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100MVAR SYNCHRONOUS CONDENSER FOR BRAZIL

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I. FOREWORD

Synchronous condensers can be classified by purpose into the following types:

(1) Power factor and stability improvement of power systems as intermediate condensing facilities.
(2) Suppression of voltage fluctuations caused by the mill load of steel works.
(3) Countermeasure against voltage flicker caused by the arc furnace of steel works and absorption of the higher harmonic current produced by thyristor loads.

A comparison list of typical Fuji synchronous condensers by application is given in *Table 1.* Since condensers (2) and (3) have already been described, condenser (1) will be described here.

In the past, synchronous condensers for power systems have been installed for power factor improvement. In recent years, the stability of high power transmission systems has become a big problem and intermediate condensing facilities containing a synchronous condenser are being researched as a means of improving stability. There are two types of such reactive power source; namely, synchronous condenser and static type (saturable reactor, thyristor controlled parallel reactor, DC controlled saturable reactor, thyristor controlled parallel condenser).

The synchronous condenser has the following advantages over the static type:

(1) For capacities of 100~200Mvar or greater, the facilities investment of the synchronous condenser is less.
(2) Leading power factor and lagging power factor reactive power can be supplied steplessly.
(3) Momentary overload capacity is large (150~170% for 1 minute).
(4) Since higher harmonic current is not generated, special countermeasures are unnecessary.
(5) Line charging is possible.

Its disadvantages are:

(1) Maintenance cost is high.
(2) Loss is somewhat large. The total losses of a synchronous condenser are about 1% of the rated capacity.
(3) Short circuit capacity of the system is increased.

In recent years the above features have been evaluated and a large number of synchronous condensers for power systems have been installed overseas. A synchronous condenser having a unit capacity of 345Mvar is already in operation.

This unit is for the above described power system use and was installed to supply reactive power for power factor improvement for power transmission to the suburbs of Belo Horizonte of Minas Gerais some 800km from the hydraulic

Table 1 Comparison list of synchronous condenser in various application

Application	Features	Typical Fuji record					
		Customer	Output(Mvar) lead/lag	Speed (rpm)	Cooling system	Exciting system*	Year of manufacture
(1) Power system	Exciting system response ratio: Large Reactance: Normal Negative excitation: Yes Exciting system: Direct thyristor exciting system	Burma	30/20	750	Air	S	1958
		Brazil	100/60	1,200	Hydrogen	S	1978
(2) Suppression of voltage fluctuation for steel works	Exciting system response ratio: Large Reactance: Normal Negative excitation: No Exciting system: Direct thyristor exciting system	Japan Steel	84/30	1,000	Hydrogen	S	1970
		Kobe Steel	50/18	1,200	Hydrogen	S	1970
(3) Ficker prevention high harmonic current absorption for arc furnace	Exciting system response ratio: Normal Reactance: Specially small Negative reactance: No Exciting system: Brushless exciting system	Funabashi Steel	61.4/20	1,000	Air	B	1975
		Qatar	40/20	1,000	Air	B	1977

*S: Direct excitation with slip ring B: Brushless excitation power station as a part of the San Simon Project.

This synchronous condenser is a 100Mvar high output, 1,200rpm high-speed machine with the following specification,

(1) a reduced voltage self-starting system had to be employed,
(2) the cooling water temperature is high,
(3) the overload capability is high,
(4) the allowable voltage dip at start is severe.

The new techniques and construction in regards to the above features will be outlined in this article.

II. SPECIFICATIONS

Type: Horizontal type salient pole synchronous condenser
Rated capacity: 100Mvar (lead), 60Mvar (lag)
Rated voltage: 13,800V
Frequency: 60Hz
Rated speed: 1,200rpm
Cooling system: Hydorgen cooling (pressure 15psig)
Standard: ANSI C50-12 (1965)
Ambient temperature: 60°C (outlet hydrogen temperature of hydorgen gas cooler)
Temperature rise limit: Stator winding 35degC
Rotor winding 60degC
Insulation class: F class
Starting system: Reduced voltage self-starting, starting time 300 seconds or less
Overload capacity: 125% for 1 hour, 150% for 1 minute
Inertia constant: 1.5kW·s/kVA or greater
Exciting system: Direct thyristor exciting system

III. DESIGN CONSIDERATIONS

1. Number of poles and rated speed

Fuji synchronous condensers are the salient pole type and the number of poles is selected from 4, 6, and 8 as standard. If the speed is increased by decreasing the number of poles, the size of the synchronous condenser becomes small. However, due to the large centrifugal force, the manufacture of high output high-speed units becomes impossible because of mechanical stress limitations. Currently, the largest salient pole type rotor has a maximum peripheral speed of 220m/s. Low speed machines have a dove-tail type pole construction, but a hummer head type and comb type construction is employed in high speed machines. The unit with which we are concerned employs six poles and has a 125% overspeed of 162m/s.

The pole shape is tapered (trapezoid shaped) and the pole construction is a 3 hummer head construction.

2. Cooling System

Fig. 1 shows the relationship between the cooling system and output and number of poles of Fuji standard synchronous condensers. Low output units employ an air cooling system which is simple to operate and maintenance. However, as the output increases a hydrogen cooling system is employed to reduce the machine size, the mechanical stresses and windage friction loss. Since the specific weight of hydrogen is 1/14.4 that of air, the windage loss is small, and cooling efficiency is good, it is used in such high-speed, large capacity machines as turbine generators. These features are incorporated directly into large high-speed synchronous condensers. We employ the hydrogen cooling system in machine having capacities exceeding about 60Mvar. When the output is more than about 300Mvar, the direct water cooling system is employed at both the rotor and stator. The 345Mvar machine (manufactured by ASEA) to Dumont of the United States is one of the example of the direct water cooled synchronous condenser.

Since the machine described here has a rated capacity of 100Mvar (lead), the hydrogen cooling system was employed.

Since increasing the hydrogen pressure improves the cooling effect, the machine becomes smaller, but the loss increases. A pressure of 15psig was employed in this machine by conducting a study to minimize the total sum of the machine cost and loss cost.

3. Cooling Water Temperature and Hydrogen Gas Temperature

Since there was no large volume water source such as river water at the installation site, a closed loop cooling circuit is employed and the hydrogen cooler and oil cooler cooling water is cooled by a cooling tower by means of outside air. The cost of the cooling tower is governed by selection of the cooling water temperature.

If the cooling water temperature and the outlet gas temperature of the cooler are lowered, a totally enclosed type machine becomes more economical, but the cooling

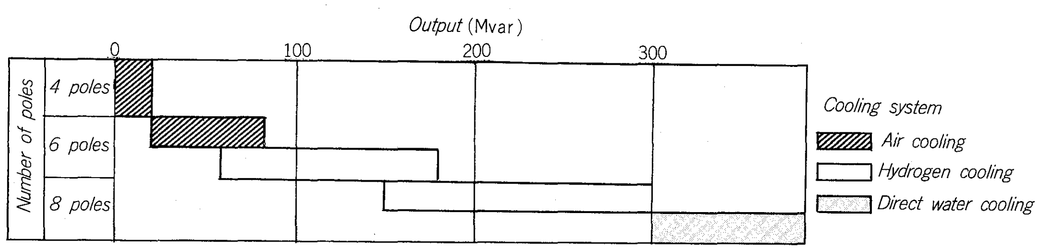


Fig. 1 Number of poles and cooling method vs. output of synchronous condenser

tower becomes expensive.

For the maximum ambient air temperature of 36°C, studies were conducted to determine the cooling water and hydrogen temperature at which the total cost of the cooling tower and synchronous condenser was most economical. As a result, the cooling water temperature was made 50°C and the outlet gas temperature of the cooler was made 60°C.

4. Starting System

For synchronous condenser starting systems, one of the following method is applied, starting by direct coupled starting motor, self-starting by damper winding, and low frequency starting. Low frequency starting is economical only when the number of installed units is large, but this case is rare because in such a case the unit output is made high and the number of installed units is made small from the economical point of view.

The damper winding self-starting system is used only when the back power is high, the voltage drop at starting stage causes no problem, and the temperature rise caused by the loss generated at the damper winding at starting is allowable. When these conditions are not satisfied, starting is performed by direct coupled starting motor.

The self-starting system is limited by the temperature rise of the damper winding. It depends on the GD^2 of the synchronous condenser, construction of the damper winding, and the starting time. As a rough criteria, the product of the output (Mvar) x rated speed (rpm) is approximately 4×10^4 (Mvar·rpm) for air cooling and approximately 15×10^4 (Mvar·rpm) for hydrogen cooling.

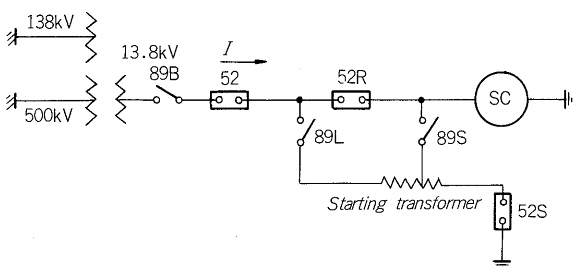


Fig. 2 Single-line diagram of starting method

This value is 12×10^4 (Mvar·rpm) for this machine and self-starting by damper winding was employed. A single-line diagram of the starting system is shown in *Fig. 2*. The voltage is reduced by a starting transformer and the machine is started and accelerated by applying this voltage to the synchronous condenser. After the slip has become sufficiently small, excitation is applied and pull-in is performed. The slip is detected by means of the current flowing in the field winding. After the neutral point of the starting transformer is open circuited (52S OFF) and operated as a reactor, the reactor is short circuited (52R ON) and the machine is connected to the 13.8kV bus line.

If the starting time is shortened by making the tap value of the starting transformer large, the voltage drop of the bus line becomes large. If the tap value is made small, the starting time becomes long, and in extreme cases, the break away friction torque and counter load torque become larger than the damper starting torque and starting becomes impossible. Therefore, selection of the tap of the starting transformer and the voltage drop across the bus line caused by the rush current when the reactor is short circuited must be adequately studied. Moreover, since the starting torque of the synchronous condenser at reduced voltage starting is generally substantially smaller than that of general synchronous motors and is a kVA base torque of approximately 2%, a so-called oil lifter must be provided at the bearing to make the break away friction torque smaller.

In the case of this synchronous condenser, the starting time had to be within 300 seconds and the voltage fluctuation of the 138kV bus line at all stages had to be within ±2.5%. Therefore, the characteristics at the starting process were amply studied and the starting transformer was designed on the most severe exciting current and reactance specifications. The current and 138kV bus line voltage fluctuation at starting are shown in *Fig. 3*.

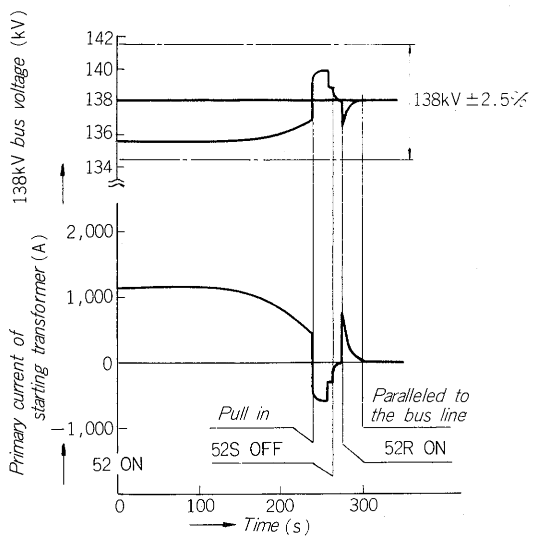


Fig. 3 Starting current and 138kV bus voltage under start

5. Damper Winding

Self-starting of a synchronous condenser is based on the same principles as the cage induction motor and heat is generated in the damper winding at starting. The loss energy Q_r (kJ) generated at the rotor at starting is given by the following equation:

$$Q_r = \int P_r dt = 2.74 \times GD^2 \times \left(\frac{N}{1000}\right)^2 \times \left(\frac{1}{2} + \int_0^1 \frac{M_L}{M_a} \times S \times dS\right)$$

Where: GD^2: Flywheel effect (kg·m²)
M_L : Counter load torque (N·m)
M_a : Acceleration torque (N·m)

N : Rated speed (rpm)

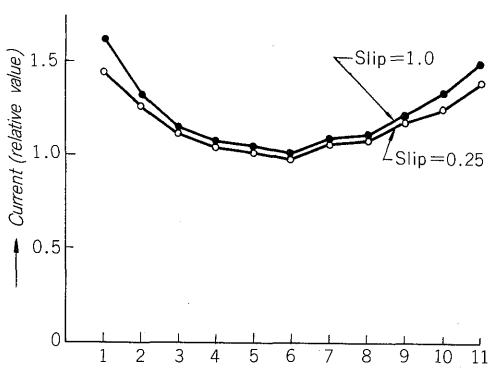
S : Slip

Loss energy Q_r is stored in the damper winding and rises damper winding temperature and is dissipated to the cooling gas through the pole core.

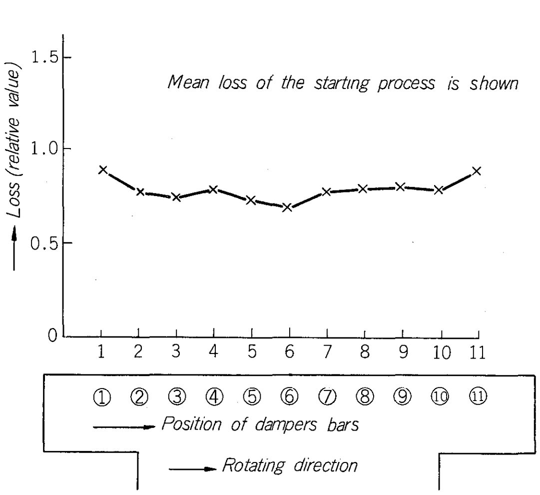
Since the duty of the damper winding of a high output synchronous condenser is large, the generation of loss and heat dissipation at the damper bars must be adequately studied. These problems were solved as follows:

(1) The self-reactance and mutual reactance of each damper winding, field winding, and stator winding, especially the mutual reactance between the damper windings, were considered and the current flowing in each damper bar was found by solving a complexed matrix with Approx. 200 variables. The results are shown in *Fig. 4* (a). As can be clearly seen from this figure, the current flowing in each damper bar differs with the position of the bar. To make the temperature of the damper bar uniform, the Joule loss, including the skin effect of each damper bar during starting, must be made uniform. This can be achieved by changing the reactance of each damper bar or by changing the resistance of the material. The latter method was used in this synchronous condenser. The distribution of the resultant Joule loss is shown in *Fig. 4* (b).

(2) The temperature rise of the transient starting stages was analyzed by means of a heat transfer network, considering the heat conduction from the damper bars to the pole core and the heat transfer from the pole surface to the hydrogen gas, based on the Joule loss of each damper bar. As a result it was found that the temperature difference between the damper bars was 30 degrees or less. Since this maximum temperature difference is produced by the damper bars of the side position, the connection of the damper bars and damper ring was made a flexible construction (patented) to improve reliability. A flexible construction was also employed at the interpole connections of the damper rings.



(a) Damper bar current distribution



(b) Damper bar loss distribution

Fig. 4 Distribution of damper bar currents and damper bar Joule losses

6. Short Circuit Ratio

The lagging capacity can be made large by means of a negative excitation method and a method which makes the short circuit ratio large. In the negative excitation method, negative excitation apparatus is added to the ordinary excitating equipment.

When the short circuit ratio is made large, the machine size becomes large, but the exciting circuit and control are simplified. For this machine, both methods were compared and the machine cost reduction accompanying a smaller short circuit ratio in the case of negative excitation was studied and the short circuit ratio was made large and a non-negative excitation system was employed.

To increase the exciting system response, the ceiling voltage at forced excitation was made 10 or more times of the exciting voltage at the rated voltage based on the gap line. The response ratio was made more than 5p.u./s.

IV. CONSTRUCTION

A sectional view of this machine is shown in *Fig. 5*.

Because this machine employs a hydrogen cooling system, the stator, rotor, bearing stand, and other parts are housed in an explosion proofed casing.

The lubrication oil pump unit, oil tank, and oil coolers are installed at the bottom of the explosion proofed casing for maintenance. These, including the piping, are designed to amply withstand a pressure of $7kg/cm^2 \cdot G$ at a hydrogen gas explosion and were confirmed by a high pressure test.

The bearing has been given an ample margin against the bearing load, considering that it is in a sealed container, and measuring terminals are provided so that insulation resistance of the shaft current insulation can be measured from the outside.

The slip ring chamber is independent from the body and is constructed so that hydrogen of the body cannot escape and only the slip ring chamber can be opened when brush replacement and other maintenance is necessary.

1. Stator

An exterior view of the stator is shown in *Fig. 6*.

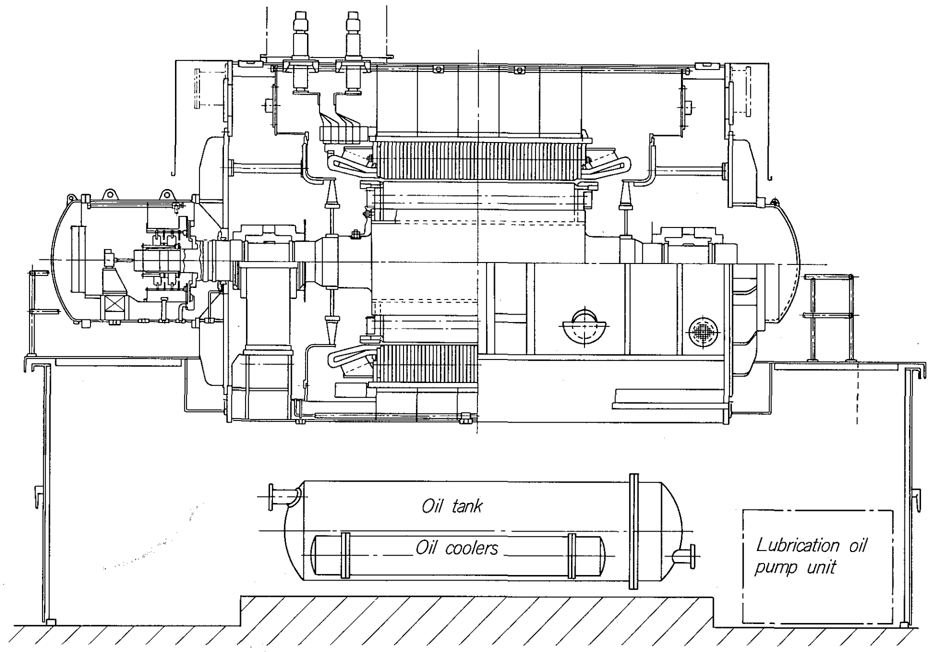


Fig. 5 Sectional view of 100Mvar synchronous condenser

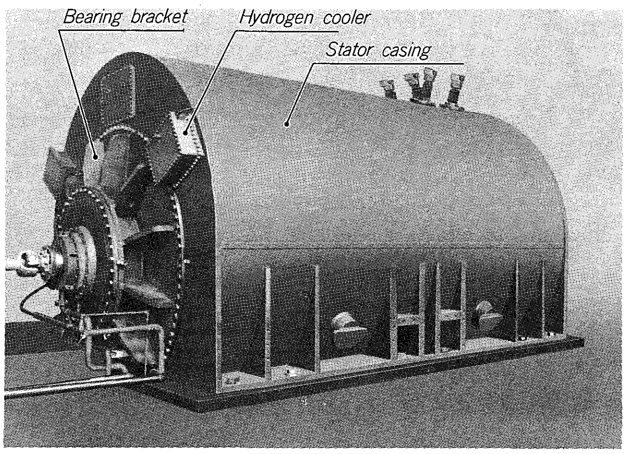


Fig. 6 Stator

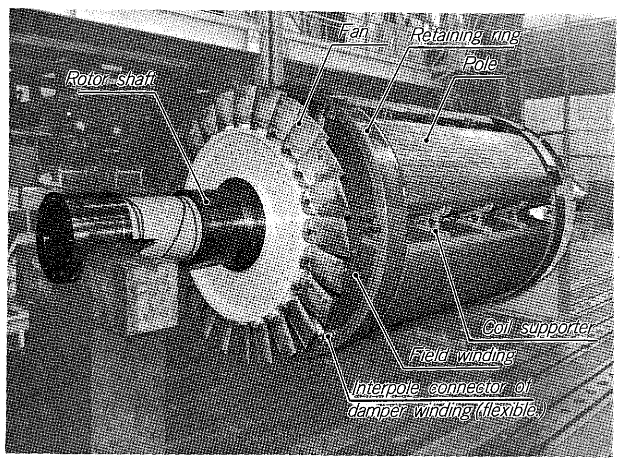


Fig. 7 Rotor

The stator core is made of high quality silicon steel to improve efficiency.

To prevent overheating of the core end portion by the leakage flux at lagging power factor, the end block is stepped and slits are provided in the teeth top for effective cooling. Furthermore, the thickness of the block and the arrangement of the cooling duct were conscientiously studied.

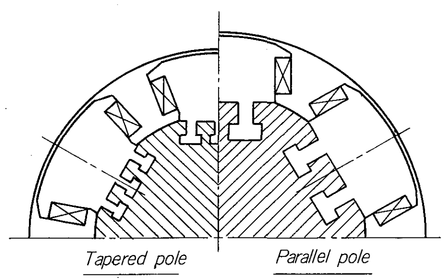


Fig. 8 Comparison of tapered pole and parallel pole

2. Rotor

Fig. 7 shows an exterior view of the rotor.

1) Pole core

The pole core is the tapered pole (trapezoid pole) applicable to high-speed machines. A comparison of the tapered pole and parallel pole is given in *Fig. 8*.

Since the cooling air area of the interpole innerdiameter-side of the tapered pole rotor coil is large, the cooling effect is improved and, as a result, the outside diameter of the rotor can be made small.

Moreover, since the tangential component of the centrifugal force which acts on the coil is extremely small, the coil supporter that prevents the coil from bending out in the tangent direction can be made small and lightweight.

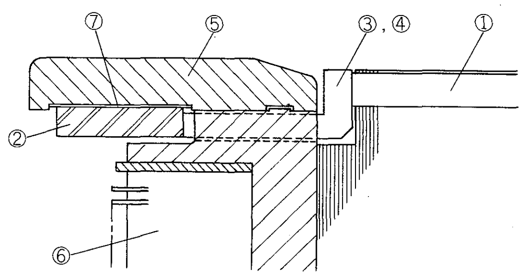
On the other hand, to reduce the mechanical stress, and to reduce GD^2 within the allowable range, in the case of the self-starting system, it is better to make the rotor diameter smaller and the core length longer. This makes the critical speed of the rotor drops, but for this machine the critical speed of the rotor was improved by making the pole leg dimensions small by making the mounting of the poles to the rotor shaft with three hammer sharped legs. And consequently the first critical speed shifted more than 20% above the overspeed and rigid shaft is employed. Moreover, a vibrometer was installed inside the enclosed casing for the monitoring of the bearing vibration.

2) Damper winding

To prevent the generation of excessive stress based on the thermal expansion difference between the damper bars described in Section **III 5** (2), the damper bar ① and damper ring ② provided at the outer surface of the pole core is connected by means of a rigid connector ③ and flexible connector ④ and its outer surface is supported by a retaining ring ⑤ through insulator ⑦, as shown in *Fig. 9.*

A liner is inserted between the damper bar and pole core as a countermeasure against thermal expansion of the damper so that the damper bar moves smoothly at starting.

The damper ring is coated with slipping material between the retaining ring to reduce the friction force produced by centrifugal force and so that the damper ring moves freely (patented).



① : Damper bar	⑤ : Retaining ring
② : Damper ring	⑥ : Rotor winding
③ : Rigid connector	⑦ : Insulator
④ : Flexible connector	

Fig. 9 Construction of damper winding

3. Slip Ring and Brush

The slip ring is also cooled by a hydrogen cooling system. The cooling circuit is independent of the body side cooling circuit so that the carbon dust of the brush does not cause a drop of the insulation resistance of the synchronous condenser windings.

After cooling of the slip ring and brush by a slip ring fan the hydrogen gas passes through a large filter at the shaft-end which removes the brush powder, and then is cooled by a hydrogen gas cooler and returned to the fan. This cooling gas is blown against the slip ring from a nozzle at the top to improve the cooling effect.

A shaft seal device is provided so that the brush can be replaced without discharging the gas of the body but by replacing only the gas of the slip ring chamber. The shaft

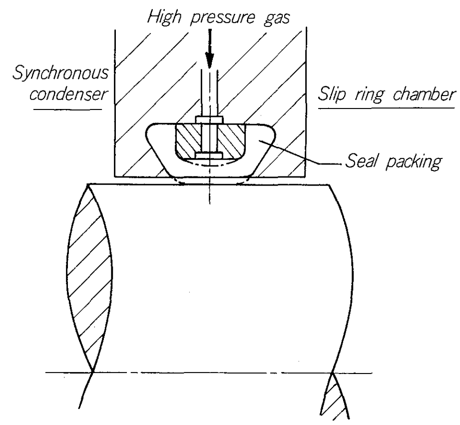


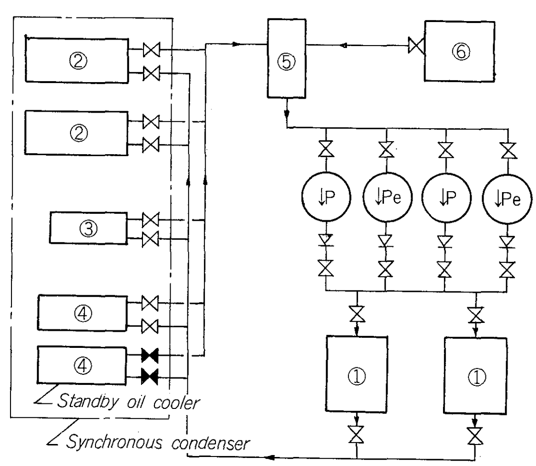
Fig. 10 Construction of shaft seal device

seal device is at the slip ring side bracket circumference. As shown in *Fig. 10*, it consists of dovetail shaped rubber expanded at the inside periphery by applying high pressure gas to the outside so that it forcefully contacts the shaft and seals the body and slip ring chamber. The shaft seal is returned to its original state by the flexibility of the rubber itself by removing the high pressure gas.

Since replacement of the brush required replacement of the hydrogen gas, the replacement period must be made as long as possible. Therefore, the brush and slip ring material are suitable selected so that abnormal wear is not produced by used in hydrogen. When the humidity of the gas is low, brush wear increases rapidly. Since the humidity of hydrogen made-up gas is especially low, a humidifier is provided to maintain it at a suitable himidity, and the humidity inside the slip ring chamber is constantly monitored by means of a hygrometer.

4. Cooling Water System

The cooling water system of this machine is shown in



P : Normal pump	③ : Slip ring cooler
Pe : Emergency pump	④ : Oil cooler
① : Air-cooled heat exchanger	⑤ : Intermediate tank
② : Hydrogen gas cooler	⑥ : Water tank

Fig. 11 Systematic diagram of cooling water

Table 2 Results of performance test

Measurement item	Test method	Test results
Characteristics and loss	Generator method by driving motor	Short circuit ratio 0.9 Total loss 985kW (at rated 100Mvar)
Vibration	Independent operation (self starting)	Bearing No. 1 / Bearing No. 2 Vertical 2.7 / 7.0 Horizontal 4.4 / 6.2 Axial 3.2 / 4.0 Units × 1/1,000mm Single amplitude
Temperature rise test	Equivalent method by driving motor	Full load estimated value: Stator winding 25deg C, Rotor winding 22deg C
Starting characteristics	Locked rotor test	At full voltage: Starting current 511%, Starting torque 41%
Reactances	Three phase sudden short circuit test	Direct axis transient reactance Xd' = 26% (saturated value) Direct axis subtransient reactance Xd'' = 16.5% (saturated value)
Winding insulation test	Voltage endurance test tan δ test	Stator winding tested voltage 28,600V Rotor winding tested voltage 4,200V tan δ test is shown in Fig. 13.

Fig. 11.

The cooling water system is a closed circulation system. The cooling water is passed through an air-cooled heat exchanger ①, synchronous condenser internal hydrogen gas cooler ②, slip ring cooler ③ and oil cooler ④ by two normal pumps (P) and is returned to the intermediate tank ⑤ and recirculated by a pump. The extremely small amount of cooling water consumed by evaporation and leakage must be replenished. The water tank ⑥ is provided for this purpose. Underground water is used as this water.

Two pumps are operated continously, but when the outside air temperature is low, operation is automatically switched to one pump to conserve power. Moreover, if trouble might occur at one of the main pump, operation is automatically switched to an emergency pump (Pe).

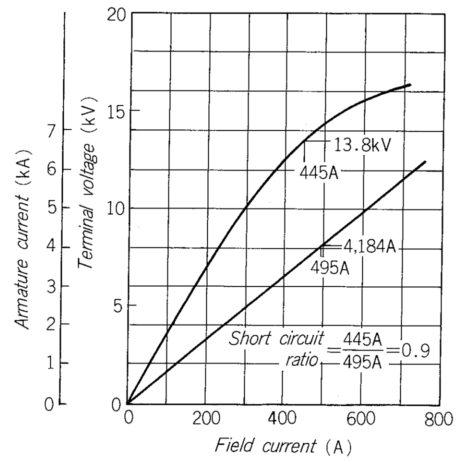


Fig. 12 No-load saturation curve and three phase short circuit curve

V. TEST RESULTS

Factory tests were conducted according to ANSI C50-12 (1965) and adequate satisfaction of the mechanical and electrical performances was confirmed. In particular, performance tests (loss, temperature rise, reactance), were conducted with a drive motor by installing a temporary test shaft to the rotor shaft for high precision measurement and the air tightness of the hydrogen gas was maintained by means of a test use sealing oil device. The main test results of this machine are given in Table 2.

1. Characteristic Curves and Losses

The no load saturation curve and three-phase short circuit curve are shown in *Fig. 12.* Short circuit ratio of 0.9 was obtained. The bearing loss, windage loss, core loss, Joule loss of the stator winding, stray load loss, Joule loss of field winding, and loss of exciting apparatus were measured segregatedly. As a result, the total loss at the rated capacity (100Mvar) was 985kW that was less than 1% of the rated capacity.

2. Vibration

The bearing vibration at the rated speed is shown in *Table 2.* Since the rotor shaft is a rigid shaft, the primary critical speed was more than 1,500rpm.

An overspeed test (1,500rpm) was conducted and the bearing vibration and bearing temperature, rotor balancing, and no abnormalities in mechanical strength were confirmed.

3. Temperature Test

As a result of an equivalent method test, the estimated temperature rise value at the rated capacity (100Mvar) was 25degC for the stator winding and 22degC for the rotor winding and the specifications were amply satisfied.

Since the specified ambient temperature (hydrogen gas cooler outlet temperature) was so high as 60°C, the cooler water inlet temperature was raised to 50°C by means of a test use heat exchanger and the temperature of the hydrogen gas was made high and the temperature was measured under conditions simulating the actual operating state. The temperature of each part at this test were as follows:

(1) Ambient temperature (hydrogen gas cooler outlet temperature): 55°C
(2) Hydrogen gas internal pressure: 15psig
(3) Hydrogen gas cooler cooling water inlet temperature: 50°C

(4) Lubricating oil inlet temperature: 54°C

(5) Lubricating oil cooler cooling water inlet temperature: 50°C

4. Starting Characteristics

The starting current and starting torque were actually measured from the locked rotor test. The value at full voltage was within ±5% of the value obtained by means of the precision calculation described in para. **5** of Section **III.** As a result of a study at reduced voltage self-starting considering on the measured value of the reactance of the starting transformer, the voltage drop of the 138kV bus line at starting was found to be 1.6% and the primary side current of the starting transformer was found to be 1,000A and *Fig. 3* was amply satisfied.

5. Reactances

The typical reactance test results are shown in *Table 2.* The customer's requirement for a transient reactance of 40% or less and a subtransient reactance of between 15% and 25% were amply satisfied. For these reactances penalties, are specified for the higher values, so a fine, high precision testing was conducted.

6. Winding Insulation Test

There are various methods of judging the quality of insulation. However, in the case of this machine, insulation resistance measurement, tan δ test, and a voltage endurance test at the commercial frequency were performed for the completed windings. The tan δ of this machine for one phase is shown in *Fig. 13.* F-resin insulation is employed at the stator winding and it is clear that of characteristic is good enough.

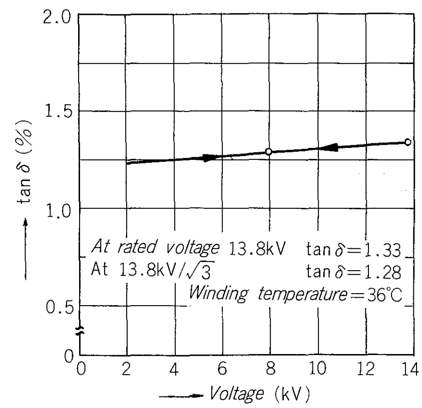


Fig. 13 tan δ—voltage characteristics (one phase)

Moreover, the voltage endurance test was conducted by applying 28,600V for one minute to each phase of the stator winding and 4,200V for 1 minute to the field winding. The voltage endurance facility between phases was confirmed by applying high voltage to each phase.

VI. CONCLUSION

The 100Mvar synchronous condenser for Brazil was outlined and its features were introduced. This unit was designed and manufactured using numerous new technologies and analysis techniques and adequate test results were obtained. The acknowledgement of the Fuji synchronous condensers shown by this article will be helpful for the understanding of the modern technologies in this field.