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2200 KW STATIC SCHERBIUS SET FOR DISTRIBUTION PUMP AT A WATER WORKS IN TOKYO

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I. FOREWORD

Demand for water is on a constant increase in line with the progress of civilization. In order to satisfy this growing demand, three sets of water-distribution pump motor and its control equipment at the fourth pumping station, Kanamachi Water-Works as part of the expansion program of the Nakagawa River project of the Water-Works Bureau of Tokyo Municipality have been delivered via Ebara Mfg. Co., Ltd. This water-distribution pump motor is designed to supply a daily quantity of 400,000 tons to the citizens of Tokyo.

In the waterwork equipment as in other industries, recent years have seen automatic control for higher productivity and better water quality. With the present equipment, the pump rotating speed is automatically controlled in order to set the pressure at Shikahama Pumping Station constant. We employed automatic control of pumps through secondary resistance control in a large numbers such as the sewerage works of Nagano City and of Kawasaki City, the Water-Works Bureau of Tokyo Municipality: Yoyogi Pumping Station, Wadabori Pumping Station, Yodobashi Station, etc. The present equipment utilizes a method of speed control by secondary excitation of induction motor of which capacity is 2200 kw and is the largest static Scherbius set in Japan. The outline of the equipment follows.

II. STATIC SCHERBIUS SYSTEM INDUCTION MOTOR

Speed control by the Scherbius system of an induction motor is a method in which the power of slip frequency of a wound-rotor induction motor is transformed into power of source frequency in some way and to feed it back to the source. In the past a rotary converter was used to transform the power of slip frequency to dc power and then to feed it back to the source by a dc motor and induction generator, or, a commutator frequency changer was used to feed it back directly to the source. But today, developing the semiconductor rectifier, the rotary converter has not been used and the semiconductor rectifier, especially silicon rectifier, is used to convert slip power into dc power. The system to use semiconductor rectifiers is called the static Scherbius system as compared with the conventional rotary converter system. At present the following two systems are usually used to convert dc power into source frequency power. The one is the MG set system of the dc motor and induction generator and the other is the mercury arc inverter system.

The following will introduce the feature of various speed control systems and the reasons why the static Scherbius system with the MG set has been taken to the speed control of the distribution pump of Kanamachi Water-Works, Tokyo Municipality.

1. Comparison of Speed Control Systems of Induction Motor

1) Rheostat control

The speed control system by means of rheostat control is the simplest and the least expensive of equipment. However, since the slip power is consumed in the rheostat as heat, the efficiency goes down as the slip increases and the expenses of

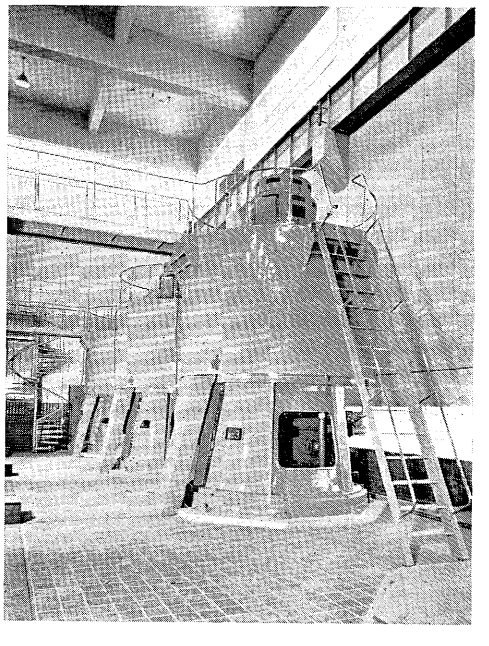


Fig. 1 Main induction motors of 2200 kw static Scherbius set

operation go up. Its torque characteristics have the defect that increasing slip, the speed regulation increases.

On the contrary, the Kraemer system and the Scherbius system are the speed control systems which recovers the slip power. These two systems are expensive to equip compared with rheostat control but they cost less to operate. They have the advantage that the speed regulation is small even if the slip increases.

2) Kraemer system

In the Kraemer system, the slip power is supplied to the dc motor directly coupled to the main motor to be used as mechanical energy. Consequently, when the loss is disregarded, the input and output of the main motor is identical and hence it has constant output characteristics. Generally speaking, its efficiency is slightly better than that of the Scherbius system but its speed is limited so the size of the dc machine tends to become large. However, its ratio is different in relation to the capacity and speed of the dc motor, and the slower the speed of the main motor becomes, the more advantageous the Scherbius system becomes. In the Scherbius system, the slip power converter may be placed at any appropriate place but there is no such freedom with the Kraemer system.

3) Scherbius system

As mentioned above, the slip power is fed back to the source so it has constant torque characteristics. Comparing between mercury-arc inverter system (MR system) and the MG set system, the efficiency of the MG set system is generally better at high speed but worse at low speed and the power factor of the MG set system is better. However, the mercury arc inverter, which is stationary apparatus, has less noise and little need for maintenance.

The above has been a general description of the speed control of various types but the selection of control system will have to be considered carefully in view of a number of conditions.

Next, regarding to the present equipment, we introduce the result of comparisons between the static Scherbius system by the MG set and other systems.

The output of the motor is 2200 kw at 475 rpm and through the speed control range: 475～380 rpm, varies proportion to the cube of speed and hence the maximum value of slip power is 340 kw. Then the operating expenses of the rheostat control system go high. *Fig. 2* represents economical comparison between rheostat control and Scherbius control after 13 years, which is allowed as the durable years of fixed assets of the waterway, with the operating time rate as the parameter and on the basis of the equipment expenses of the Scherbius set. It represents the relation between the rate of interest of the Scherbius spstem and each operating speed.

The speed of the MG set may be set for 1020 rpm so that the size of the dc motor becomes about

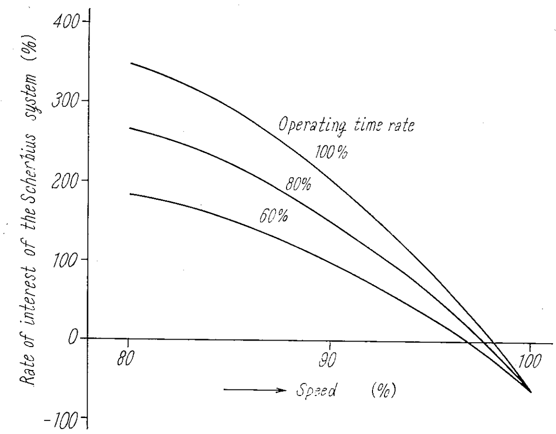


Fig. 2 Economic comparison between rheostat control and Scherbius control

one half comparing with the Kraemer system. The height of a house is limited, and, in this respect, the Kraemer system cannot be used in this pump set.

Price comparisons were made between the MR system and MG system and it has been found that the MG system is less expensive. The efficiency is about the same at 100% speed but as the speed decreases the MR system gains in advantage. However, the MR system has a poorer power factor and at 100% speed it gets the worst, which is a disadvantage. When a rough estimate is taken, the MG system becomes advantageous above the speed of 86%. In the present installation, it is likely that the speed of over 90% will be used because four sets will be put into operation in the future. Consequently, the operating expenses will be in favor of the MG system.

The following is an outline of the apparatus of the 2200 kw static Scherbius set:

2. Outline of Apparatus

Fig. 3 is a schema of static Scherbius system. The slip power of the induction motor is rectified into dc with a silicon rectifier with Grets connection (3-phase full wave rectification connection) and flows into the armature winding of the dc motor to convert mechanical power, which drives the induction

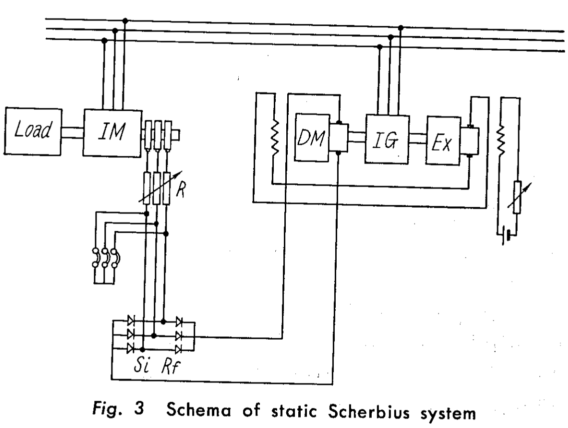


Fig. 3 Schema of static Scherbius system

generator and feeds back to the source. The speed of load is detected by the speed dynamo fitted to the induction motor, is compared with the set value, adjusts the field voltage of the exciter, controls the voltage of the exciter and hence the terminal voltage of the dc motor and is controlled.

Specifications of each equipment apparatus are as follows:

1) Main motor

Totally enclosed water-air-cooled wound type 3-phase induction motor

Model:	SUVRW 465/34–12
Kind of rating:	continuous
Output:	2200/1130 kw
Speed:	475/380 rpm
Voltage:	3000 v
Current:	580/415 amp
Frequency:	50 c/s
Number of poles:	12 poles

2) Dc motor

Open drip-proof type separate excitation shunt dc motor

Model:	aVG 334/31–6
Kind of rating:	continuous
Output:	61/347 kw
Speed:	1020 rpm
Voltage:	95/635 v
Current:	950/595 amp

3) Induction generator

Open drip-proof type special cage type 3-phase induction generator

Model:	VRK 2671–6
Kind of rating:	continuous
Output:	300 kw
Speed:	1020 rpm
Voltage:	3000 v
Current:	69 amp
Frequency:	50 c/s
Number of poles:	6 poles

4) Excitor

Open drip-proof type separate excitation shunt dc motor

Model:	aVG 65
Kind of rating:	continuous
Output:	2 kw
Speed:	1020 rpm
Voltage:	100 v

5) Silicon rectifier

Model:	S 150–60 ML
Kind of rating:	continuous
Output:	95/390 kw
Frequency:	2.5/12 c/s
Dc output voltage:	100/650 v
Dc output current:	950/600 amp
Connection:	Grets connection
Cooling method:	Air cooling
Silicon element:	Si 150F

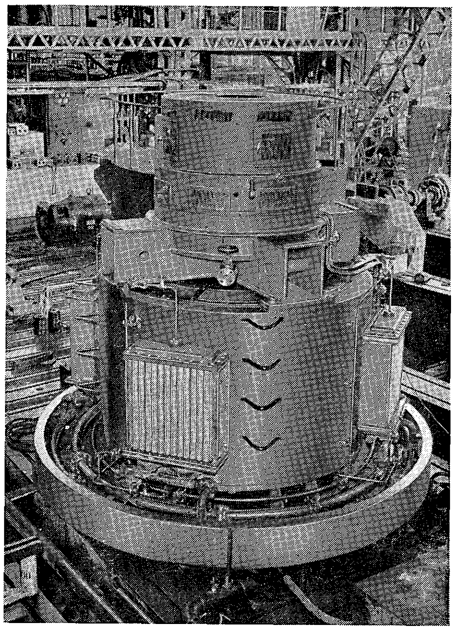


Fig. 4 Construction of main induction motor

The distribution pump, which is controlled with this motor, is made by Ebara Mfg. Co., Ltd. with the following specifications:

Vertical shaft single stage swash pump

Heads:	49 m
Discharges:	203 m^3/min.
Diameter:	1200 mm
Speed:	475/380 rpm

The construction of the main motor adopted totally enclosed water-air-cooled type because of the following reason:

(1) As the 4th distribution pump station is located near the residential quarter, it has been demanded that the noise has to be less than 85 phons. The result of noise measurement was 75 phons.

(2) The heat loss of the motor does not radiate in the room, thus it is not necessary to ventilate the room.

(3) Since this is a dsstribution pump, pure cooling water is easily obtained and may be circulated to the motor directly from the pump exhaust side.

As *Fig. 4* shows, four coolers are provided around the motor and around them wind channels serving at the same time as sound-proof covers to increase the effect of sound-proof. It is possible to run three of the four coolers when one of them happens to be under inspection. A monitoring board enables supervision of the stator winding temperature at this time. Alblack tubes are used as coolers in consideration of the safety against chlorine.

III. CAPACITY OF AUXILIARY APPARATUS

The following is a description of the static Scherbius system by the MG system concerning the capacity of auxiliary apparatus when the Scherbius system with its constant torque characteristics controls such load as varies in proportion to the square of speed.

1. Steady State Operating Time

The torque of the induction motor is given in the following formula:

$$T=K\Phi I_2 \qquad \cdots\cdots\cdots\cdots (1)$$

ϕ : gap flux, I_2: 2ry current, K: constant

When the primary voltage is constant, gap flux is considered to be constant within the usually used primary current. Consequently, from formula (1) the secondary current is almost in proportion to the torque, so it changes in proportion to the square of speed. When I_{2s} is defined as the secondary current at slip s and $I_{2\max}$ as the secondary current at minimum slip $s_{\min}$, then I_{2s} is:

$$I_{2s}=I_{s\max}\left(\frac{1-s}{1-s_{\min}}\right) \qquad \cdots\cdots\cdots\cdots (2)$$

On the other hand, the secondary voltage E_2s is in proportion to slip, so when E_2 is defined as the secondary voltage, E_{2s} is:

$$E_{2s}=sE_2 \qquad \cdots\cdots\cdots\cdots (3)$$

Therefore, the slis power is

$$P_s=I_{2s}\cdot E_{2s}=I_{2\mathrm{mrx}}\,E_{2s}\left(\frac{1-s}{1-s_{\min}}\right)^2$$

$$=A\,s\,(1-s)^2 \qquad \cdots\cdots\cdots\cdots (4)$$

Fig. 5 shows the above result. Ignoring losses, the slip power is equal to the power that goes through the MG set, of which maximum value is, from formula (4),

$$P_{s\max}=P_{ss=1/3}=0.148A \qquad \cdots\cdots\cdots\cdots (5)$$

When $S_{\min}=0.05$, the $P_{s\max}$ becomes 16.4% of the maximum output. The maximum output of a dc motor is only 16.4% of the main motor, but since the size of a dc motor is determined by the multiple of maximum voltage and maximum current, the equivalent capacity is:

$$P_{DC}=I_{2\max}\cdot E_{2\max}=s_{\max}\cdot E_2\cdot I_{2\max} \cdots\cdots\cdots\cdots (6)$$

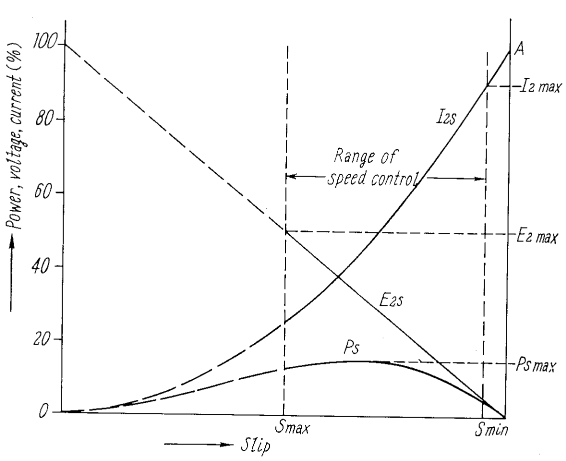


Fig. 5 Slip power, 2ry current and voltage curve at normal operation

The capacity of an induction generator is determined with the passing power i. e. the formula (5).

2. Starting Time

In the Scherbius system, if it is started with the auxiliary apparatus connected the secondary circuit of the induction motor, the maximum value of secondary voltage is equal to E_2, and the equivalent capacity of the dc motor becomes $1/s$ max. times. When it is started at $a\%$ torque, the maximum power passing through the MG set becomes $a\%$ of the rated output of the main motor. Of course, it being for a short time, the size of the induction generator does not become $a\%$ of the main motor but its torque characteristics must have enough to this power, so that the size of the induction generator has to become large and the characteristics at steady state operating time become wrong and hence very uneconomical.

In order to avoid these disadvantage, the present static Scherbius set has the short-circuit switch before the silicon rectifier short-circuited so that the slip power in the starting time may not enter the dc circuit to reduce the capacity of the silicon rectifier and the MG set.

3. Transient Time

When the set value of the rotary speed is suddenly changed, the speed decreasing, it is good to consider about only inverse voltage of the rectifier because it means that the secondary circuit of the main motor is open circuited with the silicon rectifier; however, as the speed increases, there is the danger that excessive power inflows to the MG set and if the induction generator cannot stand this power any longer, the rotation of the MG set may be subjected to over speed. This occures when the moment of inertia of the rotating system of the main motor is extremely large and the change of the speed is rather moderate in comparison with the response speed of the dc motor.

When the 2200 kw static Scherbius induction motor is running at the lowest speed (80%) the set value may be suddenly changed to the maximum speed (100%). The following is the results of calculation with computer:

Equation of motion of the rotating system is given as (7).

$$I\frac{d\omega}{dt}=T_M-T_L \qquad \cdots\cdots\cdots\cdots (7)$$

I: moment of insertia of the rotating system

$=\dfrac{GD^2}{4g}$ $\qquad GD_2=7\,500$ kg-m²

ω : rotating angular velocity of the rotating system

$=\dfrac{2\pi\cdot n}{60}$

n : speed of rotation (rpm)

T_M : torque of main motor (kg-m)

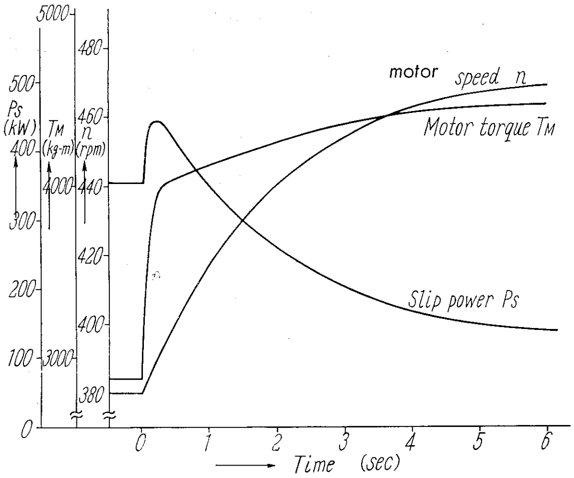
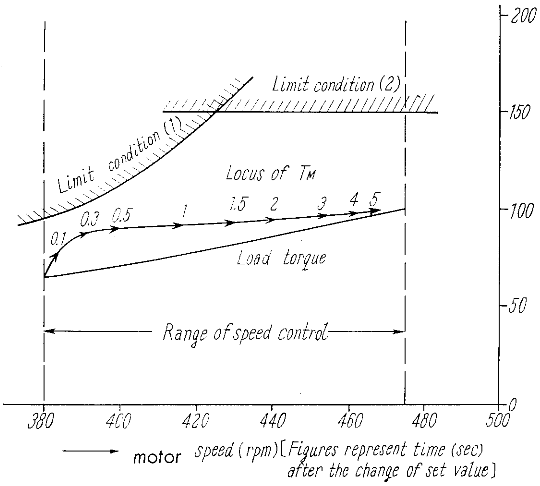


Fig. 6 (a) Transient character at sudden change of speed set value



(b) Locus of motor torque at sudden change of speed set value

T_L : load torque $\quad = T_N \cdot \left(\frac{1-s}{0.95} \right)$

$$T_N = 4\,510 \text{ kg-m}$$

The slip power is:

$$P_s = sg\omega_0 T_M \cdot 10^{-3} \quad \cdots\cdots\cdots \quad (8)$$

ω_0 : synchronous angular velocity

$$= \frac{2\pi}{60} \times 500 \text{ (rad/sec)}$$

On the other hand, in the electrical system,

$$E_e = E_f + \tau_e \frac{dE_f}{dt} \quad \cdots\cdots\cdots\cdots \quad (9)$$

E_e: field voltage of excitor (manual operation command)

E_f: field voltage of dc motor

τ_e: field time constant of excitor ($\tau_e = 0.06$ sec)

$$E_f = E_a + \tau_f \frac{dE_a}{dt} \quad \cdots\cdots\cdots\cdots \quad (10)$$

E_a : terminal voltage of dc motor

τ_f : field time constant of dc motor

As τ_f is a function of E_a, equation (10) is no linear equation. Therefore E_a is divided into several blocks and approximates with straight line. And the speed of MG set assumes constant.

Fig. 6 shows an analytical result of the variation in step of E_e with the initial condition of $n = 380$ rpm and $T_M = T_L$. (a) shows the transient character of the speed, slip power, and main motor torque. (b) shows the locus of the main motor torque on the speed-torque plane of the main motor. At the same time, the allowable limit of the MG set is illustrated. Limit condition (1) is the limit which occures the over-speed of the induction generator for the excessive inflow of power, while the limit condition (2) shows the limit which occures the over-current of the dc motor.

The above calculation shows that this set has enough capacity for the sudden change of the speed setting.

IV. CONTROL SYSTEM

1. Outline

The role of this static Scherbius induction motor played in the automatic control system is to give manipulated variable to water process as the final control element. In other words, the rotary speed is varied for constant control of the water pressure at the receiving point of a distribution pipe. The number of running motors is changed automatically according to the water flow, and then the most efficient operation can be assured.

In this chapter, the condition that the static Scherbius set is controled by this process are described on this point of view together with the points that have been given special consideration. And, finally, the protection, operation and supervisory system will be briefly treated.

2. Constant Control of Water Pressure at the Receiving Point of a Distribution Pipe

The equation of motion to send water in a water pipe is similar to one of the distribution constant circuit in a cable, as follows:

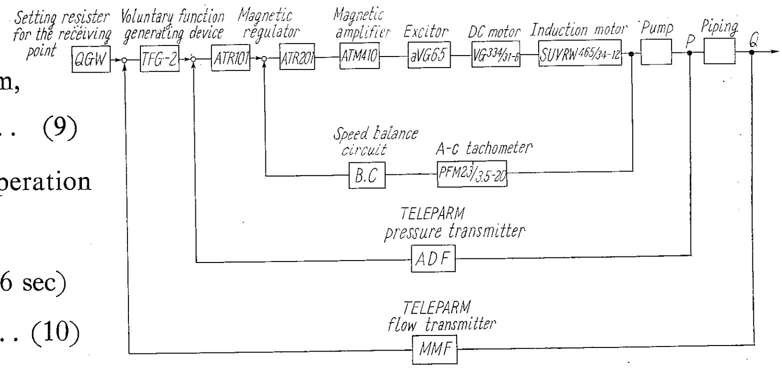


Fig. 7 Block diagram

$$\frac{\partial H}{\partial x}=-\frac{1}{g}\frac{\partial u}{\partial t}-f_r(u) \qquad \cdots\cdots\cdots\cdots (11)$$

$$\frac{\partial u}{\partial x}=-\rho g\left(\frac{1}{K}+\frac{D}{\delta E}\right)\frac{\partial H}{\partial t}-f_g(H) \ldots (12)$$

H: water pressure (m)
g: degree of weight of gravity 9.8 (m/s^2)
ρ: density of water (kg/m^2)
u: water flow (m/s)
$fr(u)=\frac{98.9\times u^{1.85}}{2gC_0^{1.85}D^{7/6}}$: water loss head per 1 m of pipe way

C_0 is a constant determined by the conditions of pipe, from 80～140.

K: bulk modulus of water (N/m^2)
E: modulus of piping material (N/m^2)
δ: thikness of piping (m)
D: piping dia. (m)
$f_g(H)$: change in flow velocity due to leakage of water per 1 m of pipe

When minute changes from a steady state of H and u are set as below

$$f_r(u_0+u)\doteqdot f_r'(u_0)u+f_r(u_0)=Ru+f_r(u_0),$$

$$\rho g\left(\frac{1}{K}+\frac{D}{\delta E}\right)=C,\ f_g(H)=0$$

then

$$\frac{\partial H}{\partial x}=-\frac{1}{g}\frac{\partial u}{\partial t}-Ru \qquad \cdots\cdots\cdots\cdots (13)$$

$$\frac{\partial u}{\partial x}=-C\frac{\partial H}{\partial t} \qquad \cdots\cdots\cdots\cdots (14)$$

which is similar to a LCR circuit.

In order to keep the pressure at the receiving point of such pipe constant, the pressure there is directly caught and controled at the sending end, then the speed of dissemination of pressure wave is

$$1\,425/\sqrt{1+KD/E\delta}\ \text{(m/s)}$$

and since the distance involved is about 10 km, there is dead time of about 10 sec. and the reflective water also affects it and it is difficult to control it.

In a steady state,

$$\partial u/\partial t=\partial H/\partial t=0$$

and formula (13) becomes formula (15)

$$H_s=H_A+\frac{98.9}{2g_0C^{1.85}}\frac{l}{D^{7/6}}u^{1.85}\cdots\cdots\cdots\cdots (15)$$

H_s and H_A represent the water pressure of a sending point and a receiving point, respectively, while " 1 " represents the length of the pipe.

Given this fact, the solution to the above problem would be this: measure the water flow u at the sending point, calculate the $fr(u)$, and compare it and the pressure of the sending end with the former added to the set pressure H_a, and then the control becomes easy. In other words, according to the present system, there is no dead time but only the first-order delay of the flow speed u. This delay causes to delay the setting of pressure and the more the delay the more stable the control becomes. In order to know this delay, formulas (13) and (14) may be obtained from the initial conditions and boundary conditions.

$$H(0,t)=H_0,\ H(l,t)=0,\ H(x,0)=0,$$

$$u=\frac{H_0}{lR}(1-\varepsilon^{-2\alpha t})+\frac{2gH_0\varepsilon^{-\alpha t}}{l}\sum_{n=1}^{\infty}\frac{1}{\beta_n}\sin\beta_n t \ \ldots (16)$$

$$\alpha=\frac{1}{2}gR,\ \beta_n=\sqrt{\frac{g}{C}\left(\frac{n\pi}{l}\right)^2-\alpha^2}$$

The second item is the advancing wave and withdrawing wave, and when this is disregarded the time constant $1/2\alpha$ represents the first-order delay which is about 60 seconds.

In order to calculate $fr(u)$ in this installation, a voluntary function generating device is used. This generates $fr(u)$ as the output from the input u, and if it is a one value function any voluntary function may be generated. By adopting this, it is easy to alter *Q–H* curve even if piping is changed. As is shown in *Fig. 7*, the pressure set by a voluntary function generator are compared with the pressure at pump delivery side by the regulator ATR101, then gets its speed matched to the other machines by the magnetic regulator ATR201 and the magnetic amplifier ATM410 excites the excitor.

3. Excitation Method of Excitor

As we have so far mentioned, a magnetic amplifier is used as the source of exciting current of the excitor to control the pressure at the receiving point of a distribution pipe continuously. This necessitated the examination of the following regarding the Scherbius set. That is, when the set pressure should go up suddenly, the output current of the excitor miget decrease and the set speed of the main motor might increase suddenly and the MG set might not be overloaded by the energy in acceleration. If there is this possibility, the method to cope with it will be to make the maximum torque of the induction generator bigger or detect the output power on the secondary side of the main motor and to limit the exciting input of the excitor so that input power will not exceed the maximum power of the induction generator. In examining this, the analytical result by a " repetitive method " or, a digital computer it was found as shown in III that its possibility will not exist without making the capacity of the induction generator greater. This is because that the load being a pump, GD2 is small and the speed control range is narrow. Consequently, in the reverse case, either one of the preventive measure is required.

4. Control for Switching of Pump Motors

Three sets have this time been delivered, but in the future five main motors including one spare will be operated in a parallel with speed control. In order to operate them in the most economical manner, the most efficient selection of the number of units according to the water flow should be selected. In pump control, the speed in decreasing the number is different according to the number of sets in parallel operation, and the more the number the higher the change speed. It is evident that the speed in increasing the numbers of running pump will be the best at 100% of speed. In order for this change-over to be smoothly and automatically carried out, it is necessary that the starting system of the Scherbius induction motor is simple.

5. Start and Stop System

In the past, there were the following two starting systems of the Scherbius induction motor. As shown in (a) of *Fig. 8*, one is to match the secondary voltage of the main motor with dc machine voltage and to change the secondary circuit, and, the other, as shown in (b) of *Fig. 8*, is to set the secondary resistance rheostat open-neutral and connect it to the silicon rectifier. The former is more economical than the latter in having a smaller silicon rectifier, dc machine and induction generator in their capacity but the change-over at the start is rather troublesome. In other words, it is difficult to match the secondary voltage of the main motor with the dc machine voltage and when the voltage of the dc machine is lower, there will be rush current at the time of change-over, and, when it is too high, the speed of the main motor is down again, so the motor does not start smoothly. At the time of change-over, the load current is cut and the contacts of switches need to be considered. Especially, when it is the matter of a large capacity motor, it is uneconomical to use magnet contactor.

With regard to the latter, the starting is smooth which does not have to cut off the load current but, as stated earlier, it is necessary to have a large capacity for the silicon rectifier, dc motor and induction generator. So it is uneconomical when the speed control range is narrow and the load torque is proportional to square of speed. That is why there is a short-circuitor as in *Fig. 8* (c). When this short-circuitor is released, it is sufficient that the dc machine voltage should be lower than the voltage at 80% speed which is main motor's minimum speed. Therefore, the dc machine voltage is lower than the main motor secondary voltage but as there still remains the starting resistor the rush current will not flow and the current instead decreases. This starting method is advantageous when one Scherbius power return device operates a few main motors in parallel. This is because while one machine is running at a given speed, the other one may be added without changing its set speed. This system has been ordered for Shiba Water Supply Pumping Station of Water-works Bureau of Tokyo Municipality and is being manufactured.

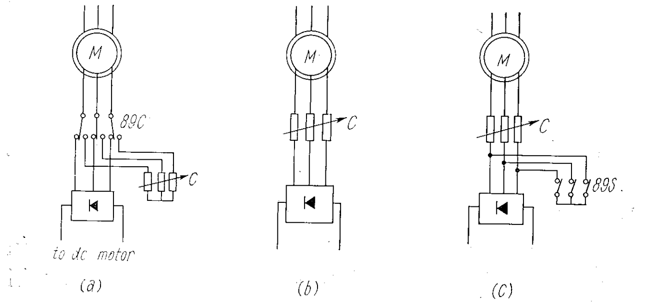


Fig. 8 Comparison of starting systems

Stop may be classified into emergency stop and normal stop. The normal stop means decreasing the speed to a minimum to avoid abrupt change, then totally closing the valve and then stop the motor. The emergency stop, on the other hand, is used when there is serious fault, where the motor stops simultaneously with the valve closing.

6. Protection

For protection, interlock is provided as well as allowance for capacity to prevent abnormal phenomena from arising. The following is a sketchy description of protective devices.

1) Main motor

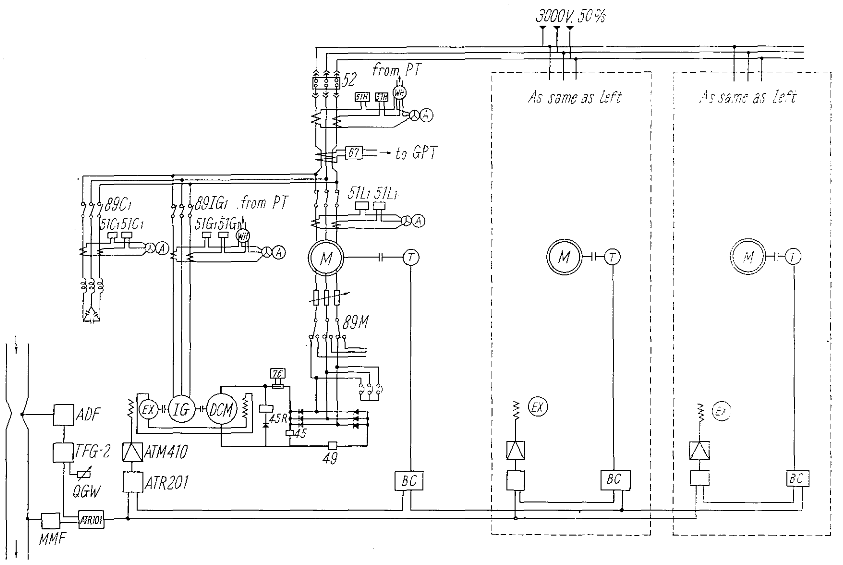
Winding is of B class and the temperature rise is of 50°C of A class. This means not only provision for allowance but to enable continuous operation under the conditions where the disconnecting switch *89M* of *Fig. 9* is changed over and detached from the Scherbius device and operated in secondary short-circuit independently with an output of 2500 kw.

Like ordinary wound rotor type induction motors, the protective devices include overcurrent, overload, main circuit low voltage, serious trouble with ground fault and emergency stop. These serious fault are annunciate with bell and flicker lamp.

Overheating of bearings, interruption in cooling water and bearing coolant are considered medium fault which cause the machine to stop in a normal way and sound a warning and flicker the lamp.

2) Silicon rectifier

The silicon rectifier is short-circuited by the above-mentioned short-circuitor against abnormal voltage at the start of the main motor, and there is no fear about this. If this starting short-circuit switch is not used, it is necessary to increase considerably the number of series of silicon rectifier elements, but the adoptation of this starting system reduces the number to two. A condenser is provided in parallel in each rectifier element to check abnormal voltage caused by carrier accumulation effect. To prevent it from short-circuit current, Fuji super rapid fuse is used. There is an allowance in the number of parallel arrangements against overload which acts in the overcurrent relay. Serious fault include overcurrent, silicon fuse breakage, dc circuit overvoltage, dc main circuit reverse voltage—which trip the main



M: Main motor
DCM: Dc motor
IG: Induction generator
EX: Exciter
T: Ac tachometer
ADF: TELEPERM Abgrif type pressure transmitter
MMF: TELEPERM flow transmitter
TFG2: Voluntary function generator
ATR101, ATR201: Magnetic regulator
ATM410: Magnetic amplifier
BC: Speed balance circuit
QGM: Setting resister for receiving point

Fig. 9 Skeleton diagram

breaker and bring about emergency stop.

Medium faults include silicon cooling fan fault, while light faults include silicon overheat.

3) Dc motor

Protection of the dc motor is provided in the same manner as in other general motors but when trouble happens the main breaker is made to trip. Against overload in the dc circuit, overcurrent and overvoltage, the foregoing relay for the silicon rectifier is made to act, in the category of serious fault.

4) Induction generator

Protection here is also the same as with the general induction motor. Overload is considered a serious fault. Phase fault protection is common to the main motor's.

5) Other

Two steps are provided against incomplete-sequence until the starter has acted completely, it may be tremendous a light fault; until the motor valve is totally opened, it is a serious fault.

As stated above, there is no possibility about the over speed of the MG set, but when it is started with the disconnecting switch *89IG* of the induction generator opened, it is liable to get over-speed. Therefore, when this disconnected switch is opened and the disconnected switch *89M* for change-over is in the side of the silicon rectifier, there is an interlocking arrangement to see that the main breaker 52 will not be closed. For further precaution's sake, in the case of overspeed, emergency stop is called by over-speed relay.

As for the condenser for phase advancement, overload current is defined as a light fault; for short-circuit current, the overcurrent relay common to the main motor protects phase fault.

7. Control and Supervision

The above explanation takes care of the fully automatic operation. In addition to the above-mentioned operation by automatic control, it is

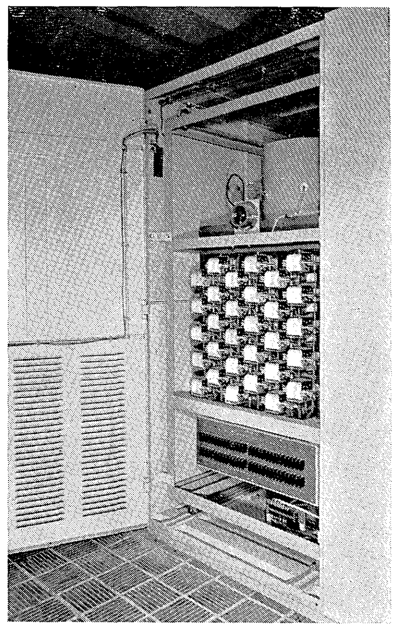


Fig. 10 Silicon rectifier

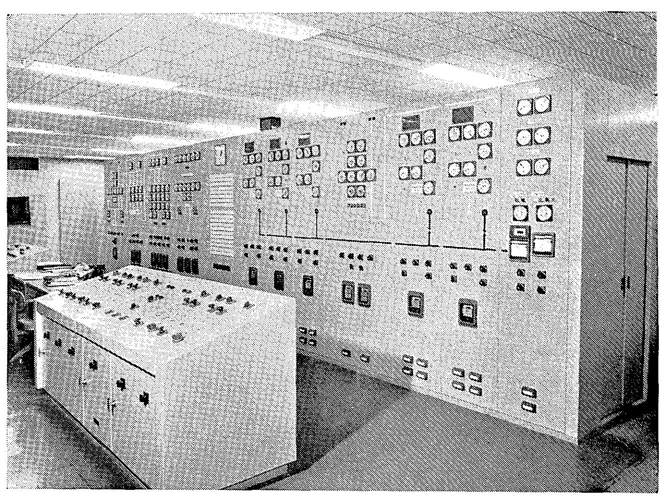


Fig. 11 Graphic panel and control desk

possible on the supervisor's control board and at site to start and stop as well as to regulate the motor speed by one man control. It is also possible to run each apparatus independently. Supervision or monitoring is done by the illuminated graphic panel in the monitoring room ; both electrical system and water system are illuminated to make the supervision easy.

V. TEST RESULTS

The steady state characteristics of the static Scherbius induction motor and transient characteristics at the change of the speed setting are reported.

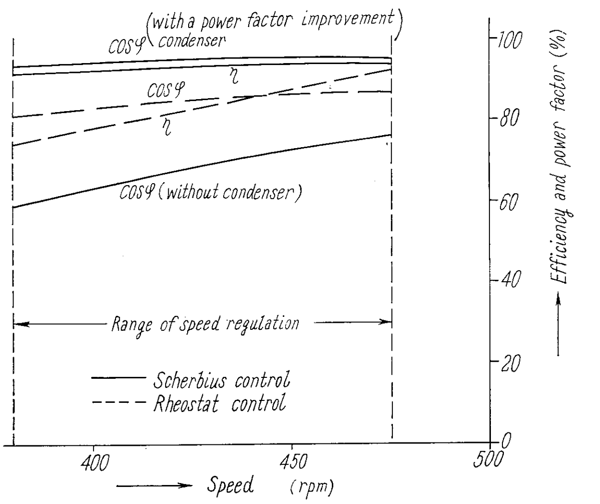


Fig. 12 Speed characteristic curves for 2200 kw Scherbius set

1. Steady State Characteristics

Fig. 12 shows the efficiency and the power factor of the static Scherbius set under rated load. The power factor is indicated for the case in which a power factor improvement condenser of 1200 kva is inserted and for the case without it. For reference, the characteristic curve of therheostat control are indicated by broken lines.

2. Transient Characteristics

Fig. 13 is a oscillogram at the change of the speed setting, which measured in our factory. Although it was measured at no load, the GD^2 of the dc machine which was direct coupled as the load was so large that the change of speed was moderate ; however this is presented to show the tendency at the transient character. When load conditions are converted, they meet the result mentioned in III. In the oscillogram there is a meandering variation of the main motor current. This occured inevitably when the speed control is done in such a manner that the semiconductor rectifier is inserted in the secondary circuit of the induction motor and in practice this does not give any trouble. In other words, the higher harmonic current flows in the secondary circuit due to the action of the rectifier and the effect of the fifth harmonic current appears as the meandering wave of the primary current around 1/6 slip of the motor. That of the induction generator current is due to the effect of main motor current since the capacity of the source in the factory where this test was made was small.

VI. CONCLUSION

The present equipment was installed on the site, adjusted and duly launched into actual operation on June 15, 1964. In closing, we would like to express deep appreciate to the customers and other people concerned for their cooperation in planning and manufacturing of the equipment.

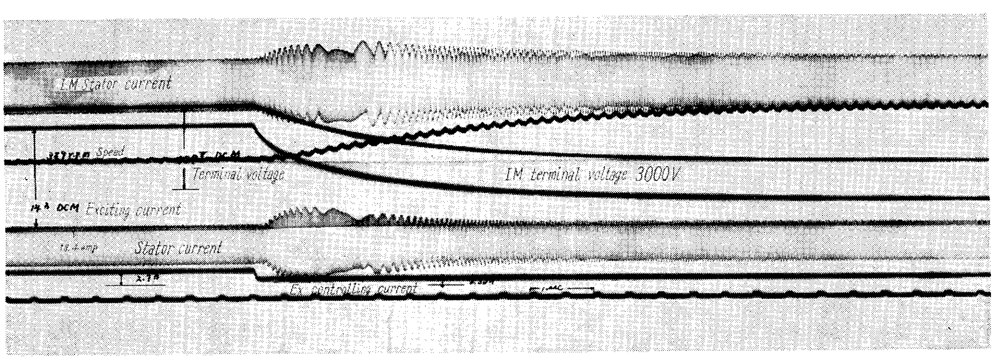


Fig. 13 Oscillogram at sudden change of speed set value