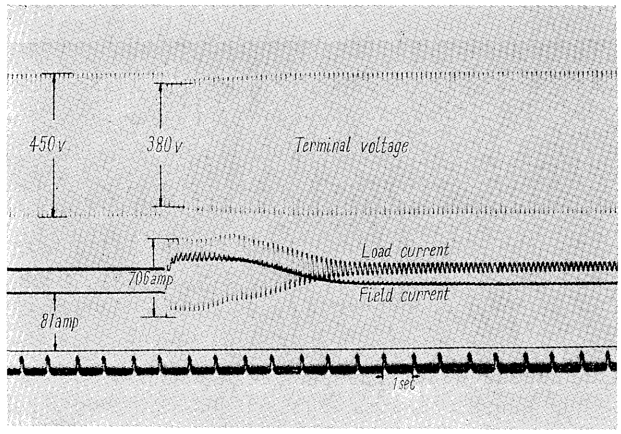


Fig. 7 Oscillogram upon starting of induction motor

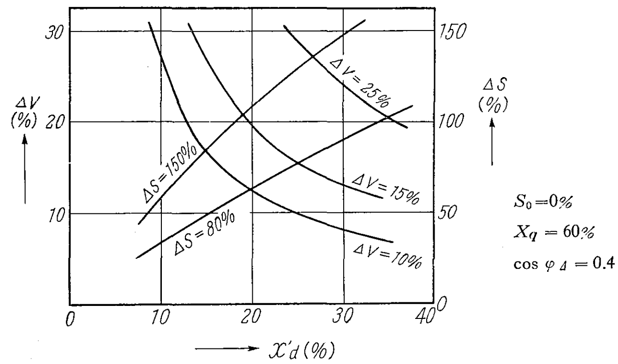


Fig. 8 Relation between instant voltage drop, suddenly applied load and X_d'

Fig. 8 indicates the voltage drop ΔV, when 80% load and 150% load ($\cos\varphi_\Delta = 0.4$) are suddenly applied to a no-load generator, and the value of the loads $\Delta S(\cos\varphi_\Delta = 0.4)$ to be applied to decrease the voltage by 10%, 15% and 25%. The horizontal axis represents X'_d.

It is understood from this diagram that the transient reactance X'_d should be less than 24% to keep the voltage drop ΔV less than 15% upon applying the load of $\Delta S = 80\%$ ($\cos\varphi_\Delta = 0.4$). [These figures have the meaning of $\Delta S = 150\%$ ($\cos\varphi_\Delta = 0.4$) and $\Delta V = 25\%$].

If a generator is designed from the sole viewpoint of restricting the temperature rise, X'_d increases with the increase of output and the number of poles. The new series marine use generators restrict X'_d to less than 24%, so their output is thermally determined in high speed machines and by their characteristics in low speed machine.

Fig. 9 shows the instantaneous voltage drop ΔV when a load of $\cos\varphi_\Delta = 0.4$ and $\Delta S = 80\%$ is applied to a generator which has a preload S_o of $\cos\varphi_\Delta = 0.8$ and 1.0. When the preload is $\cos\varphi_\Delta = 0.8$, there is almost no change in ΔV; when the preload is $\cos\varphi_\Delta = 1.0$, ΔV slightly increase with load S_o.

When the rated load with power factor 0.8 is applied to a noload generator, the voltage drop is

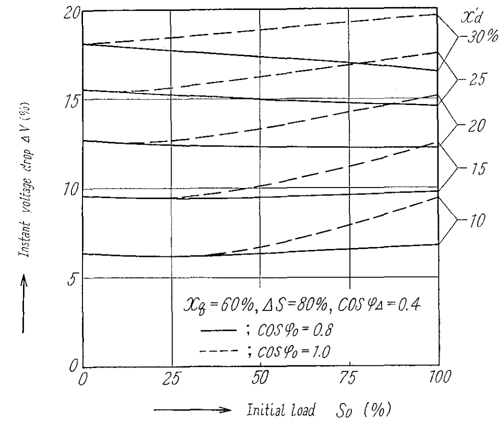


Fig. 9 Instantaneous voltage drop when load Δs is applied for generator with initial load So

less than 12%, though the percentage slightly differs according to X_q.

IV. CONSTRUCTION OF NEW SERIES OF MARINE USE AC GENERATORS

As described above, the distinctive features of the new series marine use ac generators are their high performance and compactness. Rolling, vibration, grease and oil, humidity, etc., were taken into consideration in designing these generators. We also tried to simplify the structure and decrease the weight. Some of the improvements on conventional generators are as follows.

1. Stator

The stator frame has a welded steel structure, which is designed to be compact, light, sufficiently strong, and of minimum vibration for safety.

The iron core of the stator consists of silicon steel blocks arranged in the direction of the axis; after providing cooling air ducts, the layers of these steel blocks are tightly fastened together. The thickness of these blocks and the number of cooling air ducts determine the rise and distribution of coil temperature. Our design of these sections is theoretically and experimentally the most rational one in this field and so the optimum cooling effect is obtained. At each end of the iron core is a specially devised pressring serving to prevent warping of the core layers at the inner groove.

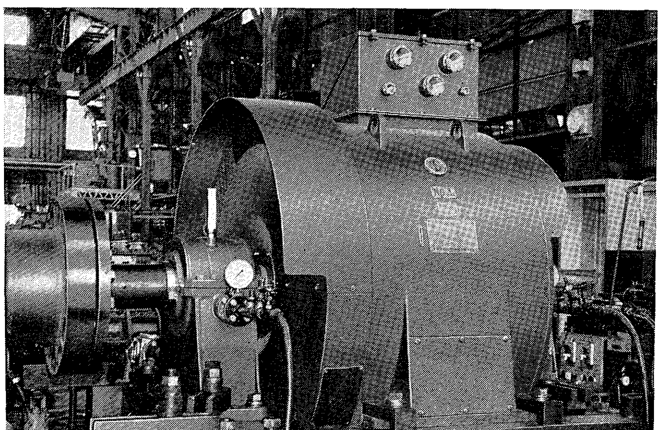


Fig. 10 New series marine use ac generator

Insulating material for stator windings has been remarkably improved recently. The B class of insulator is used for these generators, which is dependable in the atmosphere inside a ship. The B class of insulator is now easy to obtain, and also from the standpoint of making these generators compact and light, the use of this class has been standardized. We paid special attention to the high humidity in a ship. When the number of turns of a coil is small, we transpose the conductor in the iron core in order to decrease the additional loss by the skin effect and increase the efficiency.

2. Rotor

The poles have adequate damper windings effect to absorb the higher harmonic torque of a diesel engine. The construction of the pole core differs according to the number of poles and the capacity of the generator. Some cores are made of layers of laminated plates; others are constructed so that only the pole shoe is made of layers of laminated plates, being welded to the massive pole shell. There are also cores of massive contruction. The core construction is selected which is most suitable for the ratings of the generator.

Either single layer unshielded wire or multi-layer shielded wire is used, according to the ratings of the generator, for the field coil. This wire is treated with resin, which is compressed and heated, having excellent properties of strength and resistance to humidity.

The rotor center is made of cast iron, cast steel or forged steel; it is shrinkage fitted onto the shaft, using a single feather key and providing a certain interference. Since the expansion by rotation and temperature rise, as well as the cyclic irregularity of prime mover are all taken into consideration in determining the interference, the single feather key is sufficiently safe for the design.

A centrifugal fan made of welded steel plates is installed at the driving side. The blades can be separated from the fan boss, which is convenient for assembling or disassembling the fan.

3. Slip Ring and Brush

The slip ring is made of stainless steel, and except for the part shrinkage fitted into the boss, it is exposed to increase the cooling effect. The outer surface of the slip ring has diagonal grooves. The brush is made of material selected as a result of long years of experience and experiments and proven to be very effective in application to marine use equipment.

The brush holder is of the so-called constant pressure type, designed to maintain the same pressure until it reaches the limit of wear. There is no need of adjusting the spring as the brush wears. The maintenance is also very easy.

4. Shield and Brush Inspection Cover

The shield and the brush inspection cover are of the drip-proof, protective type or rat-proof type, conforming to the requirements of JEM-R.

The exhaust side shields, except those of the 4- and 6-poles generators, are standardized to exhaust in the axial direction as viewed from the position facing toward the prime mover; this prevents the exhaust from reaching people in the passageway of the room.

The shields of the 4- and 6-poles generators are of the trunk type which is recommended by JEM-R since this type generates less noise. The intake side of the shield takes air from above the center of the shaft to prevent oil fumes from entering the intake. The wire screen installed in the intake facilitates brush inspection.

A glass cover used for convenience in inspecting the brush may become broken or clouded. Instead of a glass cover, we have employed a wire screen to facilitate inspection of the brush and at the same time prevent penetration of foreign substances into the intake.

5. Bearing Stand and Bearing Bush

The bearing stand is made of steel plates and is constructed to prevent oil leakage when the slip rolls or slants. The standard lubrication system is the forced lubrication type, using the same lubricating oil as the prime mover. The oil ring lubrication type bearings are also standardized with respect to bearings of these sizes. It is also practicable to modify the former type into the latter type.

The new series generators are designed to prevent the generation of shaft voltage. However, considering the possible generation of shaft voltage by manufacture errors, all the new series generators are insulated at the bearing stand on the side opposite to the driving side to prevent formation of a shaft current circuit.

6. Space Heaters

As space heaters, sheath heaters are installed which are resistant to corrosion and vibration and have a long life span. They are arranged under the generator where they are easily accessible. These sheath heaters are connected in parallel; each of them has a thermostat which protects the stator coil from overheating.

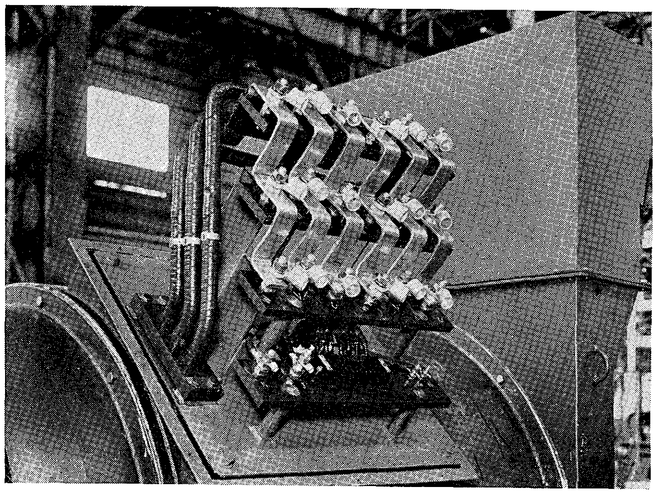


Fig. 11 Standard construction of terminal

7. Terminal Box

As the terminal voltage of marine use generators is uniform, the terminal box of the new series generators is manufactured for use with 150 mm^2 main terminal cables; 8 main terminal cables in parallel are standard. Any shipbuilder can use this terminal box for his own designed size and number of cables.

To effectively use the space inside the terminal box, the terminal boards are arranged in different step levels. Terminals are of the pressure type, which has many electrical and mechanical advantages. These terminals can be replaced by NS type terminals.

8. Vibration and Noise

The rotor of these generators is carefully balanced after completion, so that the vibration during operation of these generators is a fraction of the JEM-R requirement of less than 10 μ (one-side amplitude). The noise is also less than the JEM-R requirement of less than 100 phons. During a noise test at the factory, even the 4-pole, large capacity generator registered only 90 phons.

V. CONCLUSION

These new series marine use ac generators have already been installed on exported ships and domestic ships. They have all been favorably commented upon by customers. We are continuing our endeavors to further improve these generators, hoping that they will be more and more widely employed by the shipbuilders of the world.