UDC 621.316.761.2

COMPONENTS FOR STATIC VAR COMPENSATOR

Tsutomu Hara,
Osamu Motoyoshi
Shigeo Konishi
Kiyoshi Mukaimumine
Yoshio Yanagiya
Kohichi Ishida

I. INTRODUCTION

As detailed in other articles of this special issue, static reactive power compensators using thyristors have already been used in various industries to cope with the line voltage fluctuations (flicker) due to various fluctuating loads (Fuji Electric calls the static reactive power compensators of this kind "Static Flicker Compensator (SFC)"). Further, to stabilize power supply network system, static reactive power compensators (Fuji Electric calls the compensator of this kind "Static Var Compensator (SVC)") are applied not only to ordinary power loads but also to the utilities more and more.

As a thyristor type reactive power compensator, at present, TCR (Thyristor Controlled Reactor) type, TSC (Thyristor Switched Capacitor) type and the type which combines the TCR with TSC are used mainly.

For the thyristor valves used for the TCR and TSC, the conventionally used low voltage thyristor valves are used for small and medium capacity equipments (10 to 50 MVA or less) for industrial use because of the view point of economy. For a large capacity SFC or SVC for power supply network system, however, high voltage thyristor valve are generally employed because of the view points of economy and high efficiency.

Fuji Electric developed a thyristor equipment (maximum unit cap-city 33 kV, 165 MVA) for TCR of new series to which air insulated/direct water cooled/indirect light triggered type high voltage thyristor valve is applied. Using this new equipment Fuji Electric has manufactured and delivered a 50 MVA SVC to Mexican Power Supply Agency and is now manufacturing a 120 MVA for arcing furnace. This time, Fuji Electric developed a high voltage thyristor switch (for switching capacitor) which is applied to a large capacity TSC. Using this switch, TSC type SVCs such as a 80 MVA SVC (delivered to Mexican Power Supply Agency) are being manufactured, and thus, Fuji Electric has established the system to manufacutre equipment of the optimum system in response to various applications and purposes of use.

Being centered around the high voltage thyristor equipment applied to large capacity TCR and TSC, technologies of Fuji Electric are outlined below.

II. FEATURES OF EACH TYPE

2.1 TCR type

This type allows continuous control of reactive power and with this type, a high speed control response (for example, a control of power supply at a half cycle) can be accomplished. Therefore, this type is used widely for various applications. Especially to suppress flickers caused by arc furnace loads, this type is used in the most cases.

In case of a TCR type, the waveform of the current flowing through the reactor contains harmonics because the basic wave reactive power is adjusted by phase control of the thyristor. To stop this harmonic wave flowing into the line, generally, reactors are connected in series to fixed capacitor arranged in parallel so that they are individually tuned, to each harmonics, and thus, the circuit is used as a filter.

2.2 TSC type

The reactive power of this type is adjusted in steps decided by number of banks of the capacitor.

To avoid an in-rush current which occurs when connecting the capacitor to the line, the capacitor is charged approximately to the peak value of the source voltage in advance during the thyristor switch off period, and further, the thyristor switch is turned on only at the vicinity of the time point where the voltage across both terminals of the switch is zero. Therefore, the capacitor applicable time is once per source cycle per phase, and maximum 360° time delay can be made for controlling.

While with the TCR type combined with fixed capacitors, when operating the system with a small reactive power, almost 100% reactive power is generated at the reactor unit and the overall system reactive power is reduced; with the TSC type, reactive power can be reduced by disconnecting the condensor bank from the line. Thus, in the case of a system which is normally standing by at zero output, it is very advantageous for the operating efficiency.

In this type, as a principle, harmonic component is not contained in the current flowing through the capacitor because thyristor is not phase controlled. However, reactors are connected in series to the capacitor to suppress flow of

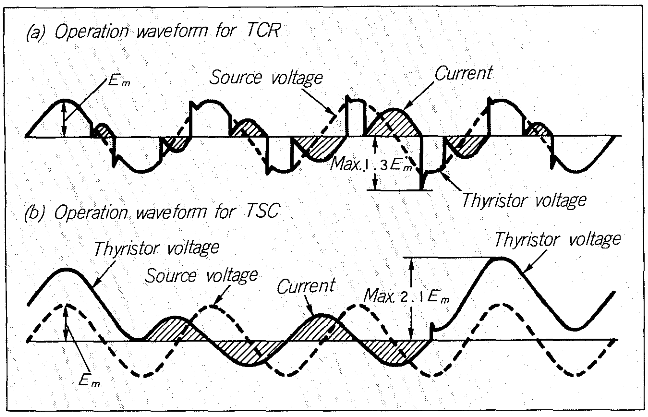


Fig. 1 Thyristor valve operation waveforms for TCR and TSC

harmonic current from other equipment connected in parallel.

Moreover, voltage waveform of the thyristor switch used in this type appears as shown in *Fig. 1*(b). While thyristor voltage in TCR type [*Fig. 1*(a)] becomes a positive/negative symmetrical voltage which is produced by superimposing the transient oscillation waveform (which is generated when turning off the thyristor) on the source voltage (normally, the thyristor voltage is about 1.3 times as great as the source voltage at the time when the thyristor is turned off); in the case of this TSC, a voltage which contains DC component of about 2.1 times as great as the peak value of the source voltage (when the series reactor is 6%) is applied. Consequently, number of thyristors connected in series in the thyristor valve is 1.7 to 2 times as great as that of the TCR type.

2.3 TCR/TSC combined type

To compensate the shortcoming of the TSC type (namely, as a principle, reactive power cannot be adjusted continuously), variable reactors are connected in parallel so that the overall system reactive power can be adjusted continuously. The combined type has advantages of both the TCR and TSC type.

This type is suited to a capacitor in the substation for power transmission lines, which must control reactive power for both the leading and lagging phases, normally is standing by at 0 Var condition, and must adjust reactive power rapidly when a fault occurs on the line.

The most suitable type is selected from those described above based various factors such as the responsibility, minimum adjustment width, operating efficiency and economy.

III. COMPONENT EQUIPMENT

The main circuit of a thyristor reactive power compensator basically consists of a thyristor valve, main transformer, reactor and capacitor for both the TCR and TSC. Some times, however, depending on the system capacity and line voltage, the main transformer is omitted and the main circuit is connected directly the line because of the view points of economy and loss. In other cases, a high impedance transformer takes place of the main transformer so that the high impedance transformer functions also as a reactor.

3.1 Thyristor valve

For both the TCR and TSC, it is standard to use air insulated direct water cooled thyristor valves, because the availability can be improved by simplifying the maintenance and inspection and replacement of parts and based on the view point of small dimensions. Further, for the same reason, an optical indirect trigger which is outstanding in the noise resistance is used. As for the construction, a module structure is employed. To be more specific, the unit modules are piled up in response to the circuit voltage, and connected in series through anode reactors so that the inspection and replacement of parts can be made easily be each module. *Fig. 2* shows an appearance of the thyristor valve for a 33 kV 120 MVA TCR.

3.1.1 Construction of the module

In the case of a TCR type, the module consists of a thyristor stack, electronic control circuit which triggers the thyristor and monitors the operation, and RC snuber circuit as shown in *Figs. 3* and *4*. In the case of a TSC type, a power supply circuit for electronic control circuit and DC voltage divider are further added to those components for the TCR type.

For both the TCR and TSC, the thyristor stacks are in same constructions. To be more specific, four to ten large capacity high voltage thyristor elements (4 kV, 1000 A) are piled up together with water coolers toward both the forward and reverse directions, and they are mesh-connected in anti parallel.

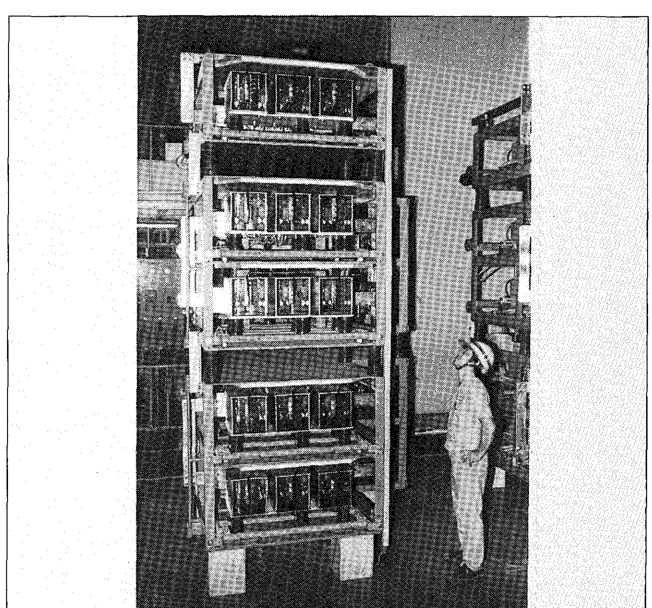


Fig. 2 Appearance of thyristor valve

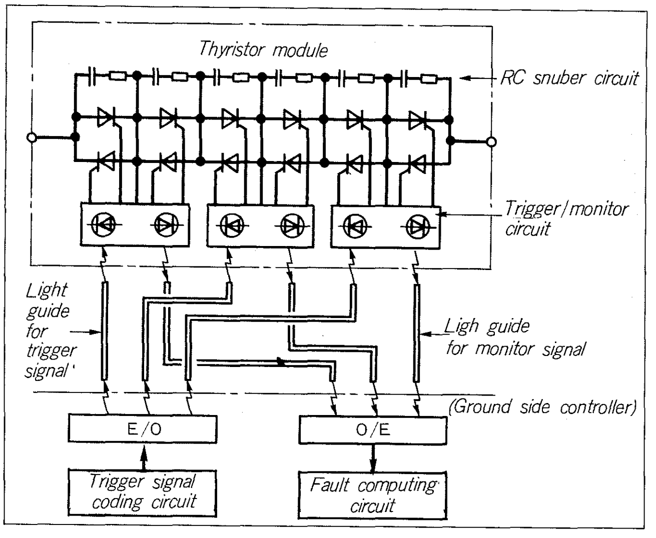


Fig. 3 Circuit configuration of thyristor module

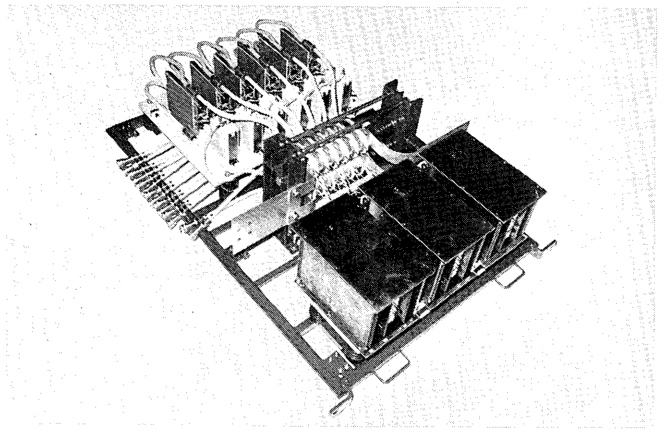


Fig. 4 Appearance of thyristor module

For this mesh connection, copper pipes which function as a water pipe and electrical connector are used to reduce the dimensions.

3.1.2 Insulating and cooling system

For the insulation, an air insulation system is used because the test, inspection and maintenance can be made easily. When the system is installed in outside, it is accommodated in a cubicle, or when installed indoor, installed in a valve hole.

Corona discharge causes an erroneous operation of the electronic control circuit in the module, gate noise and deteriorated parts. To prevent this, such countermeasures as (1) Relieving field strength of the structure and (2) Avoiding complex insulation are taken.

Pure water is used to cool the thyristor elements because of its high cooling effect and insulating performance.

In the case of a TCR type, a considerably large energy is generated on the resistor in the RC sunber circuit. Further, in the case of a TSC type, a DC voltage divider is connected to equalize DC voltages charged to the individual thyristors connected in series because voltage of the main capacitor is applied to the thyristor valve as a DC component during the period of pulse off. To cool these resistors, pure water is used, reducing the dimensions.

In addition, anode reactors (saturable reactors) are connected to the modules in series to relieve element voltage/current duty at the time when trigering the series connected thyristor elements and to equalize dv/dt against a rapid surge voltage. For this anode reactor also, pure water is used to cool them, realizing a compact construction.

For the pure water circuit, polyethylene hoses are used because of the high insulating performance and durability, and leak current which flows through the pure water is reduced so that electrolytic corrosion does not occur.

Furthermore, by-passing a part of the water flow, deposted metal ion of the coolant is eliminated with the ion exchanger, and the water is kept in a high coefficient resistance.

Figs. 5 and *6* indicate the thyristor valve cooling water circuit and standard cooling system protecting and monitoring system.

In the cooling water joints around the modules, both side stopped couplers are used so that the modules can be replaced easily without leaking the pure water.

3.1.3 Trigger and monitoring system

Fig. 3 shows the concept of the thyristor valve triggering and monitoring system. For both the TCR and TSC types, optical indirect trigger system is used to trigger the thyristors, and optical signals are used also to monitor the thyristor valve for fault. Hence, signals are transmitted and received between the thyristor valve and controller through light guides so that the thyristor valve is completely insulated from the controller electrically and magnetically, improving the noise resistance and system reliability.

The thyristor valve side trigger and monitoring circuit consists of an optical signal receiving/emitting unit and trigger circuit. Each of these is constructed on a printed circuit board to a unit, and is accommodated in the electronic control circuit whithin each module. This electronic control circuit is installed for every four thyristors (2-series anti parallel connected), one light guide for triggering/monitoring signals is attached per unit, and thus, all the thyristors are comprehensively triggered and monitored.

Fig. 7 is a block diagram of the thyristor valve trigger/monitor system, and *Fig. 8* shows the operations (In the case of a TCR type).

(1) Trigger control

For both the TCR and TSC types, trigger signals are converted to two types of coded. optical signals by the ground side controller as shown the *Fig. 8* (enlarged view), and the converted optical signals are transmitted to the individual trigger/monitor circuit of the thryistor valve through the light guide for trigger signal. At the high voltage side, the optical signals are converted to electrical signals, decoded, and after amplifying the pulse, the decoded signals are supplies as each thyristor gate pulse.

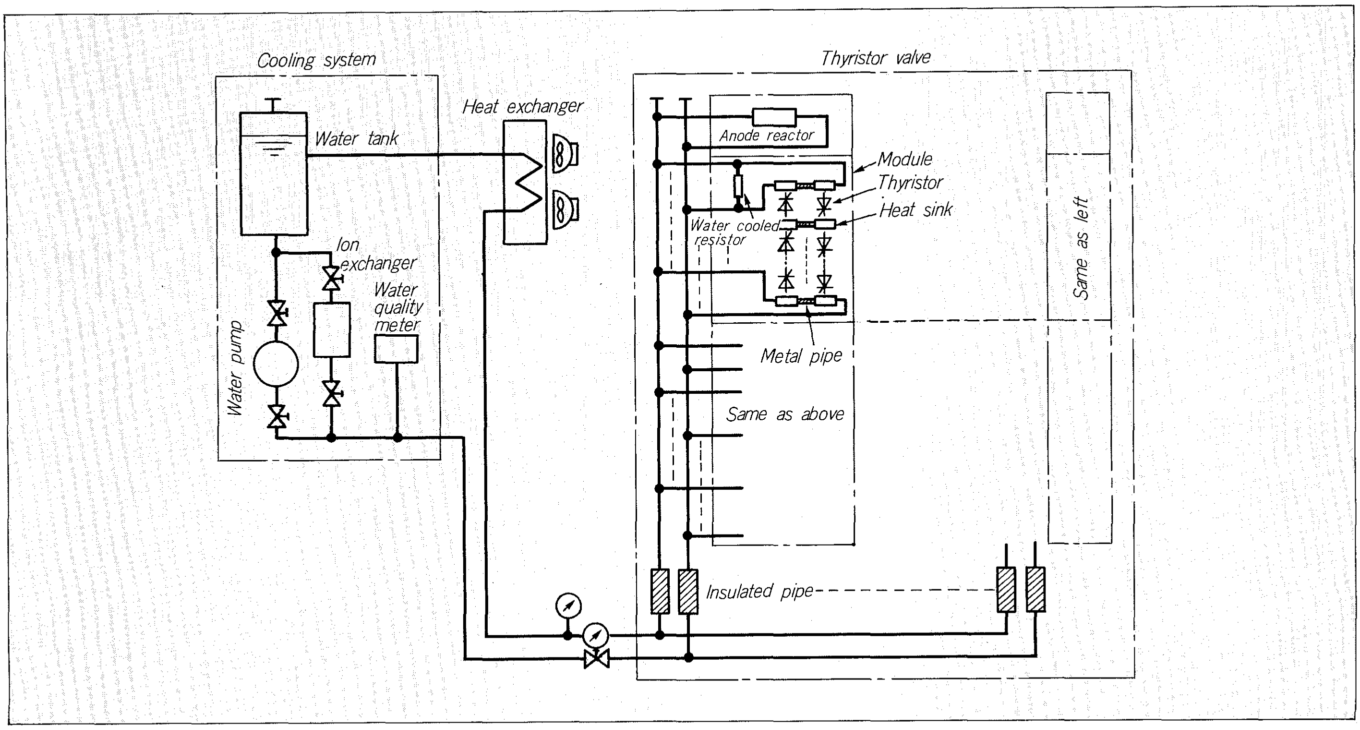


Fig. 5 Cooling water circuit for thyristor valve

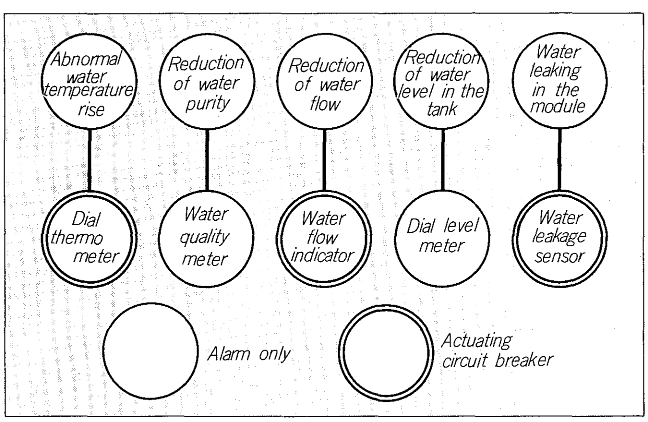


Fig. 6 Cooling system protection and monitor

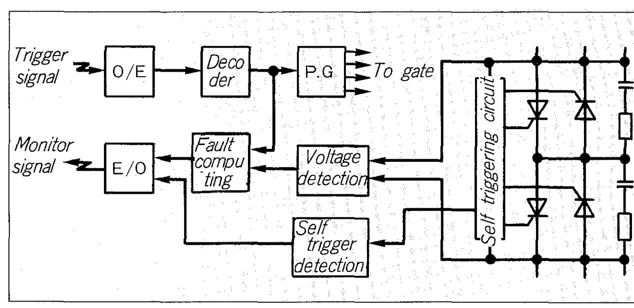


Fig. 7 Construction of trigger/monitor circuit

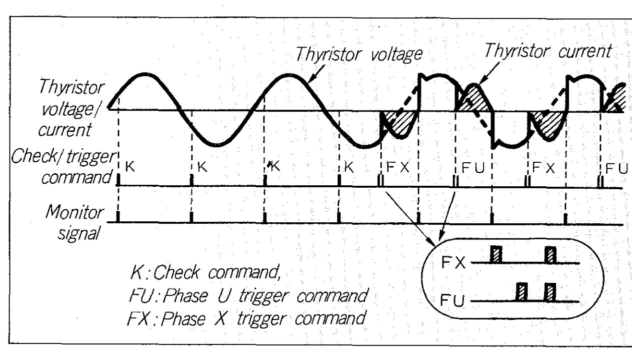


Fig. 8 Triggering and monitoring operations

By coding two types of trigger signal as described above, signals are transmitted through one common light guide, reducing number of light guides.

(2) For the thyristor valve side trigger/monitor circuit, the power supply is secured from the thyristor block voltage in the case of the TCR. On the other hand, in the case of TSC, power is supplied to the individual trigger/monitor circuits from the insulating transfromer because no voltage is applied during the thyristor on period.

(3) Monitoring for fault

The thyristor valve is monitored for a fault with the optical monitor signals transmitted from the high voltage side monitor circuit through the light guide for monitor signal.

There are two types of monitor signal. As shown in the *Fig. 8*, one of them is transmitted when thyristor voltage reaches a rated level at every half cycle (under thyristor control condition, off timing) to monitor anode voltage of thyristor element. This signal is used to diagnose short-circuit fault of the thyristor elements. The other signal is

Table 1 Monitored faults of high voltage thyristor valve

Fault display	Type of fault
Thyristor element fault	Broken thyristor element
Fault in trigger system	Fault in the trigger circuit
Overall self trigger	Overall self trigger of all thyristor elements within one arm
Continuous self trigger	Self trigger occurred continuously within a certain time

transmitted when the self-triggering circuit provided to each thyristor operates to protect the thyristor element. Not only when an overvoltage is applied to the overall thyristor valve due to lightning surge or switching surge but also when an overvoltage occurs on a part of the thyristors, causing the self-triggering circuit to operate, this signal is transmitted. In the dame manner as the above described trigger signals, these monitor signals are transmitted to the ground side through one common light guide used every four thyristors (2-series anti parallel connected).

The controller side fault computing circuit checks existence of these monitor signals and signal transmitting timing, and in either case of TCR or TSC, the fault computing circuit diagnoses and displays various faults shown in *Table 1*. Finding not only fault of a thyristor element but also types and locations of various faults such as a fault in the trigger system, inspection is eased, restoring time can be reduced and maintenanceability is improved.

3.1.4 Protection system

(1) Protection from overvoltage

Based on the causes, overvoltages applied to the thyristor valve can be classified into three types as follows. (1) Overvoltage caused by normal occurrences such as switching of the thyristor valve, (2) External surges such as lightning and switching surges, and (3) Overvoltage due to fault and abnormal occurrence within the thyristor valve.

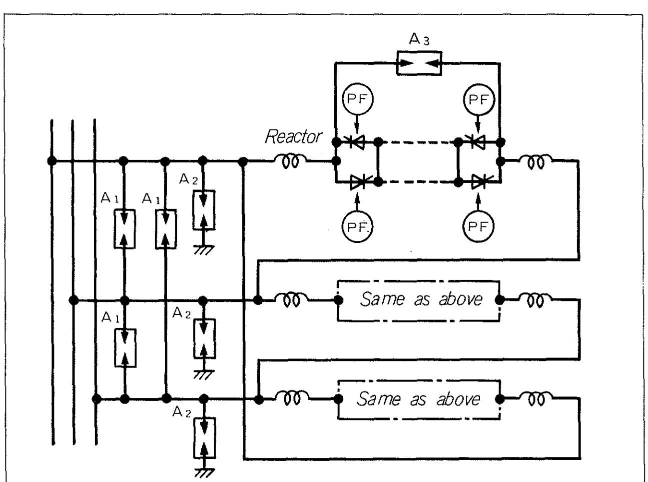


Fig. 9 Overvoltage protection

Out of these overvoltages, (1) occurs periodically, and this can be suppressed with overvoltage absorbers suppressors such as the anode reactor having high frequency characteristics connected to the thyristor circuit in series and RC snuber connected to the thyristor elements in parallel.

For (2), thyristors are protected by RC filter and arrestors connected against the line and ground and in between thyristor valve poles. In some cases, the thyrsitor valve inter pole arrestor is omitted, and thyristors are protected from overvoltage by the self trigger circuit provided individually to the thyristors connected in series. These methods are selected in response to the equipment specifications and line conditions after carefully examining the overvoltage protection harmony.

When multiple number of thyristors are connected in series to compose a thyristor valve and a certain thyristor element is not triggered or triggered erroneously or RC snumber fails, and overvoltage is applied to a part of the thyristors. This type falls to overvoltage (3) above. For an overvoltage of this type, the above described self-trigger of series connected thyristors applies. *Fig. 10* shows the operating principle of the self-trigger circuit for overvoltage protection. In this system, a breakover diode (BOD) is connected to each thyristor in parallel. When voltage of a thyristor element exceeds the rated value, continuity is produced in the BOD, causing the thyristor element to be automatically turned on, and thus, protecting the thyristor from overvoltage. Especially for the thyristor valve for TCR and TSC, in which the thyristors are connected in anti-parallel, this design has such an advantage as that thyristors can be protected from overvoltage toward both forward and reverse directions. Moreover, thyristors are protected also from the overvoltage due to partial trigger miss of series connected thyristors from which the thyristors cannot be protected by an interpole arrestor. So, this method is effective to secure protection harmony and to reduce number of thyristors connected in series.

Further, as a problem peculiar to the TSC type, when a thryistor is triggered erroneously, the condensor is charged with an excessive voltage by the LC resonance circuit as shown in *Fig. 11*(a), and as the result, the thyristor valve

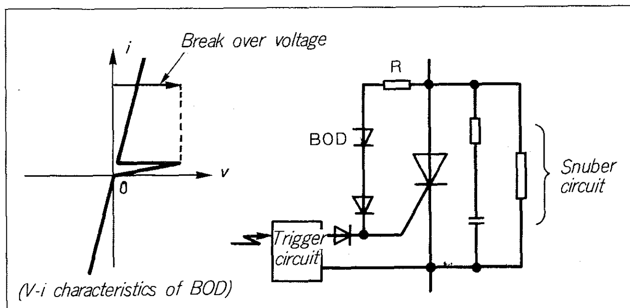


Fig. 10 Standard construction of self trigger circuit

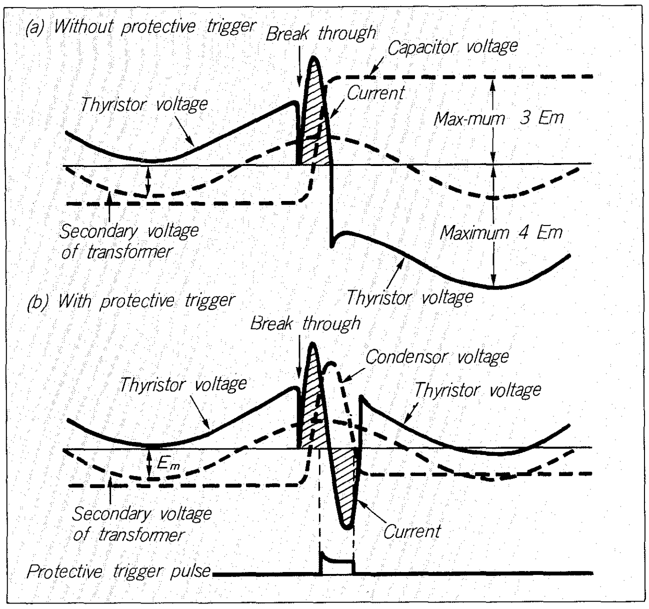


Fig. 11 Voltage and current waveforms at break through (in case of TSC)

Table 2 Standard specifications for module

Item		Fuji high voltage thyristor module
Used condition		For indoor
Cooling system		Water feeding water cooling or water feeding air cooling
Frequency		50 or 60 Hz
Rating		Continuous
Type of connection		Anti parallel connection
Used thyristor element		EGS03-40 (4,000 V, 1,000 A)
Number of elements connected in series		6 or 8
Number of elements connected in parallel		1
Rated voltage	TCR	7.8 kV (6 series) or 10.4 kV (8 series)
	TSC	4.6 kV (6 series) or 6.2 kV (8 series)
Rated current	TCR	AC fundamental wave RMS
	TSC	AC RMS
Ambient temperature		−20∼+50°C

Table 3 Circuit voltage and number of modules

Number of modules	Maximum circuit voltage (kV) (RMS)		3-phase basic wave capacity (MVA)		Current RMS (A)	
	TCR	TSC	TCR	TSC	TCR	TSC
1	10.4	6.2	52	28	1,680	1,500
2	20.8	12.3	104	56		
3	31.3	18.4	157	84		
4	41.7	24.5	209	112		

(NOTE): The above table applies to the case of thyristor 8-series module

voltage given by the sum of the source voltage and capacitor voltage may become an overvoltage. To avoid this, capacitor voltage is monitored, and sometimes, gate pulses are given continuously (protective trigger) as shown in *Fig. 11*(b) so that the thyristor switch is placed under turned on condition when the thyristor valve voltage exceeds the rating.

(2) Protection from overcurrent

An overcurrent occurs on the thyristor valve due to fault on the thyristor valve itself, erroneous trigger (break through) or external short-circuit.

For this, the thyristor valve is protected by a fuse, protective relay and/or a pulse off control using electronic devices or by suppressing overcurrent with series impedance.

In a high voltage system, pulse off control of the thyristor switch is the main protection. The major reasons are (1) In a high voltage system, generally, no parallel redundancy is taken. Therefore, when a fuse is used, operation stop down cannot be avoided due to deterioration of the fuse, and it takes a time to replace the fuse; and (2) For both the TCR and TSC, alternate current flows to the thyristor valve, and therefore, the thyristor switch can be correctly turned off only by eliminating gate pulse of the thyristor.

In this case, however, it is impossible to turn off the thyristor switch momentarily, and current continuously flows to the thyristor valve until the current becomes zero subsequently after the occurrence of an overcurrent. For this reason, this current value or i^2dt value must be suppressed within the value permitted to the thyristor element.

For both the TCR and TSC. generally, reactors are connected to the thyristor valve in series. Therefore, when selecting the inductance, examinations should be made based on the view point of overcurrent suppression, and a magnetic circuit of the reactor should be designed or an air-core tector must be used so that the desired inductance value can be maintained even in an overcurrent domain.

3.1.5 Standard series

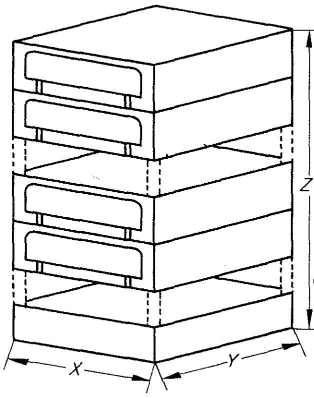
Table 2 shows the standard specifications of the module. *Table 3* and *Fig. 12* respectively show the standard number of modules piled up for each circuit voltage applied when composing a thyristor valve and dimensional view of the thyristor valve.

3.2 Transformers

At many phases, the transformers for the SFC and SVC are common to other transformers for thyristor converters. However, as the capacity of an equipment is generally large, considerations should be given on the design as described below.

3.2.1 Considerations on harmonics

In the case of a TCR, harmonics are generated by phase control of the thyristor, causing stray loss of the trans-



Number of modules connected in series		1	2	3	4
External dimensions (mm)	X	2,250 (1,900)	2,250 (1,900)	2,250 (1,900)	2,250 (1,900)
	Y	1,850 (1,700)	1,850 (1,700)	1,850 (1,700)	1,850 (1,700)
	Z	2,800 (2,600)	5,000 (4,500)	2,700 (2,500)	4,000 (3,500)
Weight (t)		2.4 (2.0)	4.2 (3.5)	2.4 (2.0)	2.8 (2.4)

(NOTE) When number of modules is 1 or 2, the dimensions and weight cover three phases. When it is 3 or 4, they cover one phase. Those enclosed in parenthesis ( ) are for thrysitor 6-series module and others are for 8-series module.

Fig. 12 Dimensional view of thyristor valve

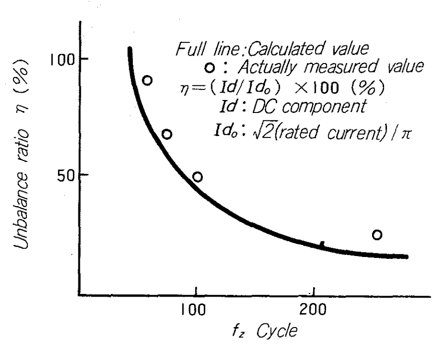


Fig. 13 Example of d.c. component size and permissible continuing time about transformer

former to increase, inviting a temperature rise. Considerations must be given to minimize generation of harmonics and to prevent abnormal temperature rise. Normally, the transformer windings or thyristor valves are connected in delta. So, when three phases are balanced during the operation, the 3rd harmonics and high harmonics in that multiple circulate within the delta circuits and they do not flow into the power line. In other cases, three-winding transformers are used, the thyristor assembly is constructed to a 12-pulse connection by providing 30° phase difference between the 2nd and 3rd windings, and low order high harmonics such as 5th order and 7th order high harmonics are reduced.

3.2.2 Suppression of magnetic unbalance

When positive and negative waveforms of secondary current of a transformer become non-symmetrical and DC component occurs, d.c. magnetitism is unbalanced on the iron core of the transformer. In a remarkable case, the iron core is suffered,noise increases and other troubles such as local overheating of the structure occur. For an occurrence of d.c. component of the secondary current like this, there are a normal type which occurs due to fluctuation of trigger angle and a transient type which occurs due to a rapid trigger angle change. Occurrence of the transient d.c. component is generally not considered as a problem because the iron core of the transformer is not rapidly saturated because of the time constant of the circuit as shown in *Fig. 13.* When d.c. component occurs normally, however, excitation current of a large capacity transformer is 1% or less than the rated current, which means that a magnetic unbalance is easily caused by even a minor d.c. component, and considerations must be given sufficiently. For the avoidance of the stationary DC magnetization, we take a counter masure, such as eliminate of distorsion from synchronizing signal wave, use of digital phase regulator and so on.

3.2.3 Selection of impedance

For SFC and SVC, a normal transformer is combined with reactors connected in series, or a high impedance transformer is used and the reactors are omitted. Which should be selected is decided depending on the system capacity, economy, efficiency and other related factors. When the high impedance transformer is used, the dimensions and weight of the transformer itself are larger than those of a normal transformer. However, it is rather economical to use the high impedance transformer because the space required for the overall system reduces. Further, in a TSC type, when secondary winding of the transformer is a multiple winding and condensor banks are connected to the individual windings, interference between the banks must be taken into consideration and equivalent primary and secondary impedance distributions of the transformer must be decided.

3.3 Reactor and capacitor

For Reactance value of series reactor for TCR, it is normally selected in 30 to 100% (100% Value correspond to the case of α_0=90°, α_0 is rated control angle.) When reactance of series reactor is selected in a small value, dimensions and weight of the reactor itself are reduced. On the other hand, however, a large rated control angle must be selected. This causes harmonics generated on the thyristor converter to increase, capacity of the harmonic filter increases, and other disadvantages are involved. Therefore, the economy of the overall system must be taken into considerations, and the optimum value must be decided. Further, in many cases, series reactor for TSC is selected at 6 to 13% based on the view points of suppression of harmonic wave current flowing from the power supply line and protection of the thyristor from overcurrent. For these series reactors, air-core reactors are used in many cases to reduce current duty of the thyristor converter by reducing ground stray capacitance and to avoide increase of current due to faults such as a saturated iron core.

The reactor used for this system is basically same as a normal shunt reactor. When designing a system, however, reduction of harmonic loss and mechanical strength against overcurrent caused by a fault must particularly be examined.

Because parallel capacitor for TCR are generally used also as a harmonics filter, they are designed after carefully examining performances as a harmonics filter such as value of harmonics permitted to the line, residual harmonics in the line, possibility of occurrence of resonance, line impedance change range and line frequency fluctuation in addition to the required leading capacity. A capacitor for TSC is same as a normal shunt capacitor basically. However, as the closing phase of the capacitor on power supply is selected, so the in-rush current at the time of closing is suppressed, and current duty of the condensor is reduced.

IV. POST SCRIPT

Centering around the high voltage thyristor converters for TCR and TSC, the major component equipment of Fuji's thyristor reactive power compensators were outlined.

Fuji Electric has manufactured thyristor equipments for reactive power compensators the total capacity of which is about 800 MVA (about 25 compensators), and they are operating effectively and efficiently. Based on the experience, we are further brushing up the manufacturing and application technique, and actively proceeding the technical development for improvements of reliability, control performance and protective monitoring and troubleshooting functions and for reduction of the dimensions and weight by applying optical thyristors and by introducing microprocessors.

Adequately adapting the results of the technical developments, we will concentrate our effort in presenting more economical products of high technologies which completely satisfy the users, and thus, we are intending to contribute to the technical development in this field. We are expecting more advices and favours from the users.

TOPICS

PARTICIPATION IN "ELECTRIC INDONESIA" SHOW

Fuji Electric Standard Products – Asia Department participated in the "ELECTRIC INDONESIA" co-organized by P.T. DUTA FUJI, a local agent of Fuji Electric, and the show was very successful.

This show was held for five days from October 18 to 22 in Jakarta. In this international trade show, about 110 companies participated from the overall world, and the large scale show was very busy with many visitors.

Fuji Electric displayed the distribution and control components such as contactors, starters, MCCBs, ELCBs, timers and P.Bs in addition to the new products such as inverters, cast resin transformers (MOLTRA), and programmable controllers.

To our booth, officers and engineers of PLN, consultants, contractors, suppliers and many other related people visited, and total number of visitors reached 3000. Out of the displayed products, the motor speed controller using the variable frequency method "Inverter" and completely molded "MOLTRA" which features its fire-free construction especially invited attentions of the visitors because of its additional feature (evergy saving). Many inquiries and requiests for data were submitted, and the show was over extremely successfully.