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CONTROL SYSTEM OF STATIC VAR COMPENSATOR

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I. INTRODUCTION

A reactive power causes a capacity increase on power supply equipment and transmission lines, increase of power loss and fluctuations on power supply network. During recent years, effective use of power supply equipment, energy saving and efficiency improvement of load electrical equipment are essential, compensation of reactive power is strongly desired, and many static var compensators, power capacitors and synchronous condensors are installed.

The size and fluctuation mode of a reactive power are decided by the characteristics of the applicable load. Therefore, the control system of a static var compensator must be selected and designed by matching it with the characteristics of the objective load.

Out of many static var compensators installed during the recent years, four typical examples classified by the load characteristics shown below are selected, and this paper explains the control systems.

(1) One of power supply network
(2) One for arc furnace
(3) One for rolling mill
(4) One for general loads

II. CONTROL OF STATIC VAR COMPENSATOR

In the most cases, a static var compensator (SVC) is of a thyristor control reactor (TCR) type and a thyristor switched capacitor (TSC) type.

The TCR regulates lagging current flowing through the reactor by phase control of the thyristor valve, and has such an advantage as that valves of reactive power can be adjusted continuously. Since the TCR operates to balance out the fluctuations in response to changes of the reactive power in the load side, in an ordinary power supply network system in which the load power factor is lagging, a shunt capacitor is required to improve the overall power factor. *Fig. 1* (a) shows the basic construction.

The TSC uses a multiple number of shunt capacitors, and switches number of capacitors in response to the size of lagging reactive power of the load. For the switching elements, thyristors are used. The control is made in steps, however, the TSC has such an advantage as that no harmonics are generated as a compensator.

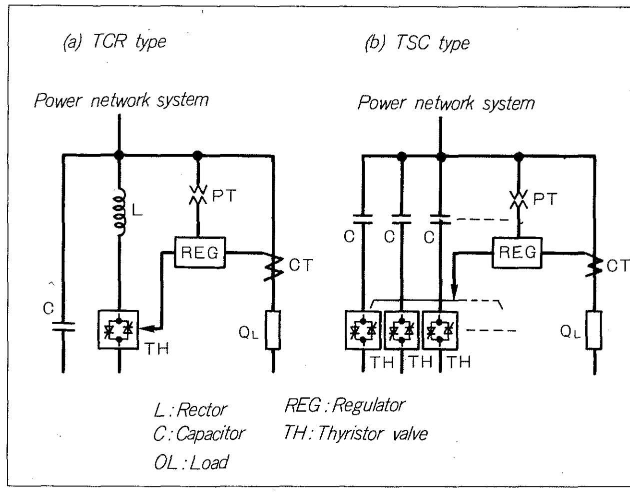

Fig. 1 Standard configuration of SVC

The control system is described by each application in the following paragraphs.

2.1 SVC for power network system

In the recent years, the power transmission line and capacity of a power network system have been greatly increased to efficiently transmit a large power generated in a remote power station due to the difficulties of obtaining area for newly constructed power station and power transmitting routes.

In a power network system like this, the reactance in high because the power is transmitted toward a long distance, transmitted power is limited with the stability, and therefore, it is important to stably maintain the voltage fluctuation (which is one of the power evaluating factors) within the rating. To be more specific, when voltage fluctuation width exceeds the rating and such a condition continues, problems of overexcitation of a transformer and insulations of the associated machines and equipment occur in case of a voltage rise, or problems of overloaded motor/generator and decrease of the power system stability occur

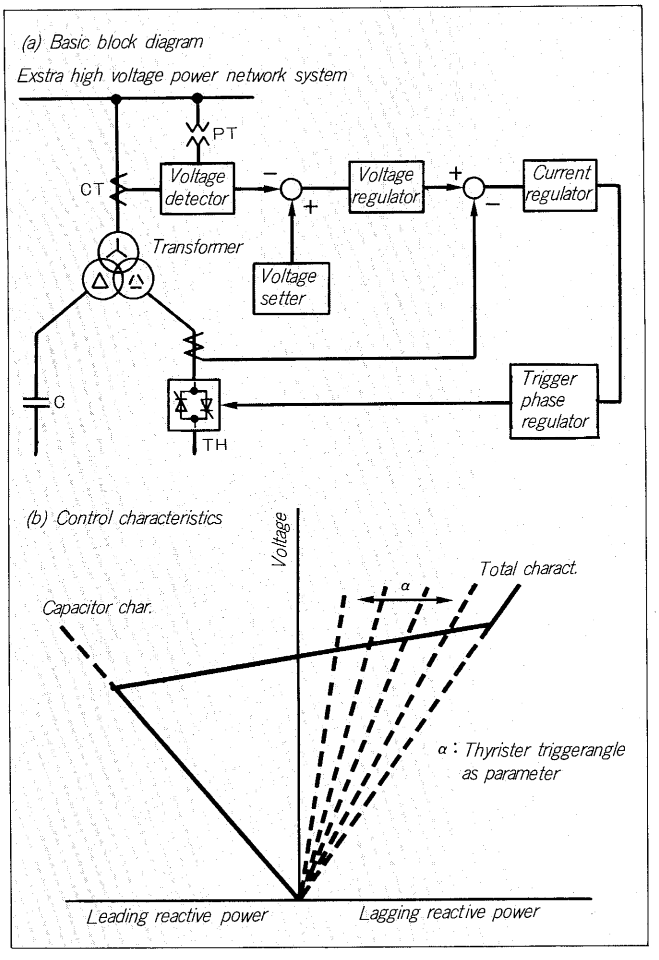

Fig. 2 Block diagram and control characteristics of TCR type SVC

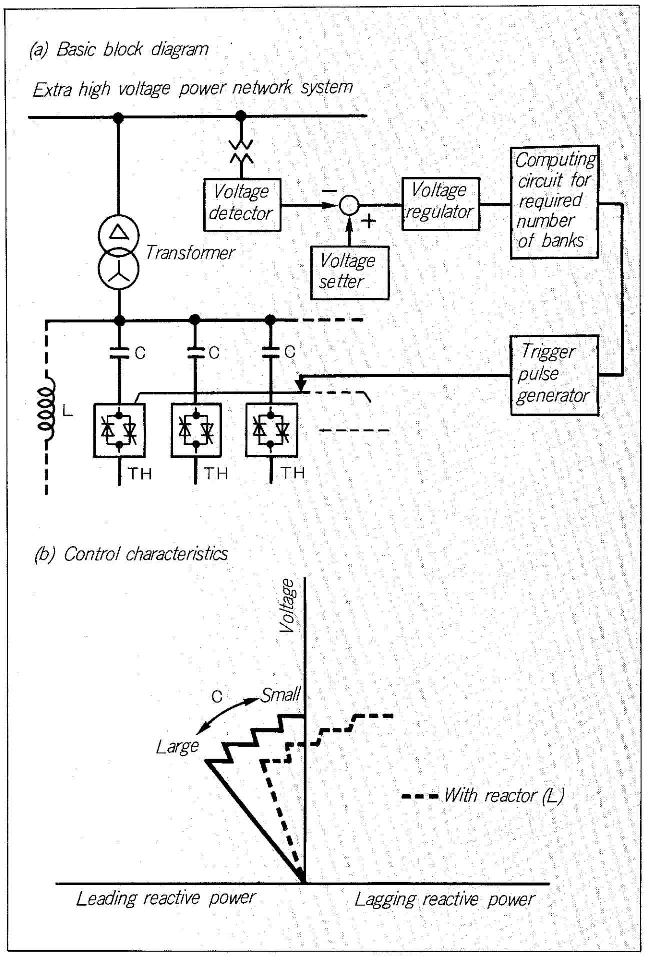

Fig. 3 Basic diagram and control characteristics of TSC type SVC

in case of a voltage drop.

The SVC functions to maintain the system voltage within the rating, and the SVC compensates the reactive power consumed by various loads, power transmission lines and transformers connected in the power supply network system.

Fig. 2 (a) is a block diagram which shows a TCR type SVC for power supply network system. In normal operation, reactive power or voltage fluctuation width and cycle are not so considerable and the power is controlled along the droop (slope reactance) shown in *Fig. 2* (b). When a fault occurs on the system, the system voltage drops momentarily depending on a type of the fault. In this case, the SVC must operate in such a way as to supply leading reactive power momentarily so that the voltage is maintained. Or, when the system voltage rises momentarily due to disconnected loads or system, the SVC must operate in such a way as to supply lagging reactive power so that the voltage rise is suppressed.

Further, the SVC applied as an intermediate phase modifyer in a long power transmission line is sometimes used to suppress the negative damping which occurs depending on the conditions of the exciter system in the power supply generator. In other words, a power system stabilizer (PSS) which uses power flow changes ΔP in intermediate substations as an input is added to the AVR function of the SVC. With this design, voltage fluctuations occurred on the generator terminal is reduced by the PSS for SVC which uses changes of power flow at intermediate substations as an input, therefore negative damping due to the generator exciter system is indirectly suppressed. The PSS consists of a detector whcih detects the component of active power deviation, leading/lagging phase regulators and gain regulator with a limiter in the exactly same manner as a power generator.

In the *Fig. 2* (a), deviation between set voltage and detected voltage is PI-operated with the voltage regulator (AVR). The voltage detector is consisted of multi-phase rectifier circuits as required, and detection delay is reduced by lowering the ripple and by simplifying the filter circuit. It is also possible to provide the voltage detector with the above described droop characteristics and deviated circuit with dead band which acts at a high gain only when the voltage changes reapidly. The current regulator operates to maintain the linearity between the control signal and reactor current, functions as a current limiter and trips an over-current. The trigger phase regulator is so designed that trigger can be made stably not only when trigger pulse occurs or signals are converted to light trigger unit but also when system voltage drops. Moreover, the *Fig. 2* (a), the transformer represents a leakage transformer, which also functions as a reactor.

Fig. 3 (a) is a block diagram which shows a TSC type SVC. The compensated values are stepped because the capacitors are split into multiple number of banks, and they cannot be controlled to the value in between the banks. For this reason, the voltage regulator is composed of a limited gain amplifier, and the voltage regulator amplifies a deviation between the set voltage and detected voltage and transfors the amplified voltage tolerance to the computing circuit for required number of banks. The computing circuit for required number of banks selects the required number of banks and decides the combining and closing sequence in accordance with the voltage tolerance. To prevent a pumping operation, the voltage regulator is equippped with a memory circuit because the voltage deviation is restored by closing and releasing the banks. *Fig. 3* (b) shows the control characteristics. In many cases, reactor L is used in parallel because leading phase can only be compensated by the capacitor

In the actual operation, the TCR and TSC are controlled in the manner of a hybrid. Namely, a large voltage fluctuation and minor fluctuation are compensated respectively by the TSC and TCR so that the equipment can be used effectively.

2.2 SVC for arc furnace

Value and phase difference (power factor) of the current flowing to an arc furnace greatly fluctuate depending on the furnace operating conditions. During the initial steel melting period, the overall mean reactive power is not so considerable, however, the reactive power fluctuates rapidly because short-circuit and are current off are repeated within the furnace. On the other hand, during the refining period, mean value of reactive power is large, but the fluctuation width is comparatively small. Further the current value frequently differs at each cycle and/or half wave, and in many cases, the waveform is a distorted wave which contains many harmonics. For these reasons, voltage fluctuation occurs at less than several cycles per second due to the reactive power fluctuation of arc furnace, and flicker occurs on the power supply network system.

Because of the above reasons, in many cases, TCR type SVC is used for arc furnaces because control can be made continuously, and as a controller, a high responsibility is required so that response can be made every half wave. *Fig. 4* is the block diagram. The main control unit consists of a predictive detector, sensitivity adjuster and non-linearity compensator. The predictive detector detects voltage amplitude and phase difference of voltage/current (E, sin φ) and predicted peak value (I_P) of current in the first half (0 $\sim$ 90°) of each half wave of the arc furnace voltage, and thus, detects reactive power ($I_P \times E \sin \varphi$) by multiplying them. The sensitivity adjuster shifts the SVC (the capacity of which is generally 30 to 50% against the maximum reactive power of the arc furnace) so that it meets with the actual fluctuation zone, and adjusts the ratio of the fluctuation against the compensated value. The non-linearity compensator compensates the non-linearity between control angle and the reactor current. As described above, the control unit performs operations at the first half (0 to 90°) of each half wave and thyristor triggering at the last half (90 to 180°) , and therefore, the control loop is an open loop. The recieved Q detector detects sudden changes of reactive power at the power receiving terminal if any, and corrects trigger of the thyristor.

2.3 SVC for rolling mill

A large reactive power fluctuation occurs on a rolling

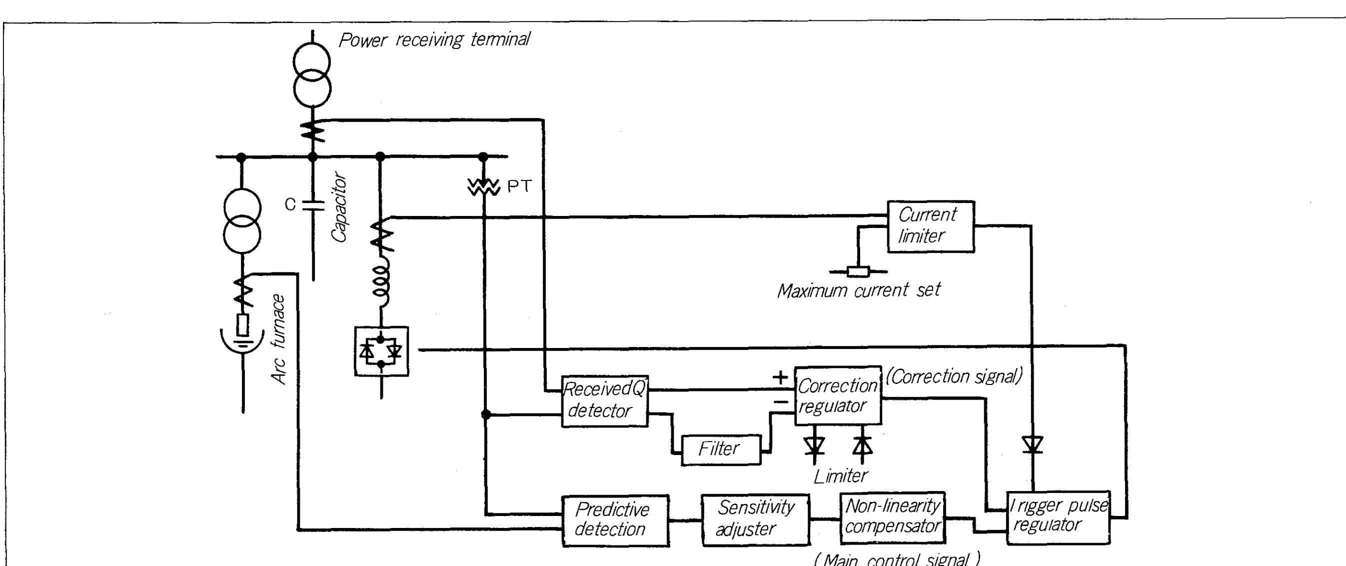

Fig. 4 Basic block diagram of SVC for arc furnace

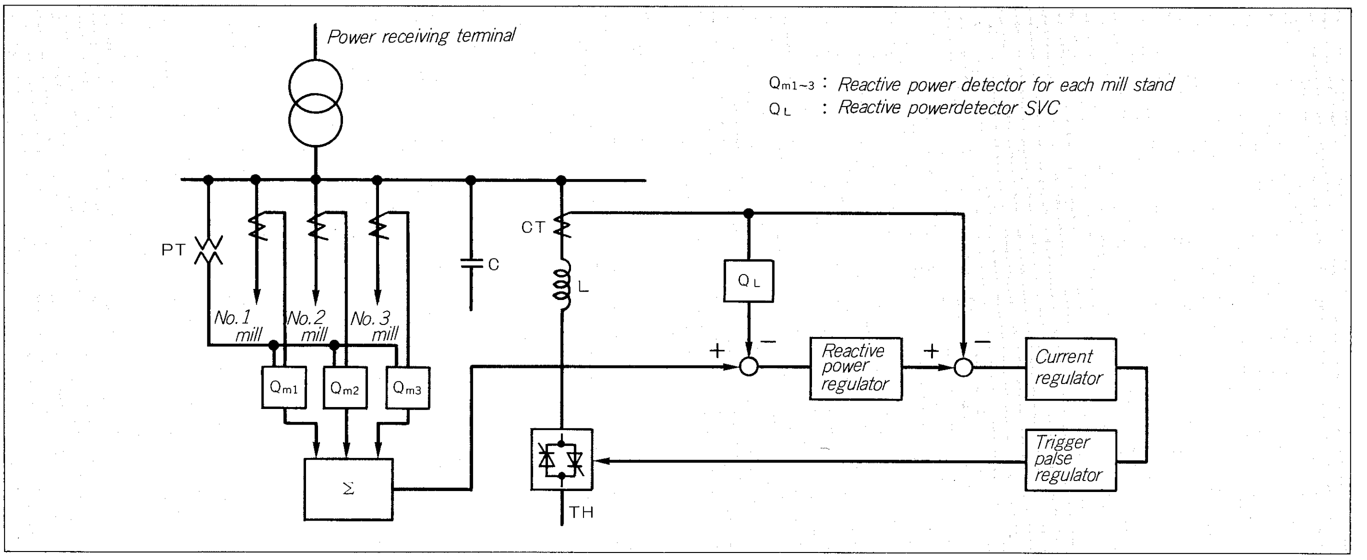

Fig. 5 Basic block diagram of SVC for rolling mill

mill because the thyristor controlled DC motor is operated by repeated loads. The reactive power fluctuating speed is slower in comparison with an arc furnace, and the load is of a three phase symmetry. Therefore, it may not be necessary to use the above mentioned predictive detector but a three-phase reactive power detector having a certain filters may be used. *Fig. 5* shows an example of the block diagram. In this example, multiple number of rolling mill feeders are used, and the TCR compensates reactive power by composing the feeders. The control loop composes a minor control loop because the reactive power increase or decrease with 0.1 to 0.2 seconds at the load side. For the detectors, it is possible to install a constant component cut circuit to take out only fluctuation component of the load and deviated circuit with dead band which acts at a high gain only when a sudden change occurs on the load of a long fluctuation period. The reactive power regulator is of a PI type, which is in the similar composition as the TCR type SVC for power supply.

2.4 SVC for general loads

In addition to those typical application examples described above, for reactive power fluctuating loads, there are welding machine, motor load group, construction equipment, etc. The system can be composed by applying or combining the above introduced examples. For the controller composition, proper selection is needed depending on the purpose of compensation, load change pattern, speed of fluctuation, etc. *Table 1* shows examples of application to general loads.

2.5 Asymmetry load compensation

Generally, the load of a power network system is of a three-phase symmetry, and in the case of a single-phase load such as a power distribution system, it is so designed that the system is symmetrize as much as possible. However, such a load as an arc furnace, spot welder or motor coach on rail way requires a large negative phase sequence active power on the power system. Division of this negative phase load current is decided by the subtransient reactance of each generator, line reactance, etc.

Table 1 Shows examples of applications to general loads

Load	Purpose	Load fluctuating mode	Control system
Welding machine (spot, flash)	Flicker compensation	Fluctuating speed is high but fluctuates comparatively regularly	TCK type, equivalent to one for arc furnace.
Construction equipment	To increase the capacity of the installed equipment and to compensate flicker	Load changes slowly (0.1 ~ 0.2 sec.), however, these pattern is irregular because various loads are involved.	TCR type, equivalent to one for rolling mill. However, detection is made loads together.
Blower fan for tunnel	To compensate reactive power	Depending on the fan motor starting characteristics	TCR type, detection is made at the power receiving terminal

On the other hand, both hydraulic and thermal power generators are limited for the negative phase current withstanding values. These values are generally, 12% for the hydraulic machine and 10% for the thermal machine. For this reason, in the case of a small system, SVC is some times applied to compensate negative phase of active and reactive components.

The operating principle uses Steinmetz's method. To be more specific, a single-phase load between lines U and V shown in *Fig. 6* (a) can be balanced as shown in *Fig. 6* (b) by properly connecting load C and load L respectively between lines V and W and between lines W and U. In this arrangement, for loads C and L, an SVC which connects

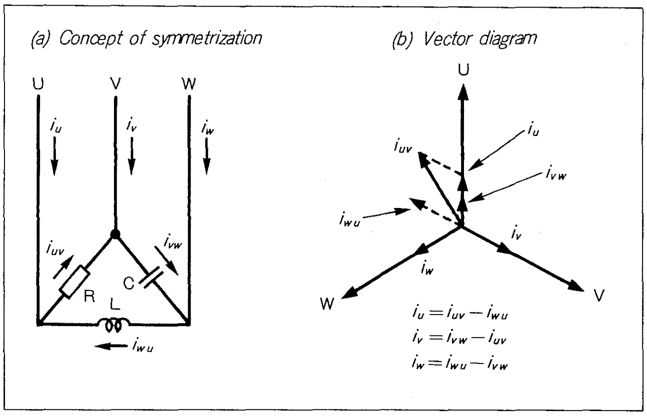

Fig. 6 Steinmetz's method

controllable L and C individually across the lines in parallel may be installed. Values of loads L and C required respectively across V and W and across W and U against the single phase load R across U and V are obtained as follows.

$$\omega L = \frac{1}{\omega C} = \sqrt{3} \cdot \mathrm{R} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

In other words, the asymmetry can be easily compensated by controlling L or C so that the equation (1) is satisfied.

Moreover, the asymmetrical component across the individual lines can be calculated and found easily by transformation from 3 to 2 phases.

III. TCR AND TSC TRIGGERING AND MONITORING SYSTEM

To control the trigger and monitor for fault of the thyristor valve of TCR and TSC, light guides are used and operations are made by optical signals. Therefore, the main circuit and triggering and monitoring system are completely insulated, and this system features its high noise resistance. Composition and operation of the system outlined below.

3.1 Triggering and monitoring system of TCR

As for the triggering and monitoring system composition of TCR, it consists of an triggering and monitoring unit (EL) pulse transmitter unit (Z) in the thyristor valve side, and gate control unit and auxiliary unit in the low voltage side. Signals are transmitted and received across the low and high voltage sides through the light guides. In the start/stop operating circuit within the auxiliary unit, the thyristors are not triggerd prior to the operation after closing the circuit breaker, but with the trigger pulse blocked, check command is generated to check the thyristor device for existence of a fault, and therefore, start command is generated based on the operation command. Using this signal, ON signal of the forward reverse thyristor sent from the AVR is coded by the encoder in the gate controller. The coded ON signal is converted to an optical signal by the electrical/optical converter circuit (E/O), and thus, the signal is transmitted to four thyristor valves (connected in 2 series anti parallel) in the form of an optical signal through one light guide. The trigger and monitoring unit (EL) in the thyristor valve returns this coded optical signal to electrical signal, interpretes if the thyristor trigger pulse is negative or positive, and then, distributes it to the pulse transmitter unit (Z) as an amplitude pulse. The pulse transmitter unit insulates this pulse with the pulse transformer, and supplies it to the thyristor devices.

On the other hand, the units EL and Z always monitor thyristor voltage. When the thyristor element is not short-circuit or broken, the units return the monitor signals

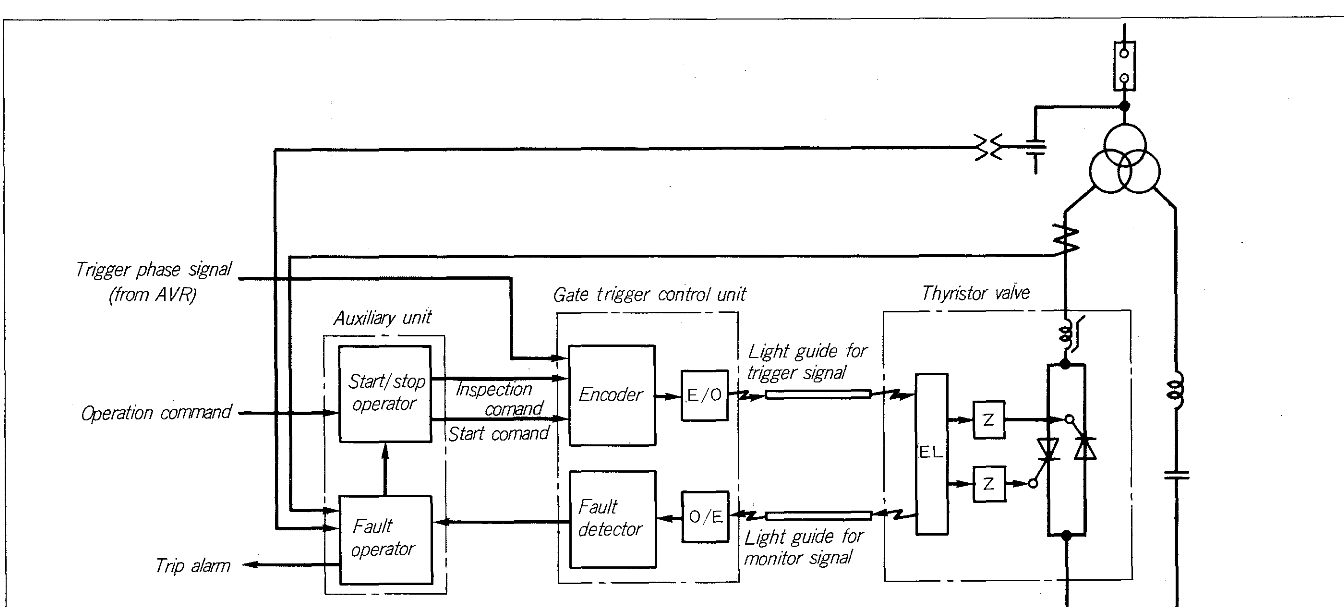

Fig. 7 Construction of TCR trigger and monitoring system

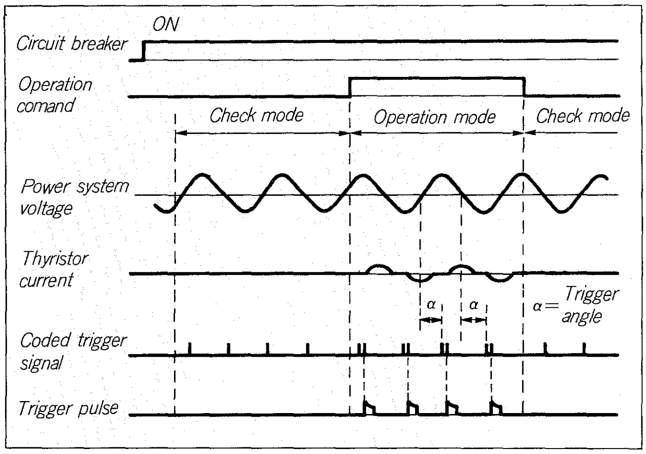

Fig. 8 Basic operations of TCR

which indicate that the thyristor element is normal. When an overvoltage is applied to the device, BOD (Breakover Diode) operates to protect the device and then, a protective trigger signal is generated. The units EL and Z return both the above mentioned monitor signals and protective trigger signal through one light guide for monitoring signal. The trigger control unit converts this signal to electrical signal with the optical/electrical converter circuit (O/E), detects faults such as 1 all device fault, 2 individual device fault, 3 triggering system fault, 4 continuous self triggering (due to fault of RC snubber circuit) and 5 simultaneous protective triggering (in the case of an external surge), and indicates a kind and location of the fault. The fault operator processes the fault detected by the fault detector circuit,

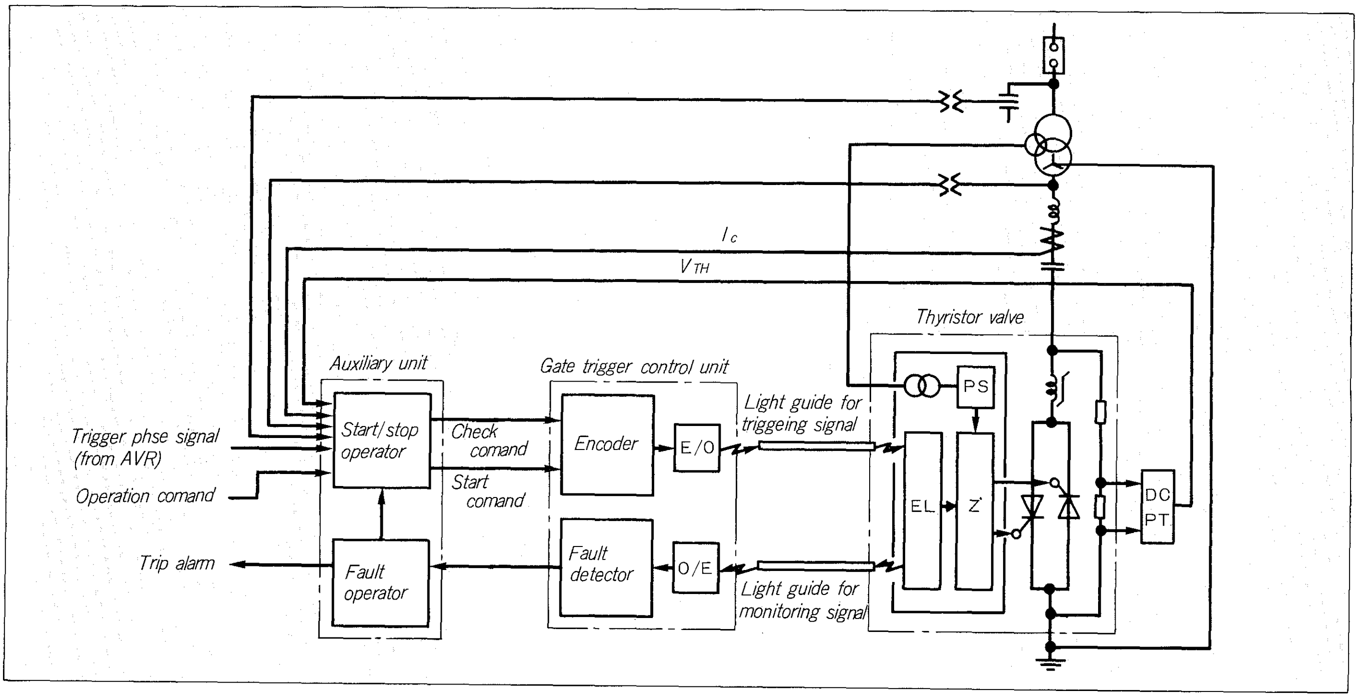

Fig. 9 Construction of triggering and monitoring system of TSC

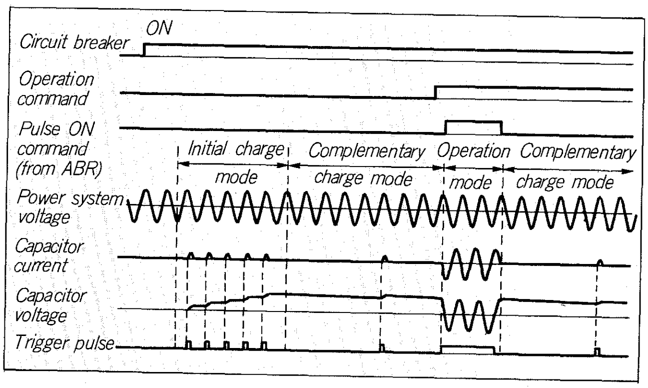

Fig. 10 Basic operations of TSC

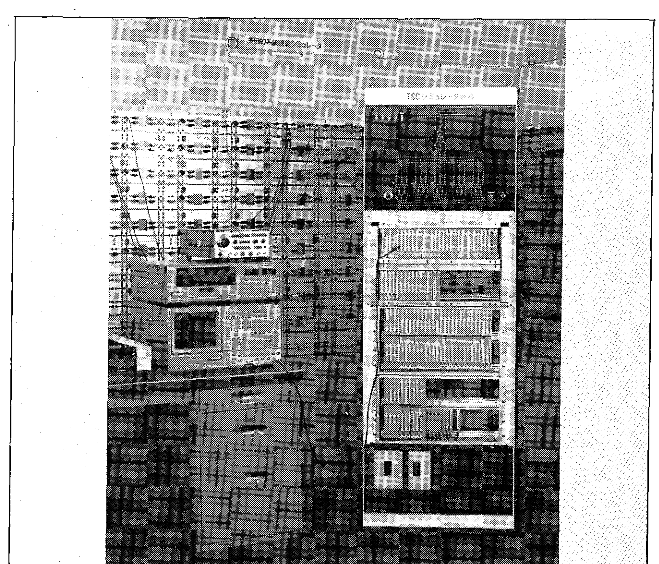

Fig. 11 External view of TNS

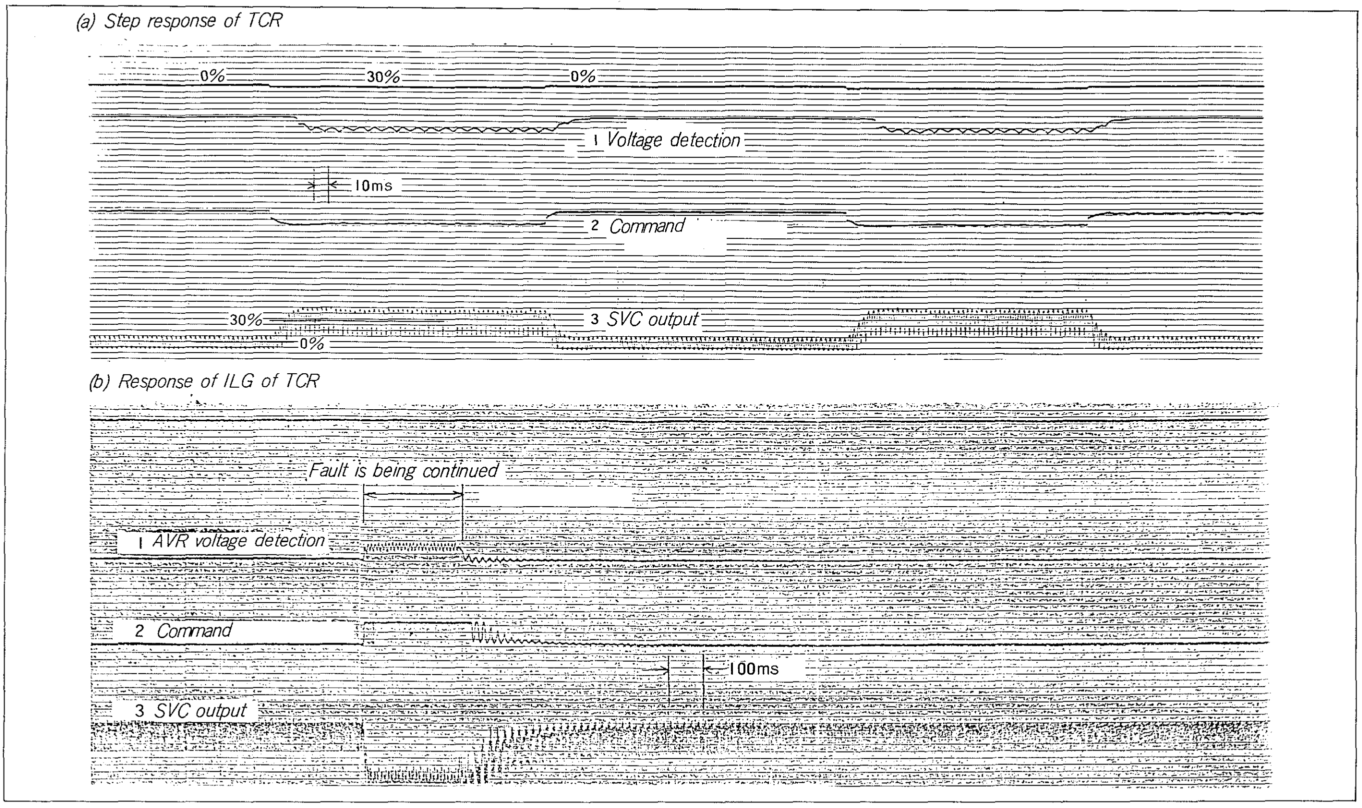

Fig. 12 Step responce of TCR and response of 1LG (one line grounding)

and makes interface with an indicator and control equipment. *Fig. 8* shows an outline of the basic operations of the TCR at each mode.

3.2 Triggering monitoring system of TSC

The trigging and monitoring system configuration of the TSC in similar to that of the TCR as shown in *Fig. 9*. The monitoring system of the TSC, however, uses an additional circuit in the auxiliary unit to calculates capacitor voltage from the capacitor current (I_C) and thyristor valve voltage (V_{TH}) detected from the DCPT. (The capacitor voltage is required in deciding thyristor ON-OFF timing and in changing over the TSC control mode (initial charge, complementary charge and operation).)

Fig. 10 shows the outline of the basic operations of the TSC. In the case of a TSC, the main circuit capacitor is charged after closing the circuit breaker (initial charge mode). When the capacitor is charged completely, complementaly charging is performed to cover the voltage drop due to discharging (complementary charge mode). When an operation command is given and pulse ON command is given from the AVR, thyristor valve is triggered at the instant of the voltage of the thyristor valve equal to zero, and thys, the system operates (operation mode). These mode switchings are computed by the start/stop operator.

Moreover, the check pulse used to check if a fault exists on the thyristor valve or not is applied at every cycle during the initial charge period and at every half cycle during the complementary charge period. The fault detect-

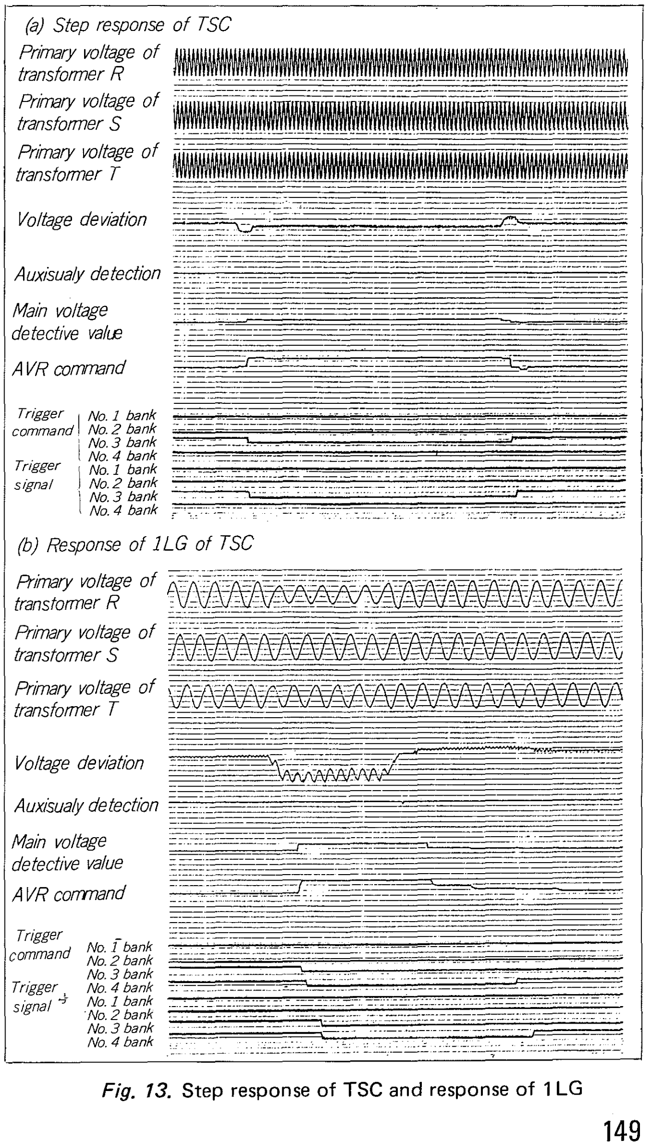

Fig. 13. Step response of TSC and response of 1LG

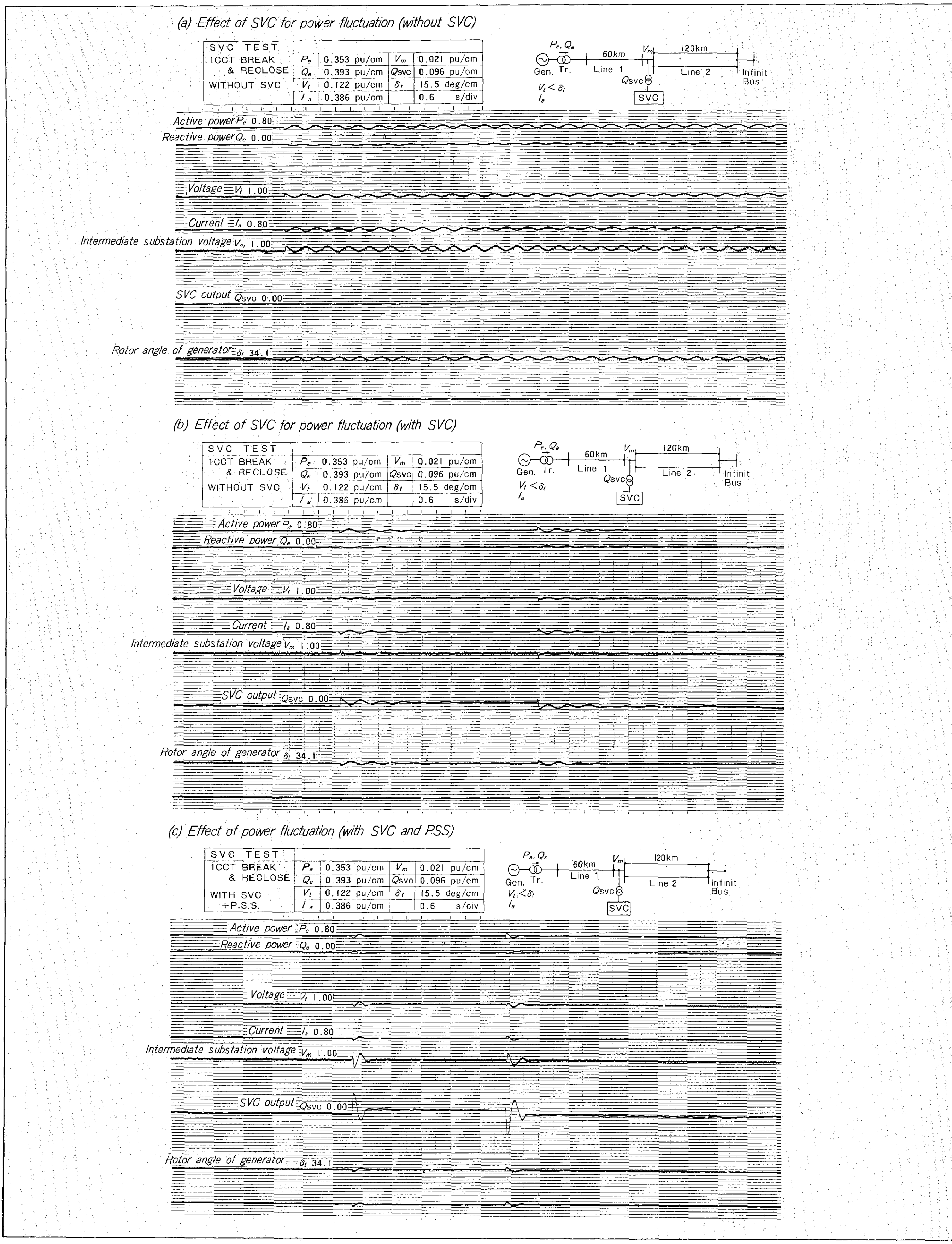

Fig. 14 Effect of SVC for power fluctuation

ing functions and descriptions are almost same as those of a TCR.

IV. PROVING BY SIMULATION

The performance of an SVC installed to suppress voltage fluctuation accompanied with reactive power fluctuation of the associated load (so called, voltage flicker) is evaluated in the improvement ratio of the flicker. The improvement ratio of flicker is decided by the control response of a compensator, compensation capacity against reactive power fluctuation width, etc. Especially, in case of an arc furnace load, it is difficult to predict the performance by examining papers only because the fluctuation is rapid and the pattern is irregular.

Therefore, using an actual load, power or current fluctuating patterns are recorded in a magnetic tape, simulation is conducted by combining the recorded fluctuation pattern with a computer model, the optimum compensator capacity and compensation capacity against fluctuating width of the reactive power are decided, and improvement ratio of flicker is evaluated in advance.

When applying an SVC to stabilize voltage of power transmission lines, the influence given by the operations of the SVC to the associated system varies and the range is wide. For this reason, not only the control performance for the normal voltage changes but also operations at the time of system failure and problems of harmonics must also be carefully examined.

For the above reasons, Fuji Electric uses a computer, transmission network simulator, TNS (Transient Network Simulator), etc. to conduct simulations on the model system in which the SVC is installed, establishes the optimum SVC control system, and conducts control performance proving test on the SVC.

Fig. 11 shows an external view of the TNS.

Figs. 12 and *13* respectively show examples of simulation results obtained from TCR and TSC type transmission network simulators. Each of these results indicates the step response and response at 1LG failure. It is proved that both of them have sufficient responsibilities.

Fig. 14 shows results of simulation obtained from the transmission network simulator for which power flicker is reduced by using SVCs (with and without PSS). *Fig. 14* (a) indicates the results obtained without SVC, *Fig. 14* (b) indicates the results obtained with SVC, and *Fig. 14* (c) indicates the results obtained with SVC plus PSS. It is obvious that flickers of power, voltage, rotor angle of generator, etc. are attenuated, proving that this SVC is effectively operating.

V. POSTSCRIPT

The typical control systems of the SVCs manufactured and delivered by Fuji Electric during the recent years were introduced. The system configuration and load characteristics and the purpose of compensation differ by each case. Therefore, when actually designing an SVC, detailed application examinations are required, and the authors hope that this paper will be an aid for the examinations.

In the future, as the power transmission line will further be extended, new power stations will be constructed in spread areas, and voltage fluctuation will be different at each point of the system, it is considered that more and more SVCs will be installed to stabilize the power supply network and to improve quality of the power. In cope with such tendency, we will continue to concentrate our efforts in further improving control performance by using digital systems, reducing dimensions of systems, and in promoting economic design by using simulation technologies.