UDC 621. 313. 333. 1-531: 621. 314. 63.07

STATIC SCHERBIUS EQUIPMENT

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I. INTRODUCTION

In some equipment, economy and service life depend on operation " recession ". Operation recession means the high cost of operating existing equipment which is inferior to " challenging " equipment and can be divided into equipment loss and out-of-date equipment. Loss is due to the fact that over the years, equipment operation fees, upkeep fees and maintenance fees increase greatly, while out-of-date means that technological progress has made possible the manufacture of new equipment i.e. " challenging " equipment which is superior to operation cost of the existing equipment. Static Scherbius equipment is challenging equipment which has appeared in the last 2 or 3 years. *Table 1* is a supply list of the static Scherbius equipment manufactured by Fuji Electric. Static Scherbius equipment in challenging equipment in now used in fans and pumps such as valve control, liquid resistance control and M-G Scherbius equipment, as well as controll equipment using electromagnetic couplings, dc Leonard systems and ac commutators employed in extractors. The reason for this challenge is that the static Scherbius equipment is superior in respect to load quality, and it is hoped that this equipment will become a challenge in many fields. This article will introduce actual example of static Scherbius equipment and their features.

Table 1 **Supply List of Static Scherbius Sets**

Customer	No.	Year	Output (kw)	Voltage (v)	No. of Poles	Frequency (Hz)	Speed Control range (rpm)	Application
Chichibu Cement Co.	2	1966	150	3000	8	50	513～730	Fans
Furukawa Chemicals Co.	4	2 units in 1967 2 units in 1968	600	3000	6	50	300～900	Extractors
Osaka Waterworks: Joto Pumping Station	3	1968	135	440	6	60	114～1140	Extractors
Osaka Waterworks: Joto Pumping Station	4	1968	1400	6600	14	60	252～504	Pumps
Kyoto Waterworks: Shinyamashina Water Purification Plant	2	1968	970	6600	12	60	322～586	Pumps
Kyoto Waterworks: Shinyamashita Water Purification Plant	4	1968	150	3300	4	60	1020～1710	Pumps
Ube Industries Co.	1	1968	2×500	3300	6	60	126～1140	Kilns
Ube Industries Co.	1	1968	700	3300	10	60	240～684	Fans
Japanese Geon Co.	1	1969	450	3300	6	60	380～1140	Extractors
Japanese Geon Co.	1	1969	400	3300	8	60	300～850	Extractors
Nagoya Waterworks: Idaka Pumping Station	1	1969	3×500	3300	10	60	477～682	Pumps
—— Co.	2	Under const.	1000	3300	6	60	228～1140	Extractors
—— Co.	1	Under const.	600	3300	6	60	228～1140	Extractors
—— Co.	1	Under const.	250	3300	4	60	342～1710	Extractors
—— Co.	1	Under const.	860	3300	16	60	142～427	Reciprocating compressors
—— Co.	1	Under const.	2000	3300	8	60	600～870	Fans

II. ECONOMY OF STATIC SCHERBIUS EQUIPMENT

When choosing the equipment with the best load quality among many types, a comparison of the economies of the various devices is absolutely essential. Economy in this case does not only mean a comparison of construction costs, it also depends or the minimum of the average annual overall load cost " U"

$$U=KC+P\cdot\frac{H}{\eta}A+M+R+Q+S \quad\cdots\cdots\cdots\cdots\cdots (1)$$

Where K: capital recovery coefficient, C: construction costs, P: required power, H: operating time, η: efficiency, A: power consumption per hour, M: upkeep fees per year, R: loss per year based on quality of goods produced, and S: loss per year based on unsafe conditions.

When considering thyristor Scherbius equipment from this standpoint:

(1) Efficiency is high over a wide range of speeds. Therefore η is large.

(2) Since maintenance is easy, upkeep costs are low. Only the induction motor brushes are subject to wear and therefore M is small.

(3) A rugged induction motor is the main component. In recent years thyristor reliability and safety have increased due to improvements in construction and adaptation techniques as well as a wide range of successful operating results. Therefore both R and S are small.

(4) Construction fees are high when compared with those of the liquid resistor and electromagnetic coupling control equipment. When compared with the dc Leonard system, the costs for small capacity equipment are about the same but for large capacities, the thyristor Scherbius equipment is cheaper. It is especially cheap when the speed control range is small.

(5) This equipment is quick-acting. For large capacities, high speed can be achieved through the use of 2 poles. This is related to " Q" in equation 1.

The way in which these comparisons vary in respect to the loads in questions will now be described.

When considering pumps used in wateworks, K is 0.12652 for a service life of 13 years and an interest of 8%. H is 4300 hours with an operating time factor of about 50%. Reliability and safely are important elements for the public, and practical experience has proven that this equipment is superior in all respects. Considering contruction costs, it is all right if the pump speed control range is small and since the power converter operates at a maximum of around 50%, half capacity is sufficient during 100% control. However, when compared with the liquid resistor, the construction costs are high, so that the Scherbius equipment was therefore chosen also on the basis of the operating time factor. When comparing the economy of liquid resistors and Scherbius equipment with loads in which the torque is proportional to the square of the speed as in pumps, M-G Scherbius equipment and thyristor Scherbius equipment, and Scherbius equipment and Kraemer equipment, please refer to the Fuji Electric catalogue " Instructions for pump electrical equipment TV-6 ". From this catalogue, it is evident that the static Scherbius equipment is superior to the liquid resistor when the speed control range is 50%, the operating time factor is over 37% and the main motor output is 100 kw or over.

In the case of extractors, K is 0.25046 for a service life of 5 years and an interest of 8% and the construction costs are relatively high. H is 7000 hours for an operating time factor of 80%. Since the speed control range is large, $PH/\eta\ A$ is small when compared with equipment using electromagnetic contacts and therefore U is small. Sufficient braking torque essential in pumps, fans, and extractors will be provided if the converter on the motor secondary side is a silicon rectifier.

Because of the advances made with thyristor equipment in the fields of electromagnetic coupling control and liquid resistors, it necessary that the load operating time factor of the existing equipment be large.

Once dc Leonard equipment was developed, the operating time factor became large and the equipment became large capacity and high speed and the speed control range became small. Braking torque is not required. Since it is sufficient to employ the main motor secondary convertor as inverter, an important advance has been made over the previous levels of research in respect to braking torque.

III. TYPES OF STATIC SCHERBIUS EQUIPMENT

There are two types of static Scherbius equipment: 1) dc control and 2) ac control. The de control systems include placing an inverter in the secondary side of induction motors so that operation is possible at forward/reverse acceleration/deceleration speeds and super-synchronous speeds. This article, however, will describe only the case when a silicon rectifier is inserted in the secondary side of the induction motor.

IV. CHARACTERISTICS

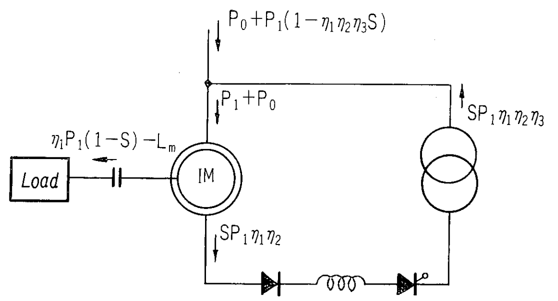
1. Energy Circulation and Overall Efficiency

When the induction motor is operating with a slip S, the energy circulates as shown in *Fig. 1.* Therefore, the overall efficiency η is

$$\eta=\frac{\eta_1 P_1(1-S)-L_m}{P_0+P_1(1-\eta_1\eta_2\eta_3 S)}\doteqdot\eta_1\frac{(1-S)}{(1-\eta_1\eta_2\eta_3 S)}\cdots (2)$$

2. Average Dc No-Load Voltage in a 3-phase Bridge

When the interline voltage is V, the average dc voltage E_{d0} is as follows



P_0: Main motor excitation loss
P_1: Main motor primary input
$\eta_1 P_1=P_2$: Main motor secondary input
L_m: Main motor mechanical loss
η_2: Efficiency in main motor secondary winding
η_3: Efficiency of Scherbius equipment

Fig. 1 Energy circulation of static Scherbius

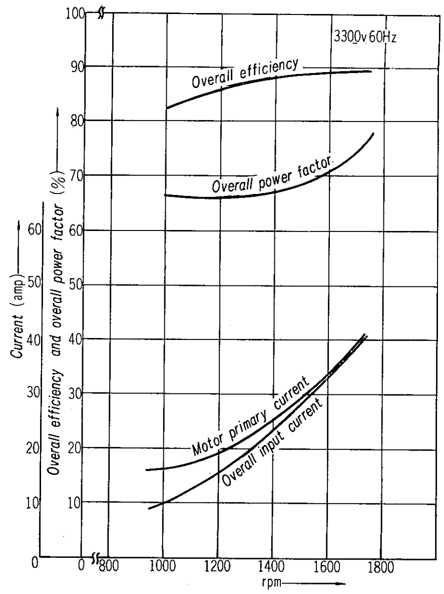


Fig. 2 Load characteristic curves

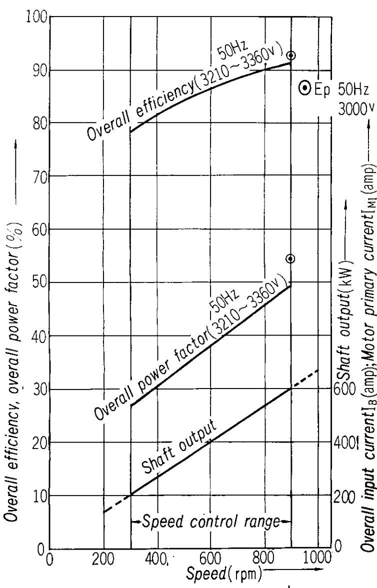


Fig. 3 Load characteristic curves (600 kw set)

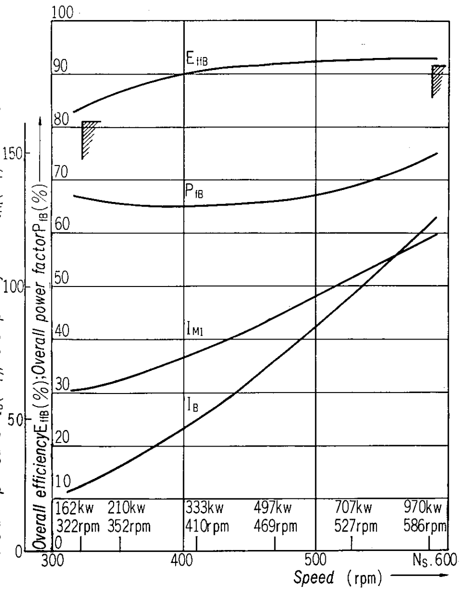


Fig. 4 Load characteristic curves (970 kw set)

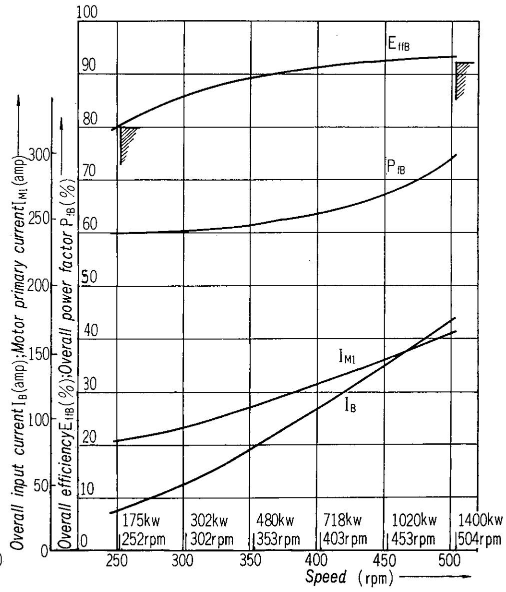


Fig. 5 Load characteristic curves (1400 kw set)

$$E_{d0}=\frac{3\sqrt{2}}{\pi}\,\mathrm{v}=1.35\,\mathrm{v}\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (3)$$

3. Relation Between the Dc Current and the Primary and Secondary Motor Currents

When the inductance in the dc side circuit in extremely large, the rectifier current is completely smooth. If there is no inductance on the motor secondary side, the secondary current will have a waveform like that shown in *Fig. 6*. When this is converted to a Fournier series, the secondary current I_2 becomes:

$$I_2=I_d\sum_{n=0}^{\infty}\frac{4}{\pi}\frac{\cos(2n+1)\frac{\pi}{6}}{2n+1}\cdot\sin(2n+1)\,S\,w\,t\cdots (4)$$

where I_d is the dc current. Therefore the effective value of the fundamental wave I_{21} is:

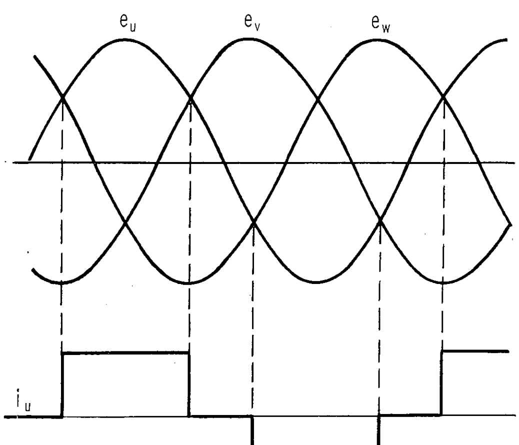


Fig. 6 Phase voltage and line voltage of three bridge connection

$$I_{21}=\frac{\sqrt{6}}{\pi}I_d=0.78\,I_d \quad \cdots\cdots\cdots\cdots (5)$$

The effective value of the fundamental wave and the harmonic wave $|I_2|$ is:

$$|I_2|=\sqrt{\frac{2}{3}}\,I_d=0.817\,I_d \quad \cdots\cdots\cdots\cdots (6)$$

The primary motor current is influcenced by the harmonic wave included in the secondary current. The distribution of the super magnetic force along the circumference of the concentration coil takes the form of a square wave, but if the fundamental wave is considered only as this, the primary current will be as follows because of the rotating magentic field arising due to the secondary current as in equation (4).

$$I_1=\frac{2\sqrt{3}\,I_d}{a\pi}\left\{\sin wt+\frac{1}{5}\sin(wt-6Swt)-\frac{1}{7}\sin(wt+6\,Swt)-\frac{1}{11}\sin(wt-12\,Swt)+\cdots\right\} \cdots\cdots\cdots (7)$$

Here α is the winding ratio between the primary and secondary windings. When S is almost 3/1, the second term of equation (7) becomes $1/5\sin(\Delta wt-wt)$ and therefore the primary current I_1 pulsates. If S is about 1/6, the second term becomes a low frequency current of $1/5\sin\Delta wt$. By joining this with the first term of equation (7), the primary current becomes a beat current. Tests with M-G Scherbius equipment have proven that this presents no problem in practice.

4. Overlapping Commutation Angle U

In the analysis given in section 3, the reactance on the secondary side of the motor was neglected, but in practice, this is not possible. Unlike transformers, inductance motors are subject to a coupling of the primary and secondary currents because of the rotating magnetic field. Since this rotating field arises only when 3-phase ac current is applied to both the primary and secondary sides, the secondary current during commutation influences the primary current only during this period.

When the resistance and reactance per phase on the motor secondary side are R_2 and L_2 respectively, the commutation overlapping angle is determined by the following equation:

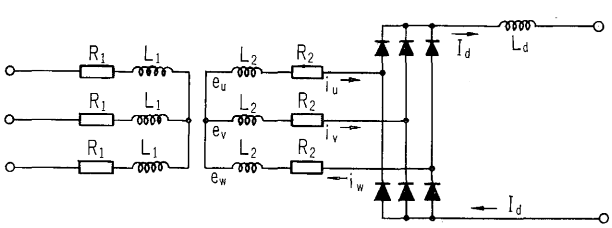


Fig. 7 Secondary circuit of induction motor

$$\frac{I_d}{2}\left(1+\varepsilon^{-\frac{R_2u}{SwL_2}}\right)=I_S\left\{\varepsilon^{-\frac{R_2u}{SwL_2\cdot\sin\varphi}}+\sin(u-\phi)\right\} \cdots (8)$$

where $I_S=\frac{\sqrt{2}\,E_2S\sin\pi/3}{\sqrt{R_2^2+L_2^2w^2s^2}}$, $\phi=\tan^{-1}\frac{SwL^2}{R_2}$ E_2: secondary phase voltage.

When the slip S is large, $SwL_2>R_2$ and u is about 0.4. Therefore, when the terms $\left(\frac{R_2}{SwL_2}\right)^2$ and $\frac{R_2u}{SwL_2}$ are neglected, equation (8) becomes equation (8)′

$$E_{d0}\left(\frac{1-\cos u}{2}\right)=\frac{3}{\pi}L_2wI_d \quad \cdots\cdots\cdots\cdots (8)'$$

5. Average On-Load Dc Voltage

The average on-load dc voltage is given by the following equation when the dc current is I_d.

$$E_d=SE_{d0}\left\{\frac{1+\cos u}{2}\right\}-I_dR_2\left(2-\frac{3u}{2\pi}\right)-2_{eS} \cdots (9)$$

where e_S is the voltage reduction in diode arm 1.

6. Secondary Input

The secondary input of the motor, P_2 can be expressed as follows:

$$P_2=\frac{E_{d0}}{2}\{I_d(1+\cos u)-I_d[\sin\phi+\sin(u+\phi)]$$

$$\sin\phi+I_S[u\cos\phi-\sin u\cdot\cos(u+\phi)]\}\cdots\cdots (10)$$

When the terms $\left(\frac{R_2}{SwL_2}\right)^2$ and $\frac{R_{2u}}{SwL_2}$ are negrected, equation (10) can be approximated by equation (10)′.

$$P_2=\frac{E_{d0}}{2}(1+\cos u)I_d \quad \cdots\cdots\cdots\cdots (10)'$$

7. Secondary Winding Loss

The secondary winding loss, P_e, is as shown in equation (11).

$$P_e=I_d^2R_2\left(2-\frac{3u}{2\pi}\right)-\frac{SE_{d0}}{2}\{I_d\sin\phi\,[\sin\phi+\sin(u+\phi)]+I_S[\sin u\cdot\cos(u+\phi)-u\cos\phi]\} \cdots\cdots (11)$$

8. Mechnical Output and Torque

When the mechanical output is P_m, then $P_2=P_m+P_e+I_dE_d+I_d2e_s+L_m$. Therefore, from equations (9), (10) and (11), the following equation can be obtained:

$$P_m=P_2-P_e-I_dE_d-L_m=P_2(1-S)-L_m \cdots\cdots (12)$$

where L_m is the mechanical loss.
The torque T can be expressed as follows:

$$T=\frac{P_m-L_m}{(1-S)w_0}=\frac{P_2}{w_0}-\frac{L_m}{(1-S)w_0} \cdots\cdots\cdots (13)$$

9. Active and Reactive Components of Secondary Current Fundamental Wave

When the active component of the secondary current fundamental wave is I_{2a} and the reactive component is I_{2b},

$$I_{2a}=\sqrt{\frac{3}{2}}\frac{1}{\pi}\{I_d(1+\cos u)-I_d[\sin\phi+\sin(u+\phi)\sin\phi+I_S[u\cos\phi-\sin u\cdot\cos(u+\phi)]\} \quad \cdots\cdots (14)$$

$$I_{2b}=-\sqrt{\frac{3}{2}}\frac{1}{\pi}\{I_d[\sin u+\sin\phi(\cos\phi+\cos(\phi+u)]+I_S[u\sin\phi-\sin u\sin(u+\phi)]\} \quad \cdots\cdots (15)$$

when the terms $\left(\frac{R_2}{SwL_2}\right)^2$ and $\frac{uR_2}{SwL_2}$ are negrected, the effective value of the fundamental wave $|I_{21}|$ becomes:

$$|I_{21}|=\sqrt{\frac{3}{2}}\frac{1}{\pi}I_d\frac{\sqrt{(\sin u-u\cos u)^3+u^2\sin^2 u}}{I-\cos u} \quad (16)$$

The secondary power factor $\cos\phi_2$ is expressed as:

$$\cos\phi_2=\frac{\sin^2 u}{\sqrt{(\sin u-u\cos u)^2+u^2\sin^2 u}} \quad \cdots\cdots (17)$$

10. Primary Voltage

The primary voltage E_1 can be expressed by the following equation when the excitation current is neglected:

$$E_1=aE_2+\frac{I_2}{a}Z_1\doteqdot aE_2+\frac{1}{a}(I_{2a}+jI_{2b})(R_1+jL_1w) \quad \cdots\cdots (18)$$

When the secondary dc voltage is substituted for the primary phase voltage:

$$E_{d1}=\frac{E_1}{a}\frac{3\sqrt{6}}{\pi} \quad \cdots\cdots (18)'$$

Using approximations, equation (18)″ can be obtained.

$$E_{d1}=E_{d0}+\left(\frac{3}{\pi a}\right)^2 I_d\{R_1(1+\cos u)+L_1wu\} \quad \cdots\cdots (18)''$$

11. Effective Values of Primary and Secondary Currents

When the harmonic component of the secondary current is I_H and the active and reactive components of the excitation current are I_{0a} and I_{0b} respectively, then:

$$I_2=\sqrt{I_{2a}^2+I_{2b}^2+I_H^2} \quad \cdots\cdots (19)$$

$$I_1=\sqrt{\left(I_{0a}+\frac{I_{2a}}{a}\right)^2+\left(I_{0b}+\frac{I_{2b}}{a}\right)^2+\left(\frac{I_H}{a}\right)^2} \quad \cdots\cdots (20)$$

12. Ac Output Voltage of the Thyristor Inverter (E_{ac})

$$E_{ac}=\frac{1}{K_V}\frac{SE_{d1}-2_{es}-2_{eth}}{\cos\gamma_{\min}} \quad \cdots\cdots (21)$$

In this equation, e_{th}: layer voltage per thyristor arm, K_V: constant determined by connection method (1.35 for 3-phase bridge connections), $\gamma_{\min}$: minimum control advance angle of inverter.

13. Torque of Thyristor Scherbius Equiqment

when the dc voltage of the thyristor inverter is expressed as E_d, then:

$$E_d=K_V E_{ac}\cos\gamma+\frac{3}{\pi}X_t I_d+2e_{th}+2R_t I_d \quad \cdots\cdots (22)$$

Where $X_t=L_{tw}$: sum of one phase of each of the reactances on the primary and secondary sided of the inverter transformer (converted to the dc side), R_t: sum of one phase of each of the resistances on the primary and secondary sides of the inverter transformer (convertered to the dc side).

From equations (8)′, (22) and (18)″, the following can be obtained:

$$I_d=\frac{SE_{d1}-K_V E_{ac}\cos\gamma-2e_s-2e_{th}}{\Sigma R} \quad \cdots\cdots (23)$$

where $\Sigma R=\frac{3}{\pi}L_2wS+R_2\left(2-\frac{3u}{2\pi}\right)+\frac{3}{\pi}X_t+2R_t+R+\left(\frac{36}{\pi a}\right)^2$

$SR_1(1+\cos u)+L_{1wu}$

$R\gamma$ is the ac reactor resistance. The torque T can be obtained by substituting equation (23) in equation (12).

14. Block Diagram

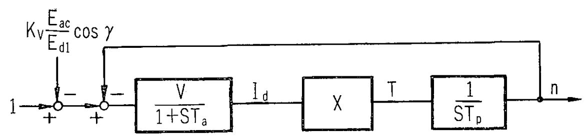
Fig. 18 is a block diagram based on equations (12)′ and (23). It can be seen from this diagram that the static Scherbius equipment ressembles Leonard equipment in respect to control.

15. Maximum Speed

The thyristor inverter is controlled in the rectifier range and, the dc reactor and inverter voltage drop can be compensated. Therefore, the induction motor is subjected only to secondary resistor and silicon rectifier voltage drops and the maximum speed can be attained. The equipment used in the Joto Pumping Station of the Osaka Waterworks has a slip of only 2% using this system. However, in this case the dc side current is increased by about 10% in respect to the rated secondary current so that care must be taken when selecting the current ratings of the dc reactor, the silicon rectifier and the thyristor inverter.

16. Harmonics

When 6-phase inverters are used in static Scherbius systems, a harmonic current of the order of $6n\pm1$ flows and a harmonic voltage arises because of power



L_r: Reactance of series reactor
x: Transfer function from equation (12)'
If 1+con μ is considered to be constant, $x=1$
T_p: Time required for acceleration to synchronous speed at rated torque
I_{dn}: Rated dc current

Fig. 8 Block diagram of static Scherbius set

source impedance. The magnitude of the $6n \pm 1$ order harmonic current is about $1/6n \pm 1$ of the fundamental wave current. The fifth harmonic is about 20% of the fundamental wave.

If the inverter is increased to 12 phases, the harmonic can be of the order of $6(2n-1) \pm 1$. In such a case, the harmonic with the maximum amplitude is the 11th and it is only about 9% of the fundamental wave. This is thus an effective method of reducing the harmonics.

When several units of static Scherbius units are connected, the inverter couplings are alternately $\Delta-\Delta$ and $\Delta-\curlywedge$ so that it is possible to arrange a 12 phase rectifier. The four 1400 kw units and the two 970 kw units delivered to the Joto Pumping Station of the Osaka Waterworks employ this system.

V. MAIN EQUIPMENT

1. Converter

The low capacity silicon rectifiers and thyristors are arranged in a stack type construction, while the large capacity equipment is in a building unit (Baustein) type of construction. The forced air type cooling system is standard for the large capacity units, while the small capacity equipment employs natural cooling. The equipment in the Inotaka Pumping Station of the Nagoya Waterworks used natural cooling.

2. Dc Reactor

In pumps and fans where the load torque is proportional to the square of the speed, the current increases and the voltage decreases if the voltage pulses occur often due to a large control angler of the dc reactor reactance. If the pulses are decreased by making the control angle small, the current decreases and the voltage increases. Therefore, it is best to have a nearly constant reactance for all speeds. However, in equipment such as extractors where the

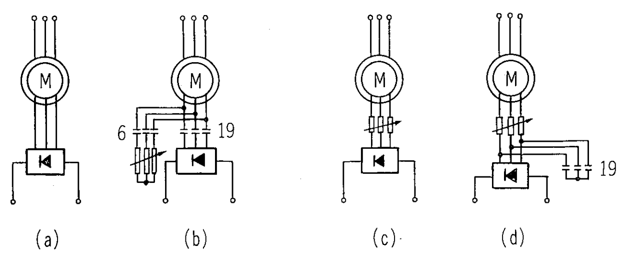


Fig. 10 Stating system of Scherbius set

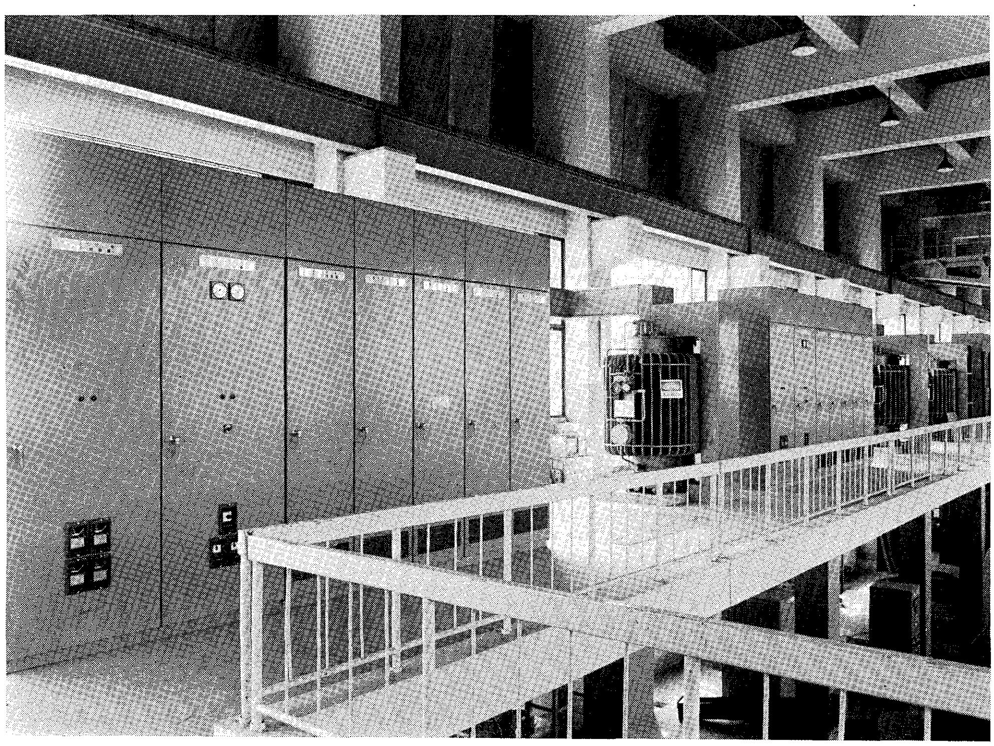


Fig. 9 Static Scherbius inverter for Osaka Waterworks

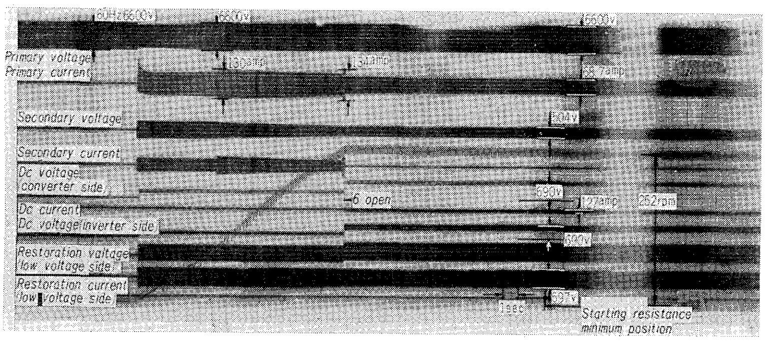


Fig. 11 Oscillogram at start of static Scherbius set

load torque is constant, it is necessary to have a large reactance when the voltage decreases.

3. Inverter Transformer

The inverter transformer can be of the oil-immeresed natural cooled type, the incombustible oil-immersed type or the dry type with H class insulation. The coupling is Δ–Δ, $\curlywedge$–Δ, or Δ–$\curlywedge$, and a grounded insulation plate is inserted between the primary and secondary windings. The inverter transformer capacity, P_1, is as shown in equation (24) where I_{dn} is the rated current on the dc side.

$$P = \sqrt{2}\, E_{as} \cdot I_{dn} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (24)$$

VI. CONTROL SYSTEM

1. Starting System

The starting system for static Scherbius equipment employs one of the following three methods.

1) Method without starting resistor

With the method shown in *Fig. 10* (a), the capacity of the power converter is about the same as the capacity of the main motor. Therefore, it can not be used for such things as pump control where the speed control range is small.

2) Method using a starting resistor with switching during starting

The method is used when the speed control range is small. A starting resistor is used until the minimum speed is reached, and at the minimum control advance angle, magnetic contactor (19) is closed and the system is switched from the starting resistor back to the starting equipment. At this time, the magnetic contactor used for the starting resistor (6) is opened. This method is shown in *Fig. 10* (b)

3) Method with starting resistor inserted in series

The method shown is *Fig. 10* (c) has the starting resistor connected in series which makes a progressive short circuit. The advantage of this method is that it is not necessary to combine the dc voltage of the power converter and the secondary voltage of the induction motor. However, it is necessary to think of the induction motor secondary voltage as the withstand voltage of the power converter. In order to aboid this kind of problem, a magnetic contactor for short circuits is provided as shown in *Fig. 10* (d). During starting, the contactor forms a short circuit and starting is carried out by the starting resistor. Once the motor reaches its minimum speed, this contactor is disconnected. At this time, there is still some resistance left in the starting resistor, and a progressive short circuit is present as long as the starting current is maintained. Therefore, Scherbius operation is employed. The Scherbius equipment delivered to the Joto Pumping Station of the Osaka Waterworks employs this starting method. *Fig. 11* shows an oscillogram obtained during starting. This starting method is effective when one Scherbius converter set is used in common with several main motors. In this way, when another motor is going to be started while one is already operating at some arbitrary speed, it is not necessary to use a voltage comparison device and starting can be performed smoothly.

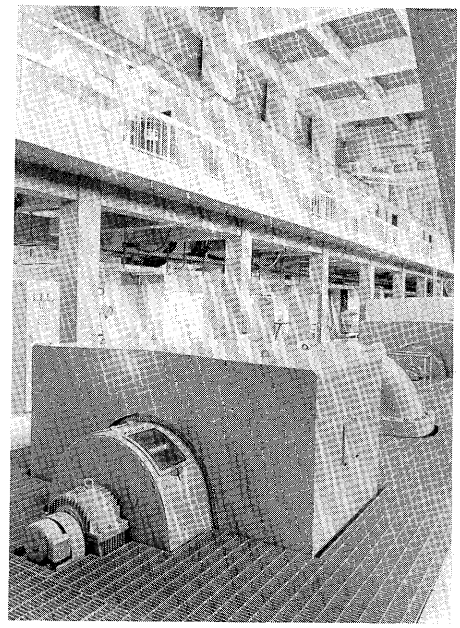


Fig. 12 Static Scherbius set for Osaka Waterworks

2. Stopping System

1) When the system in *Fig. 10* (b) is used

Magnetic contactor (6) is shorted, (19) is opened and the main motor breaker is stopped.

2) When the systems is *Fig. 10* (a), (b) or (d) are used

The dc side breaker is opened, and simultaneously, the main motor breaker is tripped. In this case, the switching surge is minimized by inserting parallel resistor in the dc side breaker. This resistor can also remain connected during normal operation. Various other mechanisms can be used in this stopping system. For example, in the equipment for the Joto Pumping Station of the Osaka Waterworks, a stopping command causes the control advance angle γ to become a minimum. The voltage on the inverter dc side then reaches a maximum and becomes more than the voltage on the secondary side of the induction motor. Operation of the silicon rectifier then causes the induction motor secondary side to open so that the dc side current is interrupted and the dc breaker is opened. With this method, the dc breaker does not switch the current so that the switching life is only determined mechanically and it is therefore possible to insure a long switching life. This system can also be used for overcurrent protection which will be described later.

3. Speed Control

When automatic speed control is performed, a minor loop is provided for motor secondary current control. This contains a current limiter.

When pumps are operated in parallel, many cases arise where the pump loads differ even when control is performed at the same speed. This is caused by the fact that the pump characteristics might not be exactly the same and the piping systems might differ. In such cases, a method by which the currents are made uniform is used in place of uniform speed conrol. The equipment for the Joto Pumping Station of the Osaka Waterworks was designed so that either the uniform current or the uniform speed control can be used.

VII. POWER FACTOR IMPROVEMENT

Since the overall power factor of static Scherbius equipment is not good as can be seen from *Figs. 2~5*, a capacitor is provided for power factor improvement. There are various capacitor insertion method which are applicable. With this capacitor, power factors of 95% and over can be attained.

VIII. PROTECTIVE SYSTEMS

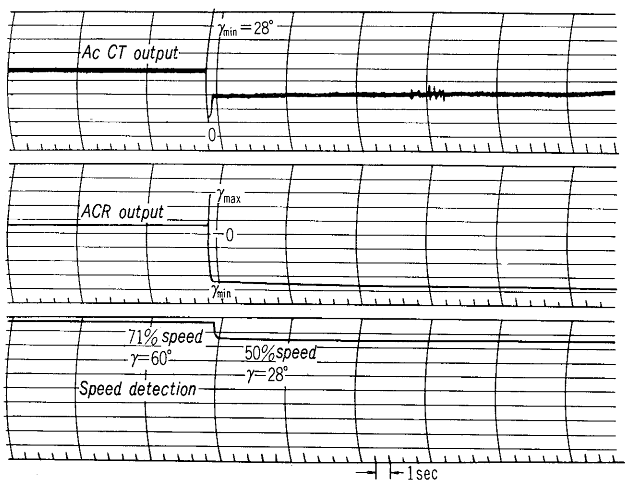


Fig. 13 Oscillogram at commutation failure by extinction method

1. Protection of the Converter

This system is the same as that used in ordinary external commutated type inverters. Overcurrents are prevented by means of the current control circuit and in case of faults, the silicon rectifier and thyristors are protected by means of high speed fuses. When it is not desirable to blow the fuses at the time of a fault, protection is provided by a high speed breaker or a wiring breaker. The overcurrent extinction system described later is effective against overcurrents caused by commutation losses etc. and faults can be handled without the use of a high speed breaker even when the fuses do not blow. This method is the same as that for the stopping system described in section VI. 2. 2) The overcurrent is detected by either an anode current transformer or a dc current transformer, the control advance angle becomes a minimum and extinction occurs. *Fig. 13* shows an oscillogram obtained using the overcurrent extinction method during commutation failure in 1400 kw thyristor Scherbius equipment. For this oscillogram, the actual circuit was altered for test purposes and when the extinction method was in progress, operation was continued at 50% of the speed. If the extinction method were used with its actual circuit, the main motor would be tripped. As can be seed from *Fig. 13*, after a commutation loss at a 71% speed, overcurrent extinction causes the secondary side of the induction motor to open and also the induction motor speed to drop. Operation continues at the speed when the control advance angle is at a minimum, i. e. 50% of the usual speed. Since over current detection takes place on the ac side of the inverter in this case, the ac side current drops to zero while the arc is passing due to the commutation loss and after an initial increase, the ACR output also drops to a mimimum. Therefore, in cases of commutation loss when overcurrent detection is on the inverter side, there are cases when detection can be converted to the dc by delaying the cerrent detection for about half a cycle. When the overcurrent extinction method is used, fuses protect against short circuits in the dc circuits. Overvoltage protection is also the same as that in ordinary ex-

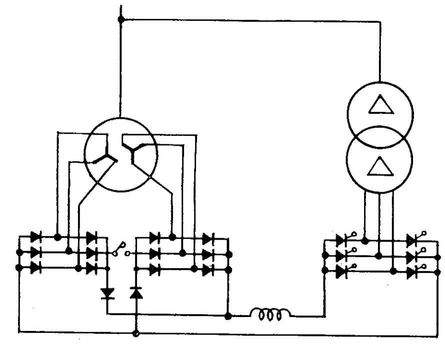


Fig. 14 Example of a modified Scherbius set

ternal commutated type inverters. An insulation plate is inserted between the primary and secondary windings of the inverter transformer and the control power source transformer and surge voltage shifts are kept to a minimum. Surge absorbers are also provided in the silicon rectifier and the CR. Protection against slip voltage increases in the induction motor is provided by means of a voltage relay. Protection of the thyristor elements is related to gate control and is handled in the usual manner. It will be omitted here.

2. Protection of the Main Motor

The same type of protection systems as used for ordinary induction motors can be used in this case, but since a voltage with a period 6 times the frequency of the power source occurs in the motor bearing, this could have an adverse influence on the bearing. In such cases, this problem can be eliminated by grounding the bearing via the brush.

IX. VARIABLE TYPE SCHERBIUS EQUIPMENT

1. Common Scherbius Equipment

One unit of this type of equipment is used as a power converter for several motors of the same specifications. It is also used for converting the connections of series and parallel elements in dc circuits. When the connections are in parallel, operation must be at approximately equal speeds since the motor secondary voltage is constant. This system was used in the three 500 kw units for the Inotaka Pumping Station of the Nagoya Waterworks. When the connections are in series, operation is at approximately the same torque since the dc load current is constant. This system was used in the two 500 kw crane-drive Scherbius devices delivered to Ube Industries.

When thyristor Scherbius equipment is used for speed control in devices such a pumps with square torque charactersitic loads, the equivalent capacity of the thyristor inverter is smaller than the maximum secondary output. The main motor secondary voltage is high at low speeds and low at high speeds, but the secondary current is just the opposite, low at low speeds and high at high speeds. Therefore, if the series connections are used at high speeds and the parallel connections used a low speeds, the capacity of the converter can be kept small.

2. Other Systems

For the same systems as described previously but with only one main motor, the main motor rotor undergoes 12-phase rectification, and two 3-phase bridge circuits are provided as shown in *Fig. 14*. The dc circuit is converted between series and parallel connections. The secondary voltage can be switched by means of a single winding voltage transformer located on the secondary side of the main motor. This system is not economical for conversion in equipment where the speed control range is small. The low limit is a slip adjustment range of 30% and this conversion system is best used in equipment with ranges of over 50%.

X. CONCLUSION

As described above, the static Scherbius equipment possesses many excellent features. All the systems described here for both forward/reverse acceleration/decleration and super synchronous operation control are now no longer in the development stage but are now being used in practice, and their field of applications will no doubt become wider as time goes on. Finally, the authors wish to give credit to those faithful customers who employed these systems in the past.