UDC 621. 313. 333. 076. 6-531

SUPER SYNCHRONOUS SCHERBIUS

Yoshikatsu Tsuji
Mikio Takeda
Toshikatsu Tsuchiya

I. INTRODUCTION

As one method for the speed control of induction motors, the static Scherbius system with a static converter which collects slip power on the secondary armature side of a wound rotor induction motor has been widely used.

The static Scherbius, when compared with the system which controls the frequency on the primary armature side, is simple and low priced in respect to the converter and its control but since the speed control range is only the positive slip range and braking operation can not be performed, it has been only used to pump loads which require no variable speed response and to loads which operate constant speed.

The super synchronous Scherbius has the following advantages when compared with the static Scherbius :

- Operation is possible above and below the synchronous speeds.
- Because of regeneration control, variable speed response is good.
- Very little reactive power is taken from the supplied system.
- The converter capacity can be small.

This system is now being applied utilizing these advantages to the utmost. In this article, an outline of the basic theory of the super synchronous Scherbius system and examples of its applications are introduced.

II. PRINCIPLE OF SUPER SYNCHRONOUS SCHERBIUS

1. Principles of Secondary Control

The induction motor generates a torque at the vector product of the flux of the rotating field produced by the primary armature current and the secondary armature current.

Fig. 1 explains the basic principles. In *Fig. 1 (a)*, voltages of the polarities shown in the figure are induced at the speed difference between the speed ω_1 of the rotating field and the shaft rotating speed ω_2. Since currents of the same polarity flow, a torque

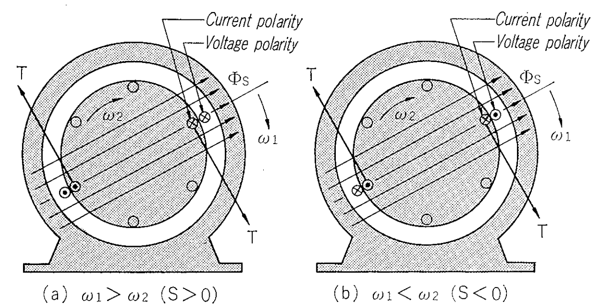


Fig. 1 Explanation diagram of basic principles

is generated in the direction shown in the diagram.

In the static Scherbius, the secondary armature current does not flow at the synchronous speed which does not induce a voltage and therefore, a torque can not be produced. If a current can flow in the secondary armature winding at the polarity shown in the figure, a torque can be produced. Under such conditions, the current increases and if the generated torque increases, the motor speed exceeds the synchronous speed.

In this case, the polarity of the voltage induced in the secondary armature winding is reversed in respect to the position of the rotating field as shown in *Fig. 1 (b)* but the current must be at the same polarity as under the synchronous speed.

In other words, no matter if above or below the synchronous speed, a torque in the same direction is produced if a current of the same polarity is flowing in the winding corresponding to the position of the rotating field and if the current polarity is reversed, a torque in the reverse direction can be obtained.

The super synchronous Scherbius achieves the operation described above. Since the direction of rotation is decided by the direction of the rotating field which is supplied to the primary armature, it is necessary to switch the phase rotation direction of the supplied voltage for reversible operation.

Fig. 2 shows the basic construction of the super synchronous Scherbius and since in principle, the diode rectifier in the static Scherbius is changed to a thyristor rectifier, the slip power can be absorbed

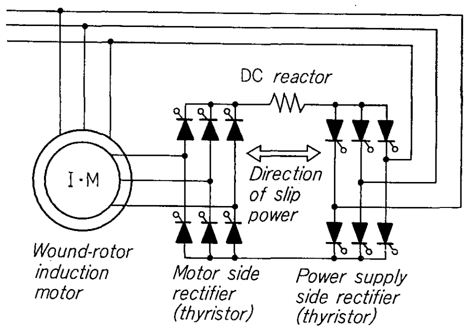


Fig. 2 Basic construction of super synchronous Scherbius

and supplied from the secondary armature.

The thyristors in each of the motor side rectifiers shown in the figure are fired in accordance with the position of the rotating field and it is possible to regulate the magnitude of the secondary armature current by phase control in the power source side rectifier.

The position of the rotating field when viewed from the secondary armature is in phase of the induced voltage with the slip frequency.

2. Power Flow

As was described previously, during driving condition, in the operation at less than the synchronous speed ($S>0$), a current flows in the same direction as the induced voltage so that slip power comes from the secondary armature. At operation above the synchronous speed ($S<0$) a current of reverse polarity to the induced voltage flows and the slip power is supplied to the secondary armature.

On the contrary during braking operation, the power flow is reverse in each speed range.

When the total input is taken as P_0, the primary armature power as P_{M1}, the mechanical output as P_m, the slip power as P_{M2} and the slip as S, the direction in which the power flows is as shown in *Fig. 3*.

The relations between the magnitudes of the power disregarding the loss are as shown in equation (1).

$$\left.\begin{aligned} P_0 &= P_m \\ P_{M1} &= P_m/(1-S) \\ P_{M2} &= S\cdot P_m/(1-S) = SP_{M1} \end{aligned}\right\} \qquad \cdots\cdots\cdots\cdots\cdots\cdots(1)$$

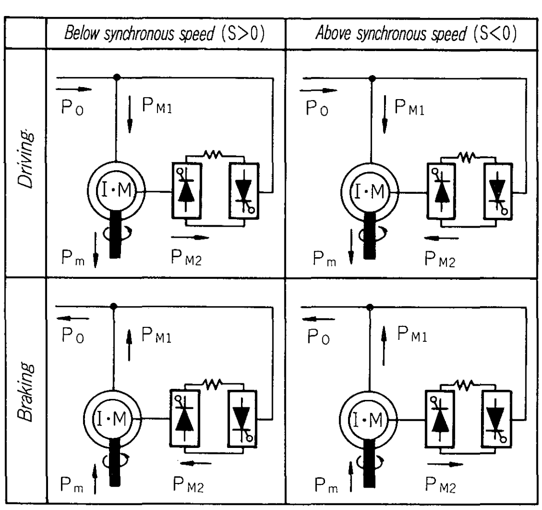


Fig. 3 Power flow diagram

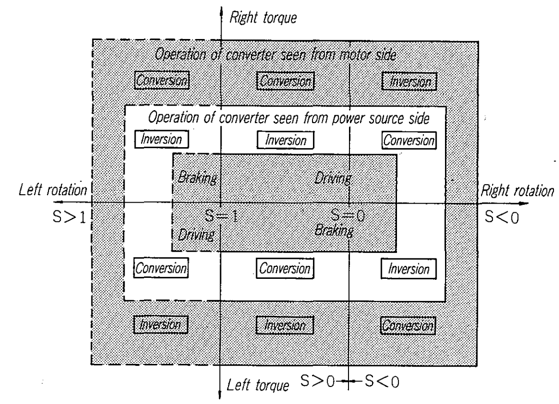


Fig. 4 Operation modes of converter

3. Operation Modes of Converter

The converter must perform forward or reverse conversion operation in accordance with the flow direction of the slip power.

In other words, when the slip power is regenerated from the secondary armature to the power supply, the motor side rectifier performs forward conversion and the power source side rectifier performs reverse conversion. When the slip power is supplied to the secondary armature, the motor side rectifier performs reverse conversion and the power source side rectifier forward conversion.

Fig. 4 gives an explanation of these conditions.

The power source side rectifier performs stable commutation by means of the power source voltage but since the motor side rectifier performs commutation by the secondary armature induced voltage, commutation is impossible in the vicinity of the synchronous speed of a small induced voltage.

Therefore, in equipment with the DC intermediate circuit as shown in *Fig. 2*, it is necessary to provide an auxiliary means of commutation.

For the converter, the cycloconverter shown in *Fig. 5* which has no DC intermediate circuit is often used to solve this problem.

In this case, even when the secondary armature induced voltage is small, commutation is possible with the aid of the AC voltage on the power source.

III. BASIC THEORY

1. Commutation Modes

Fig. 5 shows the basic circuit of the cycloconverter type super synchronous Scherbius equipment.

Since the cycloconverter combines the functions of the previously mentioned motor side and power source side rectifiers, the form is completely the same when viewed from either the motor or the

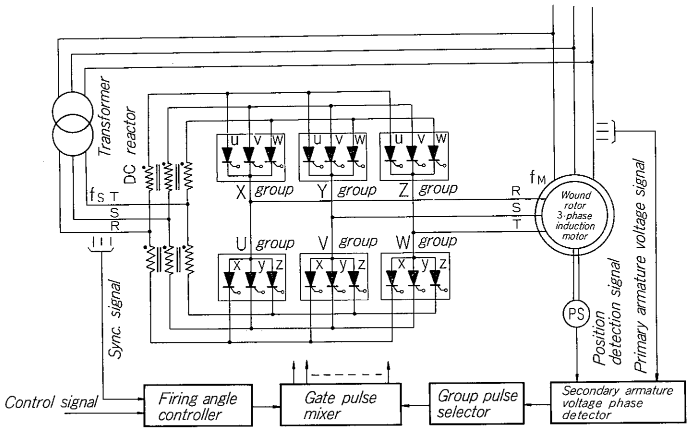
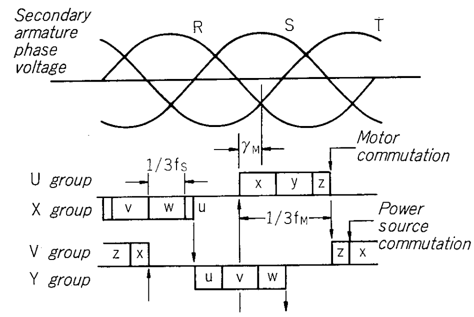


Fig. 5 Connection diagram of cycloconverter type super synchronous Scherbius system



f_M: Secodary armature voltage frequency
f_S: Power source frequency

Fig. 6 Gate pulse and commutation of cycloconverter

power source side.

In *Fig. 5*, there are 6 groups seen from the motor side and these groups are selected in accordance with the secondary armature voltage phase (flux position of the rotating field) of the induction motor. The thyristors in the groups are selected in accordance with the power source voltage phase.

Therefore, the gate signal of each thyristor is formed by the logical product of both signals (AND condition).

There are two modes of thyristor commutation. In other words, since the commutation of the thyristors in the groups is performed by means of the power source voltage, it is called "power source commutation" and the commutation between the groups is called "motor commutation" because it is performed by the secondary armature voltage.

The thyristor conducting condition, i.e. the gate pulse distribution pattern is as shown *Fig. 6*. The secondary armature current and the power source side current each have 120° conducting square-wave forms based on the motor frequency and the power supply frequency respectively.

The signal for group selection is synchronized with the secondary armature induced voltage and becomes the thyristor firing signal but the control angle γ_M in respect to this induced voltage is determined to perform the thyristor commutation reliable with consideration of the commutation overlapping angle and the margin angle of commutation.

Since γ_M is an important value which determines the power factor, torque magnitude and the equipment capacity, it is necessary to detect the electrical phase of the secondary armature voltage at a high accuracy.

2. Generated Torque

The torque generated by the induction motor is a ripple torque since it is the vector product of the sinusoidal flux crossed in the secondary armature winding and the secondary armature square wave current.

By Fourier analysis, the average torque and the ripple torque can be expressed as in equation (2).

$$\tau=\frac{\sqrt{3}P}{2\omega_1}E_{M\Delta 1}I_{M2}\Big[\underbrace{\cos\binom{\gamma_M}{\alpha_M}}_{\text{average torque}}+\underbrace{\sum_{m=1}^{\infty}\sqrt{\frac{2}{36m^2-1}}\sqrt{\frac{36m^2+1}{36m^2-1}-\cos 2\binom{\gamma_M}{\alpha_M}}\cdot\sin 6mS\omega_1 t}_{\text{ripple torque}}\Big] \qquad \cdots\cdots(2)$$

where τ: instantaneous torque
$E_{M\Delta 1}$: line voltage of secondary armature at $S=1$
P: number of poles
I_{M2}: effective value of secondary armature fundamental wave current
ω_1: angular frequency of power source
γ_M, α_M: presetting angles

The ripple torque does not become the effective torque only because of the ripple of the axis and therefore, the mechanical power P_m is obtained muliplying the average torque by the axial rotational speed as shown in equation (3).

$$P_m=(1-S)\cdot\sqrt{3}E_{M\Delta 1}I_{M2}\cos\binom{\gamma_M}{\alpha_M} \qquad \cdots\cdots(3)$$

The magnitude of the ripple torque is proportional to the magnitude of the current and its frequency drops with an increase in the rotational speed. At the synchronous speed, it is zero and when the rotational speed increases, it becomes comparatively high.

This means that the axial vibration due to the low frequency vibration during starting which causes a problem in thyristor motors, etc. can be disregarded which is a feature of all Scherbius operation.

3. Converter Capacity

The motor torque is proportional to the secondary armature current as shown in equation (2). Therefore, when assuming the torque constant load, the current flowing through the converter is constant.

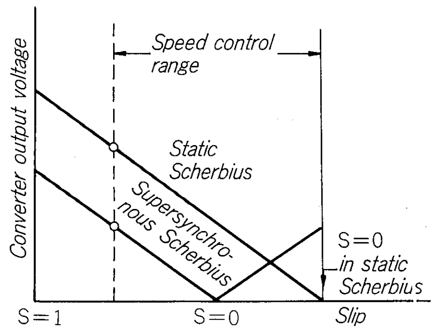


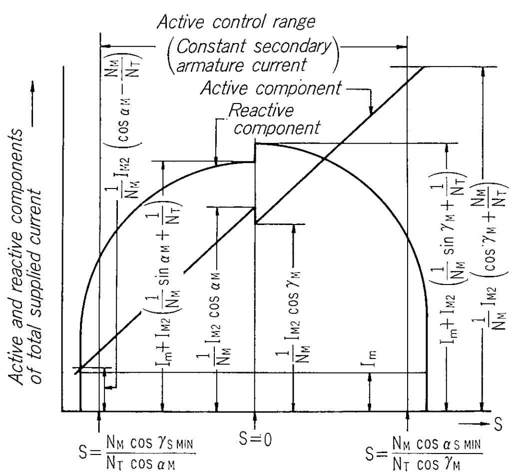
Fig. 7 **Comparison graph of thyristor converter capacity**

However, the converter voltage increases as the slip increases so that the power which the converter should handle drops as the slip decreases and reaches a minimum at the synchronous speed. As the negative slip increases, the direction of the power is reversed but it increases.

Therefore, if the speed control range is selected symmetrically above and below with the synchronous speed as the center, the secondary armature voltage of the motor is 1/2 when compared with the static Scherbius as shown in *Fig. 7* which means that the converter capacity can be halved.

Since the converter is phase controlled in respect to the AC power source in accordance with the rotational speed, reactive power occurs in the input. The total supplied current from the system is the vector sum of the motor primary armature current and the converter input current.

Fig. 8 shows the changes in the active and reactive components of the total supplied current in respect to slip. The active current increases as the rotational speed increases and the reactive current forms an approximate semicircle based on the



N_M : Turn ratio of induction motor
N_T : Turn ratio of transformer
I_m : Exciting current
α_M, γ_M : Motor side presetting angles
α_{SMIN}, γ_{SMIN} : Power supply side minimum control angle
I_{M2} : Effective value of secondary armature fundamental wave current

Fig. 8 **Total supplied current**

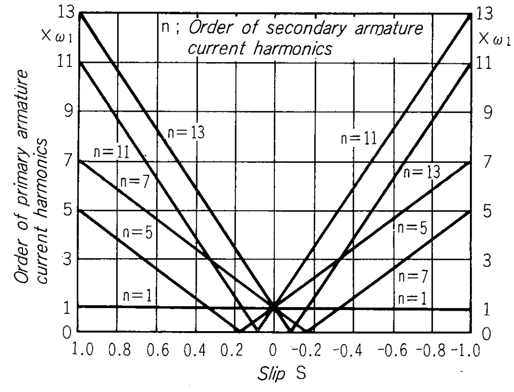


Fig. 9 **Frequency of secondary armature current harmonics seen from primary armature side**

excitation current component. The reactive current is a maximum at $S \doteqdot 0$ (condition under which the control angle of the power source side rectifier $\alpha_S \doteqdot 90°$).

This means that the rated rotational speed is to be selected at the value where the absolute value of the slip above the synchronous speed is large and operation with a high power factor and a small reactive power is possible.

4. Harmonics

The secondary armature current waveform is a square wave because of the action of the DC smoothing reactor and it contains harmonics. Therefore, a harmonic current flows in such a way that the flux is eliminated by the current in the primary armature also.

The order of the primary armature current harmonics in respect to the source frequency is $6NS \pm 1$ ($N = 1, 2, 3......$) and there is a fractional harmonic in respect to the slip.

Fig. 9 shows the relation between the harmonics of the primary armature current vs. the slip.

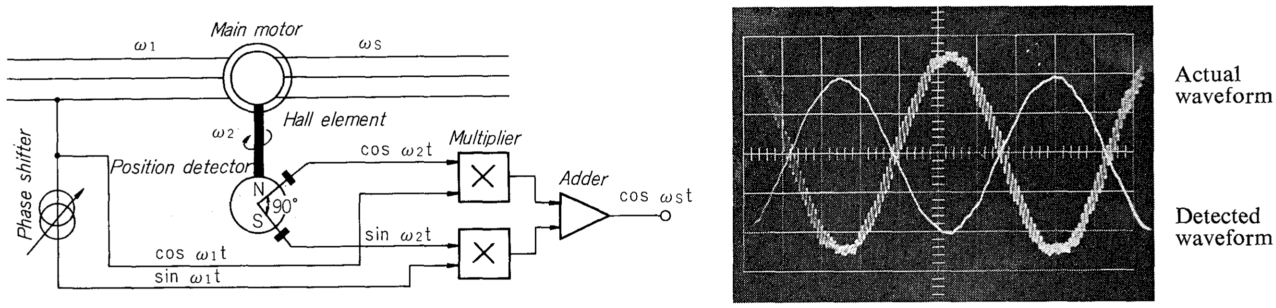
IV. CONTROL SYSTEM

1. Detection of the Secondary Armature Voltage Phase and the Gate Pulse

The signal which selects the thyristor group of the cycloconverter should be determined in respect to the secondary armature voltage phase and it is necessary to detect the secondary armature voltage phase as was described previously.

In practice, the secondary armature voltage amplitude changes with the slip and it becomes zero at the synchronous speed. Therefore near the synchronous speed, it is impossible in practice to detect directly the secondary armature voltage phase.

The secondary armature voltage of the induction motor is induced by the linking of the rotating field at the power source frequency and the secondary armature winding. A detection method has



(a) Circuit construction (b) Detected waveform ($S=-0.4$)

Fig. 10 Secondary armature voltage phase detector

been conceived on the basis of this fundamental principle (patent applied for).

If the angular frequency of the primary armature voltage is ω_1, then the angular frequency of the secondary armature voltage becomes $S\omega_1$.

This corresponds to $\omega_1-\omega_2$ when ω_2 is the rotational angular velocity of the secondary armature.

Therefore, the phase of the secondary armature voltage is as follows when $S\omega_1=\omega_S$:

$$\cos\omega_S t=\cos(\omega_1-\omega_2)t$$
$$=\cos\omega_1 t\cos\omega_2 t+\sin\omega_1 t\sin\omega_2 t \quad \cdots\cdots\cdots\cdots\cdots\cdots(4)$$

If the cos $\omega_1 t$ and sin $\omega_1 t$ of the rotating field and the cos $\omega_2 t$ and sin $\omega_2 t$ of the mechanical rotation position of the secondary armature are detected and equation (4) is processed, the phase of the secondary armature voltage can be obtained.

The position of the rotating field can be represented by the primary armature voltage and the secondary armature position is coupled to the magnet of the same number of poles in the motor shaft and the position can be detected in a sinusoidal waveform by a search coil or magnetically sensitive element such as the Hall element located at a 90° position electrically.

Fig. 10 (a) shows the principle circuit of the secondary armature voltage phase detection method and *Fig. 10 (b)* shows an example of the detected signal waveform and the actual secondary armature voltage.

The selection signal for the thyristor group of the cycloconverter is formed from the signal voltage detected in the circuit in *Fig. 10.* The phase relation between the secondary armature voltage and the thyristor group selection signal is shown in *Fig. 11* in respect to the operating modes of the super synchronous Scherbius.

As was described previously, the gate pulses given to each of the thyristors in the thyristor groups are taken as the AND (logical product) of the group selection signal and the pulse for the power source voltage phase.

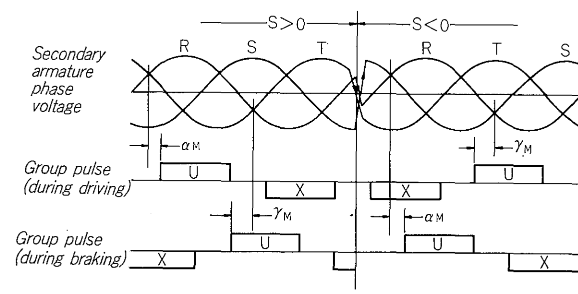


Fig. 11 Relations between secondary armature voltage and group selecting signal

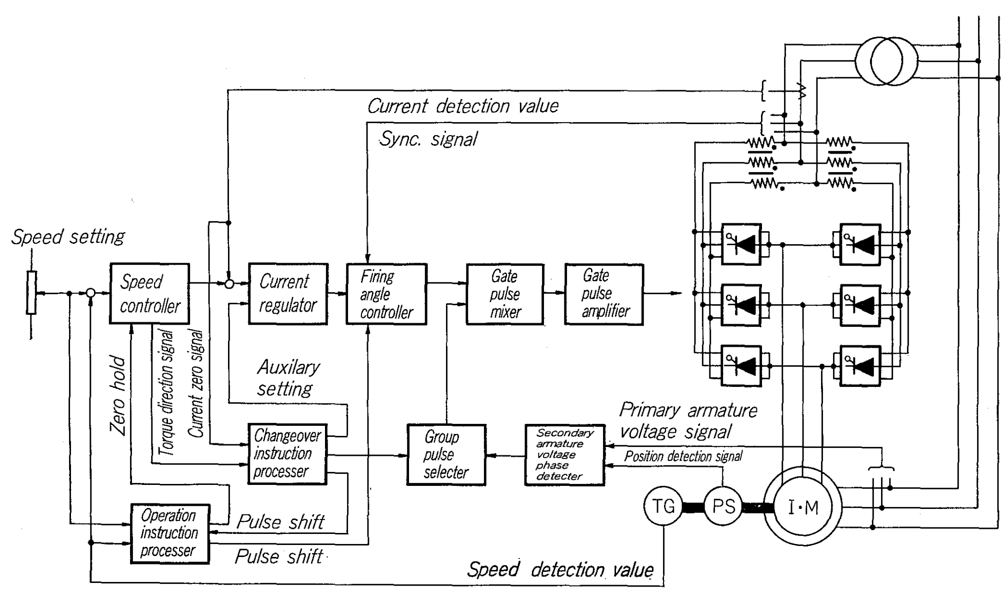


Fig. 12 Skeleton diagram of automatic speed control system

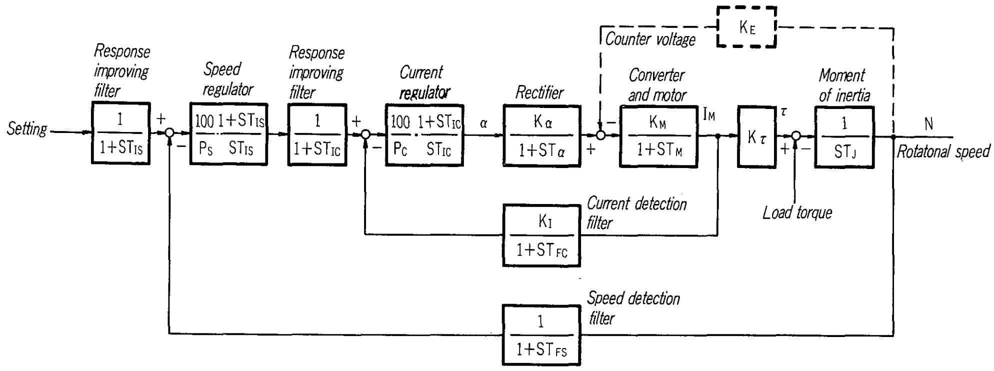


Fig. 13 **Block diagram of automatic speed control system**

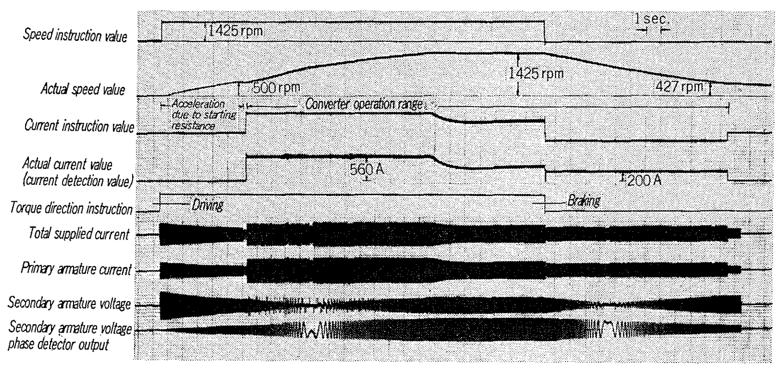


Fig. 14 **Oscillogram at acceleration and deceleration conditions**

2. Automatic Speed Control System

Fig. 12 shows an example of the super synchronous Scherbius speed control system consisting of a speed control loop as a major loop and a current control loop as a minor loop.

The changeover instruction processor in the figure is used to change the torque direction and it can change the pulse relation between the secondary armature voltage and current phases.

Fig. 13 a block diagram of the system including the transfer functions. If the current control loop response is fast and the gain high, there is no influence from the counter electromotive force loop in the current loop response and the counter electromotive force loop can be omitted.

When the speed control range is narrow and it is not necessary to control the speed in the low speed range, a starting resistance is connected in the secondary armature and when the speed control range is achieved, operation can be switched over to the converter.

Fig. 14 shows an oscillogram of the acceleration and deceleration operation above and below the synchronous speed.

V. EQUIPMENT CONSTRUCTION

The super-synchronous Scherbius equipment consists of a wound rotor induction motor as the main motor, a thyristor converter, a position detector which receives signal for the processing of the secondary armature voltage phase, etc.

1. Motor

The motor used in the super synchronous Scherbius is basically the same as the conventional wound rotor induction motor and has been designed considering the speed control range, load torque characteristics, etc. Special consideration was paid to the operating characteristics of the super synchronous Scherbius.

(1) Because of operation at speeds above the synchronous speed, the mechanical strength was designed on the basis of the maximum rotational speed.

(2) The number of poles and secondary armature voltage were selected, including the starting system, in consideration of the economy of the overall equipment.

(3) The cooling system and heat capacities of the various parts were determined by considering the load torque characteristics.

(4) The loss generated by the harmonic current included in the armature current was considered.

(5) The power factor drop and ripple torque based on the existence of the presetting angle γ_M were taken into considesation.

(6) Since the slip frequency increases when the speed control range is wide, a construction was employed so that the copper loss and other stray losses would not increase too much.

(7) The design was such that the reactance was small.

Fig. 15 shows an example of a 380kW vertical shaft motor delivered for operation of a sodium

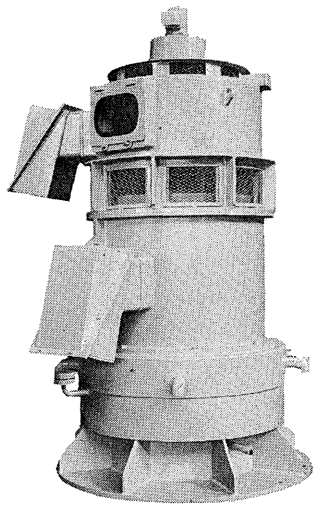


Fig. 15 Exterior view of 380kW motor

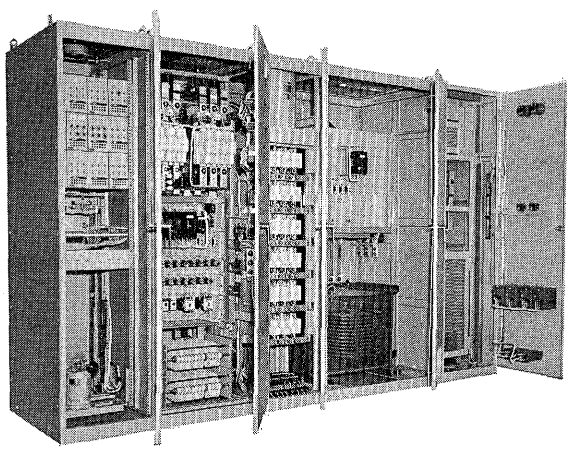


Fig. 16 Exterior view of converter cubicle for 380kW motor

circulation pump.

On the top of the motor in the figure is attached a tachogenerator for speed control and a secondary armature position detector.

2. Converter

The converter consists of a cycloconverter and its electronic control equipment, a DC reactor, a transformer, etc.

The thyristors of the cycloconverter were determined in consideration of the scattering and concentration of the current arising in relation to the power source frequency and the secondary armature frequency.

The DC reactor is used to decrease the current ripple and stabilize commutation as well as to suppress the abnormal harmonics and ripple torque. The coil layout in the reactor has been designed so that the commutation reactance is as small as possible.

The transformer for the rectifier has been decided by considering the presetting angle, the minimum control angle of power source side and the voltage drops in the various parts so that a voltage opposing the secondary armature voltage is given.

Fig. 16 shows the exterior view of the converter for a 380 kW motor.

VI. CONCLUSION

The Scherbius system has the feature of a low converter capacity when compared with variable speed operating equipment which controls the power to the primary armature. Therefore, such systems are useful in applications with narrow speed control ranges.

Descriptions have been given of the basic theory and the features of the super synchronous Scherbius. It is expected that application of these systems will increase in the fields requiring speed response because of their braking operation functions.

Referencee:

(1) Kazuno: Improvement of power factor for the static Scherbius system with double-range adjustable speed, Yamanashi University Engineering Research Reports, No. 22, 1971.

(2) Sakata: Static Scherbius system, Fuji Journal, 42. (7), 1969.

(3) Tsuji and Tsuchiya : Rotor position detection in super-synchronous Scherbius control induction motor, 48th All Japan Electrical Engineering Conference, 1973–742.