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HIGH-VOLTAGE LARGE CAPACITY THYRISTOR CONVERTERS (FOR POWER SYSTEMS AND LARGE-CAPACITY SYNCHRONOUS MOTOR STARTERS)

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1. INTRODUCTION

Fuji Electric Co. has been accumulating successful results in the field of high-voltage large-capacity power electronics. In the power generating field, for example, we have delivered 50MVA and 80MVA reactive power compensators to la Comisión Federal de Electricidad, Mexico and 40 MVA to Hokkaido Electric Power Company, Japan. In the industrial power field, a 4 MVA reactive power compensator has been furnished to Furukawa Aluminum Co., Ltd., a 120 MVA to Treganu Steelworks, Malaysia and a 90 MVA to Sanko Seiki Co., Ltd. And we have also supplied Asahi Chemical Industry Co., Ltd. with a 50/60 Hz different-frequency linkage system. Thus, we have effected many deliveries of equipment.

High-voltage converters have advantages: (1) Equipment can be simplified by omitting the transformers to step up and down voltages, (2) Wiring cable can be saved and (3) System efficiency can be increased. For recent years, these systems have come to be designed and manufactured far more easily than ever thanks to the appearnce of high-voltage power devices and to the application of optical firing pulse transmission systems.

The high-voltage converter is to operate, with lots of power devices connected in series. It is necessary, therefore, to take a way of thinking different from that for low-voltage systems, especially concerning (1) Function of normally monitoring individual devices and (2) Protecting and coordinating devices. A progressive establishment of these thoughts may be considered as one of the significant reasons why the high-voltage converter has been expanding the scope of its applications.

This paper is to outline some exemplary applications of those starters for pumped storage power generator motors and blast furnace blower drive motors and a static var compensator (SVC), which have been selected out of the latest typical products of ours.

2. THYRISTOR STARTER FOR PUMPED STORAGE POWER GENERATOR MOTORS

2.1 Ratings and Specifications

Table 1 Ratings and specifications, thyristor starter

Quantity	1	
Ratings	Source side converter	Machine side converter
Output capacity	21.8 MW	21.8 MW
DC voltage	15.7 kV	15.7 kV
DC current	1,391 A	1,391 A
Frequency	50 Hz	50 Hz
AC voltage	16.5 kV	16.5 kV
Acceleration/ Deceleration time	150 (sec.)/150 (sec.)	
Time rating	Continuous (start-stop: 37 cycles/day)	
Cooling system	Deionized water cooling	
Device configuration	3 phase double way, 16S 1P-6 A, 4 kV-1,000 A, indirect opto electric triggering system	
Synchronizing system	Low-voltage synchronizing	

Fuji Electric has delivered a set of thyristor starter and main controllers in addition to two 250 MVA generator motor as the equipment to be employed in Plamiet Pumped Storage Power Station.

The Plamiet Pumped Storage Power Station is of dedicated pumped storage underground type, employing two 203.5 MW Francis type pump turbine and generator motors. To operate it rationally in relation to another steam power stations, the Palmiet Power Station is intended to adjust system peak loads, frequencies and voltages.

Thyristor starter has been employed to start the pumped storage generator motors in the power station. The thyristor starter has been most prevailing recently, coupled with the remarkable progress of power electronics.

Table 1 shows the thyristor starter's ratings and specifications.

2.2 Starter Circuit Configuration

Fig. 1 shows the main circuit configuration. This configuration permits one starter to selectively start up two generator motors. In the event of an abnormality in the equipment on the one source side, another system power supply circuit is to start up the generator motor, thus

Fig. 1 Single-line connection diagram, main circuit, thyristor starter

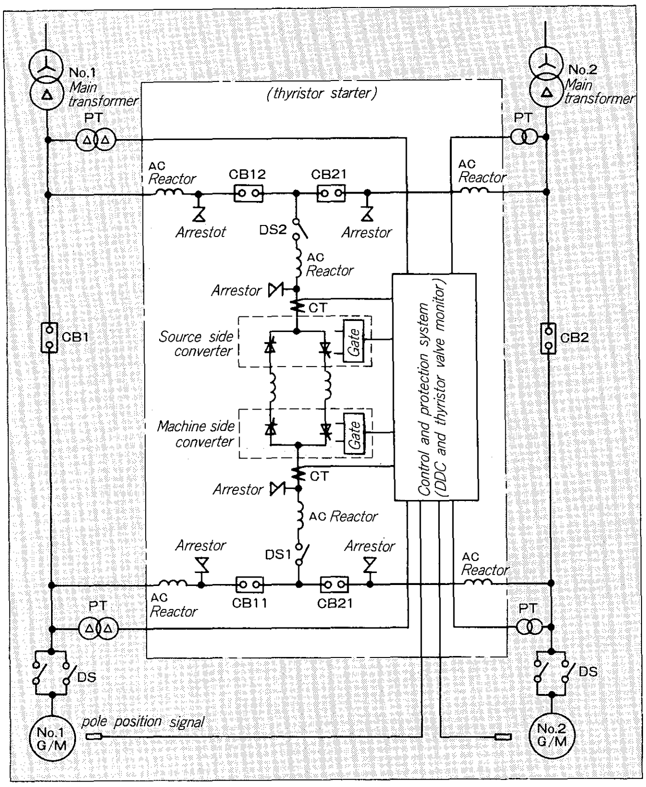
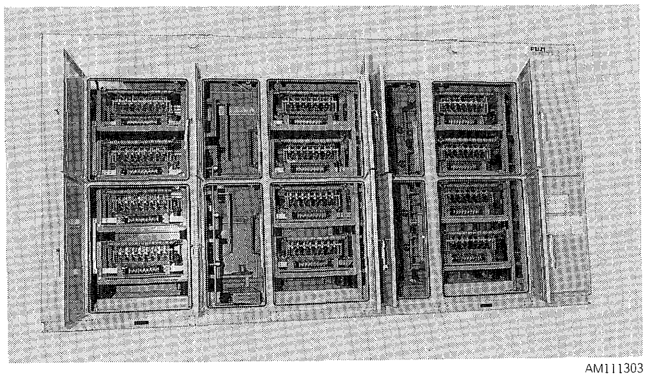


Fig. 2 Thyristor starter (source side converter)



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accounting for a cross-feed feature. In the event of an abnormality on the starter, moreover, the generator motor bus is used so that the generator motor can be started up synchronously, too.

The thyristor starter comprises a source side converter, a machine side converter, a dc reactor, an ac reactor, and a control and protection system.

2.3 Thyristor Converter

2.3.1 Configuration

Fig. 2 is an apearance of the machine side converter. (The source side converter has also the same appearance as that of the machine side one.) Both source- and machine-side converters employ a Fuji large-capacity thyristors (EGS03-4, 4 kV and 1,000 A). And they have a three-phase double-way configuration of the 16S1P-6A. The thyristor valve comprises the 8SIP thyristor module as the minimum component unit, with one arm composed of two modules.

The module comprises a thyristor stack, an opto-electric converter, a triggering circuit, an RC snubber and a cooling water intake. To facilitate an inspection operation, these components are so configured as to be easily removable and re-mountable.

To trigger the thyristor, an indirect opto-electric triggering system is employed while optical signals are used to send and receive to and from the high potential unit in the converter and the controller on the earth potential side. And these are electrically insulated completely. A pair of triggering circuits, moreover, are provided in every two thyristor devices. Should one triggering circuit fail, therefore, the other wholesome triggering circuit will be capable of supplying the pulse to trigger the thyristor device. (parallel redundant configuration). This redundancy has increased the reliability upon the system.

2.3.2 Cooling system

To cool down the thyristor device, a deionized water cooling system is employed, which is highly efficient in cooling and excellent in insulation properly.

2.3.3 Fault monitor

To normally monitor a status of the thyristor device, a monitoring system (thyristor valve monitor) is provided, which employs a microcomputer. To increase reliability in computing a failure, moreover, a 2-out-of-3 redundant system is employed to output the result of a majority decision made by three monitors. Should an abnormality be detected, the monitor will stop the converter while both abnormal device number and status just before the occurrence of abnormality will be printed out in our efforts to increase the maintenance efficiency.

2.4 Control system

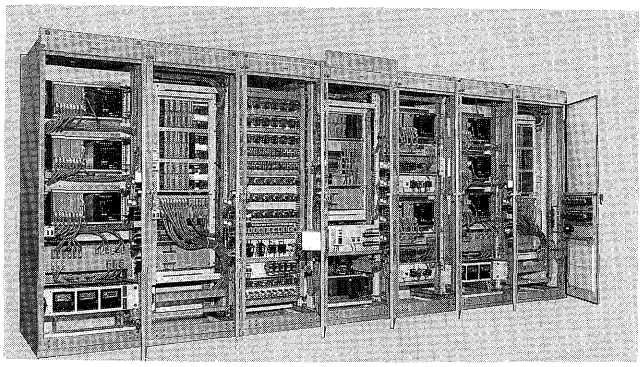
2.4.1 DDC

A configuration of controls is the multi-CUP DDC system in which a 16-bit microcomputer is operating as the master while 8-bit microcomputers are working as slaves. This DDC system has the software materialize those functions, such as synchronous control, etc., which are essential to the starter. In addition, a protective function is added for the high-voltage large-capacity converter.

To improve reliability on the control system, two DDC units are provided, both comprising identical hardware and identical software. While one DDC unit is in operation, the other is standing by. Should the one in operation fail, an immediate switchover will be made to the unit standing by. The standby redundant system employed will permit the high-voltage thyristor converter to continue on operating. With DDC applied, moreover, the high voltage thyristor converter has attained a high level of functionality backed up with a plenty of self-diagnostic features, trace-back for analysis of failure causes, digital setting of adjustment factors with an exclusive loader, and so on.

Fig. 3 shows an appearance of the DDC unit.

Fig. 3 DDC unit



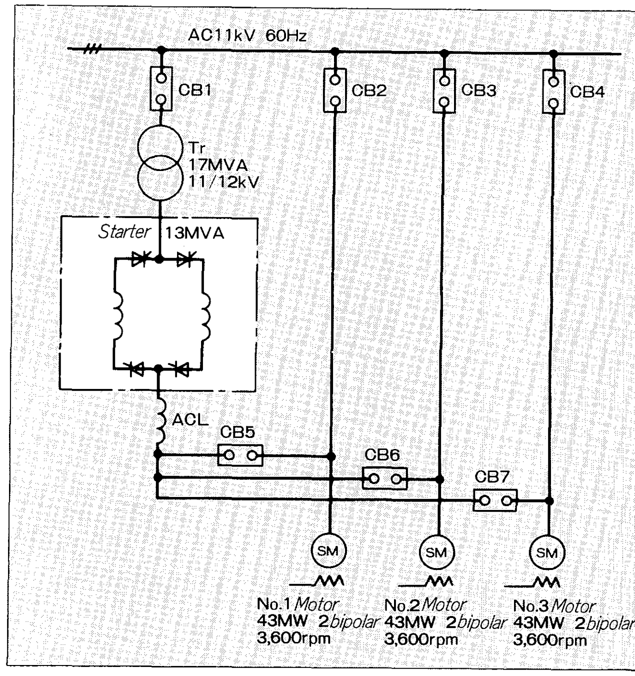


Fig. 4 Single line connection diagram

2.4.2 Acceleration control

Once the STARTUP command has been given to the starter, a constant exciting current will flow to the field winding of the generator motor. The three-phace alternating current supplied from the system by way of the main transformer is converted to a direct current once in the source-side converter. Then, it is fed to the machine-side converter through a dc reactor. This direct current is supplied to the armature winding through each arm of the machine-side converter corresponding to a pole position of the generator motor. An action of the field current with the magnetic flux causes a turning torque to be generated, resulting in acceleration.

2.4.3 Synchronous closing control

Once the generator motor has approximated the synchronous speed after accelerated, the speed is controlled according to a value proportional to the source frequency. The voltage, on the other hand, is regulated, with the field current controlled by a signal from the automatic synchronizer.

Once the generator motor has had both voltage and phase coincide with those of the system, a circuit breaker closing signal from the automatic synchronous detector causes the generator motor to be put into operation parrallel with the system. At the same time, the source-side converter is pulse-shifted to have a direct current of zero. After that, both source- and machine-side converters have pulses turned off, resulting in a shutdown of the equipment.

2.4.4 Regenerative braking control

This control is used for braking when the generator motor is shutdown under the power generative control. The generator motor's turning energy is regenerated as electric power so that the motor speed will rapidly slowdown, resulting in a shutdown.

3. THYRISTOR STARTER FOR BLAST FURNACE BLOWER DRIVE MOTOR

3.1 Outline of Thyristor Starter

A bipolar high-speed large-capacity synchronous motor is employed to drive a blast furnace blower in a steelworks. To start up this motor, a low-frequency starting system is employed so as not to apply any shock to the power source. More recently, in particular, a thyristor starter has been being employed in a remarkably increasing number of applications.

Table 2 Ratings and specifications

Item	Rating/Specification
Rated capacity	13,000 kVA
Input voltage/frequency	12 kV 60 Hz
Output voltage/frequency	11 kV 60 Hz
Time rating	30 min.
Overload capacity	120% 10 min.
Starting cycle	max. 3 cycles per 30 min.
Pause time	3 hours (1 restarting cycle) 8 hours (2 restarting cycles)
Device configuration	3 phase, double way 12S 1P-6 A EGS03-40 4,000 V 1,000 A
Cooling system	Internal air circulating type unit cooling system with water/air heat exchanger employed

Fuji Electric has delivered three 43 MW blast furnace blower synchronous motors and a set of thyristor starters to POSCO, Korea. *Fig. 5* shows its single-line connection diagram while *Table 2* indicates the ratings and specifications of the thyristor starter.

3.2 High-Voltage Converter

3.2.1 Configuration

The converter system comprises a source-side converter, a machine-side converter and a dc reactor. On High-voltage Valve Panel 1, a air-cooled high-voltage valve tray with six thyristors is stacked. For cooling, an internal air circulation type unit cooling system is employed, having

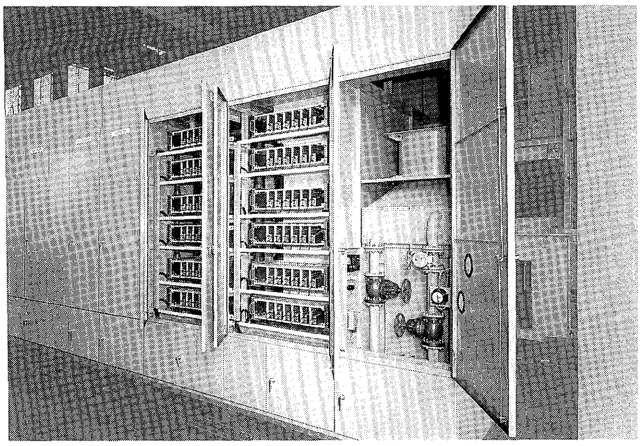


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Fig. 5 Thyristor starter

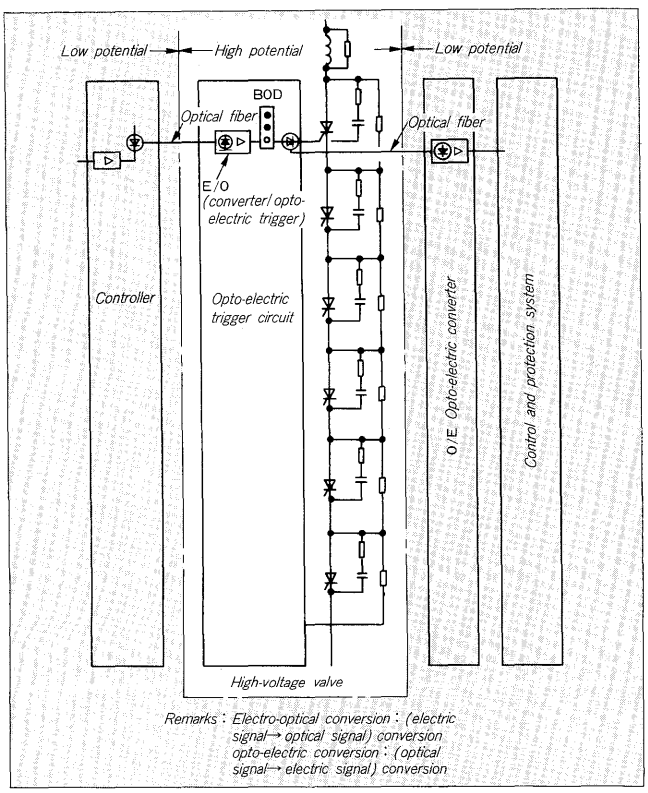


Fig. 6 Configuration, air-cooled high-voltage valve

a water/air heat exchanger housed on the cooler panel. Thus, the cooling system is so constructed as to protect high-voltage valves against the dirt and dust, which may enter during a long-time operation. *Fig. 5* shows an appearance of the high-voltage converter equipment.

3.2.2 Air-cooled high-voltage valve tray

The air-cooled high-voltage valve tray comprises six 4,000 V thyristors connected in series, their snubber circuits, triggering circuits, etc., having a configuration as shown in *Fig. 6*.

The triggering system employed is of indirect opto-electric triggering type, with optical fiber applied. The

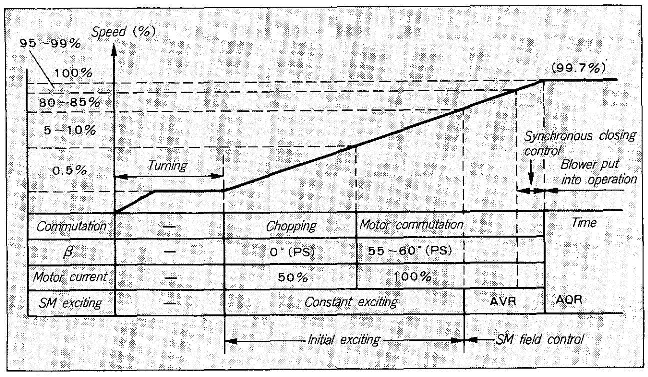


Fig. 7 Starting schedule

functions built in the triggering circuit are (1) Blocking pulses against reverse voltage, (2) Generating re-firing pulses and (3) Self-firing in an emergency. Thus, a due consideration is given so that the converter with many thyristors connected in series can be operated with safety.

3.2.3 Fault monitor

A valve monitor is normally monitoring how each of the thyristor devices in the high-voltage valve is operating. In the event of an abnormality, the related device number will be indicated with an LED. And a fault processing signal will be issued to inform what the fault is.

3.3 Controller

3.3.1 Control system

Fig. 7 shows a schedule of the commercial synchronous control for a start by the thyristor starter. An acceleration up to around the synchronous speed is made on a current limiting basis. During the start, the motor is controlled to a constant level of excitation. Around the synchronous speed, the motor is switched over to the AVR control mode so that the motor terminal voltage will coincide with the commercial power source voltage.

For synchronous closing, a MAKE command is issued during the advancing time equivalent to that required for the switch to close after both source and motor have had their phases matched. This will permit the equipment to be synchronously switched on without giving any shocks to either motor or pour source.

3.3.2 Starter's function of checking

The starter must wait for a long time while being ready to start up the motor subsequently. The present system, therefore, is additionally provided with a function of checking every critical part while the starter is ready to operate. This function permits the control circuit to be checked for performance on a simulation basis as well as the converter to be checked for performance.

4. STATIC VAR COMPENSATOR

4.1 Outline of Compensator

The reactive power in a power system varies with a fluctuation of loads, their switching, generator's switching, phase regulator's switching, a change in system configuration, etc. And these factors may lead to a fluctuation of the system voltage or receiving substation's bus voltage. Such a voltage fluctuation may result in an overexcitation of the transformer, an overload of the armature in a revolving machine, a decline of system stability, etc. Such a random load fluctuation as seen in an arc furnace, moreover, might cause lighting to flicker.

The static var compenstor (SVC) is installed to suppress such a voltage variation in the system and to improve stability.

Now available for practical use as an SVC are the thyristor controlled reactor (TCR) system to control a reactor current, the thyristor switched capacitor (TSC) system to switch on and off a current flowing through a capacitor and a combination of TCR with TSC.

For the thyristor converter to be employed in the SVC, a high-voltage thyristor valve is adopted from both economy and efficiency points of view. Fuji Electric has developed a high voltage thyristor valve of air-insulted, directly water-cooled and indirect opto-electric triggering type, which has been successfully applied to the SVC sold in Japan in its earlier stages.

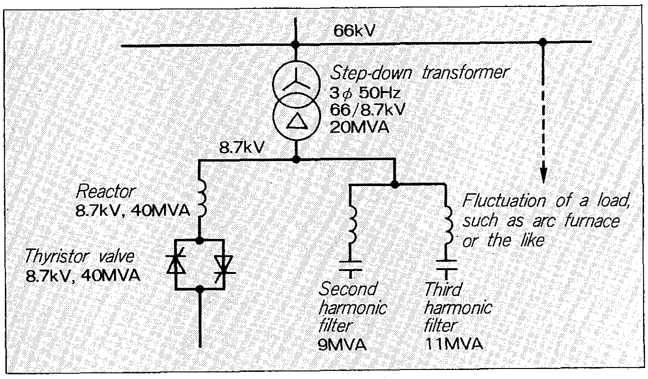
4.2 SVC Delivered to Hokkaido Electric Power Co.

For a utility application, we have recently delivered an SVC to Muroran Substation, Hokkaido Electric Power Co. This SVC will be introduced hereunder.

The SVC equipment has been installed for the purpose of suppressing the fluctuating reactive power generated by the user's arc furnace loads connected to a 66 kV feeder in Muroran Substation and of improving the voltage flickering. *Fig. 8* shows the single-line connection diagram of the static var compensator while an outline specification of the main equipment employed is given in *Table 3*.

Since the loads are connected to a 66 kV system, the voltage is reduced to 8.7 kV with a transformer. Connected to this line are a reactor, a high-voltage thyristor valve and a capacitor bank serving also as a higher marmonic filter. *Fig. 9* depicts an appearance of the high-voltage thyristor valve. The outdoor equipment is of double sound-proof construction, which has achieved a low noise level of 55 phones and below.

Fig. 8 Single-line connection diagram, SVC delivered to Muroran substation, Hokkaido Electric Power Co.



Besides, the SVC has employed a control system based on a new reactive power detection principle, which has significantly improved the flicker-compensating performance. *Fig. 10* shows the control system configuration.

The control system comprises Q_f Detector Circuit, ΔQ Compensator Circuit and ΔP Compensator Circuit. The Q_f detector highly accurately and instantaneously computers an arc-furce-generated reactive power (Q_f) from an integral value of the reactive power flowing through the substation's feeder and an effective power value. The ΔQ compensator detects the reactive power residual in the system for compasation. And the ΔP compensator compensates for the voltage fluctuations caused by a mutual unequilibrium of the effective power. To reduce the required compensator capacity, moreover, another economy-oriented system is also employed so that a mean value of the loads' reactive

Table 3 Specifications of SVC equipment delivered to Muroran substation, Hokkaido Electric Power Co.

Rating specifications	Adjustable range of reactive power		−20 MVA (gain) ~ 0 ~ 20 MVA (lag)
	Rated voltage		66 kV
	Rated frequency		50 Hz
	Main circuit system		TCR
Equipment specifications	Step-down transformer	Rated voltage	$\frac{66}{\sqrt{3}}$ /8.7 kV
		Rated capacity	20/20 MVA
		Cooling system	O.N.A.N.
	Reactor	Rated voltage	8.7 kV
		Rated capacity	40 MVA
		Cooling system	O.N.A.N.
	Thyristor valve	Rated voltage	8.7 kV
		Rated capacity	40 MVA
		Insulating system	Air insulation
		Cooling system	Deionized water cooling
		Triggering system	Indirect opto-electric trigger
	Filter bank	Filtering system	Second/Third harmonic shunt filter
		Rated voltage	8.7 kV
		Rated capacity	9 MVA (second) + 11 MVA (third)

Fig. 9 High voltage thyristor valve

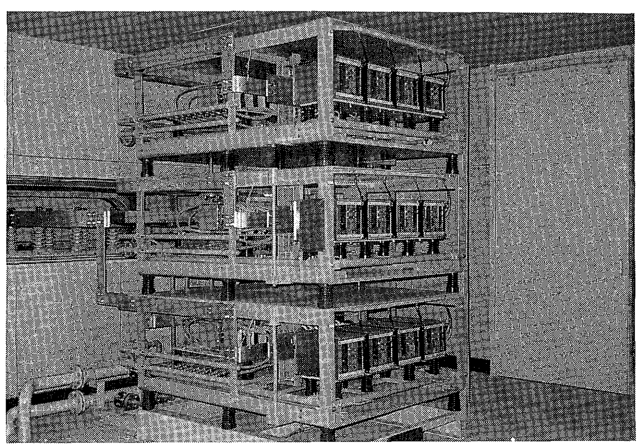


Fig. 10 Control system configuration

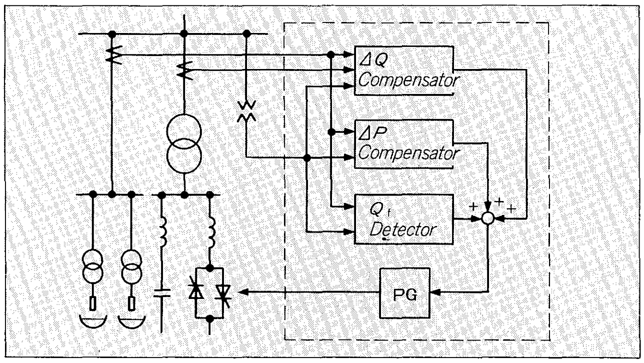
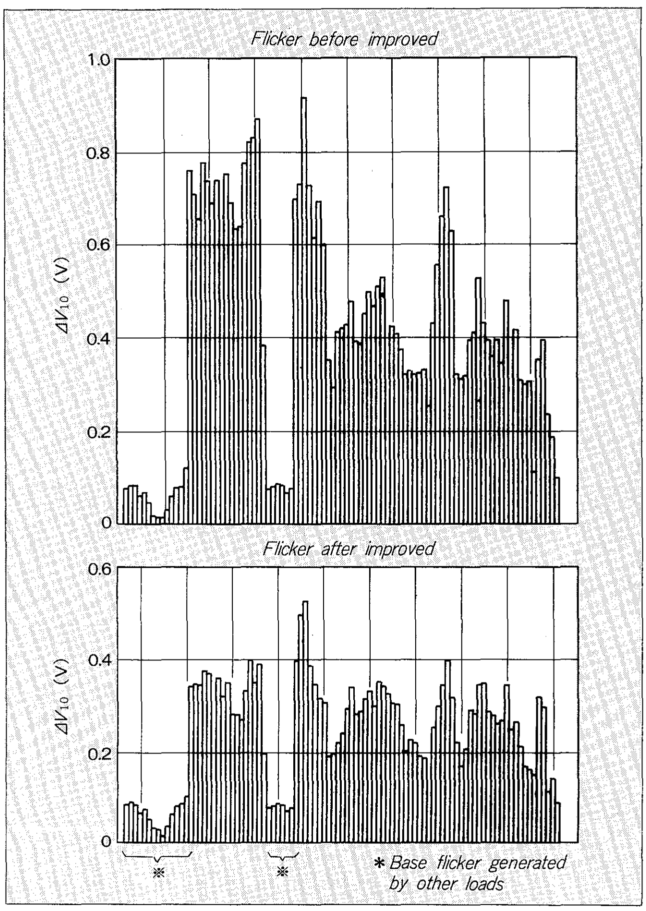


Fig. 11 An example of flicker measurements



power is followed to compensate for those fluctuating components from which such mean value has been subtracted.

The control system satisfies a warranted value of flicker improving performance (that is, Produced Flicker $\Delta V_{10} = 0.75$ V is reduced to 0.45 V). At the same time, a flicker improvement rate of as high as 48%, as really determined, has been achieved under the condition that a ratio of the compensator capacity to the short-circuitting capacity of two furnaces combined (compensation ratio) is 45%. *Fig. 11* shows an example of the flicker data determined before and after the improvement.

5. POSTFACE

In addition to its applications referred to above, the high-voltage thyristor converter is applicable to a variable-speed operation of large-capacity wind and water power generators, to an ultra-high-speed motor drive for compressors and to a frequency converter for different frequency linkage. And there have been many cases already manufactured.

In addition, the self-exciting converter whose voltage is increased has a wider range of applications than an externally excited type converter. Though there are few cases practically applied, a high-voltage self-exciting inverter is considered likely to popularize in the near future, employing those GTO devices which have recently made rapid progress in withstanding a higher voltage. We except that the advent of such a new converter will surely open the way to a new applicable field and to a new demand as well.