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TRANSIDYN C SYSTEM CONTROL DEVICES (Part II)

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V. THYRISTOR LEONARD (LEONIC) CONTROL SYSTEMS

In the case of the DC motor control, there is speed and torque because of control due to load requirements. To control the speed of a DC motor, the armature voltage or the field current may be changed. And to vary the torque, the armature current or the flux, i.e. the field current may be changed. The direction of rotation in the DC motor may be reversed by changing polarity of these.

In DC motor control whether from the armature side, the field side or in some cases from both sides, control of the required load is achieved. In cases which do not require reversible operation or regenerative torque, a non-reversible control system may be applied. The method of control in the case of reversible operation depends on the frequence and response of switching between forward and reverse, motor capacity, and costs. Ordinarilly when the switching frequence and response are low, an armature or field switching system with an electromagnetic contactor can be used. When the switching frequence and response are high, on the other hand, circulating current control, circulating current-free control, or reversible field control is used. In the case of high capacity motors, field capacity is usually a few percent of armature capacity, and reversible field control is used from the standpoint of converter capacity and cost, but this system has a demerit of low response on about one second.

1. Non-Reversible Control System

This system is used in cases where the DC motor rotates in only one direction and regenerative torque is not required or regeneration can be provided by a dynamic brake. This system is often used in LEONIC G device. Only one group of thyristor converter is employed.

2. Reversible Thyristor Leonard Control for Switching Armature Circuit

This system is used when reversing is required but the number of switchings are comparatively few. The basic circuit is shown in *Fig. 17*. Only one group of thyristor converter for armature circuit is employed. An electromagnetic contactor is provided in the armature circuit for reverse changeover. The changeover operation is performed as follows.

1) Stopped condition

The electromagnetic contactor of the armature circuit is released and the speed controller is in the zero hold condition. The auxiliary setting is applied in the current controller and the firing angle pulse is shifted to $\gamma_{min.}$ position.

2) Starting

When the starting command is applied, the contactor on the side in accordance with the torque polarity is closed, the armature circuit is connected, the zero hold condition of speed controller is released and current flows in the line circuit.

3) Reversing

When the output polarity (torque polarity) of the speed controller is reversed, the speed controller is placed in the zero hold condition and the auxiliary setting is applied to the current controller. The firing angle pulse of the firing angle regulator then shifts to $\gamma_{min.}$ position and the current in the line circuit becomes zero.

After the current in the line circuit becomes zero, the electromagnetic contactor in the armature circuit is released and the electromagnetic contactor is closed again on the other side. The zero hold of the speed

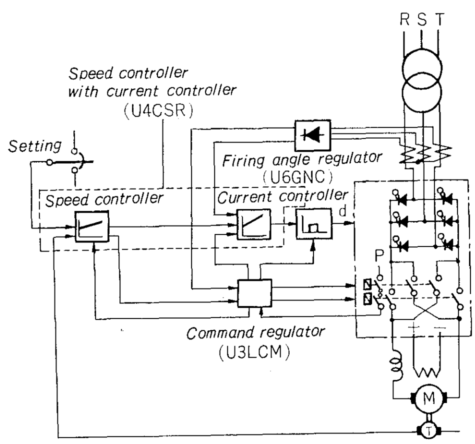

Fig. 17 **Block diagram of reversible thyristor Leonard control system for switching armature circuit**

controller on the other side is released, the auxiliary setting of the current controller is released and the control condition starts.

The polarity evaluation and changeover command is produced by the logic circuit in the command regulator and electromagnetic contactors of line circuit is switched over by this command. *Fig. 18* shows the acceleration and deceleration characteristics and the switching characteristics of this system. The outerview of control panel is shown in *Fig. 19*.

3. Circulating Current Reversible Thyristor Leonard Control System

The system is shown in *Fig. 20*. When the command is given from the speed setter to the unit integrator and start-stop regulator, the release command of zero holds is given to each controller under the set conditions and the speed command with a constant gradient from the unit integrator is given to the speed controller. The output of the speed controller becomes the setting of the current controller. For example on *Fig. 20*, when output (1) of the speed controller is positive (at this time, output (2) is always negative), the setting of current controller (1) becomes sum of the output of the speed controller and the setting of the circulating current. The setting of current controller (2) becomes only the setting of the circulating current because the negative setting from the speed controller is cut off by the diode of the current controller. At this time, thyristor converter group (1) supplies acceleration current to the motor and the motor speed is controlled at the set value. When a braking current becomes necessary, output (2) of the speed controller becomes positive and the setting of current controller (2) becomes the sum of the output of the speed controller and the setting of the circulating current so that a braking current flows in a thyristor converter group (2).

4. Circulating Currrent-Free Reversible Thyristor Leonard Control System

This system also employs two groups of thyristor converters in a anti-parallel connection system. However, the system with the circulating current because of the cross connection has the disadvantages

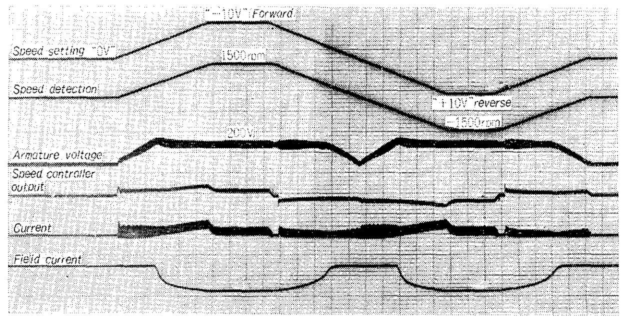

Fig. 18 **Oscillogram of reversible thyristor Leonard control system for switching armature circuit**

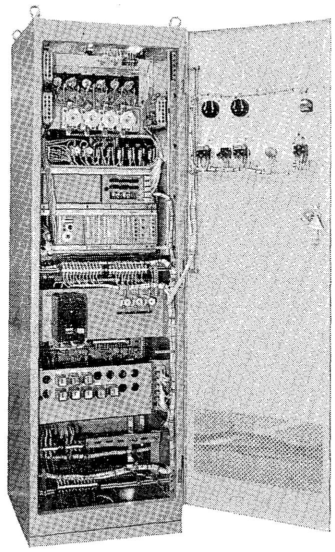

Fig. 19 **Outerview of reversible thyristor Leonard control system for switching armature circuit**

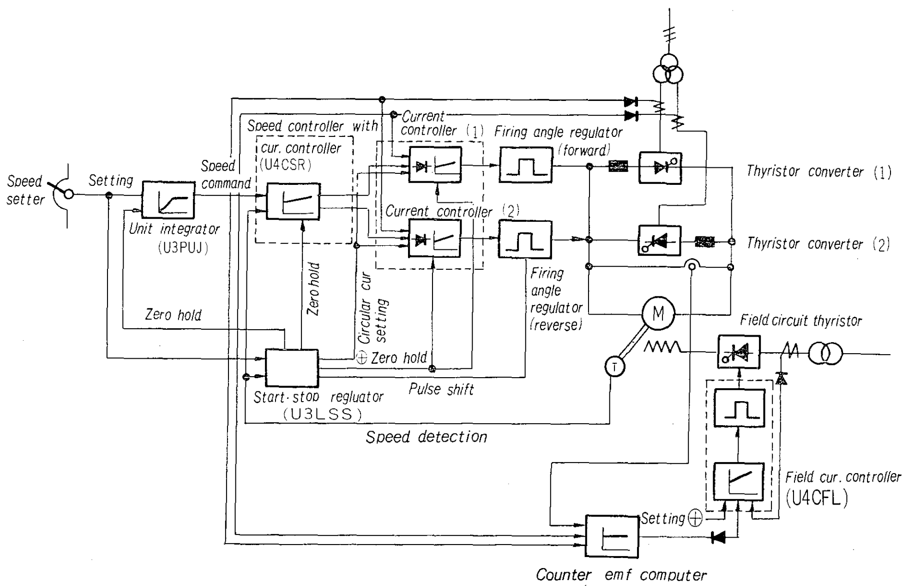

Fig. 20 **Block diagram of circulating current reversible thyristor Leonard control system**

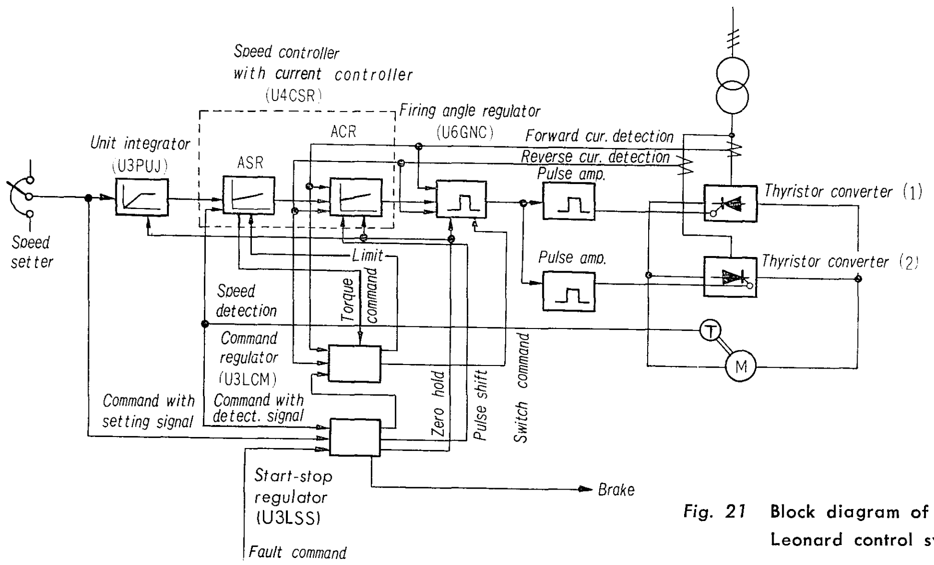

Fig. 21 Block diagram of circulating current-free reversible thyristor Leonard control system

of increased capacities of transformers and thyristor converter due to the circulating current, the generation of extra power losses and the need for a reactor to suppress the circulating current. These disadvantages can be eliminated if the two groups of thyristor converters are connected directly in anti-parallel so that only one group is operating at a time. *Fig. 21* shows a block diagram of this system. The switching of the thyristor converters is performed by evaluation of the torque polarity on the command regulator. The switching is performed in the following sequence.

1) The torque polarity of the motor to be used is reversed by changing the speed setting or the load torque.
2) When this torque polarity is detected on the speed controller, the switching commands are given to the speed controller by the command regulator.
3) The current in thyristor converter group (1) becomes zero.
4) It is confirmed that the current which has been flowing has become zero.
5) The gate pulse of thyristor converter group (1) is cut off.
6) Gate pulse is supplied to thyristor converter group (2) which was cut off and operation begins. (At this time, the following confirmation is performed, i. e. the new torque polarity is evaluated, and the thyristor converter on the side of this polarity is selected.
7) The current in the armature flows in the opposite direction to that before the switching.

In switching thyristor converters, commutation failure must not occur, the converters must not both conduct at the same time, and idle switching time must be held to a low value. Logic decision and protection are handled by the command regulator. *Fig. 22* shows the switching characteristics and *Fig. 23* shows an outerview of the control panel.

By adding the switching follow-up regulator to this system, switching time can be reduced and the control response can be almost the same as that with circulating current control.

5. Reversible Thyristor Leonard Control with Reversible Field Circuit

One thyristor converter is installed in the armature circuit of the DC motor, and two converters in the field circuit. When the polarity of the output torque is changed polarity of the motor field current is

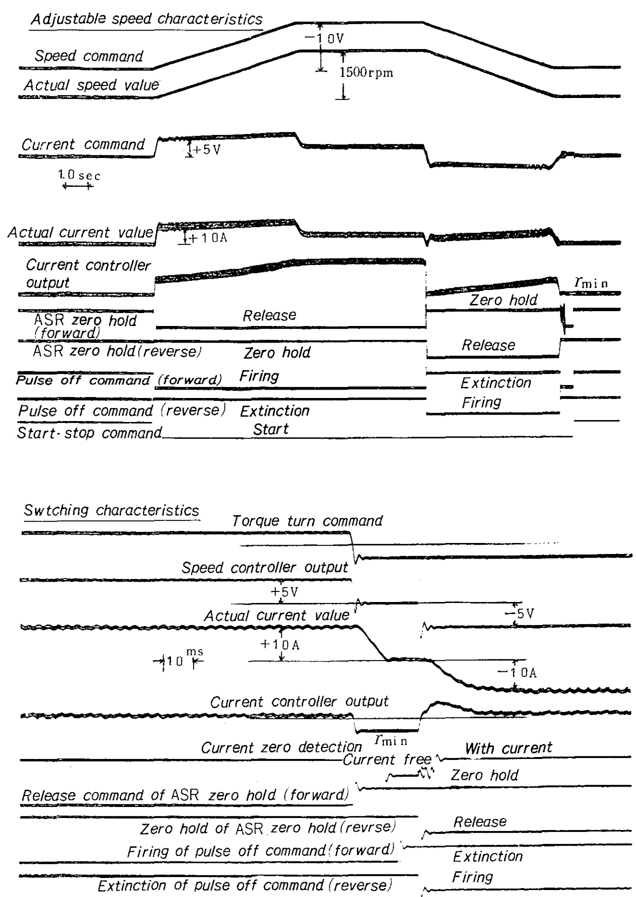

Fig. 22 Control response oscillogram of circulating current-free reversible thyristor Leonard control system

inverted between the two groups of thyristor converters. Armature switching is not used.

In comparing the armature switching control with the separate group of thyristor converters, switching response time for torque change and deceleration required field switching is delayed by the amount of time required for the field control loop.

torque from the speed controller is given to the field setting computer. The field setting of the correct polarity is then supplied to the field controller.

Fig. 25 shows a time chart of the field reversing operation in accordance with torque reversing. When the torque command has been reversed, the output of the speed controller is held down to zero V by

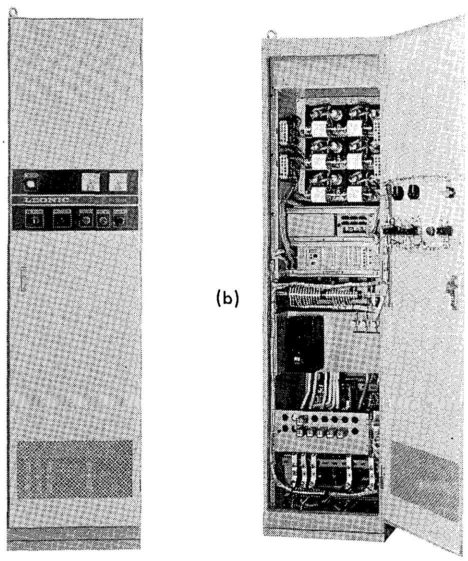

Fig. 23 (a) Control cubicle "LEONIC"
(b) Control cubicle of circulating current-free reversible thyristor Leonard control system

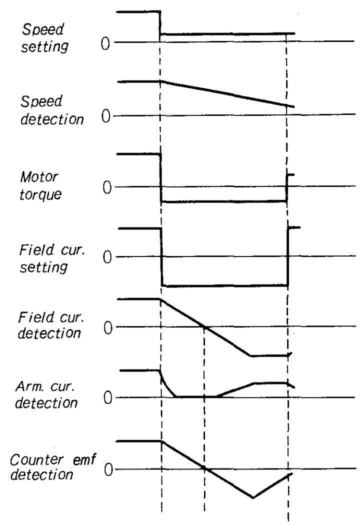

Fig. 25 A time chart of the field reversible operation

Fig. 24 shows a block diagram. The polarity of the armature circuit is generally the same so that the output of the speed controller changes in accordance with the polarity of the torque. However, the absolute value of the output of the speed conttroller is given as the armature current setting. The direction of rotation and the polarity of the generated

the current limit regulator and the torque reversing command is applied to the field setting computer. The field setting value is changed over to that with the correct polarity and the speed controller output remains at zero V until the field current polarity is reversed. After the reversal, the armature current limited by the current limit regulator again begins

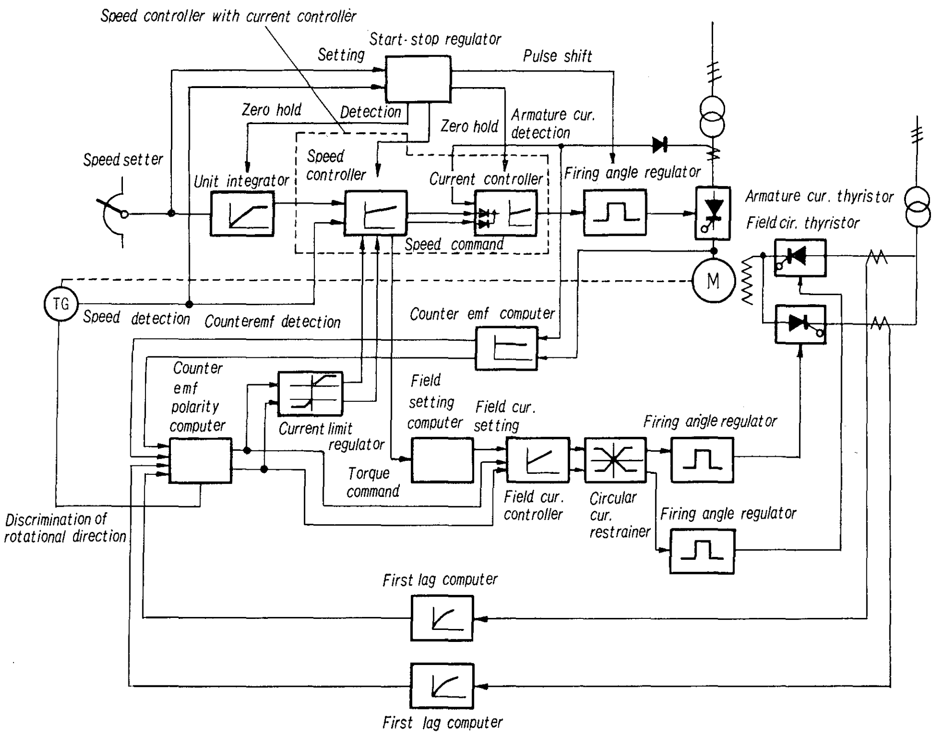

Fig. 24 Block diagram of reversible tyhristor Leonard control system with reversible field circuit

to flow and gradually increases. The armature current reaches the value matching the required torque and the field reversing operation is completed.

6. Reversible Thyristor Leonard Control with Field Switching Circuit

This system consists of one group of rectifiers in a armature circuit, electromagnetic contactors for field switching and a thyristor converter in the field circuit.

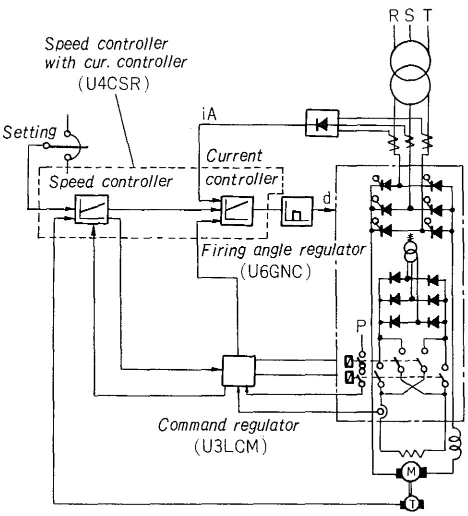

Fig. 26 **Block diagram of reversible thyristor Leonard control with field switching circuit**

Polarity of the required torque is detected by the command regulator, armature current is driven to zero, and field current is switched by means of the magnetic contactor. A new operating state results. With this system, idle time is more than the field reversing system, but the cast is more economical. *Fig. 26* shows a block diagram.

VI. AC MOTOR CONTROL

1. Brushless Mortor Control Device (PERMOTORON)

Fig. 27 shows the principle circuitry of the bruschless motor. In the DC motor, the commutator segments are attached to the armature windings and brushes are fixed to the equivalent position of the field poles current flows in the armature windings when the field poles reach the required positions, and a torque is generated.

In the brushless motor, the thyristor elements equivalent to the commutators in the DC motors are connected to the armature windings and the firing and cutting off of these elements is performed in accordance with the equivalent positions of the field poles and armature windings. The position of the field poles is detected electronically by the rotor position sensor which is directly coupled to the motor shaft. This rotor position sensor can be said to be equivalent to the brushes in the DC motors.

The brushless motors can generally be classified into two types: the DC type and the AC type.

The DC type bruschless motor, as can be seen in *Fig. 27*, receives power from a DC power supply. Thyristor converter is used in general industry as a DC power supply and chopper is also used to obtain

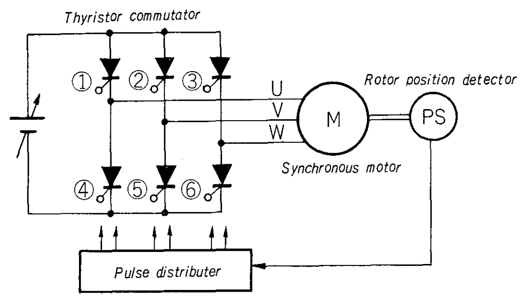

Fig. 27 **Principle circuitry of the brushless motor**

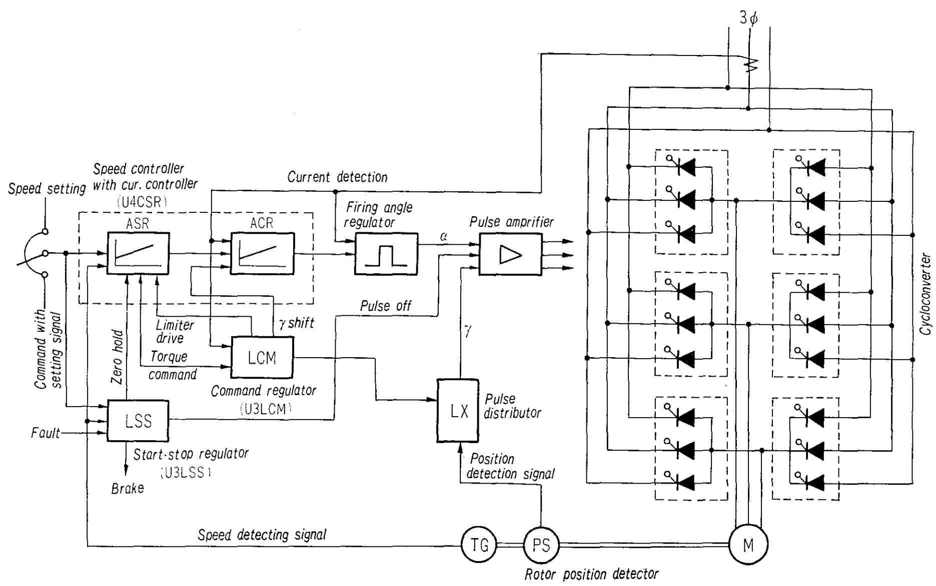

Fig. 28 **Block diagram of speed control system of AC brushless motor**

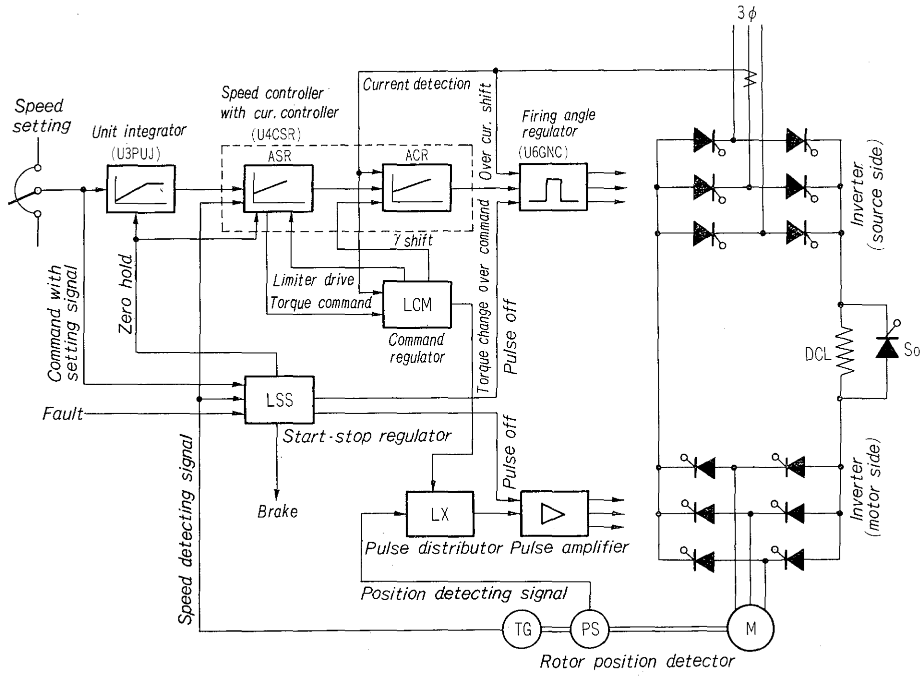

Fig. 29 **Block diagram of speed control system of DC brushless motor**

variable DC voltage in rolling stock, etc. which use only DC power supply such as batteries.

The AC type brushless motor is driven by a cycloconverter and unlike the DC type, it can receive power directly from an AC power supply.

Except for the rotor position sensor, the motors are synchronous machines and employ various techniques to make them completely contactless. The Fuji standard types are the claw-type field pole type and the winding rotating field pole type.

Fg. 28 shows a block diagram of the speed control system of the AC brushless motor, and *Fig. 29* shows the same type of system for the DC type brushless motor. The main features common to both types are as follows:

(1) The converters are not switched over and reversible operation is also possicle with the same wiring.

(2) Commutation of the thyristor converters which are equivalent to commutators is controlled by a signal from the rotor position sensor so that there are no disorders or fluctuations unlike synchronous machines.

Fig. 30 shows an outerview of the AC PERMOTORON. The control method of the AC PERMOTORON can be explained simply in accordance with *Fig. 28*. The control system is a speed control system which has an armature current control system as a minor loop. The pulse distributor receives the signal from the rotor position sensor and produces two series of pulses, the forward (drive) pulse and the reverse (brake) pulse. The selection of the pulse to be used is made by the switching command signal of the command regulator. The firing pulse is produced by the product of propositions of the pulse from the pulse distributor and the pulse from the gate shifter. The pulse amplifier is an AND circuit in order to possess this function.

The cycloconverter is equivalent to a bridge connection converter if the three thyristors connected to each phase of the motor are considered as one group. Commutation between these thyristor groups is by means of motor commutation utilizing the induced voltage of the motor. For this reason, the motor phase current must be further advanced in phase than the motor terminal voltage. This angle of lead is known as γ and the signal from the rotor position sensor is added to it. The commutation of the three thyristors in one group is controlled by the power source frequency. This is known as power source commutation. Thyristor commutation is

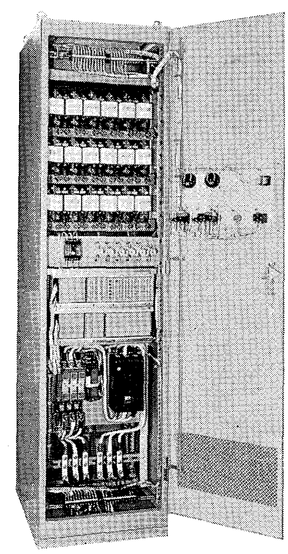

Fig. 30 **Outerview of control cubicle AC PERMOTRON**

guaranteed even during starting when the motor induced voltage is zero or very small and no special method need be considered during starting. This is a major feature of this system.

The DC type brushless motor differs from the AC PERMOTORON in the point that the converters which plays the role of the commutators are separated from the converter on the power supply side. Therefore, the counter EMF during starting is small and motor commutation is impossible. At the time of commutation of the thyristors on the motor side, the firing pulse of the thyristors on the power supply side is always shifted to the γ side. After the current is cut off, the firing signal is supplied to the next thyristor. This is known as the current cutting commutation method.

The thyristor shown by S_0 in *Fig. 29* is intended to shunt the DC reactor of the intermediate DC circuit and quickly dampen the current when the firing pulse of the source side converter has been shifted to the γ side. In the speed control system which forms a minor loop in the armature current control system, the unit used for control does not have any basic differences from the AC PERMOTRON.

2. VVVF Inverter (FRENIC-1000)

Fuji Electric uses the VVVF inverter (variable frequency source) as the most ideal equipment for speed control of AC motors such as synchronous motors and induction motors. This FRENIC-1000 features high performance and compactness, and by combining with a wide range of options, it can be

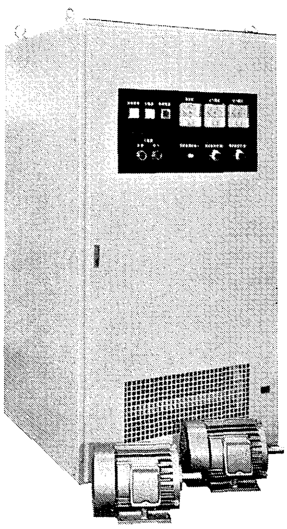

Fig. 31 Outerview of FRENIC-1000

arranged so that various types of control are possible. Naturally, it can be used widely as variable speed equipment for general industrial use although it was formerly used mainly in the textile and related industries. *Fig. 31* shows an outerview of the FRENIC-1000.

Fig. 32 shows a block diagram of the FRENIC-1000. The AC input is changed into DC by a rectifier. A smooth DC voltage is produced by a filter in the DC middle circuit and this voltage is again turned into squarewave AC voltage by an inverter. The control equipment consists of the voltage control system with a voltage controller and a firing angle regulator, and of the frequency control system with a V/F converter and a pulse amplifier (including a pulse distributor). The voltage control system is a closed loop which is controled by detecting the output voltage of the rectifier, but the frequency control system is an open loop in which the signal voltage supplied by the frequency setter is converted into a frequency signal by the V/F converter and the inverter is driven via the pulse amplifier. Therefore, the inverter output frequency is immediately determined by the signal voltage from the frequency setter and there are absolutely no other influences. The accuracy of the output frequency is determined by the accuracy of the V/F converter. The output frequency accuracy of the FRENIC-1000 is $\pm 0.1\%$ in the frequency range of 10~200 Hz. If speed control is performed in combination with a synchronous motor, a speed accuracy of $\pm 0.1\%$ can be obtained.

The handling operation part is only one automatic no fuse breaker in input AC power line, and the start-stop operation and the reset for the release from the fault condition can be performed by this breaker. And by combining with this breaker and the electronic sequence unit, the thyristor converters are protected from the overcurrent. Therefore, absolutely no other operations are necessary. The sequence unit also has the function of continuing stable operation during some disturbance in the power supply.

Commutating circuits on inverters have been used for some time in forced commutating circuits. The feature of this system is that stable commutation can be performed in respect to the load and voltage variations which are arisen by the motor drive. Because of the improvements in this commutating circuit, the stability of the commutation has not been harmed and a highly efficient commutation circuit has been achieved. The inverter efficiency is over 95~96% at an output frequency of 200 Hz.

3. Inverter Motor (Current Control Type Inverter) (FRENIC-2000)

The demands for speed control of the durable, economical squirrel cage induction motor as in the DC motor are gradually increasing. The inverter motor (FRENIC-2000) is a typical speed control device which can meet this requirement. *Fig. 33* is a block diagram of the inverter motor (FRENIC-2000). The line circuit consists of a thyristor converter which makes possible forward and reverse operation and an inverter with a forced commutation circuit. Each is connected mutually via a reactor in the DC middle circuit. No condenser for smoothing DC power supply is connected in the DC middle circuit in the FRENIC-

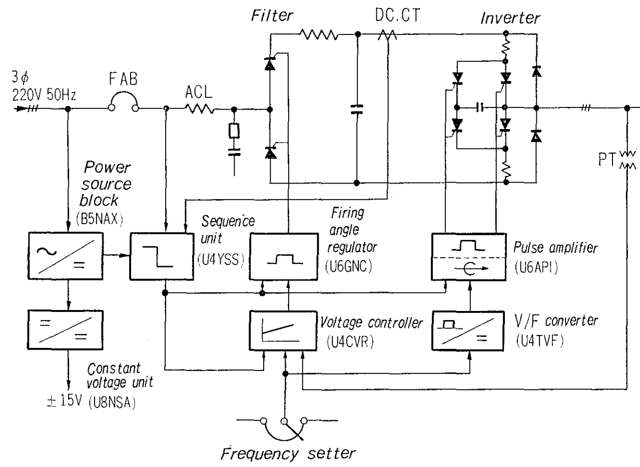

Fig. 32 Block diagram of VVVF inverter FRENIC-1000

2000 like in the FRENIC-1000. There is also no feedback diode in the inverter part. Therefore, the current which flows into the motor cuts the smooth DC current and becomes a square wave form. The motor terminal voltage has a sine waveform because of this induction voltage. *Fig. 34* shows the current and voltage waveforms of the inverter motor (FRENIC-2000). When the motor is driving, the voltage and current in the DC middle circuit of the FRENIC-2000 have the same direction and polarity, and drive the motor, but when the motor is braking, the voltage polarity in the DC middle circuit is reversed and the braking energy of the motor is regenerated on the power supply side. Therefore, one of the features of the inverter motor (FRENIC-2000) is that the braking of the motor can be performed without adding any special control circuit. The example of the speed control loop shown in *Fig. 33* is the most simple speed control loop which detects the motor terminal voltage and controls the magnetic flux density of the motor at a constant value. However, in such a simple speed control loop, the torque is insufficient during starting and low speeds. Thefofore, various types of speed control loops can be considered. At present, the output capacity of the inverter motor (FRENIC-2000) manufactured by Fuji Electric is 0.2～ 90 kW by conversion of the motor shaft output.

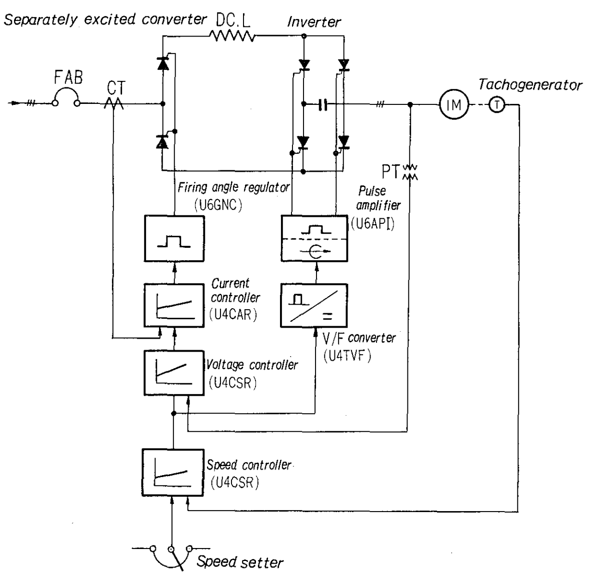

Fig. 33 Block diagram of inverter-motor FRENIC-2000

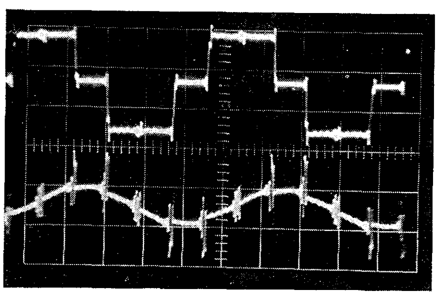

Fig. 34 Current and voltage waveforms of inveter-motor FRENIC-2000

4. Thyristor Scherbius Control System

The thyristor Scherbius equipment is a system which is used in the control of wound-rotor type induction motors, converts the secondary slip power arising between slip rings into an AC power of the same frequency as the primary power source and causes regeneration to the power source side.

In one system, the secondary slip power is converted into DC voltage oy a silicon rectifier and this output causes regeneration in the AC power supply by means of the thyristor inverter. There is another system in which regeneration of the secondary slip power is performed directly in the AC power supply by the thyristor cycloconverter. In the former case, the slip S is driven in the $0<S<1$ range and this is known as the static Scherbius system. In the latter case, motor and regeneration drive are possible throughout the range $0\leq S<1$, $S<0$. This is known as the super synchronous static Scherbius system.

1) Static Scherbius system

In this system, if the firing angle of the thyristor inverter is controlled, the DC current, i. e. the secondary current of the motor can be controlled. Therefore, when the motor torque is changed, the speed can be changed until it is balanced with the load torque.

The relation between the motor rotational speed (N) and the control advance angle (γ) is as follows:

$$N=N_0\ (1-K_1\ \cos\ \gamma+K_2\cdot I)$$

N_0: Motor synchronous speed

I: Motor secondary current

K_1 and K_2: Constants

Since $K_2\cdot I$ generally has a value of several percent, it is possible to perform speed control at constant γ operation particularly when highly accurate control is not required. When highly accurate speed control is required, TRANSIDYN system is used on the speed constant control.

Fig. 35 shows a block diagram of the speed constant control system of the static Scherbius equipment. When circuit breaker 6 is closed, the motor is started by starting resistor StR. Then the automatic control circuit is operated by the closing of 19 and constant speed control begins.

2) Super-synchronous static Scherbius system

This system performs speed control by regulating the secondary slip power by means of selection of thyristor group in the cycloconverter and control of the firing angle. *Fig. 36* shows a block diagram of this system.

The command regulator judges whether driving torque or braking torque is to be generated by the motor. The slip-phase detector detects the secondary slip frequency and phase by means of the primary and secondary voltages of the motor. The thyristor groups through which current are to flow are selected from the cycloconverter connected to the motor secondary side by the pulse distributor connected this detector.

Since the phase control angle in respect to the primary supply voltage is determined by the firing angle regulator, the pulse amplifier is operated by the AND condition between this signal and the previously described group selection signal, and the final firing thyristor and firing angle is decided.

Therefore, not only can the secondary slip power be regenerated to the power supply by the selection of flowing groups and control of the firing angle, but also power can be supplied to the secondary circuit from the power supply side so that the braking torque can also be regenerated and the motor speed can be controlled above and below the synchronous speed.

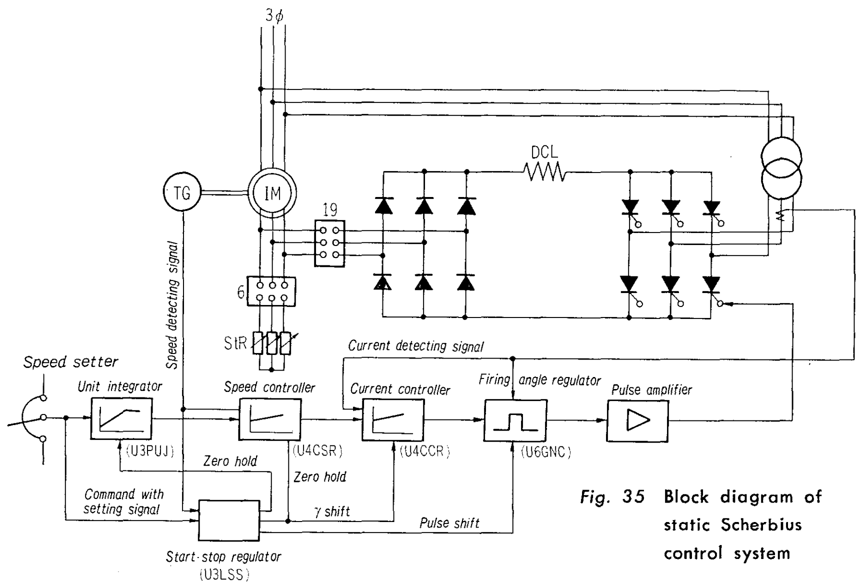

Fig. 35 **Block diagram of static Scherbius control system**

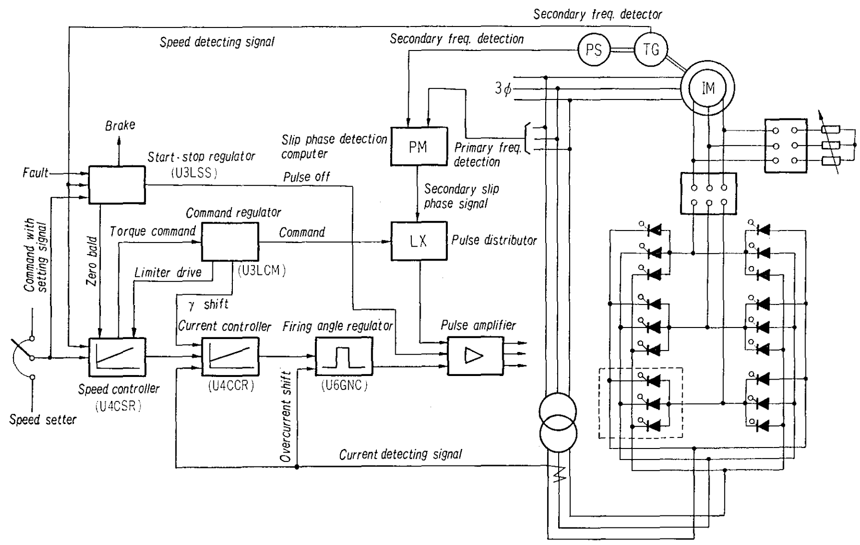

Fig. 36 **Block diagram of super-synchronous Scherbius control system**

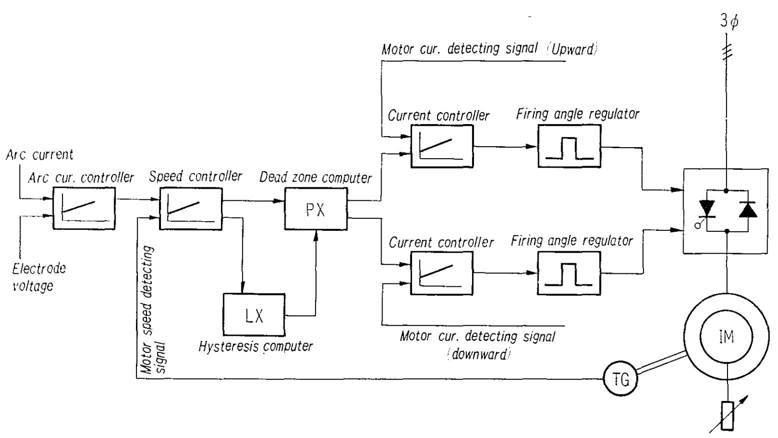

Fig. 37 **Block diagram of thyristor type electrode regulating device**

5. Thyristor Type Electrode Regulating Device

This electrode regulating device is used to control the arc current in steel-making arc furnaces by changing the gap between the electrodes and the scrap. *Fig. 37* is a block diagram of the thyristor type electrode regulating device.

Electrode voltage and current are used as input signals for an arc current controller. Output is used as a speed command for an electrode up-down motor, and enters the speed controller. Output from the speed controller becomes input for the dead zone computer in such a way that the thyristor conducting when the electrodes are raised and the thyristor conducting when the electrodes are lowered do not fire simultaneously. Outputs of this computer become the current commands for either the up-motor or the down-motor. There is a considerable difference between minimum torque reguired to keep the electrode from dropping of its own weight and minimum torque required to raise the electrode. Therefore, if the dead zone computer were to supply a current command corresponding to the midpoint between these values for a long period of time,motor temperature would rise rapidly. In order to prevent this, the speed controller output gives the minimum torque command required to prevent a natural drop of the electrodes in such a way that the output of the speed controller is not given out from the dead zone computer when the torque command value is not sufficient to raise the electrodes. However, in order to provide good control characteristics after the motor once operate the above operation must be inhibited without relation to the magnitude of the output of the speed controller only as long as there is a speed detection signal. A hysteresis computer is applied so that such an operation can be performed.

VII. OTHER TYPES OF CONTROL EQUIPMENT

1. Power Control Equipment

The requirement for various types of automation are gradually increasing as network capacity and unit capacity of the turbine increase. In this type of analogue control, high accuracy TRANSIDYN control systems are being employed.

In the control of typical thermal power plant as shown in *Fig. 38*, the following control equipment is being applied; electrohydraulic turbine governors (ESG) which perform constant control on turbine speed and output; turbine wall temperature monitoring equipment (WT) which monitor and control the wall temperature of the turbine and the thermal stress of the inlet valves to within the required values; the automatic dispatching control equipment (ADC) which is systematically with the central supply unit or internal computer, automatic turbine starting equipment (ATS) and electronic oil pressure governor, and performs cooperative operation with the boiler; and the economical load dispatching control equipment (ELDC). For the generator, the following are being employed; the automatic voltage regulator (AVR) to control the output voltage and var power; automatic voltage and var power control equipment (AVQC) which controls by regulating the taps of the main transformer. It is also possible to add accessory control equipment such as APC, AFC, AQR and var power etc.

Fuji Electric was the first in the world to apply the electronic oil pressure governor (ESG) and the turbine wall temperature monitoring equipment (WT) into practical use in thermal power facilities. This equipment has con-

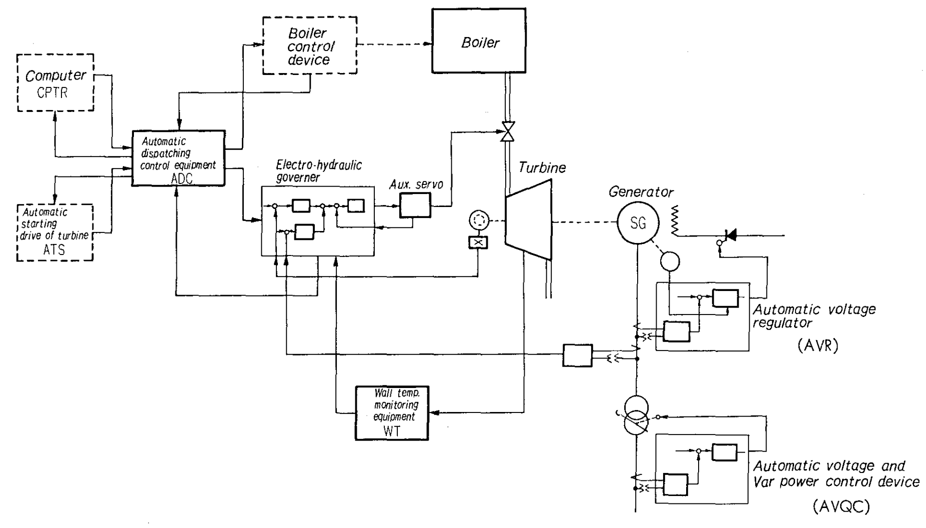

Fig. 38 Block diagram of thermal power plant control system

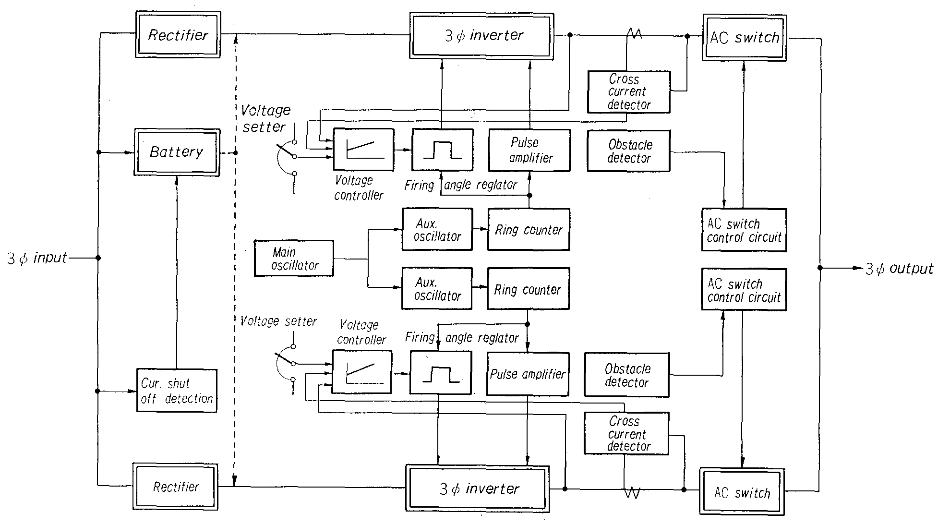

Fig. 39 Block diagram of CVCF power supply equipment

tributed considerably turbine automatic starting, rapid load changing cooperative operation with boilers, inprovements in operating efficiency, accurate control, etc.

Special attention must be paid to reliability in power control equipment. For this reason, efforts have been made to raise the reliability of various control units but redundant design is used in important circuits where two circuits are connected in parallel.

2. Static No-break Power Supply System (CVCF Power Supply Equipment)

No-break power equipment with thyristors and inverters are now widely used to supply computers, communication equipment and industrial in-struments.

As shown in *Fig. 39*, the control circuit consists of an output voltage control loop, a reference frequency circuit with a master oscillator, the firing circuit for thyristor switchs, and power failure detector for switching the load to battery power. The equipment is constructed of multiplex circuits so that even when one unit is defective, operation will continue no matter what the fault on the output side.