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VAR COMPENSATOR FOR INDUSTRIAL PLANTS

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I. INTRODUCTION

A heavy industry consumes a large electric power, and melting arc furnace, large scale rolling equipment, welder, etc. possibly cause voltage variations and flickers on the power system.

May, 1950, Japanese Electro-Thermal Technology Committee organized a sub-committee to survey problems of flicker caused by illuminations and to examine the preventive countermeasures, and the sub-committee has continued its activities.

As a well known permissible standard for flickers caused by illuminations, this committee established 0.45V (maximum) and 0.32V (mean value) (measured with a ΔV_{10} meter. Further, this committee suggested that the maximum instantaneous variation should be 2%.

When a heavy industry is in the operation and the flicker and voltage variation are not within the above standards, a countermeasure must be taken.

Fuji Electric has concentrated its efforts since the early stage for the countermeasures and devices to solve these problems, and even in the early 1960s (at that time, thyristor applied products were not developed), Fuji Electric manufactured and delivered a number of compensating equipment to which synchronous condensors called a rotary condenser were applied.

A typical example of the compensating equipment is the 84 MVA synchronous condensor delivered to Kimitsu Works of Nippon Steel Corp. in 1970 to cope with the voltage variations caused when the large size rolling equipment operated.

For flicker suppression of an arc furnace, Fuji Electric delivered a 61.4 MVA synchronous condensor to Funabashi Steel Corporation in 1974, and up to this date, 17 units of the same kind of machines have been delivered to the customers.

On the other hand, the recent power electronics has been remarkably developed, applications of thyristor power converter have been expanded, and the conventional rotary condensors which require maintenance service are now being taken place by thyristor power converters the maintenance of which is easy. Fuji Electric has developed SFC-TSC (Thyristor Switched Capacitor) as well as SVC-TCR and SVC-TSC (SVC: static Compensator), and since 1974, Fuji Electric has applied them to the various purposes.

A typical example is the 120 MVA 33kV high voltage SFC-TCR to be delivered to Trengganu Steel Works in Malaysia which is presently being manufactured for the melting arc furnace.

Further, for rolling mills, Fuji Electric has delivered a 55 MVA SVC-TCR to POSCO of Korea.

For an example of the SVC-TSC, Fuji Electric delivered a 4 MVA SVC-TSC to Fukui Works of Furukawa Alminum Co., LTD. There are many other examples such as the SFC-TCR for welding machines, SFC-TCR for dam construction site and SVC-TSC for high way tunnel blower. This paper introduces the technologies of Fuji Electric for the var compensators for industrial use.

II. PURPOSE OF VAR COMPENSATION

The main purposes of the reactive power compensation for industrial installations are to cope with instantaneous voltage variations and flickers caused by illumination, and subsidiary purposes are to compensate negative phase sequence and to eliminate harmonics.

Table 1 shows the typical application examples of var compensators for industrial plants, and they are outlined below.

2.1 Melting arc furnace

To stabilize arc, a melting arc furnace requires 30 to 60% reactance in the circuit, and because of this reactance, reactive power is necessarily generated.

In the arc furnace, 3-phase alternate current arc is discharged in between the graphite electrode and scrap (raw material), and arc current fluctuates periodically or non-periodically due to electromagnetic force caused by melting down of scrap, short-circuit and/or mutual interference with other phase arc.

Then, reactive power fluctuates, the fluctuation cycle changes at the vicinity of 10 Hz which is most sensible by human eyes, and therefore, flicker occurs on illumination light and TV, giving the watching people an unpleasant

Table 1 Fuji's static var compensators for industrial use

Type	SFC-TCR	SVC-TCR, SVC-TSC	SFC-TCR, SVC-TCR, SVC-TSC	SFC-TCR, SFC-TSC
Application	Melting arc furnace	Large size rolling mill	General motor-driven machines	Welding equipment
Purpose	Flicker suppression	Voltage fluctuation suppression	Voltage fluctuation and flicker suppressioons	Flicker and voltage flucutation suppressions
Capacity (single unit)	5~165 MVA (33 kV)	2~165 MVA (33 kV)	500~5,000 kVA	500~5,000 kVA
Voltage	3~70 kV	3~70 kV	0.4~6 kV	0.4~6 kV
Control method	(1) Predictive control (2) Corrective control (3) Compensative control	(1) Instantenous value control (2) Corective control (3) Multiple number set input operation	(1) Instantaenous value control	(1) Predictive control (2) Corrective control (3) Instantaneouse value control
Features of load	(1) Current rapidly changes by every positive and negative half wave. (2) Mode of current variation changes as the melting proceeds.	(1) Current changes symmetrically among three phases. (2) Load fluctuation width is large. (3) Load fluctuation speed is slow.	(1) Current changes symmetrically among three phases (2) In many cases, the system impedance is especially large.	(1) Current rapidly changes by eavery positive and negative half wave. (2) Many number of welders are turned on and off in random. (3) In many cases, the system impedance is especially large.

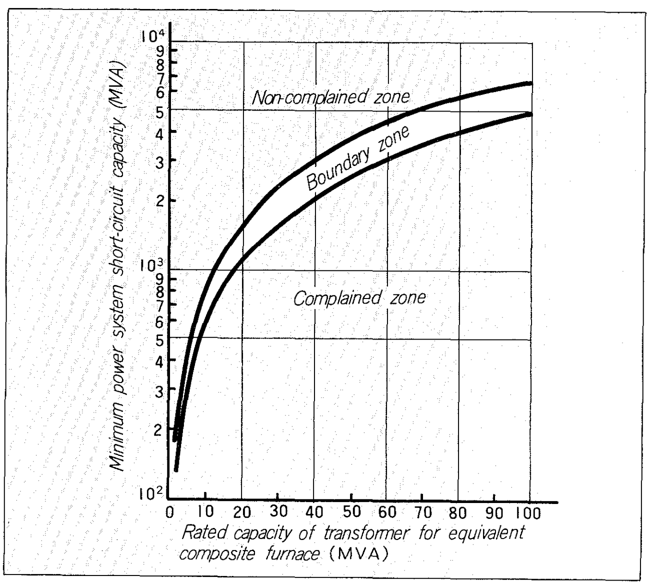


Fig. 1 Relationship between rated capacity of transformer for equivalent composite furnace and minimum power system short-circuit capacity

feeling.

To prevent occurrence of this flicker on illuminations, about 50 to 80 times as great short-circuit capacity of power system as the arc furnace transformer capacity is required, and when short-circuit capacity of power system is smaller than this, some reactive power compensating countermeasure is required. For your reference, *Fig. 1* shows the relationship between arc furnace capacity and power system.

2.2 Rolling mill

A rolling mill differs from another depending on the mode of rolling load. Those rolling mills which require a reactive power compensation are block mills and thick plate mills.

Generally, to these rolling mills, large capacity thyristor leonards are applied. For this reason, the thyristor converter generates reactive power which contains a harmonic current, causing voltage interference on the power supply system. However, a rolling load differs from melting arc furnace (the load is a 3-phase symmetry load) and the fluctuation cycle is generally several seconds or longer. Therefore, the ΔV_{10} (flicker) which is involved in a melting arc furnace may be disregarded and only ΔV_{max} (maximum voltage regulation) is involved in the caused voltage fluctuation. The permissible value of this ΔV_{max} is 2% in the boundary line with a general power consumer. But with an industrial installation, it increases to 5 to 10%, and

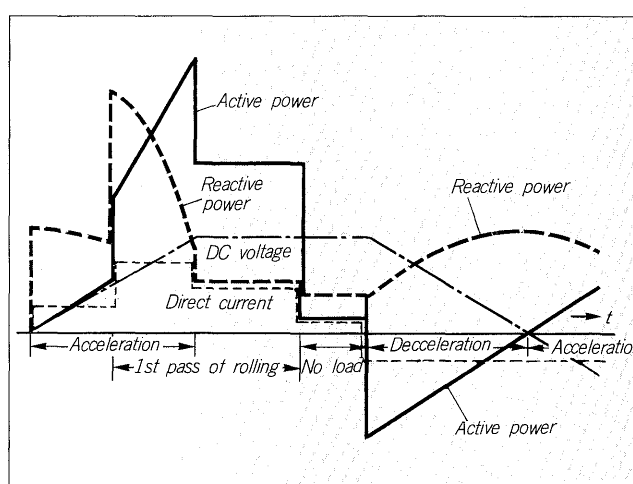


Fig. 2 Active and reactive power variations of resersible mill drive

when the voltage fluctuation exceeds this limit, some reactive power compensators must be installed.

2.3 Welding equipment

For those welding equipment which use electric power, there are an arc welder and resistance welder, and out of these welding equipment, flicker is involved on the resistance welder. The resistance welder flows current to the welded metal and melts and welds the metal with joule heat generated in between surfaces of metals. Therefore, a large current flows repeatedly for a short-period of time. Then voltage fluctuates, and when many number of welders are operated frequently, the problem of flicker occurs.

2.4 General motor-driven machine

For other load involved with fluctuations of reactive power, there are various machines and equipment. For example, there are crashers, blowers and cranes which are started and stopped repeatedly and frequently.

III. APPLICATION TECHNIQUE

3.1 Selection of var compensator

Table 2 shows the typical var compensators for industrial use which are presently used most practially.

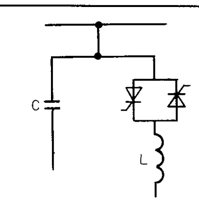
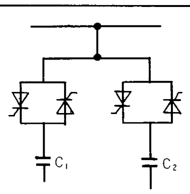
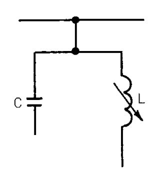
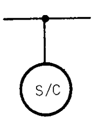
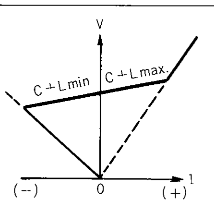
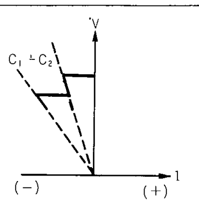
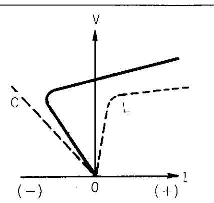
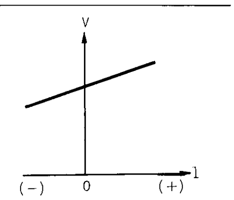
Each one of those compensators has the individual features, and after carefully examining the application, purpose and economy, the optimum one should be selected.

In case of a melting arc furnace, it must instantaneously respond to changes of every half cycle, and generally, SFC-TCR which is capable of predictive control at each half cycle and outstanding in the control responsibility is applied. When improvement of more than 70% flicker improvement ratio (See note below) is required, however, SFC-TSC has not sufficient, and a hybrid system which combines a synchronous condensor with the SFC-TCR or other special technique must be applied.

In a rolling mill, the control response is about 100ms, and generally, high speed control is not required, and compensation can be made sufficiently with an SVC-TSC. When it is necessary to increase speed of the control response, a continous control is required, problem of resonance is involved due to the condensor on/off, or when other limitation are involved, an SVC-TCR is applied. *Fig. 2* shows the typical example for reactive and active power variations for reversible rolling mill for your reference.

In case of a welder, the weldrer can be operated with a compensator as a pair, and in many cases, about 20 ms control response delay is permitted. Therefore, generally, SFC-TSCs are used. When multiple number of welders are operated in random, load on-off repeating cycle is short (such as a seam welder) and high response is required, or

Table 2 Features of various var compensators

Item/method	TCR	TSC	Capacitor+Saturable reactor	Synchronous Condenser
Main circuit configuration				
Operational characteristics				
Neccesity of control	Yes	Yes	No	Yes
Response time	0~0.01	0.01~0.02	0~0.2	0~0.2
Var adjustment	Continuous	In steps	Continouous	Continuous
Asymmetric load compensation	Possible	Possible	Impossible	Impossible
Countermeasure for harmonics	Required	Not required	Required	Not required
Power loss	Small	Small	Medium	Large
Overload	Impossible	Impossible	Impossible	Possible
Noise	Medium	Small	Large	Large
Maintenance	Easy	Easy	Easy	Required

Note: Flicker improvement ratio $= \frac{\Delta V_{10} - \Delta V'_{10}}{\Delta V_{10}} \times 100\ (\%)$ ΔV_{10} before improvement, $\Delta V'_{10}$ after improvement when other special conditions are involved, however, an SFC-TCR is used.

Further, in response to the applications or based on the economical view point, each system or hybrid system which combines different systems (for example, hybrid system of TCR and TSC) is selected.

3.2 How to decide leading capacity

The TCR system suppresses voltage fluctuations by controlling the system so that the sum of reactive power fluctuation of the load (Q_F) and compensating value (Q_L) by the reactor of the compensator is constant as shown in equation (1), and the capacitor does not contribute directly to suppress the voltage fluctuation.

$$Q_F + Q_L = \text{Constant} \quad \cdots\cdots \quad (1)$$

Hence, when countermeasure for voltage fluctuation is taken into considerations primarily to compensate reactive power, the reactive power fluctuation width may be minimized, and in the SFC-TCR or SVC-TCR, value of the reactor and value of capacitor must not necessarily be always balanced, and capacity of the capacitor may be decided based ont he required power factor improvement, harmonic suppression value (when composing the system by using the capacitor as a harmonic filter), etc.

3.3 Countermeasure for harmonics

The SFC-TCR or SVC-TCR controls the current flowing through the reactor by phase contral of the thyristor. Therefore, when reactor current is as such that the positive current wave is symmetrical with the negative current wave, the basic component (I_1) harmonic component (I_n) of the reactor current can be obtained by equations (2) and (3) below (when the resistance is neglected), and relationship between the control angle (α) and harmonic contained value is expressed as shown in *Fig. 3*.

$$I_1 = \frac{E\phi}{\pi\omega L}(2\pi - 2\alpha + \sin 2\alpha) \quad \cdots\cdots \quad (2)$$

$$I_n = \frac{2E\phi}{\pi\omega L}\left\{\frac{\sin(n+1)\alpha}{n+1} - \frac{\sin(n-1)\alpha}{n-1}\right\} \quad \cdots\cdots \quad (3)$$

where, $E\phi$: Effective value of phase voltage
L : Inductance/phase

To reduce harmonics, there are various methods such as;

(1) Harmonic filters are connected in parallel.
(2) SFC-TCR or SVC-TCR is arranged in multiple phases (12-phases, 18 phases, etc.)
(3) Hybrid (combining TCR with TSC)

On the other hand, harmonics are generated also from the melting arc furnace or rolling mill itself, and when applying a compensator, harmonics generated by both the load and compensator must be examined comprehensively.

Most unfarorable case the sum of SFC-TCR or SVC-TCR and load harmonics amount to arithmetic sum. Actually, however, harmonics are generated at different time points and phase, and the experience value becomes similar to Pythagorean sum. Also for harmonics generated by TCR, under the actual operating conditions, the actual value is generally smaller than the theoretical value, and therefore, the system can be designed economically by taking harmonics generated under the actual operations into considerations.

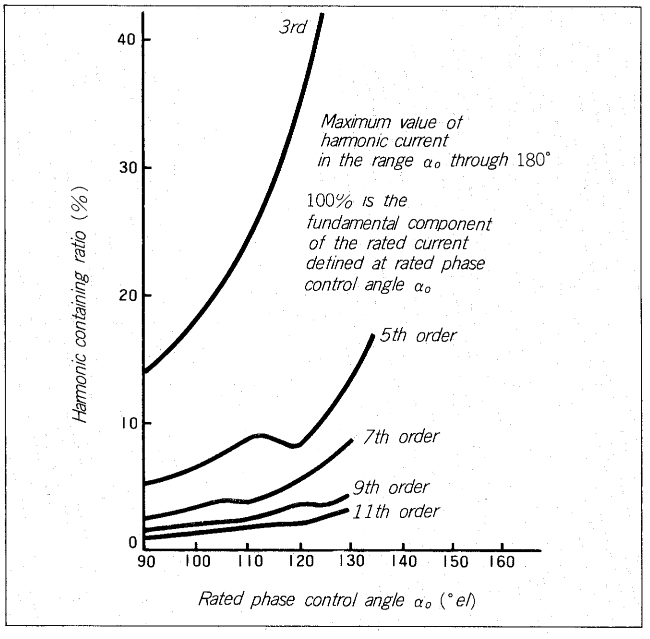


Fig. 3 Harmonic contents of SFC-TCR or SVC-TCR

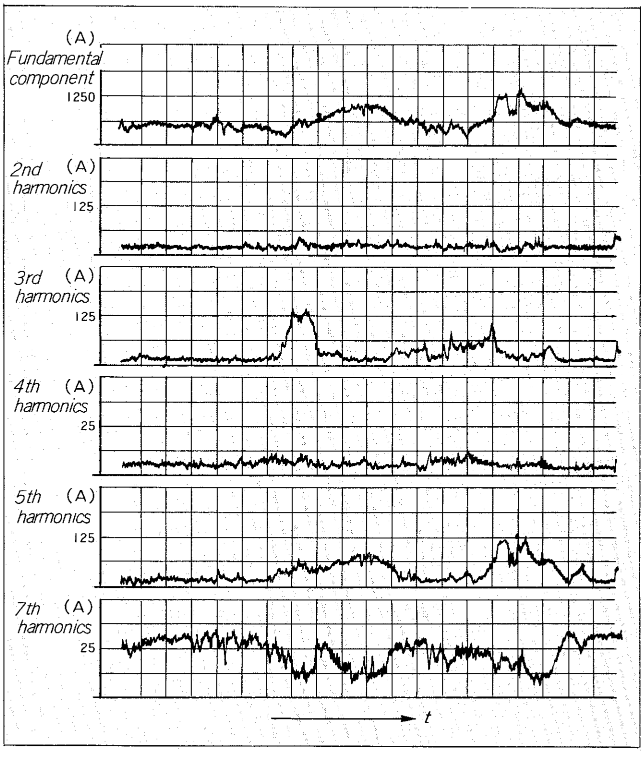


Fig. 4 Example of analysis for the current generated on an SFC-TCR (with an analogue computer used)

For your reference, results of the analysis on the actual load data collected from a melding arc furnace are shown in *Fig. 4*.

When harmonic filters are used, the system must be carefully examined and study must be conducted in advance because a parallel resonance may occur depending on the system condition. In addition, harmonics flowed into the system from other load must also taken into considerations.

3.4 Reactor

For reactors of the SVC-TCR and SFC-TCR, there is a system which uses impedance of a step down transformer (high impedance transformer system) in addition to an air-core reactor and gap iron core type reactor. The optimum reactor is selected based on the applicable voltage, capacity and system condition, and the high impedance transformer system is used when capacity of the compensator is 50 MVA or less.

Reactive power value Q is expressed by equation (4).

$$Q=\frac{3\,E\phi^2}{\pi\omega L}\left\{2\,\pi-2\,\alpha\mathrm{min}+\sin 2\,\alpha\mathrm{min}\right\}\cdots\cdots\cdots \quad (4)$$

where, $E\phi$: Phase voltage
L : Reactance (100% value is given at α_{min}=90°)
α min : Minimum control angle

Consequently, the reactance (L) of a reactor can be selected based on the relationship with the minimum control angle (α_{min}) and reactance value is selected within the range from 30 to 100% depending on the control characteristics, current harmonics, power loss and economy. The relationship between the cost and reactance value is generally expressed as *Fig. 5*. Fuji Electric uses 50% reactance value as the standard. In this case, α_{min}=114°.

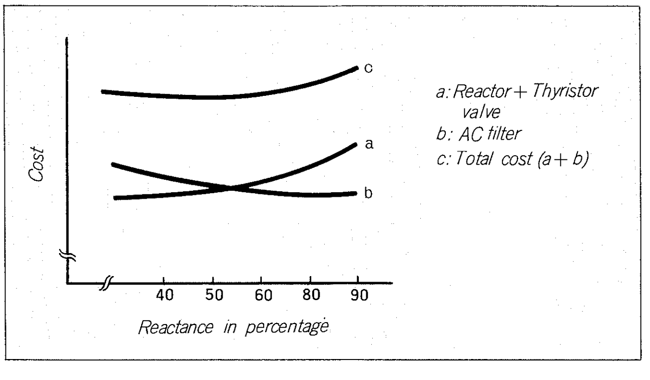


Fig. 5 Relationship between cost and reactance value for SFC-TCR and SVC-TCR

3.5 System study

When installing a reactive power compensator, the system must be studied thoroughly in advance for the stability of power network system, occurrence of abnormal

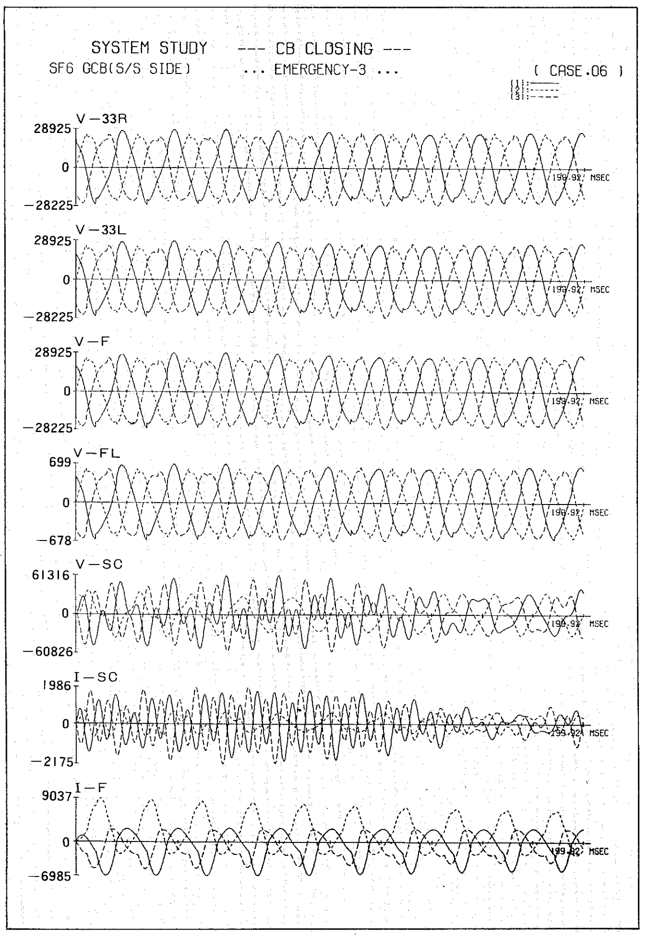


Fig. 6 Computer analysis example for system study (with all filter circuits turned on simultaneously)

voltage, harmonic current flowed into the power network and other problems such as voltage distorsion because the capacitor and reactors are connected to the power network system in parallel and harmonics are generated in accordance with the equation (3). Fuji Electric uses a similar actual load data, and using analogue and digital computers, conducts studies by performing simulation analyses.

Fig. 6 shows an example.

IV. APPLICATION EXAMPLES

Fuji Electric has manufactured a number of var compensators to be applied to the industrial plants. The typical examples are introduced below.

4.1 Melting arc furnace

Typical examples of applications to melting arc furnaces are indicated below.

(1) 60 MVA SFC-TCR delivered to Quatar Steel Works

In this system, the 60 MVA SFC-TCR is connected to a 40 MVA synchronous condensor in the form of a hybrid as shown in *Fig. 7*. This system should be noted for its high

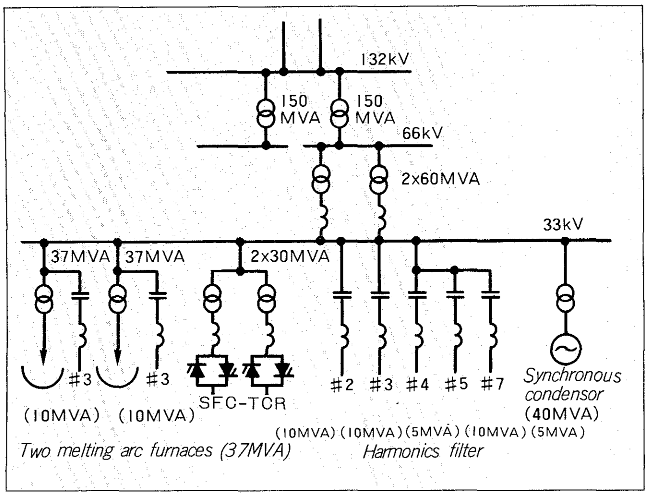


Fig. 7 System diagram for SFC-TCR delivered to Quatar Steel Works

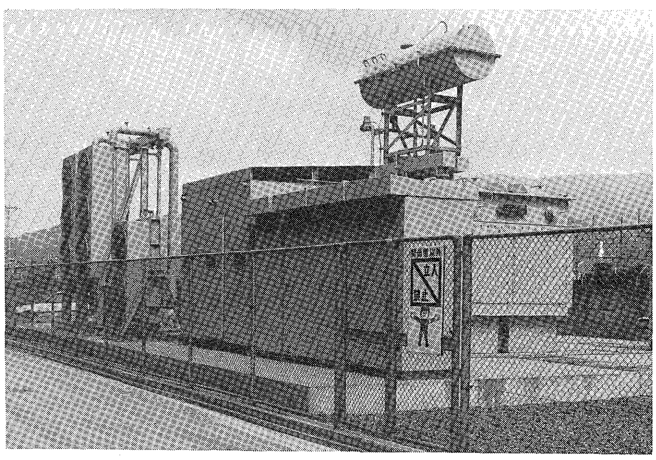


Fig. 8 External view of SFC-TCR for arc furnace delivered to Kotobuki Industry Co., Ltd.

improvement ratio reaching 82.6%.

(2) 120 MVA SFC-TCR to be delivered to Trengganu Steel Works in Malaysia (Being presently manufactured)

This SFC-TCR uses a 33 kV high voltage thyristor valve, and the high voltage thyristor valve is composed by the standard module piling method.

The high voltage thyristor uses a special indirect light triggered system in which the number of light guides is reduced (described in other article in this special issue) to improve immunity of electromagnetic noise and to reduce dimensions of the trigger device. Further, each thyristor is monitored by optical signals, over voltage protection is made individually by self-trigger, and thus, the operating stability is improved.

To cool the thyristor valve, an air insulation direct water cooling is employed, and by improving the cooling efficiency, the dimensions are reduced.

For the coolant, pure water is used, and using an air-water heat exchanger, water is cooled by the enclosed circulation method.

This SFC-TCR is installed in the outdoor location.

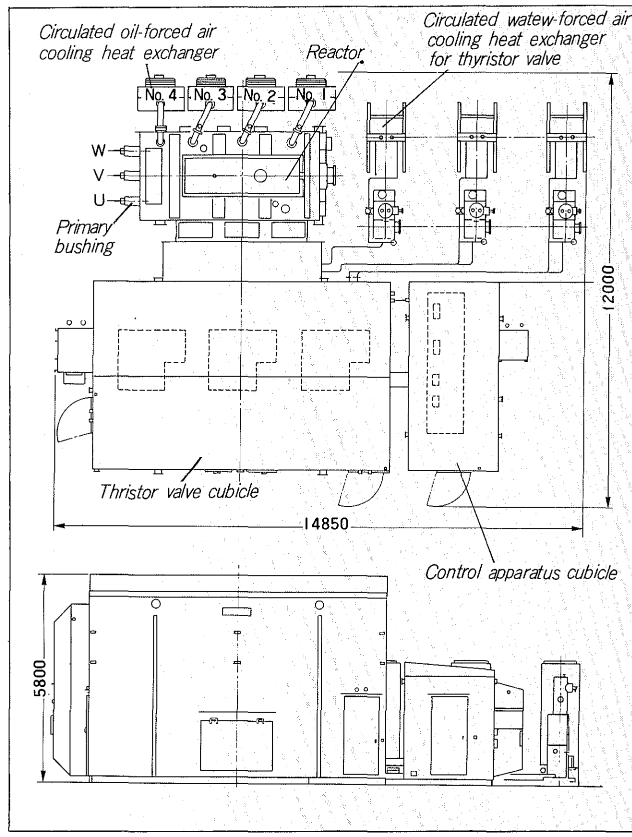


Fig. 9 Dimensions of the 120 MVA SFC-TCR to be delivered to Trengganu Steel Works

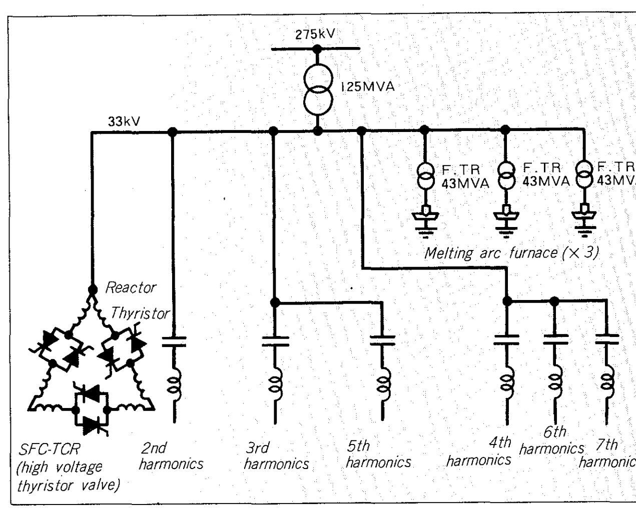


Fig. 10 System diagram of the SFC-TCR to be delivered to Trengganu Steel Works

Fig. 9 and *10* respectively show the external dimensions and single wire system diagram.

4.2 Rolling mills

As for application examples to rolling mills, Fuji Electric has delivered synchronous condensors into Kimitsu Works of Nippon Steel Corporation, Kakogawa Works of

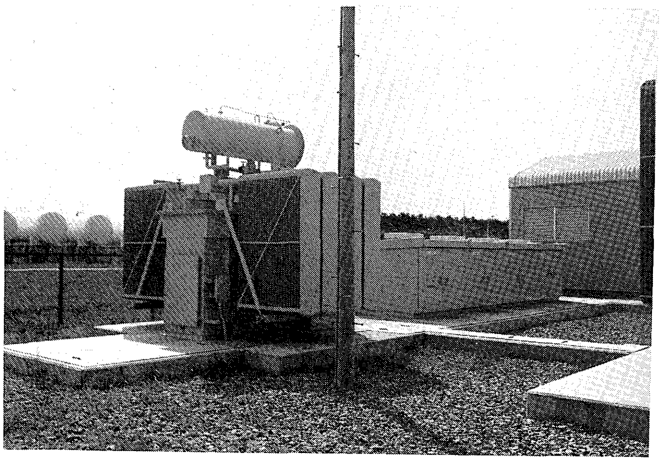


Fig. 11 External view of the SVC-TSC for rolling mill delivered to Furukawa Alminum Co., Ltd.

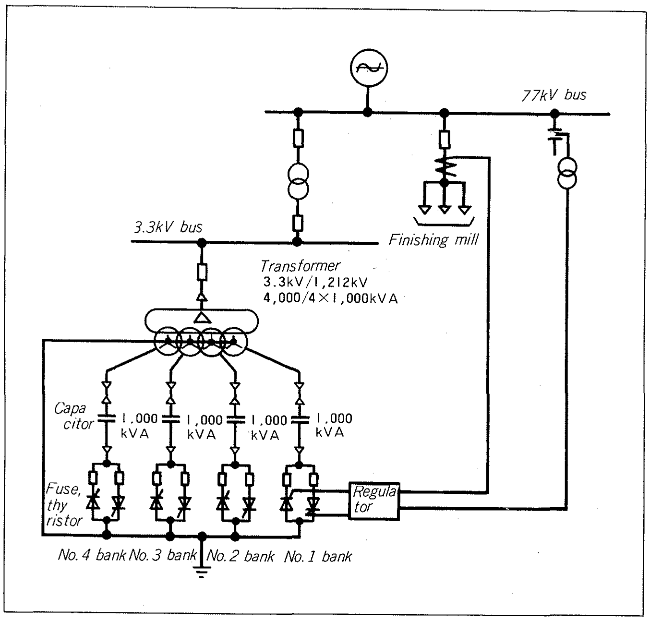


Fig. 12 System diagram for the SVC-TSC delivered to Furukawa Alminum Co., Ltd.

Kobe Steel, Ltd., POSCO of Korea and Keihin Works of Nippon Kokan K.K.

As for the SVC-TSC, Fuji Electric recently delivered a 4000 kVA (1000 kVA x 4 banks) SVC-TSC to Fukui Works of Furukawa Aluminum Co., Ltd. (See *Fig. 11.*)

For this system, Fuji Electric was requested to manufacture such a compensator as that no harmoics is generated from the equipment.

This equipment compensates reactive power (about 10 MVar) generated from the final rolling mill directly connected to the 77 kV line. The SVC-TSC the compensated capacity of which is 4000 kVA is installed on the 3.3 kV system within the same sub-station, and it has been so planned that the reactive power is compensated for the overall system. (See *Fig. 12.*)

For the thyristor converter transformer, the series reactor of each capacitor bank (divided into four) is used commonly.

To turn on and off the condensor without having transient occurrence, on-off phase timing of the thyristor is calculated from the synchronous signals and voltage across the anode and cathode of the thyristor. Further, for the operation preparing mode, supplementary charging operation is made to compensate voltage drop due to capacitor discharging during off period of the thyristor in addition to the initial capacitor charging operation. *Fig. 13* shows the operations of the SVC-TSC.

For the transmission of thyristor signal, detected voltages of capacitor and thyristor valve and signal of thyristor valve faults; optical signal was used.

4.3 Other application examples

As for the examples of applications to welding equipment, Fuji Electric delivered a 3600 kVA SFC-TCR to an automobile parts manufacturer, and 1500 kVA SVC-TCR to Hayade River Dam construction site.

Further, recently, Fuji Electric delivered a 1700 kVA

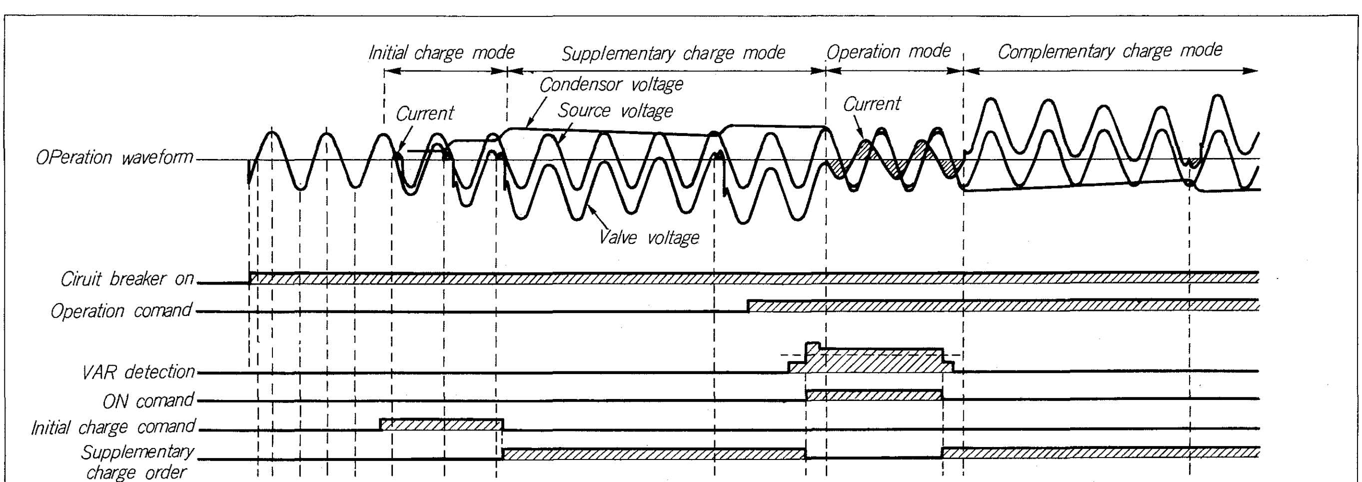


Fig. 13 Operations of the SVC-TSC delivered to Furukawa Aluminum Co., Ltd.

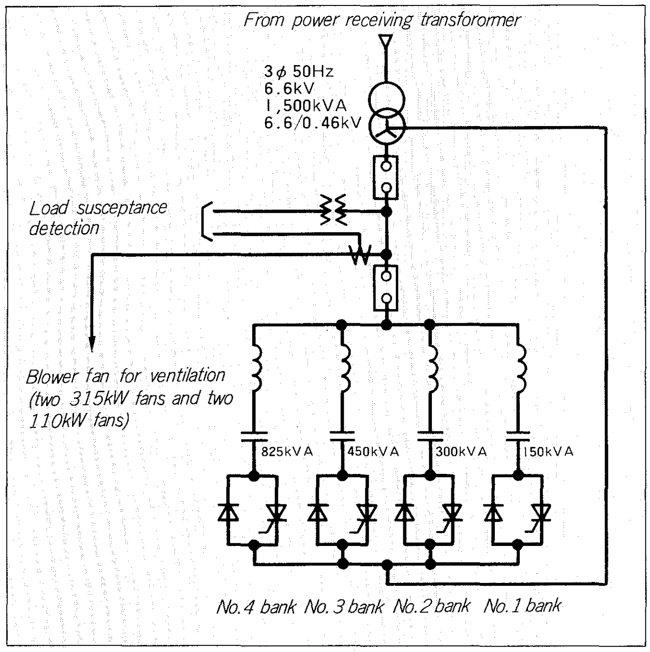


Fig. 14 System diagram of the SVC-TSC for tunnel blower

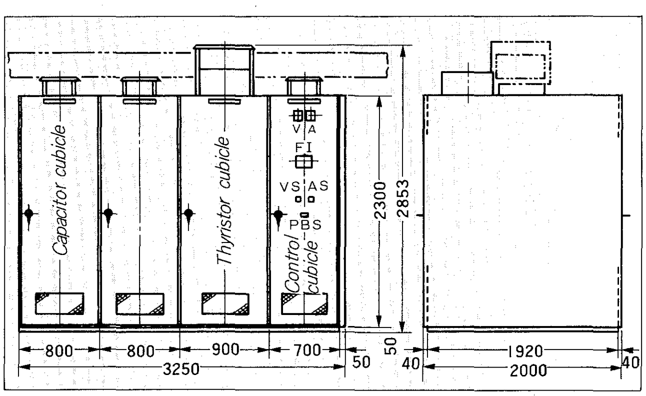


Fig. 15 External dimensions of the SVC-TSC for tunnel blower

SVC-TSC for tunnel blower in the Kanmuriyama Tunnel of Chugoku High Way managed by Hiroshima Construction Bureau of Japan Highway Public Corporation.

This SVC-TSC uses four banks of capacitor with thyristor switches (thyristor diodes are connected in anti-parallel), and four indoor cubicles are used to accommodate the components. The major features are introduced below.

(1) The capacities of the individual capacitor banks are respectively 150, 300, 450 and 825 kVA, and by turning them on selectively, 13 steps of compensating capacity is obtained from 150 kVA to 1725 kVA.

(2) The initial turn-on is made after charging the capacitor to the rated voltage and polarity. Thus, is protected from in-rush current at the time of the initial turn-on.

(3) Reactive power is compensated without having an error due to power network voltage fluctuations. This is realized by detecting load susceptance and deciding capacity of the turned on capacitor.

(4) The thyristor valve are monitored for faults based on a disagreement between thyristor gate pulse and leading capacitor current.

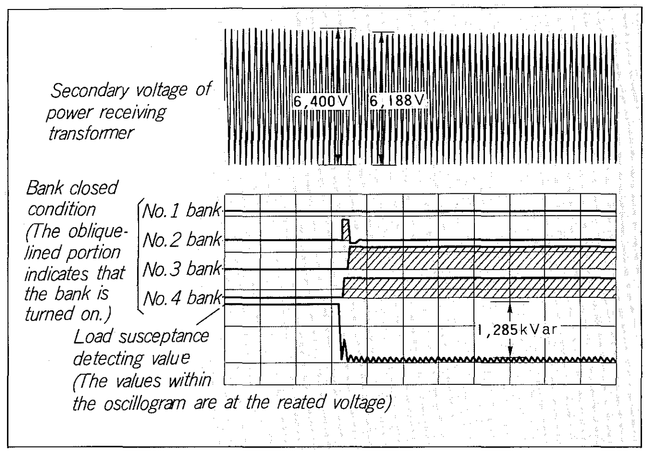


Fig. 16 Oscillogram for starting one 315 kW blower fan

Fig. 16 is an oscillogram which shows voltage fluctuations at the time when starting the 315 kW blower fan, voltage compensator bank turned on condition, etc. As it may be understood from the *Fig. 16*, the capacitor banks are turned on from 4+2 banks (1125 kVA) to 4+3 banks (1275 kVA) in response to the increase of load susceptance from 0 to 1346 kVar (converted value at the rated voltage). With this operation, voltage drop at the secondary terminal of the power receiving transformer is suppressed to about 3% in four cycles after starting the blower fan (the response characteristics of the SVC are taken into considerations). (When no voltage compensator is used, the voltage drop is calculated to be about 30%)

In this system, the above mentioned four blower fans are started independently or sequentially. With this SVC-TSC operated, the voltage fluctuation at the secondary terminal of the power receiving transformer is always suppressed within +0% to −4%.

V. POSTSCRIPT

To receive power supply without generating power line interferences such as flickers and voltage fluctuations, the above described var compensating technique must be used effectively.

Because the var compensators themselves are not required directly to manufacture products, they must be of a low price, maintenance-free, low power loss and small in dimensions. As a result of the recent remarkable development of the power electronics, these requirements have been greatly accomplished.

Since a number of papers have introduced the var compensating technique, this paper has omitted those which are duplicated with the previously reported articles. The report in this paper is centered around the application technique and most recent application examples.

For the above described var compensating technique, we will intend to further improve the technique, and continuously concentrate our efforts to provide the industries with var compensators of higher performance and reliability and lower price.