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STATIC VAR COMPENSATOR FOR ELECTRIC POWER NETWORK SYSTEM

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I. INTRODUCTION

In the recent power network system, unit capacity has increased, transmission line is greatly extended and system construction has been complicated more and more, and in the other hand, it has been requested to supply higher quality power stably. To supply high quality power, it is necessary to maintain frequency and voltage constantly in certain levels, and for these purposes, to maintain voltage in a constant level, reactive power compensators have been used.

For the reactive power compensators, power capacitors, shunt reactors and synchronous condensers have conventionally been used. Recently, static var compensator (SVC) was developed by applying the power electronics technology, and has already been used practically.

This paper describes the purpose of reactive power compensations in the power network system, SVC application technique and SVC manufacturing examples.

II. PURPOSE OF REACTIVE POWER COMPENSATION

In a power network system, reactive power is compensated to suppress line voltage flucutations and to improve the stability.

To be more specific, voltage fluctuation at a reference point of voltage variation is, when indicated in a unit method, expressed approximately as equation (1) in a power system reactance (X_s) and reactive power variation of the load (ΔQ).

$$\Delta V \fallingdotseq X_s \cdot \Delta Q \quad \text{.......................(1)}$$

Hence, to suppress voltage variation ΔV, either the power system reactance X_s or reactive power variation of the load ΔQ must be reduced. To reduce X_s, power capacity of the system may be increased. However, the execution is not easy, and generally, reactive power variation of the load ΔQ is rather reduced.

Reactive power of a power network system fluctuates due to the factors shown below, causing the line voltage or bus voltage of the substation to fluctuate.

(1) Variation of load
(2) On/off of load
(3) Connection and disconnection of alternator
(4) Connection and disconnection of var installation
(5) Change of power system construction

When voltage fluctuation width exceeds a certain range and it continues over the predetermined period, the transformer is over-excited and machine insulation in adversely affected (in case of voltage rise) or an overcurrent of armature occurs on a rotary machine, field over exciting current occurs on synchronous machine and system stability drops (in case of voltage drop). When the load is an arc furnace for which the mode of reactive power variation is random and the fluctuation cycle is short, a flicker occurs.

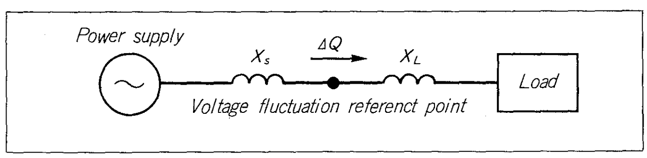

Fig. 1 System diagram

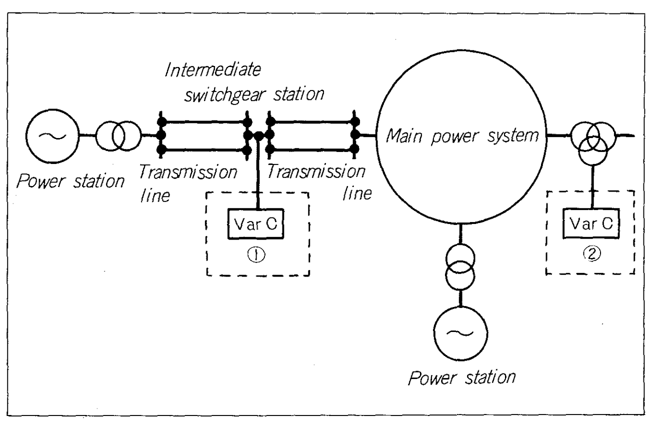

Fig. 2 Application examples of var compensators

Voltage on a power line differs from the frequency, where voltage differs at each point in the power line while the frequency is same over the power line. Therefore, it is desirable to control voltage at each point of the power line. In a power station automatic voltage regulator (AVR) is used, and in a substation, transformer tap is adjusted, power condenser and shunt reactor are connected and disconnected, and/or synchronous condenser and static var compensator are operated.

There are two purposes of using reactive power compensators in a power network system. One of them is indicated in *Fig. 2* as (1). In this case, the var compensator is installed in the intermediate switchgear station to sustain the voltage at that place so that the power network is stabilized. The other is indicated in the *Fig. 2* as (2). In this case, the var compensator is installed in the primary substation which connects the main power system to the middle voltage system to suppress mainly the bus voltage fluctuation of the substation due to the load fluctuation.

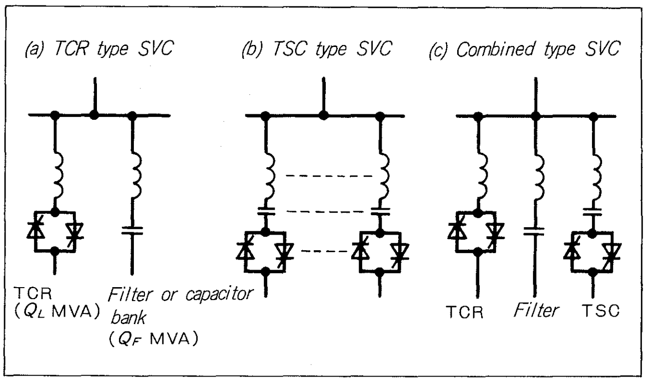

Fig. 3 Various types of SVC

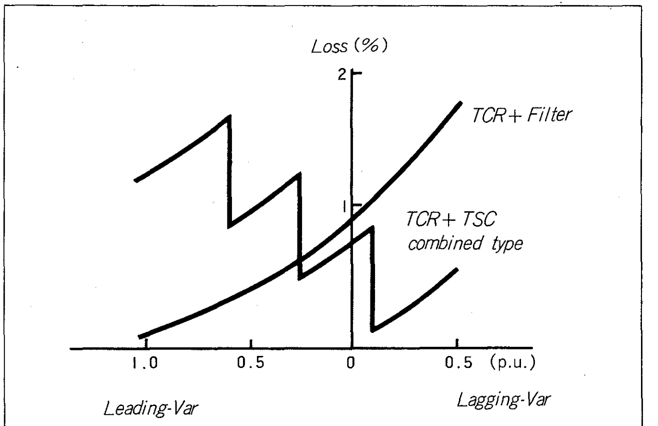

Fig. 4 Loss curve

III. APPLICATION TECHNIQUE

Before applying the SVC, various system studies must be conducted, and the type of equipment, specifications, installed position, etc. must be decided adequately and correctly.

3.1 Capacity of the reactive power compensators

The required above mentioned capacity is decided by a load flow study. To be more specific, for a case in which the power system is constructed in the minimum capacity, it is assumed that the maximum load is connected to each position on the transmission line, and capacity and installed position of the SVC required in sustaining the receiving voltage at each position within the allowable value are obtained. Then, the leading var of the SVC can be decided. Subsequently, the SVC capacity required in suppressing voltage of each position at the minimum power flow or no load within a predetermined range is obtained. Then, the lagging var of the SVC can be obtained. In this study, the already existing var installations and static capacity of the transmission lines are greatly involved, and therefore, it is necessary to decide the optimum specifications by using the impedance map which includes the existing conditions and by coordinating the capacity of the reactive power compensators with the operating conditions of the power network systems.

3.2 Types of SVC

As for types of SVC, at present, thyristor controlled reactor (TCR) type, thyristor switched capacitor (TSC) type and types which combine the TCR and TSC are used.

The TCR is capable of continuously regulating lagging var reactive power from zero to the rated capacity (Q_L MVA), and as it absorbs generated harmonic current, a filter (Q_F MVA) is always connected. For this reason, capacity of the SVC is adjustable from the leading Q_F MVA to lagging Q_L-Q_F MVA. The leading adjustable range can be expanded by adding a capacitor bank, however, to hold the original lagging adjustable range, capacity of the TCR must be increased.

The TSC is capable of adjusting leading reactive power in steps because it connects and disconnect a capacitor bank. The adjusting range can be expanded to the lagging reactive power by connecting a shunt reactor to this case. Actually, however, this is not used but it is combined with the TCR as describec below.

Instead of combining a fixed capacitor bank with the TCR, TSC is combined with TCR. When operating at the lagging range, the TSC is disconnected and when operating at the leading range, the TSC is connected. Then, in comparison with the TCR + fixed capacitor bank type, capacity of the TCR can be reduced, and as the results, occurrence of harmonic current and power loss are reduced. In this case, use of thyristor valve for TSC cannot be avoided.

To this thyristor valve for TSC, capacitor voltage and line voltage are added, and for this reason, in comparison with a valve for TCR, number of thyristors connected in series must be increased in about twice. Consequently, the dimensions and loss are larger than those of the valve for TCR.

For this reason, when the system covers both lagging and leading ranges, the loss must also be obtained from the leading and lagging capacities during the operation and operating times, by including this data in the items to be examined, type of SVC must be selected. *Fig. 4* shows examples of loss comparison between the TCR + fixed capacitor combined type and TCR + TSC combined type.

3.3 Stability

Against disturbances in power lines due to a load fluctuation and fault, the condition under which the internal displacement of angle of each alternator can be kept in a certain range and synchronous operation can be maintained is called "stability". There are steady state stability agiainst stationary load variation and transcient stability against recovery state after clearance from the fault.

The SVC differs from a shunt capacitor or shunt reactor, and has an automatic voltage regulation (AVR) function. For this reason, when applying an SVC, time required in clearing out from various fault states must be obtained and control characteristics of the SVC and SVC and line protecting system must be checked.

In addition to the function of automatic voltage regulation (AVR), power system stabilizer (PSS) can be built in the SVC so that the stability can be enhanced, and the effect can be confirmed by simulations.

3.4 Harmonic current

In a TCR type SVC, the reactor current is phase-controlled by a thyristor, and harmonic current shown in *Fig. 5* occurs on the current. When this harmonic current flows into the line, temperature rise occurs on the machines on the line and electromagnetic interference may occurs on the communication lines. For this reason, the harmonic current must be limited.

Normally, in TCR type SVC, flow out of the 3rd harmonic current is prevented by by delta-connecting the reactor or providing the step down transformer with a delta winding. For a large capacity installation, occurrence of low degree harmonics can be prevented by using multi phase connection such as 12-phase connection. Generally, however, AC filters are used in the most cases.

Because the AC filters are selected with regard to the power line impedance, proper filters are selected from 5th, 7th the 11th series resonance capacitors and by-path capacitors, and by combinining the selected filters, the optimum filter is used by taking the following factors into considerations.

(1) Hormonic current generated from TCR
(2) Power system impedance for each order harmonics
(3) Deviation of power system frequency
(4) Harmonics conventionally existing on the system.

3.5 Coordination with the existing var-installations

From those SVCs which are capable of high speed responding and highly frequent operations, good results can be expected by achieving the optimum coordinations with

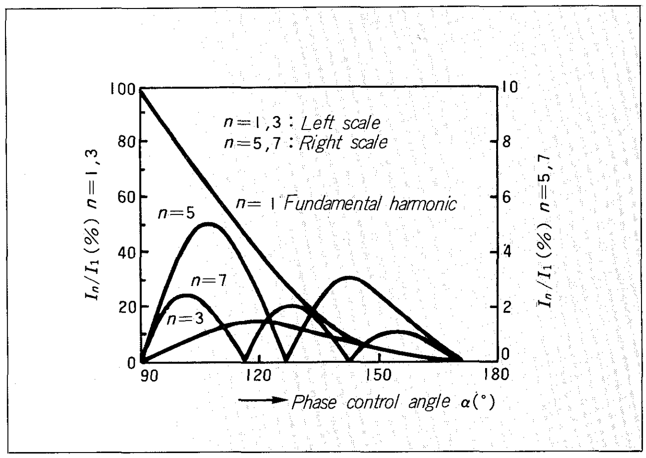

Fig. 5 Harmonic current generated from TCR

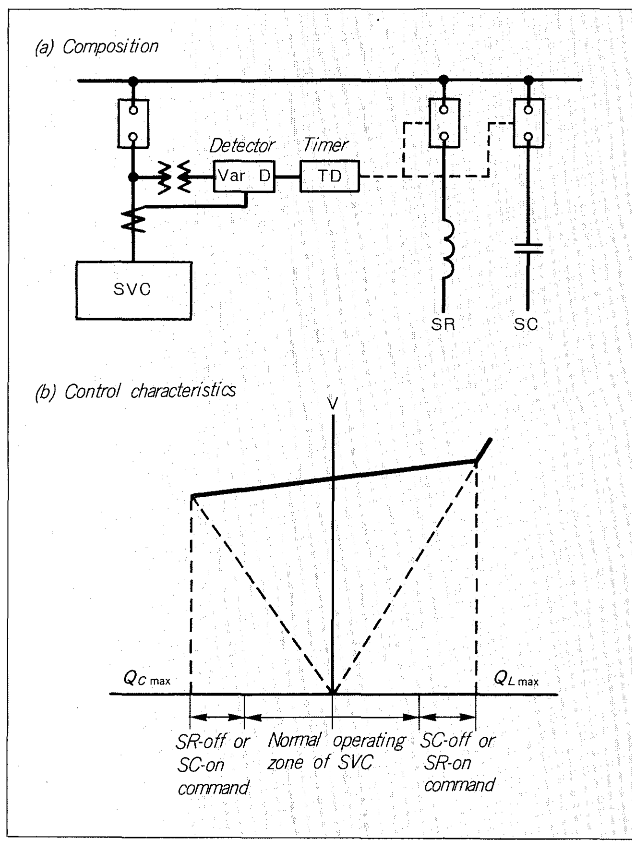

Fig. 6 Coordinated operations of static var compensator and shunt reactor and shunt capacitor

the existing shunt capacitor (SC) and/or shunt reactor (SR) with a mechanical switch gear.

In this case, each equipment displays its own function. Namely, the SVC operates to cope with rapid fluctuations such as a flicker and fault, and SC and SR operate to cope with a continuous and wide range fluctuations caused by the line switching and day-night shifting.

The control of SVC features that the SR is disconnected or SC is connected when the state stays in the maximum lagging var zone for a certain period of time as shown in *Fig. 6*. Further, when the state stays in the maximum leading var zone for a certain period of time, the SC is disconnected or SR is connected. As the results, the SVC can always be standing by at the zero var, and the maximum var capacity can be stored, allowing a high speed responce.

IV. STATIC VAR COMPENSATOR DELIVERY EXAMPLES

The TCR-SVC that Fuji Electric recently delivered to CFE (Comission Federal de Electricidad) of Mexico and TSC-SVC presently being manufactured by Fuji Electric are outlined.

4.1 230 kV 50 MVA TCR type SVC

This SVC has been delivered into Santa Ana substation, and as shown in *Fig. 7*, it is installed on the intermediate position of the 230 kV line to suppress voltage rise on the bus of the substation during night time and cold season when the load is reduced and to improve the system stability. *Fig. 8* shows the main circuit configuration and *Table 1* shows the general specifications of the main equipment.

A thyristor valve is connected to the secondary winding of the 3-winding type transformer, and to the 3rd winding, a harmonic current filter is connected. Using a high impedance on the leakage reactance between the primary and secondary windings of the transformer, a.c. reactor is omitted. This system composes an SVC of TCR type which is capable of continuously regulating the range of 0 to 50 MVA lagging reactive power. The harmonic current generated from the TCR is absorbed by the filter connected to the 3rd winding of the transformer. For the filter condensers, one out of three banks is used as a stad-by bank, and when a fault occurs on a condenser, the faulty condenser is automatically switched over to the stand-by bank.

In addition to the SVC, a 17 MVA shunt reactor with mechanical switch gear is installed in this substation as shown in *Fig. 8*, and on or off control is made automatically when this SVC output exceeds the maximum lagging or leading capacitor for a certain period of time.

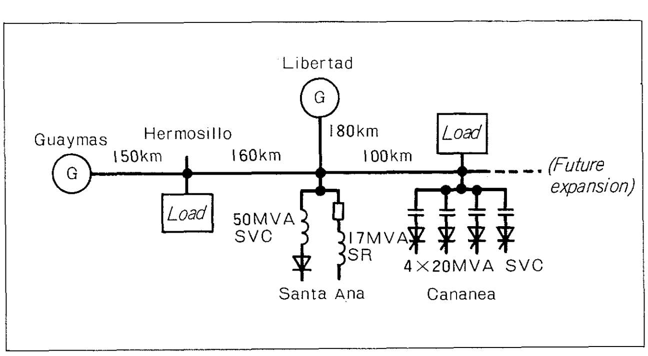

Fig. 7 System diagram

Fig. 9 shows an example of 24 hour operating record of the SVC. Capacity of the SVC operated at the rated capacity during night time reduces as soon as the sun rises, and it continues operating at low capacity during the morning. After the noon, the SVC is manually caused to stop, the 17 MVA shunt reactor is automatically turned off because capacity of the SVC reached the lower limit after restarting the operation, and the SVC is operating under the same state thereafter. As the time is elapsed to about 10 PM and capacity of the SVC reaches the upper limit, the 17 MVA shunt reactor is automatically turned on.

The thyristor valve is of a air insulated water cooling type, and is accommodated in the building shown in *Fig. 10*. *Fig. 11* shows the overall layout of this SVC. The transformer unit consists of four single-phase transformers, and out of these four, one in the stand-by transformer. Switching to the stand-by transformer can be made easily by changing the connection to the bus without moving the transformer.

Table 1 Specifications for SVC delivered to Santa Ana Substation

Rated specifications	Reactive power regulating range		0 ~ 50 MVA (Lagging)
Rated specifications	Rated power line voltage		230 kV
Rated specifications	Rated frequency		60 Hz
Rated specifications	Type of SVC		(TCR) Type
Control characteristics	Type of control		Automatic voltage regulating (AVR) control
Control characteristics	Voltage setting range		230 ±5%
Control characteristics	Droop characteristics		0 ~ 5%
Control characteristics	Control response		34 ms or less
Apparatus specifications	High impedance transformer (4 units × single-phase)	Rated voltage	$\frac{230}{\sqrt{3}}$ /12.3/6.6 kV
Apparatus specifications	High impedance transformer (4 units × single-phase)	Rated capacity	$\frac{50}{3}$ / $\frac{56}{3}$ / $\frac{6}{3}$ MVA
Apparatus specifications	High impedance transformer (4 units × single-phase)	Type of cooling	O. N. A. F.
Apparatus specifications	Thyristor valve (3 units × single-phase)	Rated voltage	12.3 kV
Apparatus specifications	Thyristor valve (3 units × single-phase)	Rated capacity	56/3 MVA
Apparatus specifications	Thyristor valve (3 units × single-phase)	Type of insulation	Air insulation
Apparatus specifications	Thyristor valve (3 units × single-phase)	Type of cooling	Water cooling
Apparatus specifications	Filter bank (3 banks × 3-phase)	Type of filter	5th harmonics filter
Apparatus specifications	Filter bank (3 banks × 3-phase)	Voltage, capacity	6.6 kV, 6 MVA
Apparatus specifications	Filter bank (3 banks × 3-phase)	Capacitor bank	3 banks (1 standy)
Apparatus specifications	Filter bank (3 banks × 3-phase)	Capacitor rating	6.6 kV, 3 MVA/bank
Apparatus specifications	Filter bank (3 banks × 3-phase)	Series reactor	1 × 3-phase, 6.6 kV, 0.237 MVA
Apparatus specifications	230 kV SF_6 gas circuit breaker (1 unit)	Rated voltage	245 kV
Apparatus specifications	230 kV SF_6 gas circuit breaker (1 unit)	Rated current	1,250 A
Apparatus specifications	230 kV SF_6 gas circuit breaker (1 unit)	Short-circuit current	25 kA
Apparatus specifications	230 kV disconnecting switch (3 units)	Type	Center brake type, motor operate
Apparatus specifications	230 kV disconnecting switch (3 units)	Rated voltage	245 kV
Apparatus specifications	230 kV disconnecting switch (3 units)	Rated current	1,250 A
Apparatus specifications	230 kV disconnecting switch (3 units)	Short-circuit current	25 kA

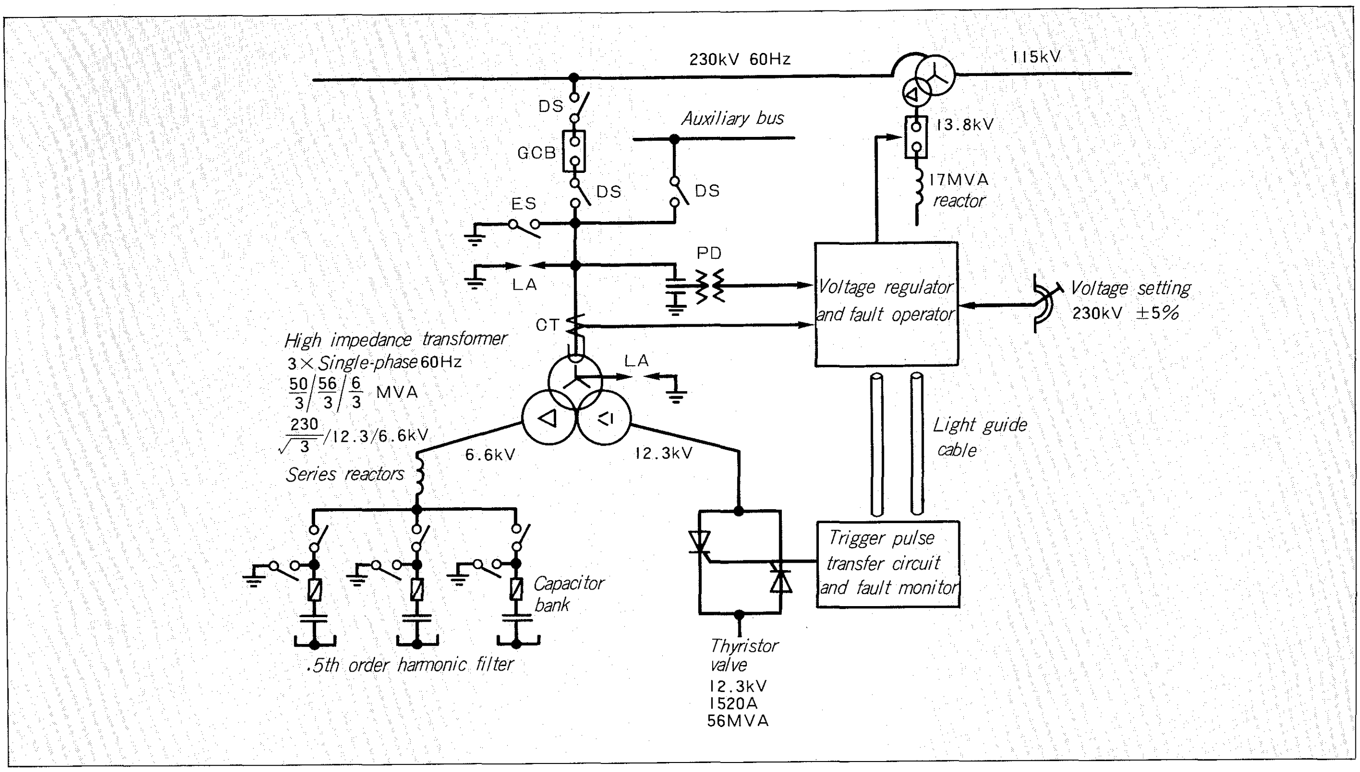

Fig. 8 Single line wiring diagram

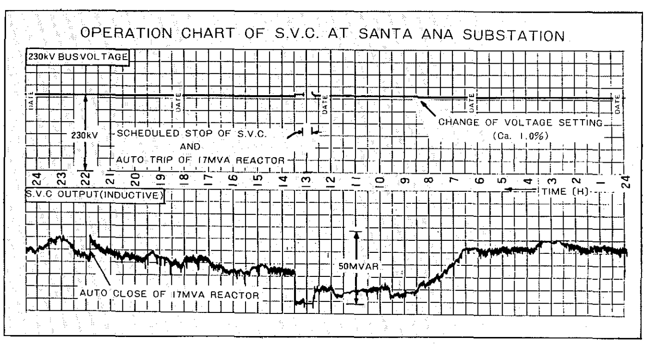

Fig. 9 Operation record

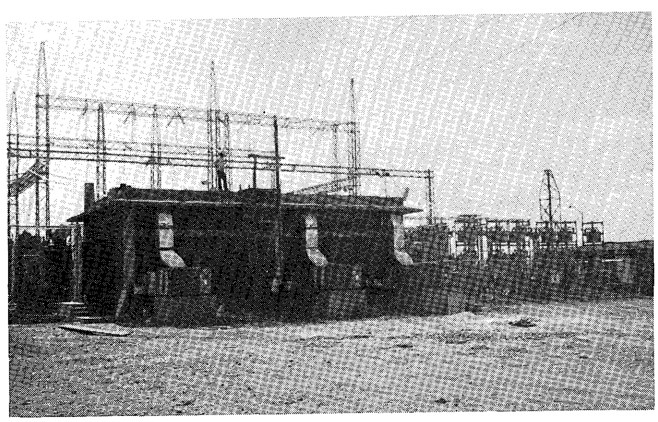

Fig. 10 Valve accommodated building

4.2 230 kV 80 MVA TSC type SVC

This TSC type SVC has been delivered into Cananea Substation of the CFE. Cananea substation is located in the system end distanced about 410 km from the power station as shown in *Fig. 7*, and copper mine is near the Substation. This Substation supplies power to the loads of air conditioners rapidly increased during hot season in addition to those industrial loads such as the large capacity motors in this copper mine and electric furnaces in the refineries. Under this circumstance, this SVC has been installed to sustain voltages against the rapidly flucutating industrial loads and air conditioner loads. *Fig. 12* and *Table 2* respectively shown the main circuit configuration and specifications of the major components.

On the secondary bus the voltage of which has been dropped to 8.7 kV by the step down transformer, four banks of 20 MVA thyristor on/off type capacitor (TSC) are installed, and the design allows one more bank installation in the future. With this construction, four steps (five steps in the future) can be controlled with the 20 MVA step.

Fig. 13 shows the layout of this SVC. The step down transformer consists of four single-phase transformers, out of which, one is a stand-by transformer. The bus is so composed that anyone of three transformers can be switched

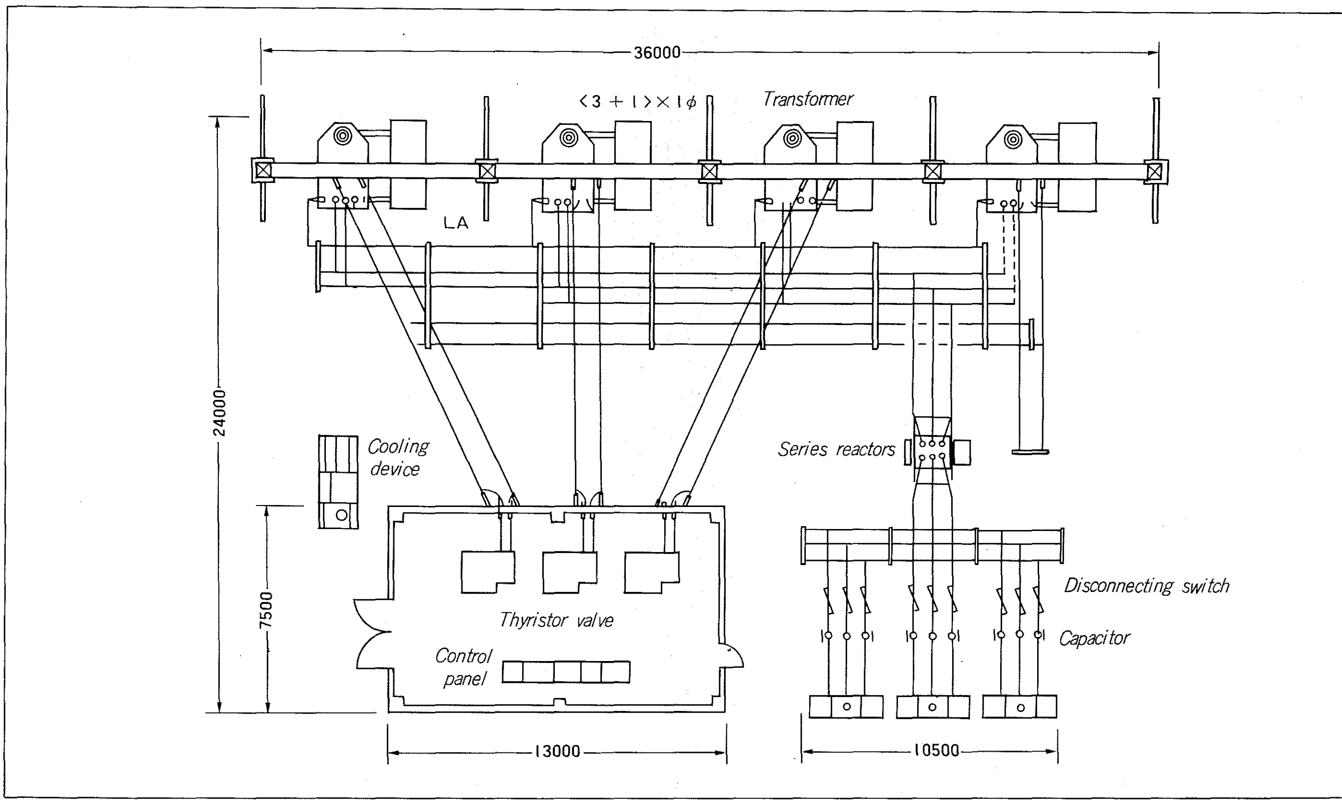

Fig. 11 Layout

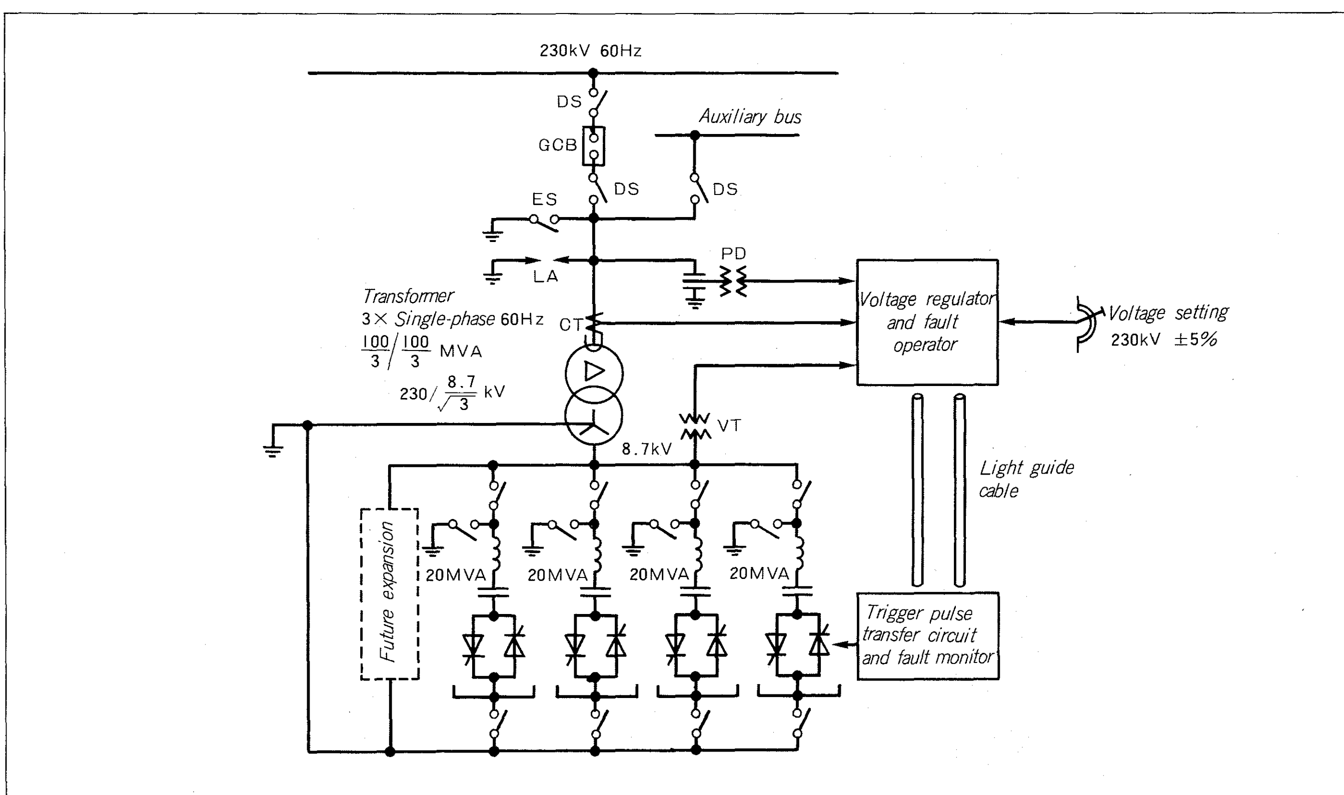

Fig. 12 Single line wiring diagram

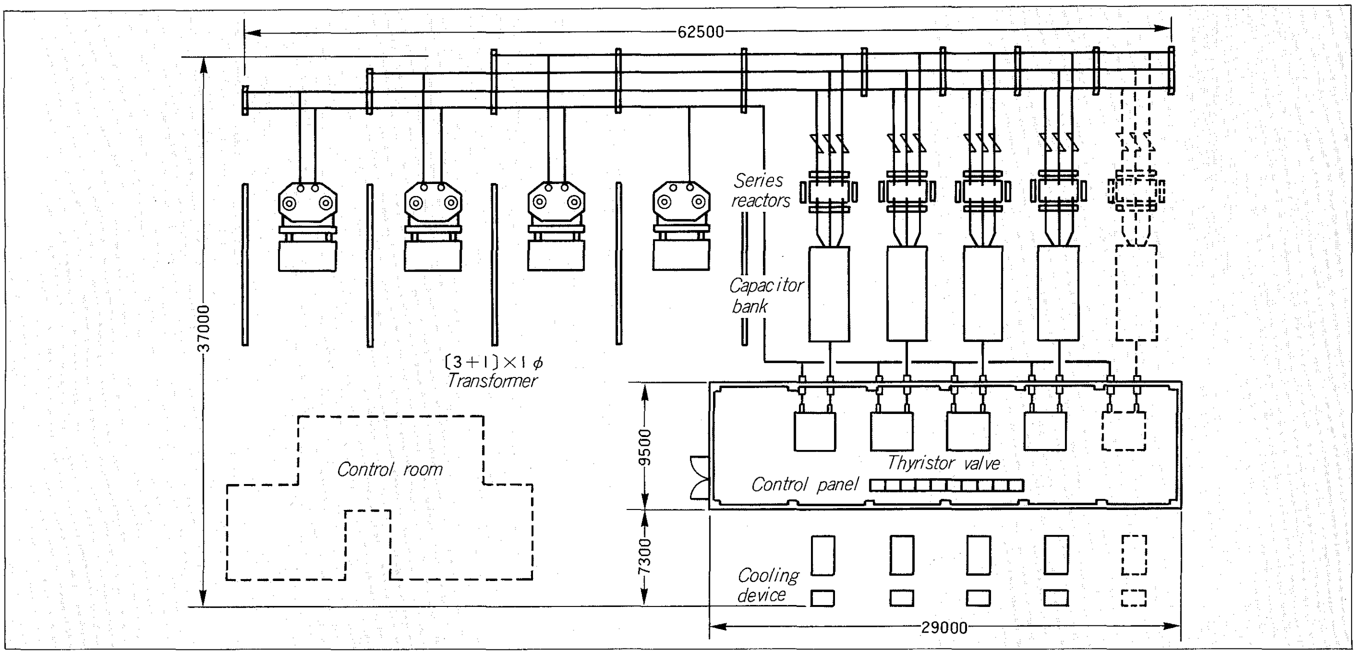

Fig. 13 Layout

Table 2 Specifications for SVC delivered to Cananea Substation

Rated specifications	Reactive power regulation range		0 ~ 80 MVA (leading)
	Rated power line voltage		230 kV
	Rated frequency		60 Hz
	Type of SVC		TSC
Control characteristics	Type of control		Automatic voltage regulating (AVR) control
	Voltage setting range		230 ±5%
	Droop characteristics		0 ~ 5%
Apparatus specifications	Step down transformer (4 units × single-phase)	Rated voltage	$230/\frac{8.7}{\sqrt{3}}$ kV
		Rated capacity	$\frac{100}{3}/\frac{100}{3}$ MVA
		Type of cooling	O. N. A. F.
	Thyristor valve (4 units × 3-phase)	Rated voltage	8.7 kV
		Rated capacity	20 MVA
		Type of insulation	Air insulation
		Type of cooling	Water cooling
	Capacitor bank (4 banks × 3-phase)	Rated voltage	8.7 kV
		Rated capacity	20 MVA
		Capacitor rating	23.3MVA(10.14kV)
		Series reactors	6.6% (20 MVA base)
	230 kV SF_6 gas circuit breaker	Rated voltage	245 kV
		Rated current	1,250 A
		Short-circuit current	25 kA
	230 kV disconnecting switch	Type	Center brake type, motor operate
		Rated voltage	245 kV
		Rated current	1,250 A
		Short-circuit current	25 kA

over to the stand-by transformer without moving the transformers.

V. POST SCRIPT

For the SVC for power network, the summary and manufacturing examples are introduced. The equipment delivered to Santa Ana Substation has continued its operations smoothly since September, 1982, and displaying the atmost effects. The equipment delivered to Cananea Substation in presently under the construction, and it will starts its operation by the end of 1983. The results will be reported in the future.