Var Compensators

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1. Introduction

In each field of power system, industry, and electric railway, static var compensators (SVCs), taking full advantage of power electronics technology, have lately been applied widely for the suppression of voltage fluctuation, the stabilization of power system, the suppression of voltage flicker, and the regulation of voltage phase in electrical supply systems.

This paper describes the latest technical trends of SVCs as well as converter technology and application examples.

2. Technical Trends of SVCs

SVCs can be classified into two types, namely external-commutated SVCs with thyristors and self-commutated ones with the switched valve devices, such as GTOs (gate turn-off thyrisotrs) and IGBTs (insulated gate bipolar transistors). The typical external-commutated SVC is a thyristor controlled reactor (TCR) type. Fuji Electric has been manufacturing a large number of the TCR type of SVC since manufacturing the TCR type of flicker compensators in the 1970s earlier than other company. Nowadays the TCR type of SVC is still used widely due to its comparative low price. It has, however, some problems such as the restriction of control speed and the generation of lower-order harmonics. In addition to the problems, the TCR type of SVC generates the reactive power loss in proportion to the square voltage in the region of voltage drop shown in Fig. 1.

Compared to the external-commutated SVCs, self-commutated SVCs have the better ability to maintain voltage in the voltage drop region since they have constant current characteristic.

Furthermore, self-commutated SVCs can output not only leading/lagging-phase reactive power but also negative-phase-sequence power by controlling the amplitude and phase of inverter voltage as against those of line voltage as shown in Fig. 2, and can compensate higher harmonics as well.

Against the background of the development of large capacity GTOs, self-commutated SVCs have been realized and have been utilized as SVC for electric railway and flicker compensator.

However, GTOs require anode reactors and an individual snubber for each device due to the restriction of capability for *di/dt* and *dV/dt* as shown in Fig. 3. In addition, the snubber power regenerating circuit is necessary to avoid the deterioration of efficiency since the reactors and the snubber cause the large amount of loss. Therefore, the configuration of inverter circuit applying GTOs becomes complicated. In contrast, by applying the flat-packaged IGBT which is the large capacity voltage-driven switched valve device developed by Fuji Electric, peripheral circuits can be vastly simplified, and the number of the circuit component and the size of inverter circuit can be reduced by more than 50 %.

Practical use of SVCs, which apply flat-packaged IGBT and are of compact size, high efficiency, high reliability and low price, encourages utilization of high performance self-commutated SVCs in power systems.

Fig.1 Voltage control characteristic of SVC

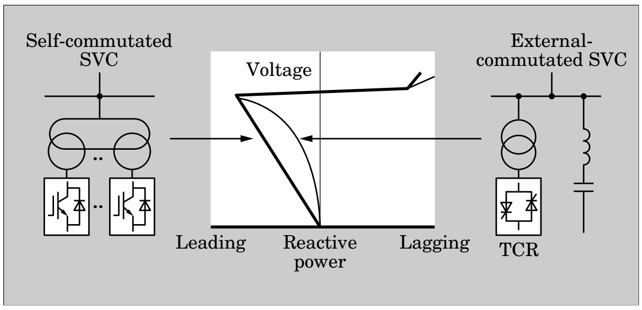


Fig.2 Reactive power/negative-phase-sequence power output operation of self-commutated SVC

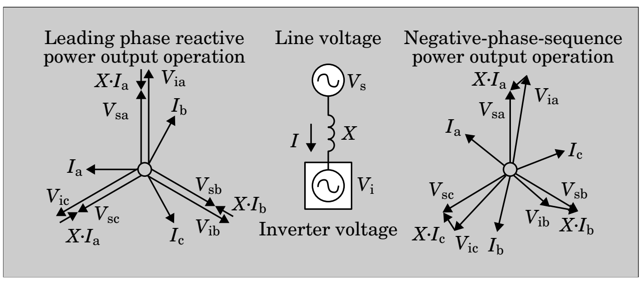
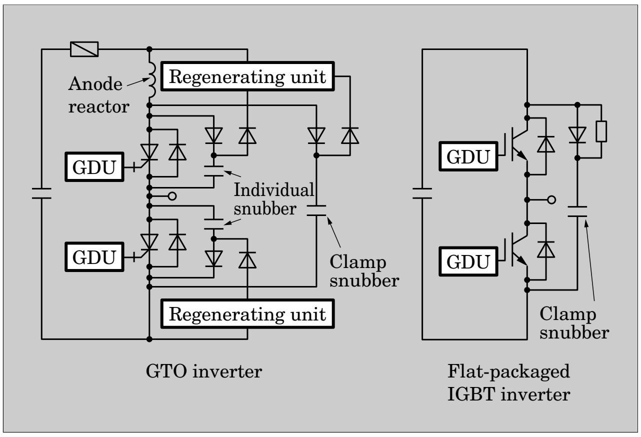


Fig.3 Comparison of GTO inverter and flat-packaged IGBT inverter configurations



3. Converter Technology

This Chapter describes the latest technical trend and essential technology about converters for the var compensators, taking IGBT type converters which are of the latest technical trend as example.

3.1 Gate drive and protection technology

3.1.1 Gate drive circuit

IGBTs can perform not only a simple on-off control but also fine control such as regulating the switching speed by controlling gate voltage. Therefore, the configuration of the gate drive circuit has a large effect on the function and reliability of the converter.

A typical functional block diagram of the gate drive circuit for an IGBT is shown in Fig. 4. The gate drive circuit has the fundamental function with which the on-off control signals for devices sent as optical signals from a controller are formed into adapted signal for devices. Besides the function, in order to realize the stable operation for the system required the high reliability and the protection of spreading the system trouble, the gate drive circuit has the following functions.

(1) Status monitoring function

A device abnormality is detected by comparing the device status with ignition/extinguish commands, and the device status is monitored based on the voltage difference between the collector and emitter. If an abnormality occurs within the device or control supply voltage of the drive circuit, an inverted signal is fed-back to the controller as shown in Fig. 5. This monitoring function enables high-speed protection of the system.

(2) Short circuit protection function

Short circuit protection function has been established for conventional converter which does not apply the series connected devices. The function detects the rising voltage caused by short circuit current in devices as short circuit failure occurs and turn off the devices softly by reverse-biasing the gate-voltage so that the devices are damaged.

Fig.4 Block diagram of gate drive circuit for IGBT

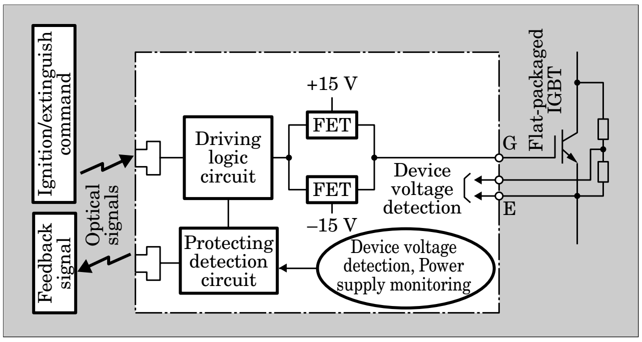
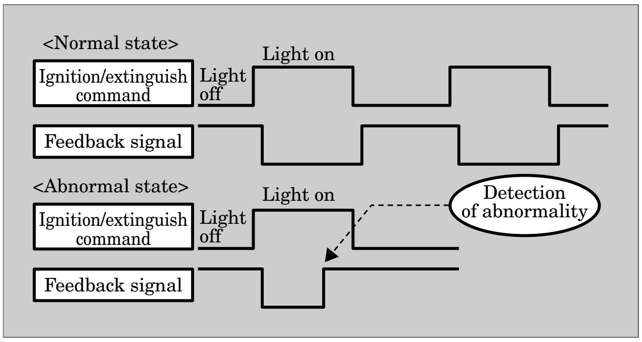


Fig.5 Processing of state monitoring signal



In general, fuses are used to provide short circuit protection for devices connected in series. The establishment of fuse-less protection technology is an outstanding technical problem at present.

(3) Drive circuit technology for series connected devices

For high voltage converters in which devices are connected in series, equalization of the voltage distribution among devices has become a problem. The problem can be solved by adding both a function which compensates for the different switching times among devices and an active gate control function which operates during transient switching states to the gate drive circuit. In addition, a technology that secures the insulating performance suitable for high voltage operation has been established by adapting a self-feeding method in which power for the gate drive circuit is fed from the main circuit.

3.1.2 Flat-packaged IGBT's resistance to case rupture

Flat-packaged devices provide remarkably high resistance to case rupture compared with module-packaged devices. However, because of the low inductance wiring in main circuit and the increasing circuit current during a short circuit, the occurrence of case rupture of the device is feared. Consequently, the verification test of ability to withstand case rupture of the flat packaged IGBT was implemented by simulating the short circuit failure. This verification test demonstrated compatibility with the other components and the safety of the flat-package IGBT.

3.2 Stack construction technology and cooling technology

(1) Stack construction

In order to obtain optimal device performance of the flat-packaged IGBT, uniform contact pressure on the device electrode surface is necessary. On the other hand, lower inductance wiring is required to reduce both spike voltage and generated loss which are caused by the high frequency switching of devices to enhance the compensation performance of reactive power compensators. Furthermore, regardless of whether the stack expands or contracts due to changing thermal conditions corresponding to the operational state, the distribution of contact pressure among devices must be kept uniform and the stack construction must be able to endure this pressure cycle. In addition, the stack construction must provide high insulating performance. The stack of flat-packaged IGBTs shown in Fig. 6 is an example of a construction that fulfils these requirements.

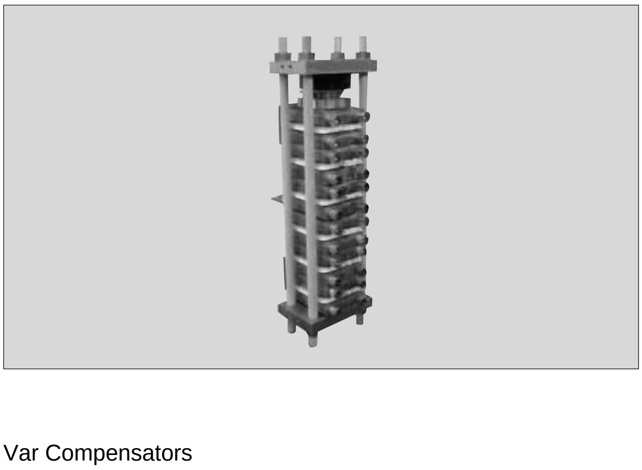
(2) Water cooling system

A water-cooling system is utilized to remove generated loss to improve the device's utilization rate and to make the size of equipment more compact. In this system, high reliability is assured by applying closed circulation of pure water as the primary cooling water. In addition, a new type of heat sink was developed to remove the large loss generated by high frequency switching, and superior cooling ability of 0.005 K/W was achieved.

(3) Prevention of DC circuit resonance

The inverters contain DC capacitors that serve as voltage sources to induce the voltage on the opposite side to the line voltage. These capacitors must be distributed for reasons related to the construction of the inverter, and therefore may cause DC circuit resonance phenomena due to voltage difference among capacitors or circuit constants. In order to analyze these phenomena, a simulation test of DC circuit resonance was performed using a model with distributed capacitors and copper wiring. DC circuit resonance is prevented by incorporating the analytical result into the construction. Figure 7 shows the simulation circuit diagram and an analysis example.

Fig.6 Flat-packaged IGBT stack



3.3 Multiple-stage transformer technology

(1) Core design

A core with a gap is employed in the multiple-stage transformers for SVCs to equalize voltage distribution among the multiple stages when excited with the line. The structure is attached more solidly than a conventional transformer by using connecting bolts to suppress vibration and noise.

The duty of these transformer cores, excited by the inverter, is far more severe than sinusoidal excitation because a PWM (pulse width modulated) voltage waveform having a square waveform is applied. To verify this fact, basic characteristic data such as loss, saturation, and DC magnetization of both sinusoidal wave excitation and inverter excitation have been acquired. Figure 8 shows an example that compares the verified result. Based on this experimental data, achievement of the dual goals of device reliability and downsizing is sought through determining the optimal flux density in consideration of the over-excitation condition during leading-phase operation of the SVCs and of the precision of magnetization control.

(2) Cooling design

In the case of multiple-stage transformers excited by an inverter, there are several factors causing iron loss and copper loss to be larger, compared to conventional transformers, such as increased excitation loss by 20 to 30 % and increased iron loss and excitation

Fig.7 Circuit for simulation of DC circuit resonance and analysis example

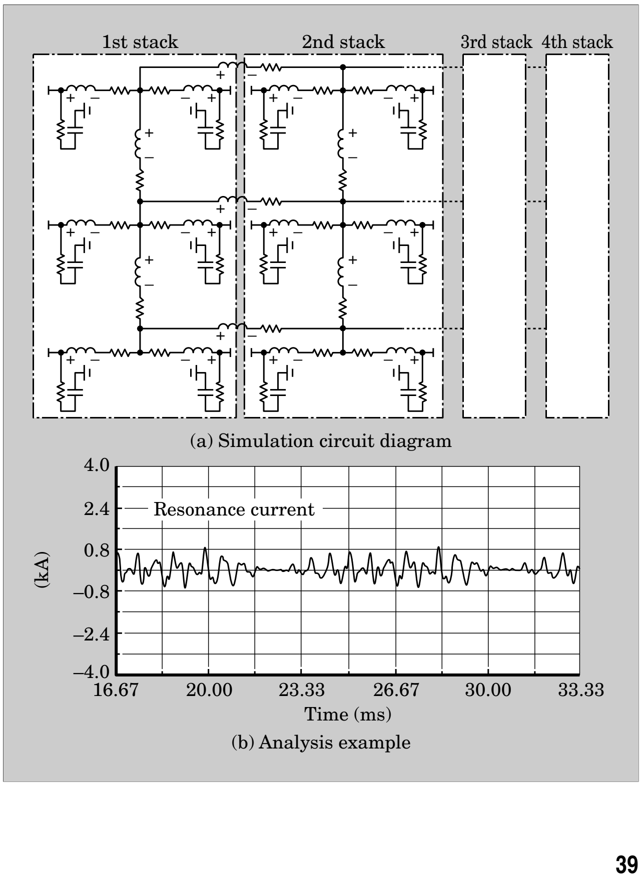
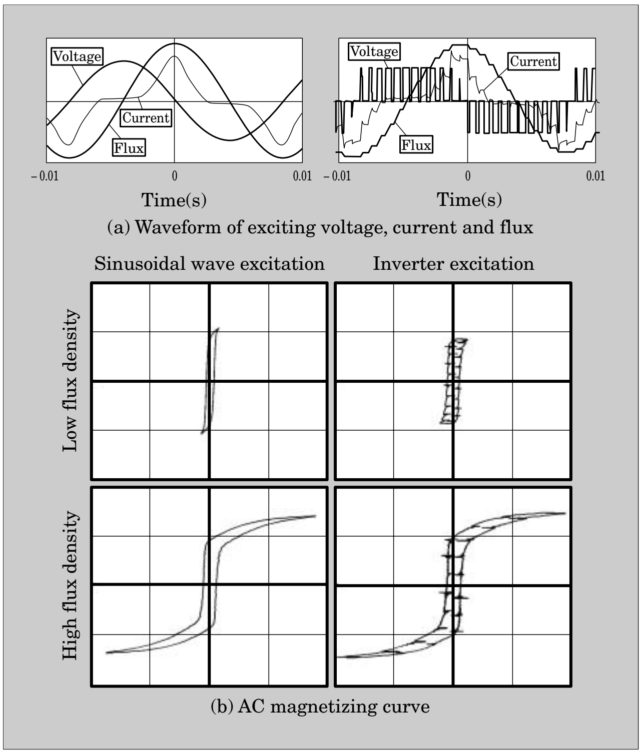


Fig.8 Comparison of sinusoidal wave and inverter excitations



current due to the fact that the core does not have a gap.

The cooling design is optimized by considering this larger loss, and by positioning the cooling ducts in locations where the construction causes heat to become concentrated.

3.4 Control technology

The controller of self-excited SVCs employs an entirely digital control system equipped with a modern CPU and DSP, and it realizes the system with superior reliability, maintainability, and with a self-diagnosis and trace-back function in addition to high-speed precision control.

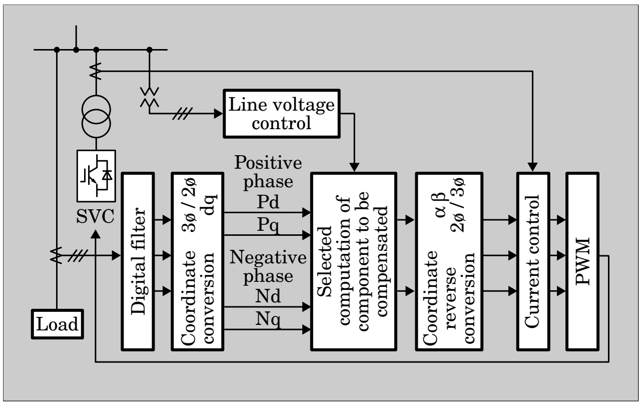
Figure 9 shows a block diagram of the control circuitry of the self-excited SVC. High performance compensation is realized by the following procedure. First of all, compensating components such as reactive current, transient active power, negative-phase–sequence current and high harmonic current are computed selectively corresponding to the desired purpose such as line voltage control, fluctuating load compensation or flicker compensation. Next, a high-speed current control circuit to which these computed values are fed-forward as command values performs output current control. Thus, high compensation performance is achieved.

4. Application Examples of SVC

4.1 SVCs for industrial use

Electric facilities for industrial use may induce

Fig.9 Control block diagram of self-commutated SVC



reactive power fluctuation disturbances (voltage fluctuations) in the connected power system due to the frequent load fluctuations of large capacity equipment that has been put into operation. Typical examples of such loads are arc furnaces for steel manufacturing-use, rolling mills and welding machines.

A disturbance that causes lights or TV displays to flicker due to voltage fluctuation is called “flicker disturbance” and is distinguished from normal voltage fluctuation. Among electric facilities for industrial use, arc furnaces for steel manufacturing have a capacity level, fluctuation frequency of reactive power and three phase unbalance condition that make them prone to cause flicker, and therefore most of the furnaces provide some counter plans.

Conventionally, external-commuted equipment equipped with thyristors were used widely as flicker compensators. However, self-commutated equipment using switched valve devices such as GTOs and IGBTs has become the majority now supported by the rapid progress of device and application technology in the field of power electronics.

An overview and some application examples of external-commuted and self-commutated equipment are described below.

4.1.1 External-commutated flicker compensators

Figure 10 shows the main operating principles of the TCR type flicker compensator (SFC). The SFC suppresses voltage fluctuation by controlling reactive power supplied from line (Q_S) to the minimum stable value. This is realized by compensating the reactor’s lagging phase reactive power (Q_L) with the capacitor’s leading phase reactive power (Qc), where the Q_L connected to the load in parallel is controlled by thyristors so that the resultant value combined with lagging phase reactive power (Q_F) becomes constant. As a rule, the capacitors provide a filtering function that absorbs higher harmonic current generated by the thyristors, and the adjustable range of leading or lagging phase is determined according to the relative capacity of the capacitor and reactor.

This equipment provides high economical performance for large capacity units, and a unit capacity of up to one hundred and several tens of MVAs has been realized. This equipment is often used in hybrid systems, installed together with self-commutated equipment or synchronous condensers.

Figure 11 shows an application example of a TCR type flicker compensator installed as a countermeasure for steel manufacturing-use arc furnaces. This example, which is composed of an 80 MVA TCR, which uses low-voltage large-current thyristors, and 140 MVA compensation capacitors, suppresses flicker generated by arc furnaces and ladle furnaces to less than 53 % and maintains the power factor of receiving power at a level higher than 0.95. In addition, this example suppresses the higher harmonics generated by each furnace and TCR to within the regulated value by configuring the capacitors to filter the second through fifth harmonics.

4.1.2 Self-commutated flicker compensators

The self-commutated flicker compensators are equipped with a rapid PWM-based momentary current control using switched valve devices (GTO, IGBT). Enhanced flicker compensation, compared with the external-commuted equipment, is achieved because the compensation is provided not only for fundamental-wave reactive power but also for negative-phase-sequence power and higher harmonics (active filter). Furthermore, a reduction in size of the total compensating system can be achieved since equipment volume relative to compensating capacity can be reduced to less than half, resulting of the ability to output both lagging and leading phase polarities so that necessary capacitance of the leading phase capacitor (higher harmonics filter) can be reduced.

(1) Application example of GTO type flicker compen-

Fig.10 Principle of TCR type flicker compensator

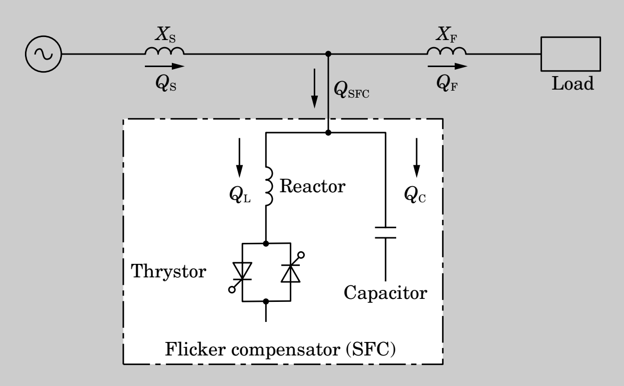
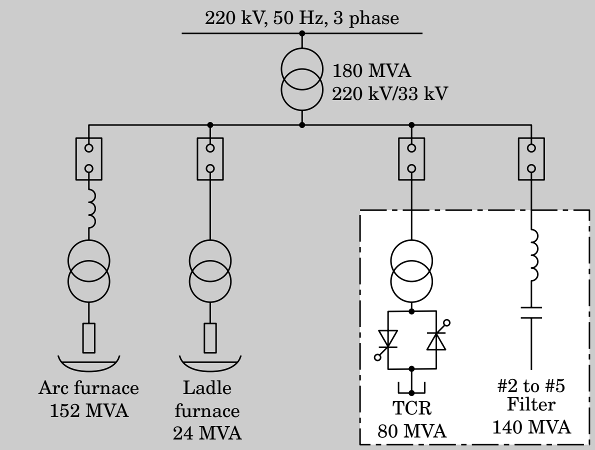
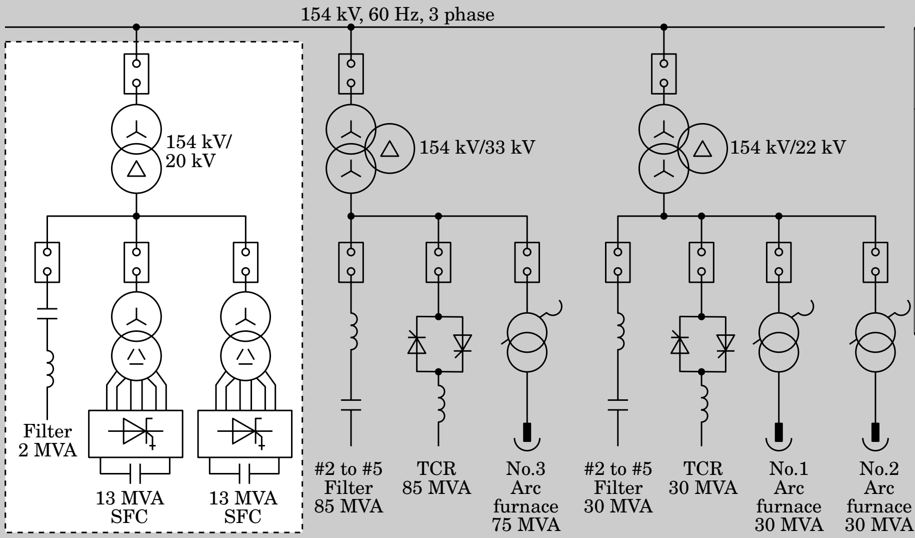


Fig.11 Electric power system equipped with TCR type flicker compensator and specifications thereof



Connecting transformer	Capacity	80 MVA
	Voltage	33 kV/1,420 V
	Impedance	50 %
Inverter	Device	Thrystor (1,500 V, 2,800 A)
	Device configuration	10P6A2G

Fig.12 Electric power system equipped with GTO flicker compensator and specifications thereof



Specifications of flicker compensator

Output	Capacity	13 MVA
	Voltage	20 kV
	Current	376 A
Inverter	Configuration	Single-phase inverter × three phase × six stages
	Voltage	885 V
	Current	816 A
	DC voltage	1,900 V
	Switching	540 Hz
	Device	Reverse conducting GTO thyristor (4.5 kV, 3 kA)
	Cooling	Pure water cooling system

sators

Figure 12 shows an example of a system equipped with the self-commutated flicker compensator using GTO devices.

This system is composed of a 154 kV to 20 kV step-down transformer, two sets of 13 MVA compensators connected with 20 kV line, and associated 2 MVA high frequency filters.

In this compensator, a three-phase single multi-connected inverter is composed of three sets of single-phase inverters equipped with a large capacity reverse-conducting GTO (4.5 kV, 3 kA), and six sets of these three-phase inverters are series-multi-connected via a transformer. Phase shift winding is not provided in this multiple transformer, and multiplexing is realized by phase shifting of the pulse width modulated triangle-wave carrier signal.

High pass filters absorb high-order upper harmonics caused by inverter switching and are provided to prevent burnout of the 20 kV line cable and/or absorbers. The effect of this equipment in reducing flicker is shown in Fig. 13. The target of a greater than 50 % improvement is achieved, and flicker is suppressed to within the regulated level.

(2) Application example of flat-packaged IGBT type flicker compensators

Figure 14 shows an example of a system equipped with a self-commutated flicker compensator using flat-packaged IGBT devices.

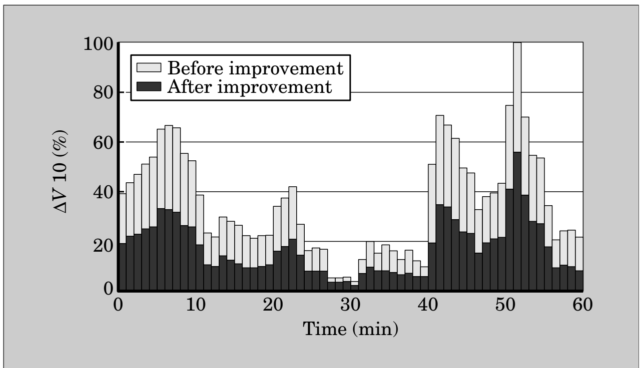
In this case, a 12 MVA self-commutated flicker compensator is added to two sets of pre-existing TCRs (15 MVA+25 MVA) to configure a hybrid system.

In this compensator, a three-phase single multi-connected inverter is composed of three sets of single-phase inverters equipped with a flat-packaged IGBT (24.5 kV, 1.8 kA) and four sets of these three-phase inverters are series-multi-connected via a transformer.

Figure 15 shows an exterior view of a flat-packaged IGBT inverter module for a flicker compensator. This module realizes a compact configuration by assembling four sets of a flat-packaged IGBT, gate drive circuit, clamp snubber and DC capacitor.

This compensator was put into operation on Aug. 2001.

Fig.13 Flicker compensation effect



4.2 SVCs for electric railway

As reactive power compensators for electric rail-

Fig.15 Flat-packaged IGBT inverter module for flicker compensator

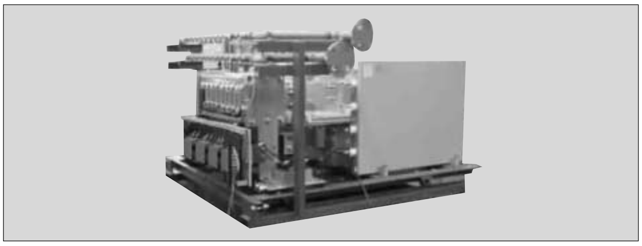
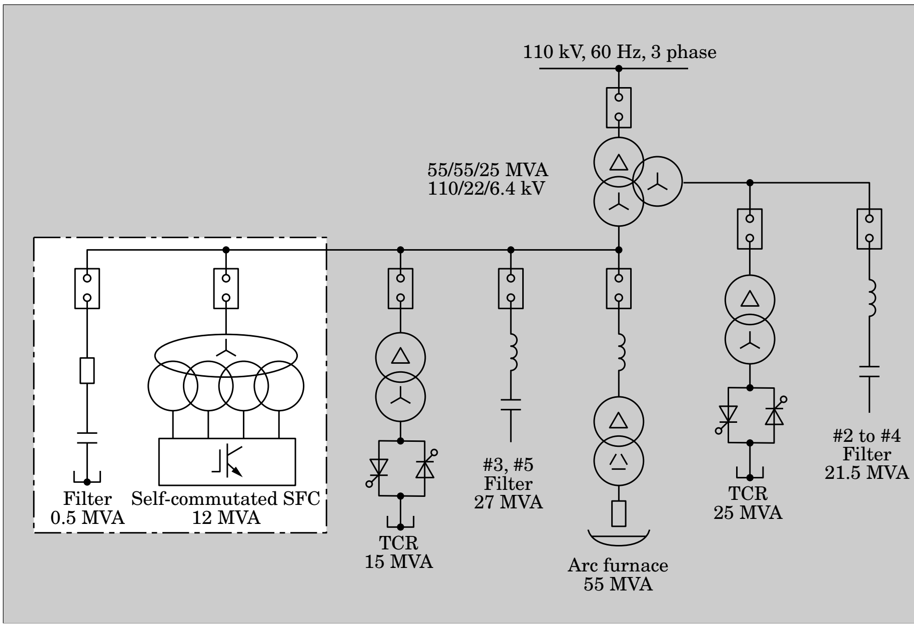


Fig.14 Electric power system equipped with flat-packaged IGBT flicker compensator and specifications thereof



Specifications of flicker compensator

Output	Capacity	12 MVA
	Voltage	22 kV
	Current	315 A
Inverter	Configuration	Single-phase inverter × three phase × four stage
	Voltage	735 V
	Current	1,360 A
	DC voltage	1,400 V
	Switching	720 Hz
	Device	Flat-packaged IGBT (2.5 kV, 1.8 kA)
	Cooling	Pure water cooling system

ways, the external-commuted single-phase SVC has been installed on the power system side at a Shinkansen substation to compensate for voltage fluctuation, and the self-commuted SVC has been installed on the three-phase line side to compensate for reactive power and unbalance power. Tokaido Shinkansen has installed this equipment at several locations as one of its measures to reinforce its power supply. Fuji Electric supplied a GTO type self-commuted SVC having ±1.7 MVA capacity to the Shin-maibara substation of Tokaido Shinkansen, and has experienced a successful history of operation. Now Fuji is studying the development and application of large capacity self-commuted SVCs, having ±30 MVA unit capacity and utilizing flat-packaged IGBTs, for the goal of providing the self-commuted SVC with compact size, high efficiency and simplified configuration. The outline of this system is described below.

Fig.16 Total system configuration of self-commutated SVC

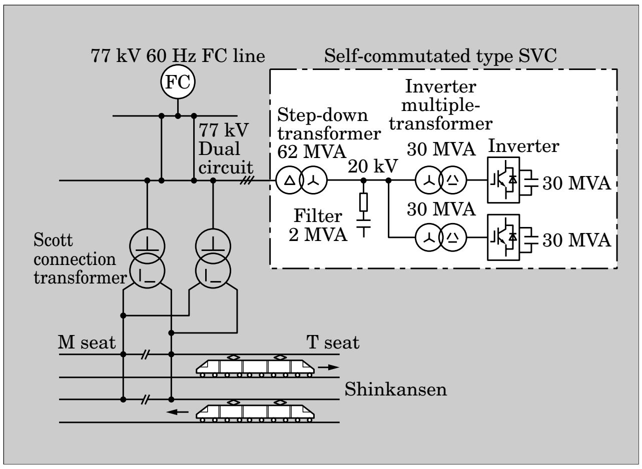


Table 1 Specifications of self-commutated SVC

Item		Specification
Line voltage		Three phase, 77 kV, 60 Hz
System capacity		Leading phase 62 MVA to lagging phase 58 MVA
Inverter	Inverter type	Voltage type multiple-connected inverter Single-phase inverter ×three phase × four stages (48 phase)
	Inverter capacity	30 MVA/bank × 2
	Devices	Flat-packaged IGBT 2.5 kV, 1.8 kA
	Cooling method	Water circulated air cooling (pure water cooling)
	Control method	12 pulse PWM, reactive power, negative-phase-sequence power compensating control
Multiple transformer		30 MVA, three phase, 20 kV/1.95 kV, 人/open△× four stages, oil circulated air cooling
Step-down transformer		62 MVA, three phase, 77 kV/20 kV, △/人, oil circulated air cooling
High harmonics filter		CR filter for removal of 95th and 97th harmonics

Figure 16 shows the total system of the three-phase self-commuted SVC, and Table 1 lists a summary of its specifications. This SVC system is installed on a 77 kV

Fig.17 Inverter module configuration of three series-connected flat-packaged IGBTs

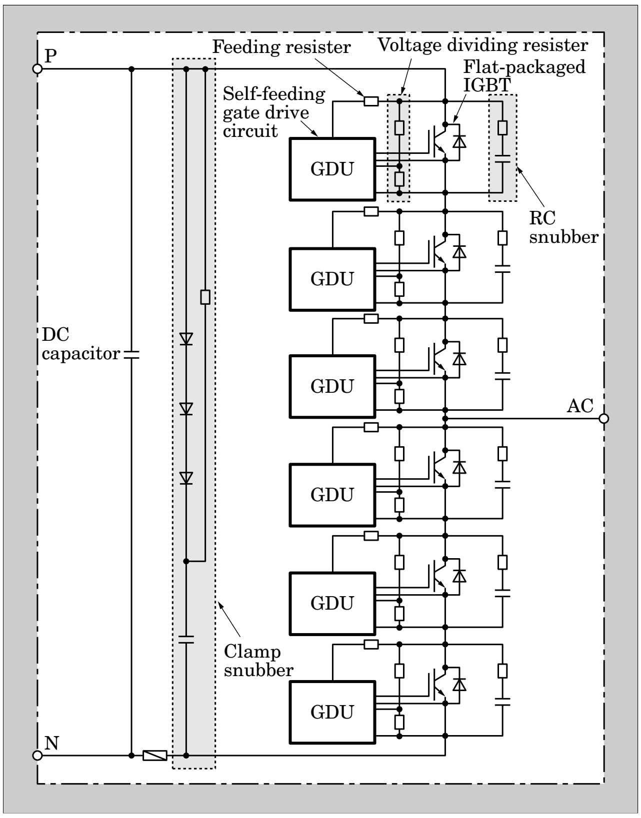


Fig.18 Prototype of inverter module

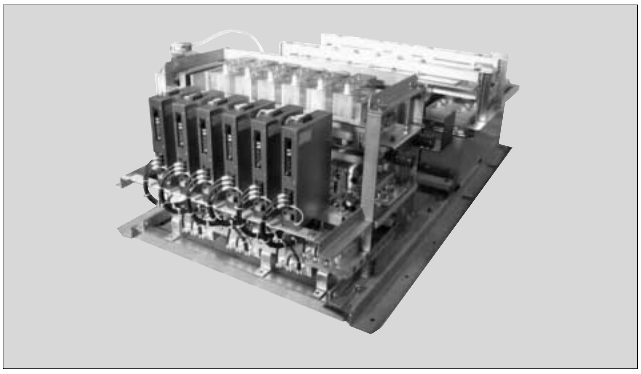


Table 2 Specifications of inverter module prototype

Item	Specification
DC voltage	3,600 V ±10 %
Output voltage	1,950 V
Applied devices	Flat-stacked IGBT 2.5 kV, 1.8 kA
Configuration of devices	3S1P2A
Feeding method for gate drive circuit	Self-feeding
Cooling method	Water circulated air cooling (pure water cooling)

three-phase line side and suppresses feeding voltage fluctuation by compensating reactive power and unbalance power generated by the Shinkansen train. The regulation range is from a leading phase of 62 MVA to a lagging phase of 58 MVA. The self-commuted SVC is has a 4-stage configuration that consists of two banks of inverters with leading-/lagging-phase of 30 MVA and 2.5 kV and 1.8 kA flat-packaged IGBTs which are equipped as application devices.

Figure 17 shows the circuit diagram of a prototype module assembled from three series-connected flat-packaged IGBTs in each phase of the top and bottom arm. Figure 18 shows the exterior view and Table 2 lists its specifications.

5. Conclusion

SVCs are expected to play a much more important roll in the future in order to maintain and improve power quality in diversifying power systems. Fuji Electric will endeavor to provide SVCs with higher performance in response to market needs by utilizing its vast experience and the latest technologies.

Finally, we wish to express our gratitude to all concerned parties who provided guidance and cooperated with us in the application of SVCs.

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