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FUJI ELECTRIC REVIEW

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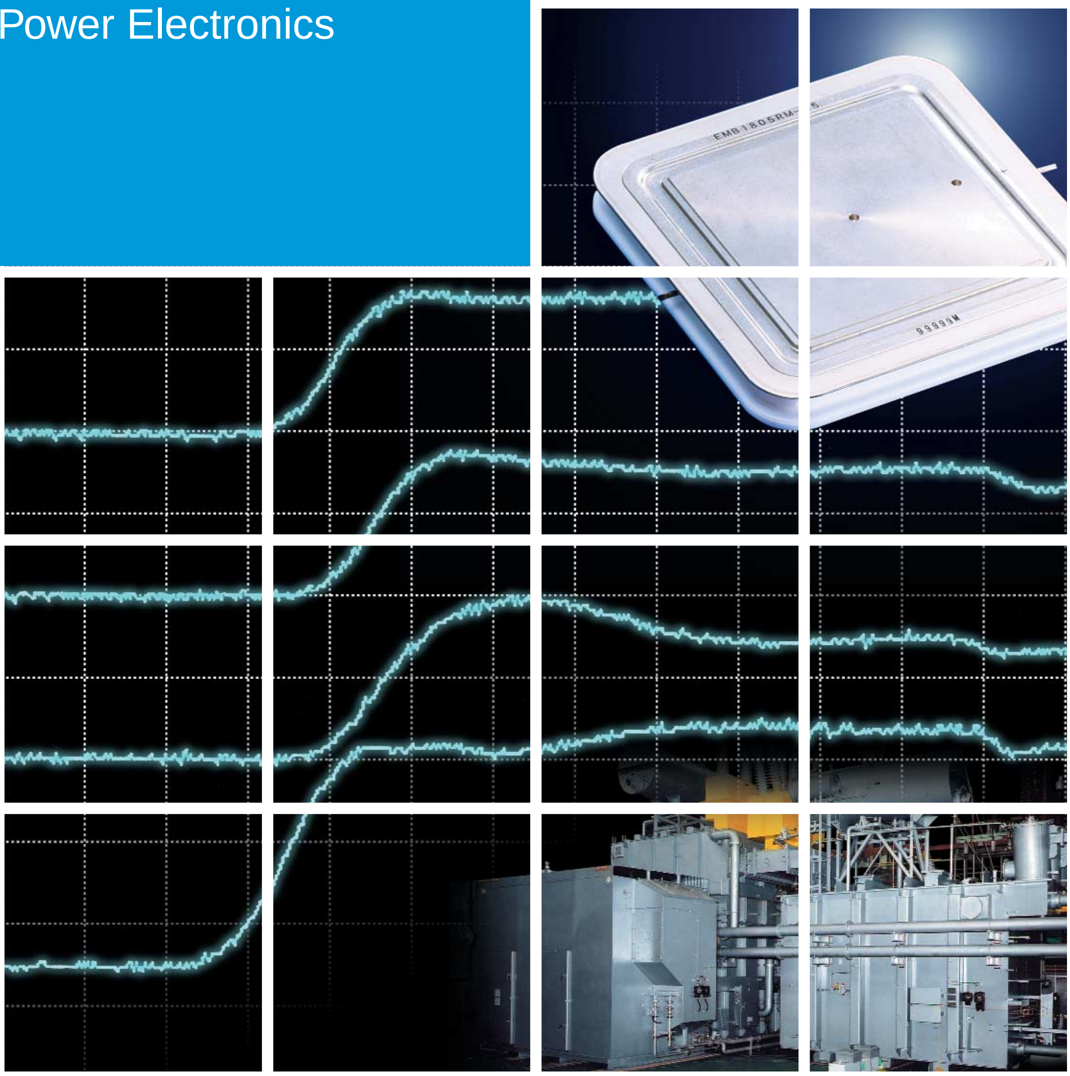
Power Electronics



FUJI ELECTRIC

Creating a Better Tomorrow with Trustworthy Technology

Introducing a high-efficiency, compact and environment-friendly silicon rectifier utilizing pure water

No impact on the environment
The innovative vaporization-cooling silicon rectifier uses pure water as the cooling media.

Small size, light weight, and high efficiency
Volume, weight and power dissipation of the rectifier have each been reduced by 60 % compared to Fuji Electric's 6,000 kW Freon-cooled rectifier. These reductions are achieved through the adoption of large-capacity silicon diodes that incorporate the latest power device technology.

Safe, maintenance-free and all-weather resistant
The rectifier is fully enclosed in a grounded cubicle, guaranteed to be safe, dust proof and suitable for underground and outdoor installation.
No auxiliary machines are necessary.

Large-capacity silicon diode
Type: ER3211FL-50
Repetive peak reverse voltage: 5,000 V
Average forward current: 3,200 A
Surge current: 58,000 A

Water Vaporization-Cooling Silicon Rectifiers for Traction Substations

FUJI ELECTRIC
REVIEW

2

2002 VOL.48

Power Electronics

CONTENTS

Cover Photo:

Power converters for electric power companies and industrial applications have been made larger in capacity and enhanced in functionality, together with advances in semiconductors and faster operation of controllers, and are contributing to improved productivity and higher quality. Large-capacity power converters should have high quality, especially in reliability since they are used in very important plant and power systems. In addition, intelligent power units, controllers and supervisory units are strongly required for the purpose of reducing running costs.

To meet these demands, Fuji Electric is leveraging its expertise in power electronic technology to manufacture and develop large-capacity power converters.

The cover photograph is a composite image showing a typical large-capacity power converter, a large-capacity semiconductor device manufactured by Fuji Electric, and their voltage waveforms.

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Present Status and Prospects of High-Power Conversion Systems

Ginjiro Yanai

1. Introduction

General industry, electric utilities and electric railways consume or transmit large amounts of electric energy. In these fields, electric energy is chiefly utilized for heating, chemical reactions and motive power. For those purposes, large-capacity power electronics equipment is installed at intermediate locations to meet respective requirements and to effectively utilize electric energy.

In the past, these fields have required averagely controlled electric power. Nowadays, however, the quality of electric power has also to be considered from the viewpoint of whether it enhances product quality, speeds up production, and is suitable for improving the environment we live in, such as by stabilizing system voltage and incinerating waste disposal. As a result, it is required of power supplies that voltage, current and frequency are not only averagely controlled, but that the voltage and current waveforms can be instantaneously controlled and generated freely according to load requirements. For that purpose, the configuration of power supply systems and the performance of power semiconductors, particularly switching speed, must be improved.

Power semiconductors used in power electronics devices have been improved substantially and large-capacity, high-speed power semiconductors have been developed and commercialized one after another. High-speed processing by controllers has been made possible due to the progress of microprocessors. The functionality of power electronic devices has remarkably been enhanced, allowing power supplies to meet market demands.

This paper describes the present status and prospects of power supplies in the fields of general industry, electric utilities and electric railways.

2. Power Supply Equipment for General Industries and Electric Utilities

Figure 1 shows the relationship between the types and applications of large-capacity power supplies for industrial use. Industrial applications can roughly be classified into the categories of heating and melting, metal surface treatment, welding and cutting, radiation-applied chemistry, voltage stabilization, electrolysis and other special applications. Each application requires a power supply suitable for that particular application. Requirements of power supplies are no power interruption and good quality, low equipment cost, and high adaptability to the application. Therefore, manufacturers of power supply equipment are concentrating their energies on improving power semiconductors, making smaller size and space saving power units and systems, and enhancing reliability and efficiency through the adoption of proper system configurations and components.

This paper describes power supplies for electrolysis, metal surface treatment, heating and melting, and voltage stabilization, but does not include descriptions of power supplies for motor applications such as variable speed drive and UPS (uninterruptible power supplies).

2.1 Electrolysis

Electrolysis used for aluminum reduction, chlor-alkali and other material production requires an extremely large amount of DC current from a DC power supply. The power supply voltage is 1,500 V or less.

The voltage and current of aluminum reduction furnaces have been increased in order to reduce cost. The largest capacity reduction furnace currently in operation is 400 MW. Construction of a 550 MW (1,550 V, 350 kA DC) furnace is planned, and in the future much larger capacity furnaces may be realized. Figure 2 shows the transition of the rated voltage and current of aluminum reduction furnaces. As can be inferred from the figure, technology for large-capacity power supplies plays an important role in the field of reduction furnaces. For details, refer to another paper, "Transformer-Rectifier Package (S-Former) for Aluminium Smelting," in this special issue.

There are several types of cells for chlor-alkali. These days, bi-polar cells are used in most cases due to their high production efficiency. A bi-polar cell has multiple cells, for which three types of power supply

Fig.1 Applications of large-capacity power supplies

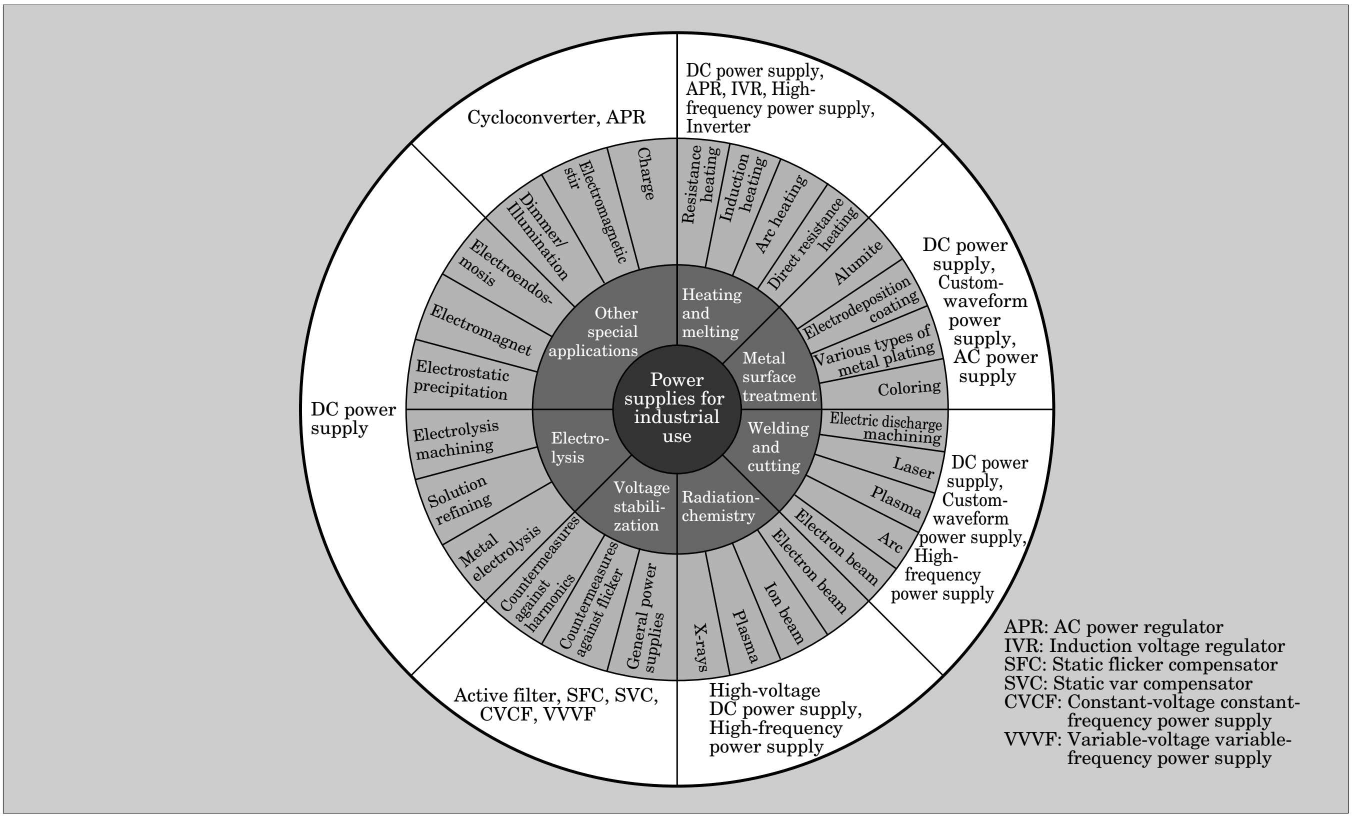
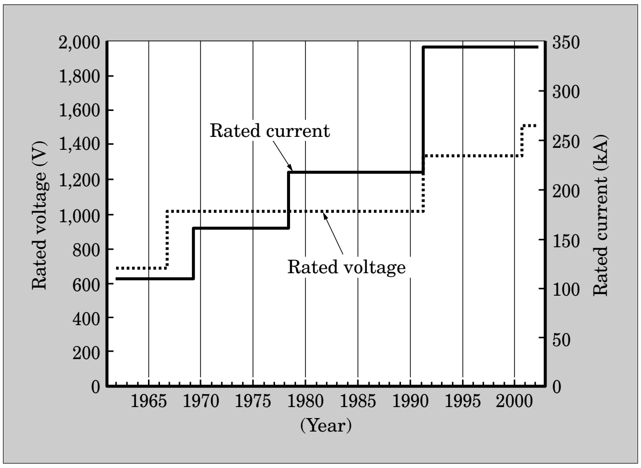


Fig.2 Transition of the rated voltage and current of aluminum reduction furnaces



system configurations are available as shown in Fig. 3.

The most suitable power supply system configuration is chosen from among these three kinds, based on considerations of equipment cost, installation space and reliability. The system configuration used most commonly these days is type (b), because of its excellent characteristics with regard to cost and space. Type (c) has the advantage of a higher power factor and lower harmonics, and will be preferable to the two other types if large-capacity self-commutated semiconductors are developed. The development of large-capacity self-commutated semiconductors and their application technology will be necessary in the future.

2.2 Metal surface treatment

Plating and coloring are typical metal surface treatments. The rather small power supply capacity for these treatments is 1,000 kW or less. To improve quality and productivity in metal surface treatment, each metal surface treatment company possesses their own proprietary processing solution and expertise in applying special voltage and current waveforms. Typical examples of metal surface treatments are as follows.

(1) Coloring of aluminum sashes

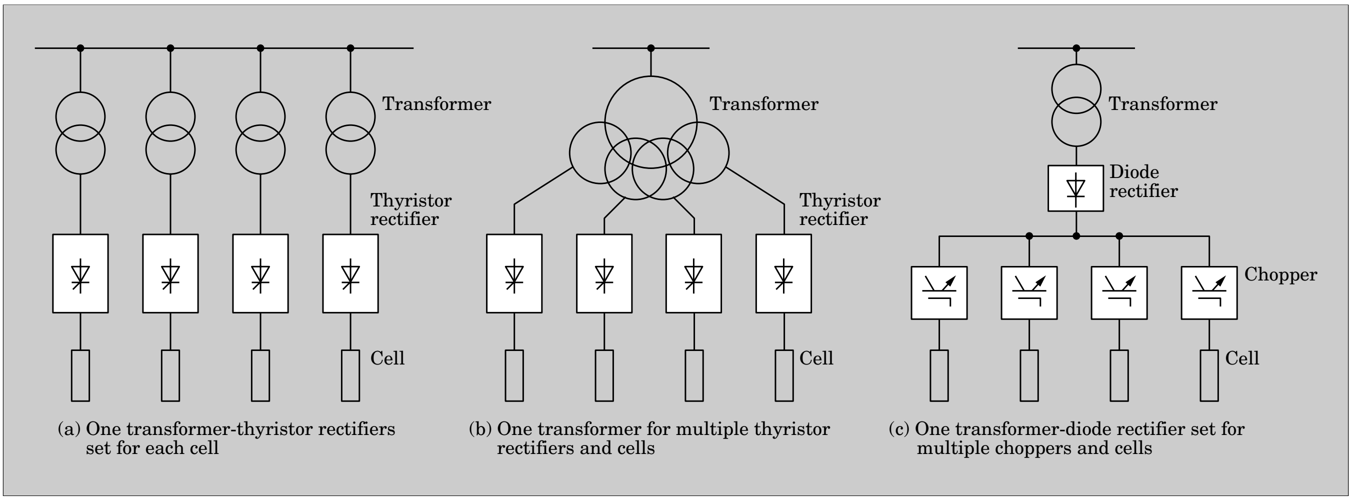
Coloring with uniform quality can be performed on an aluminum sash regardless of its size and its position in the cell, leading to an excellent yield rate.

(2) Plating of printed circuit boards

Through-holes can be plated in the same quality as the surface of a printed circuit board.

Large-capacity power supplies with special voltage and current waveforms are required in these fields. Programmable power supplies that utilize large-capacity inverter technology can be applied. Recent large-capacity, self-commutated, high-speed semiconductors enable the manufacture of 150 V, 10 kA-class programmable power supplies. A certain surface treatment company has introduced this power supply into an aluminum coloring process and has achieved excellent performance results. For details, refer to another paper, “Custom-Waveform Power Supply for Metal

Fig.3 Power system configuration for chlor-alkali



Surface Treatment," in this special issue.

2.3 Heating and melting

Heating and melting applications are found in a wide variety of processing fields. This paper describes the melting of ash from urban waste incinerators, which is attracting attention from the viewpoint of environmental preservation.

The disposal of municipal waste in Japan is increasing year after year, and in 1997 reached 51.2 million tons annually, and incinerated ash exceeded 6 million tons. Owing to a shortage of landfill sites for incinerated ash, recycling systems to melt and solidify the ash, and then to utilize the solidified product as construction material (gravel) are recently attracting a great deal of attention.

There are two types of these recycling systems, electric and combustion types. An electric-type system facilitates easy separation of heavy metals, and is environmentally friendly.

Arc furnace systems are currently widely used in electric-type recycling systems and have a power supply capacity of 70 to 100 kW/t. The rated voltage of the power supply for the arc furnace is set to a voltage higher than the normal operating voltage in order to prevent the arc from being extinguished. Its power supply circuitry is not composed of thyristor, but of 10 kA-class high current choppers, because thyristor rectifier would substantially reduce the power factor.

2.4 Voltage stabilization

The recent progress of semiconductors has enabled their use in various applications to improve production operations and to make daily life more convenient. On the other hand, semiconductors introduce various disturbances into the power supply networks, such as light flickering, make the system more susceptible to unstable system voltage and power supply equipment breakdown, and reduce the utilization factor. The use of var compensators resolves these issues and stabilizes system voltage. Var compensators mainly consist of the following three types:

(1) Thyristor-controlled reactor (TCR)
(2) Self-commutated static var compensator (STAT COM)
(3) Thyristor-switched capacitor (TSC)

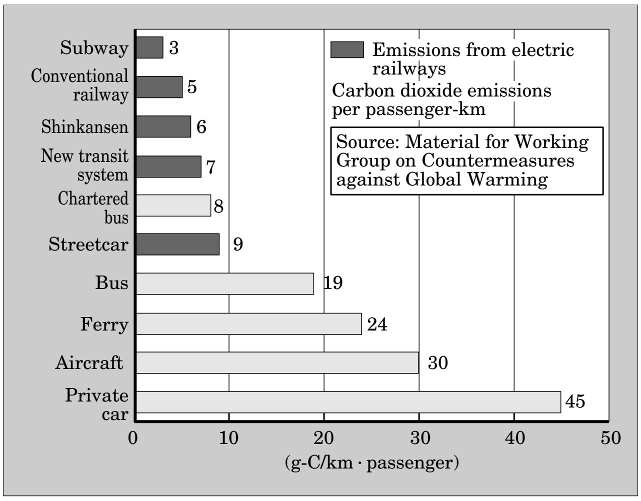
The total capacity of var compensators installed annually throughout the world is 4 to 5 GVA. Two thirds of the total installed capacity is for power supply systems, and TCR is the dominant type in this field. Introduction of the STATCOM started approximately 10 years ago, and STATCOM now accounts for several percent of the total installed capacity. The number of STATCOM installations is, however, expected to increase in the future due to its advantages such as three-phase unbalance compensation, high-speed control, compact size and non-harmonic property. In addition, a new type of var compensator provided with series-connected self-commutated semiconductors, directly connected to a power system via a reactor has been proposed and is being put into practical use, although the number of installed units is low now. Once large-capacity, high-voltage self-commutated semiconductors are developed in the future, the STATCOM will surely become more popular. For details, refer to another paper, "Var Compensators," in this special issue.

3. Power Supply Systems for Electric Railways

The total length of railways in Japan is approximately 15,000 km. Figure 4 shows the carbon dioxide emissions of various passenger transport vehicles. It is evident from the figure that electric railway vehicles emit the least amount of carbon dioxide and consume the least amount of energy as compared with other transport vehicles. An electric railway is a high-speed, mass transporting mechanism that meets the needs of the age, namely energy conservation.

Figure 5 shows electric railway feeding systems.

Fig.4 Carbon dioxide emissions from passenger transport vehicles



There are two types of feeding systems, a DC feeding system widely used in urban areas and an AC feeding system as typified by the Shinkansen Line (New Trunk Line). The AC feeding system is further classified as an AT (auto transformer) feeding system, which is the present standard, or a conventional BT (booster-transformer) feeding system. Figure 6 shows various technical challenges unique to electric railway systems. Most of these challenges were solved by the power electronics technology.

3.1 DC electric railway

Major challenges for DC electric railway power supplies are surplus-power regeneration and environmental protection.

(1) Surplus-power regeneration

Electric trains provided with inverters for regenerative braking have become commonplace. Regenerated electric power is, however, not always effectively utilized for powering trains because the loads are random and mobile, sometimes resulting in the loss of regenerative braking during intervals when the train schedule is not busy. The loss of regenerative braking has been indicated as a factor that may prevent the effective use of regenerated energy, be counterproductive to attempts to reduce the maintenance of brake shoes, and moreover may obstruct the highly accurate position stopping function in automatic train operation. As a result, regenerated energy absorbers are increasingly being installed on the ground side.

(2) Environmental compatibility

To meet such requirements as smaller size and maintenance-free operation, vaporization-cooling systems have been used with silicon rectifiers, the main components in DC substations, for over 20 years. These systems have been using CFC (chlorofluorocarbon) or PFC (Parfluorocarbon) as the cooling medium. These media were, however, specified as environment-disrupting substances conducive to ozone layer deple-

Fig.5 Electric railway feeding systems

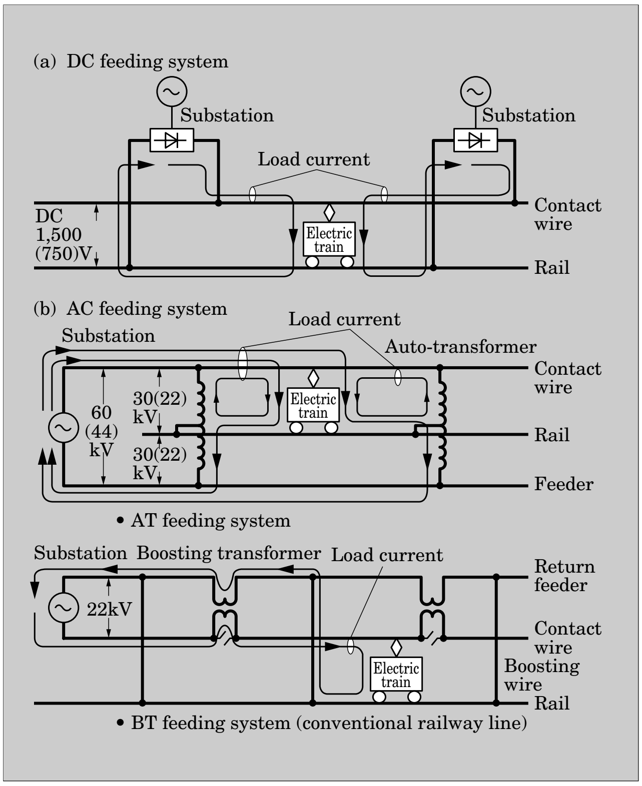
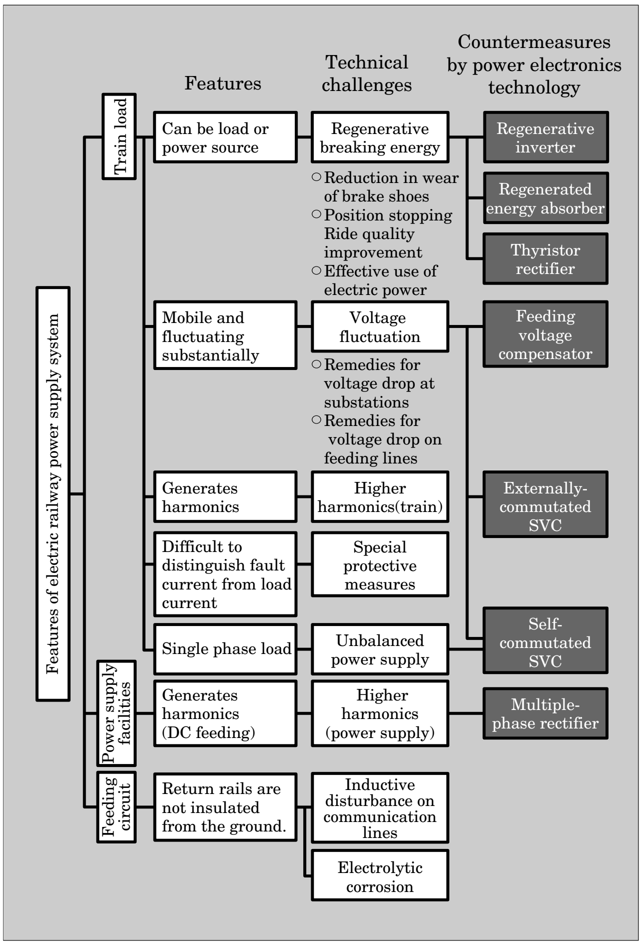


Fig.6 Technical challenges unique to electric railways



tion and global warming in The Montreal and Kyoto Conferences. To fundamentally resolve these environmental problems and to realize much smaller size and higher efficiency, Fuji Electric has developed and commercialized an innovative new-type vaporization-cooling silicon rectifier using pure water as the cooling medium.

3.2 AC electric railways

A typical challenge in AC electric railways is the implementation of countermeasures against voltage drop on the feeding lines, and the unbalance between phases on the power supply side caused by mobile, single-phase train loads. Particularly, in the Tokaido Shinkansen Line, which has the heaviest train load, var compensators utilizing power electronic technology have been introduced to solve these problems.

4. Future Prospects

The power supply system consists of three components: a power unit, controller and supervisory unit.

Today, most power units contain self-commutated semiconductors, and the units can easily generate voltage and current suitable for users' needs and load conditions. As a result, dramatic improvement in productive efficiency can be expected, reactive power and harmonics can be suppressed, and the utilization factor of the power supply can be improved, yielding great benefit to users.

Power semiconductors will continue to be improved in the future. If SiC semiconductors become commercialized, they will enable dramatically higher-speed and lower-loss operation of power units, thereby improving efficiency, reducing the necessity for heat exchangers, and consequently expanding the application range of power supply systems.

Controllers will be made smaller in size and higher in performance.

Supervisory units use an HMI (human-machine interface) to facilitate operation monitoring and the collection of maintenance information. In the future, the operating conditions of various devices, maintenance information and failure records will be monitored by the manufacturer via the Internet, allowing various parameters to be changed, preventive maintenance measures to be recommended and the implementation of quick restoration from failures.

In the past, the three components of power supply systems–power units, controllers and supervisory units–have been made with higher capacity, more enhanced functions and higher reliability, contributing to improved productivity, energy saving and low cost in equipment and plants. Additionally, for the future, excellent environment-friendliness is required. For example, CFC, which had been used for many years as the cooling medium for power units, was replaced by PFC, a more environment-friendly cooling medium. Recently PFC is being replaced by pure water, which is harmless to the environment. Low-acoustic noise power supply systems using high-speed power semiconductors are in widespread use. In addition, power converters free from reactive power and harmonics are increasingly being used to effectively utilize electric energy. Thus, power supply systems will be developed based on four key concepts of "higher capacity," "higher level functionality," "higher reliability" and "excellent environment-friendliness."

How will energy consumption change in the 21st century? Growth in demand for electric power has been sluggish due to the promotion of energy conservation and a stagnant Japanese economy in recent years. Electric power will, however, remain a dominant energy source because it is clean, safe and flexible. The use of fossil fuels as a direct energy source for engines and other applications is restricted because they are considered to be chief causes of air pollution. It will take a long time before nuclear fusion energy can be used as a daily energy source because its control technology is not yet established. Biogas energy is still under development. Utilization of natural energy such as solar and wind will surely increase, but it is limited in quantity and is basically transformed into electric power before application.

In recent years, power generation has increasingly become distributed. The installation of distributed power supplies requires consideration of their effects on power systems, because they are relatively small in scale. Particularly, distributed power supplies require the installation of electric power storage equipment to ensure electric power quality, and the control of distributed power supplies based on the network performance of power systems. The wireless transmission of electric power can be cited as a future technology, however its implementation will require examination of the role of the power supply and of a suitable configuration for this technology.

5. Conclusion

Power supply systems have been utilized for a wide range of applications for many years. Electric power will undoubtedly remain a safe, convenient energy source in the future. There are, however, many challenges to be overcome. To meet market needs, Fuji Electric has determined to do its best to develop and provide easy-to-use, clean power supply systems utilizing its accumulated expertise along with new innovation.

Var Compensators

Shigeo Konishi
Kenji Baba
Mitsuru Daiguji

1. Introduction

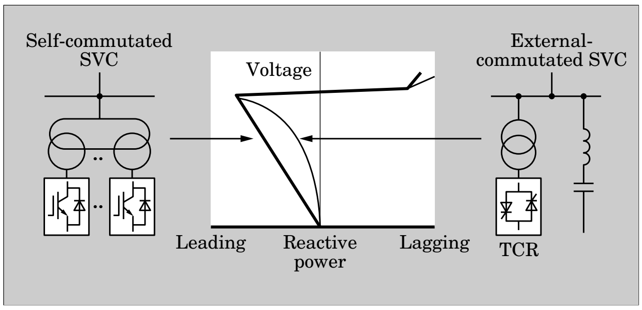
In each field of power system, industry, and electric railway, static var compensators (SVCs), taking full advantage of power electronics technology, have lately been applied widely for the suppression of voltage fluctuation, the stabilization of power system, the suppression of voltage flicker, and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

Fig.1 Voltage control characteristic of SVC



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

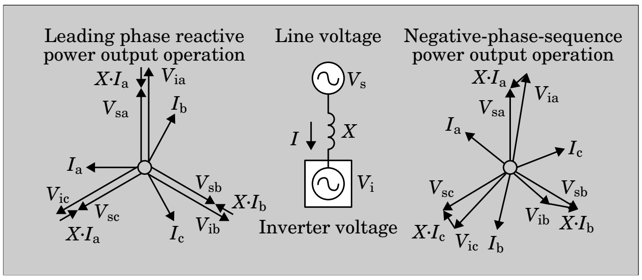


Fig.3 Comparison of GTO inverter and flat-packaged IGBT inverter configurations

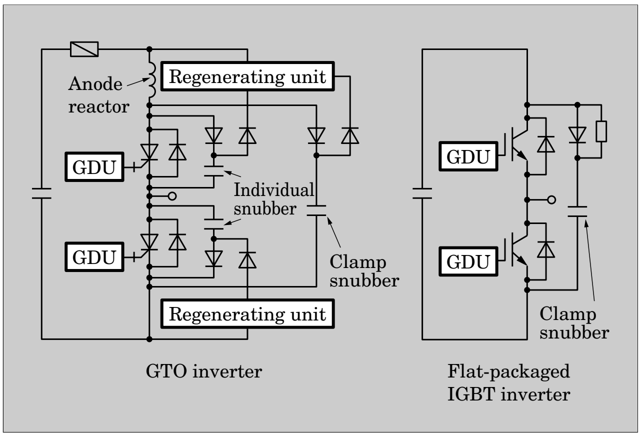


Fig.4 Block diagram of gate drive circuit for IGBT

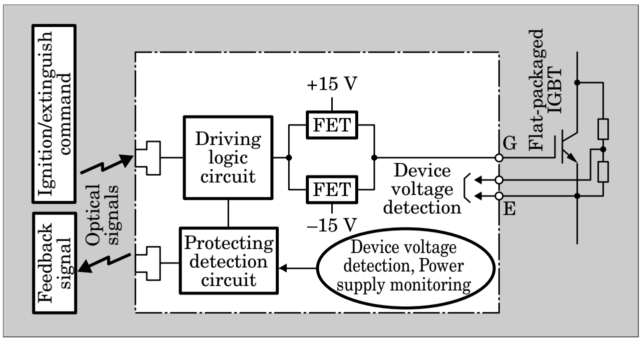
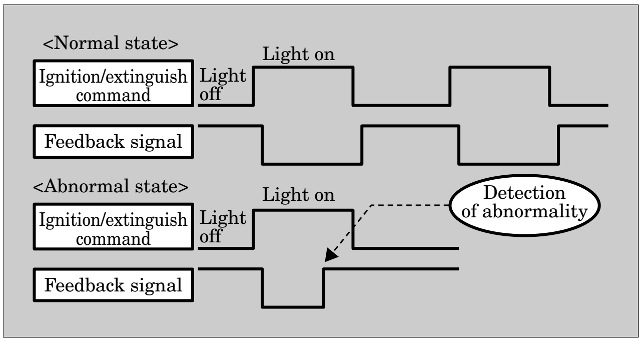


Fig.5 Processing of state monitoring signal



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.

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

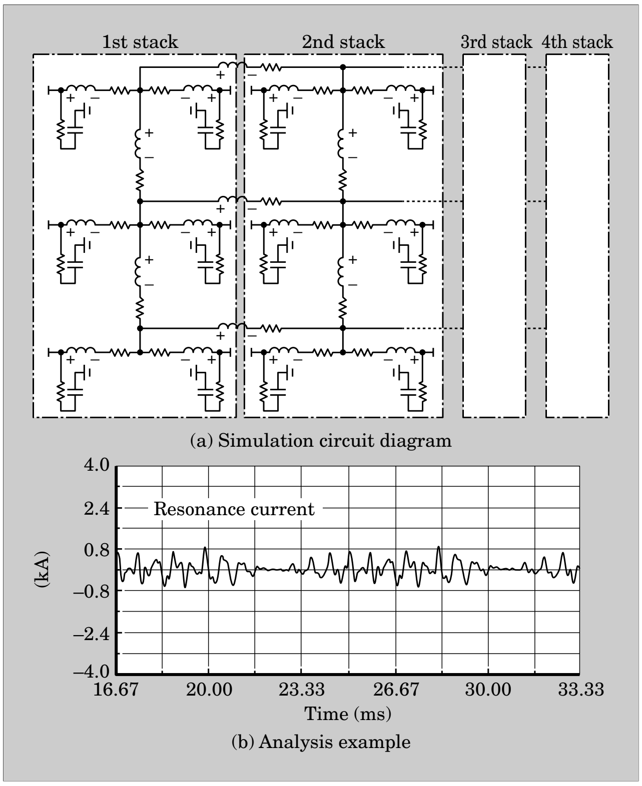


Fig.8 Comparison of sinusoidal wave and inverter excitations

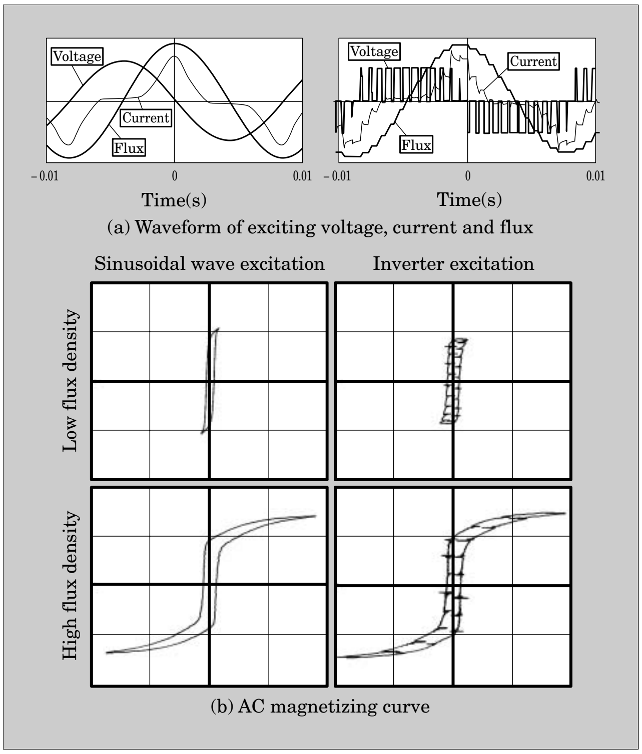
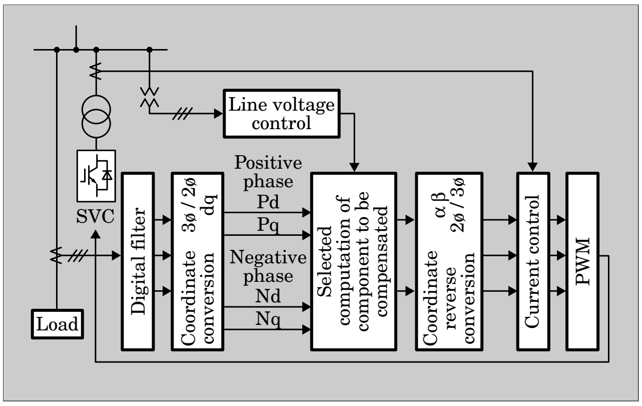


Fig.9 Control block diagram of self-commutated SVC



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 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

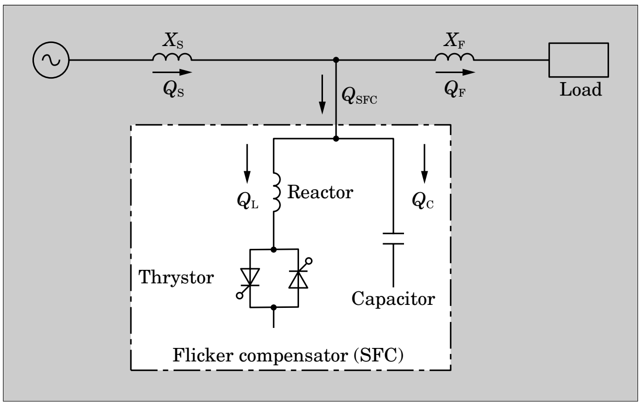
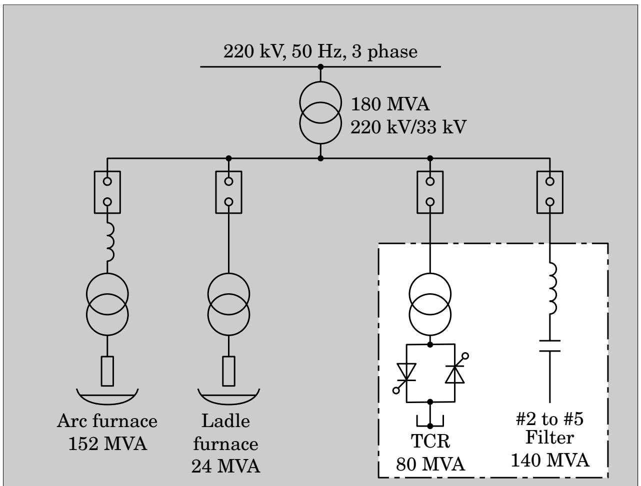
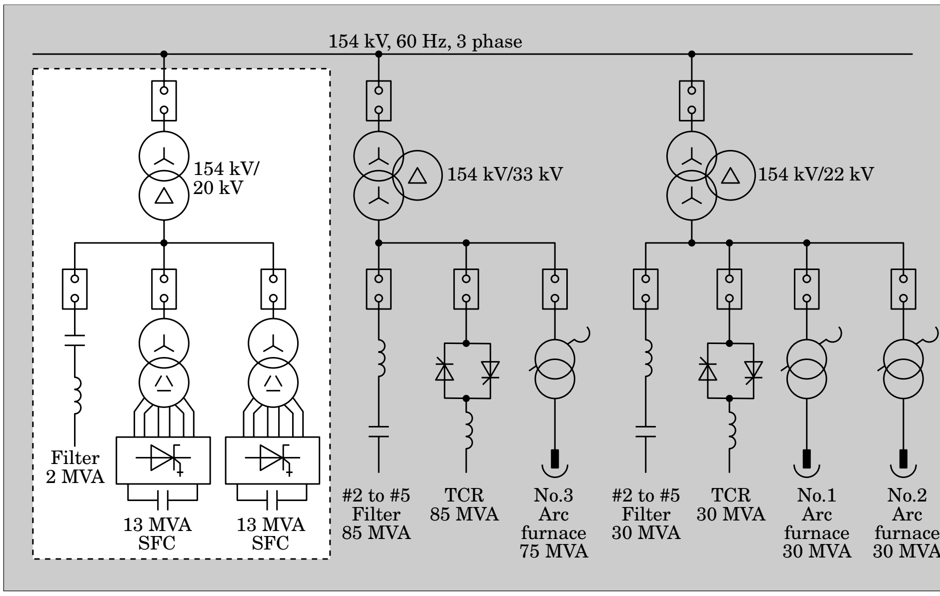


Fig.11 Electric power system equipped with TCR type flicker compensator and specifications thereof



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.

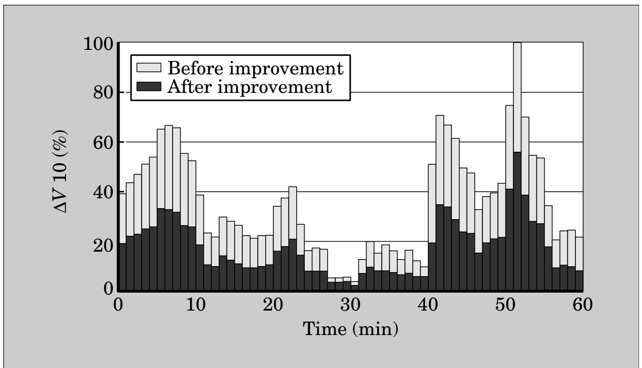
In this case, a 12 MVA self-commutated flicker compensator is added to two sets of pre-existing TCRs (15 MVA+25 MVA) to configure a hybrid system.

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

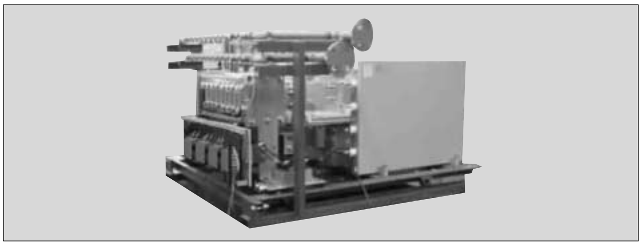
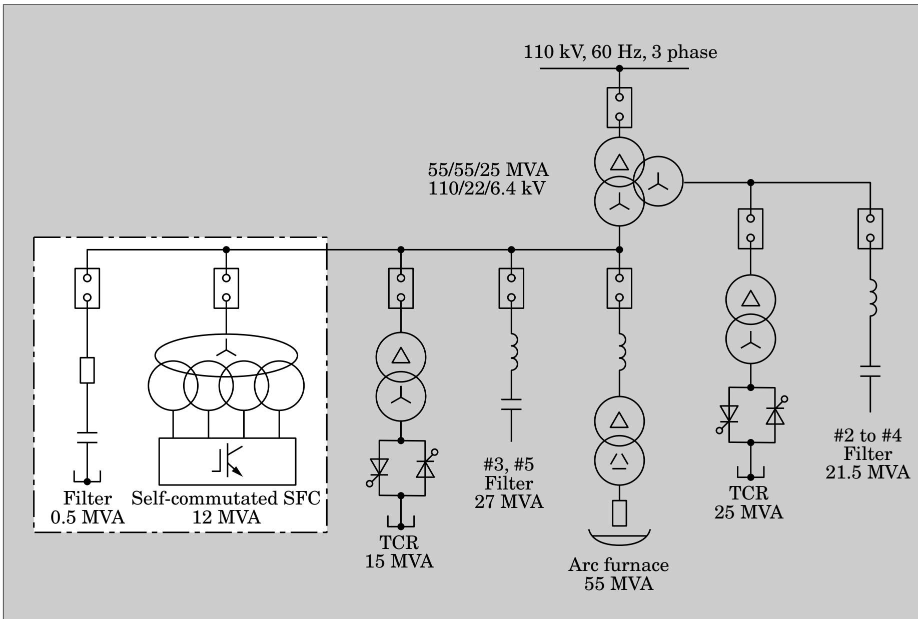


Fig.14 Electric power system equipped with flat-packaged IGBT flicker compensator and specifications thereof



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

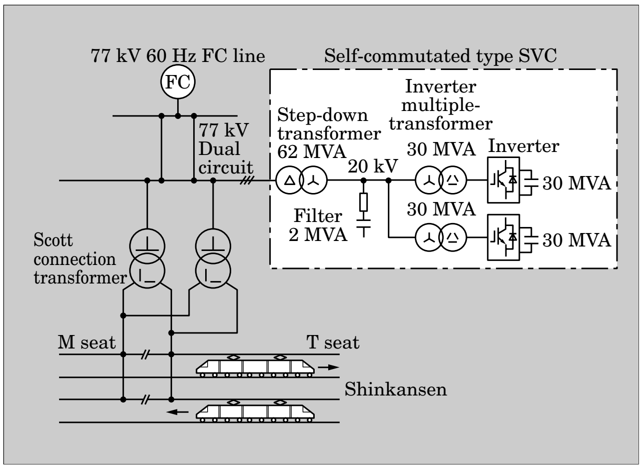


Table 1 Specifications of self-commutated SVC

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

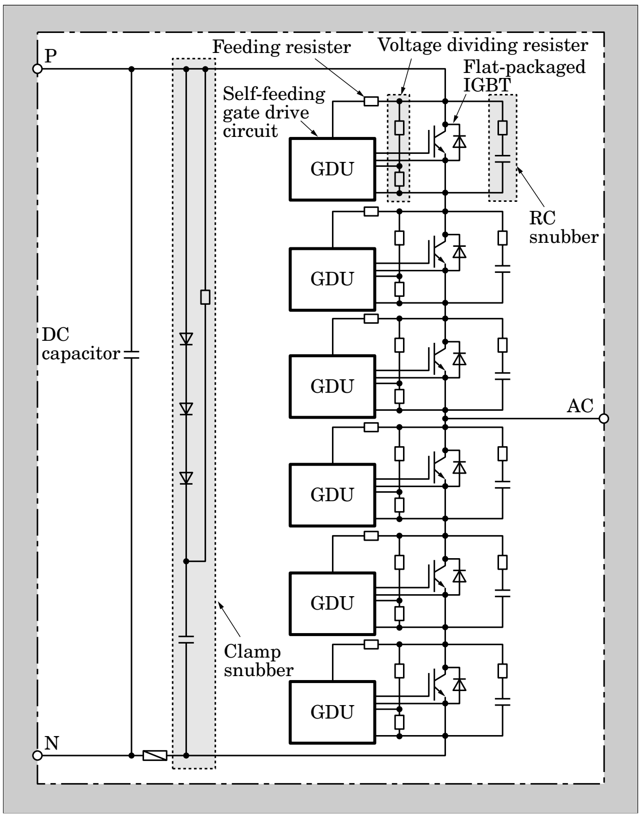


Fig.18 Prototype of inverter module

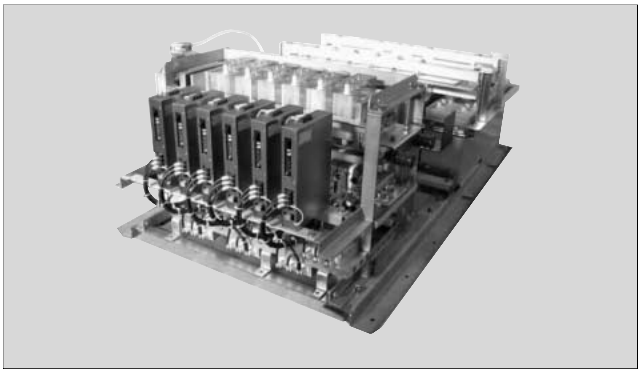


Table 2 Specifications of inverter module prototype

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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Transformer-Rectifier Package (S-Former) for Aluminum Smelting

Shinichi Furuki
Ginji Ishizuka

1. Introduction

At the time when aluminum was discovered in 1807, it was predicted that aluminum could be decomposed by electrolysis. But, at that time, it was extremely difficult to obtain inexpensive and powerful electric energy for this purpose. In the 1860s, inexpensive and stable DC electric energy was made available by the achievement of Mr. Siemens of Germany and Mr. Gram of Belgium. Thus, a means for performing aluminum smelting by electrolysis was established.

In this process, bauxite, a raw material of aluminum, is first dissolved by a caustic soda, and the alumina is extracted. Next, the alumina is dissolved using cryolite as a solvent, and is smelted by electrolysis using a DC power source. This method (aluminum smelting) replaced the metal deoxidization methods used previously. Aluminum smelting has been utilized industrially since 1888 in Europe and North America. In Japan, aluminum smelting has been utilized since 1894.

Aluminum smelting requires a high DC current for the electrolytic process. Generally, a high DC current is obtained from an AC power source using rectifier equipment. As the result of technical innovation from the 1960s, older type rectifier equipment, i.e., rotary converters, mercury rectifiers and contact converters, have been replaced by semiconductor rectifiers using selenium and silicone technology. Recently, even higher voltage and higher current rectifier equipment has been realized thanks to the development of semiconductor elements for this purpose.

Since 1959, Fuji Electric has received 74 orders for rectifier equipment consisting of transformers and rectifiers. Presently, we have the top market share in the world. The rectifier equipment we supplied for MOZAL (Mozambique) started operation in 2000 and holds the world record for unit capacity of 1,330 V, 100 kA DC and 133 MW. Figure 1 shows current carrying test on the equipment at the factory.

In this paper, we explain the market requirements and recent technical trends of the rectifier equipment for aluminum smelting.

Fig.1 Current carrying test at the factory

N99-2491-1

2. Features of Transformer-Rectifier Package for Aluminum Smelting

As the aluminum smelting industry consumes huge amounts of electric energy, the conservation of electric energy has always been a prime target for improvement. For this purpose, the development of smelting has emphasized the use of larger pots, improved electrode construction, and automatic computer control of the electrode position. Measures for balancing current in the pot were also established.

As aluminum smelting technology has progressed, requirements for the rectifier equipment have changed as shown on Table 1.

The following characteristics are required of rectifier equipment for aluminum smelting.

(1) Reliable power source

Because aluminum smelting uses the molten salt process, if the power source is shut down, molten

Table 1 Electrical requirements applicable to aluminum smelting

Year	1960s	→	After 1995
DC voltage	500 V	→	1,200 to 1,500 V
DC current	50 to 120 kA	→	Approx. 340 kA or more
DC output capacity	25 to 60 MW	→	400 to 510 MW

aluminum will coagulate. This will cause serious damage to the smelting facilities. High reliability is essential.

(2) 0 to 100 % wide-range voltage regulation

At the start of operation, 1 to 2 pot(s) will be energized, and thereafter 3 to 4 pots will be energized successively until all the pots have been energized. Therefore, wide-range voltage regulation is required.

(3) Automatic constant current control

The anode effect (AE), a phenomenon occurring in the molten salt process, has to be considered. When a shortage of raw material (alumina) occurs or the electrode (positive pole) wears away, gas is generated between the surfaces of the electrode and alumina, and the pot voltage is increased by 30 to 60 V. This means that the load resistance, as seen from the power source, becomes larger. If the output voltage of the rectifier equipment remains the same, the output current will be decreased. As a result, the production of the aluminum will be decreased. To prevent this, automatic control is required to keep the output current at the set value.

(4) High unit capacity

Normally, the smelting facilities will be provided with several rectifiers (4 to 5 units) to handle the rated DC output current. In addition, one rectifier unit will be always installed as a spare to insure the availability of DC power supply. High DC capacity rectifiers are required from the following reasons.

① To reduce the total power loss of rectifier equipment
② To reduce the space occupied by all the equipment, including equipment for the AC substation
③ To reduce the number of equipment that requires maintenance

(5) Digital control

The constant current control of the rectifier equipment will be implemented by PLC/HMI. Optimum control will be achieved by online control of the variables.

3. Transformer

To cope with the requirements for higher capacity rectifier equipment, many issues have to be resolved. Examples of some solutions achieved by Fuji Electric are listed below.

3.1 Full-range on-load tap changer

As rectifier equipment ratings have increased, transformer unit ratings now range from 100 to 160 MVA. As mentioned before, the rectifier equipment for aluminum smelting requires a voltage adjustment range of 0 to 100 %. To comply with this requirement, the transformer has to be separated into a voltage regulating transformer and a rectifier transformer as shown in Fig. 2. Normally, this voltage regulating transformer has a no-voltage tap changer (NVTC) with 3 to 4 taps and an on-load tap changer (OLTC) with about 33 taps. By combining the NVTC and OLTC, about 100 taps can be achieved. In this case, magnetizing inrush current of the voltage regulating transformer after the closing of the circuit breaker will include that portion due to the rectifier transformer. The magnetizing inrush current will be much larger than that of the regular transformer. This may cause a disturbance in the power supply system.

As a countermeasure, we decided to utilize an on-load tap changer with about 100 taps so that the output voltage can be adjusted simply by the OLTC. The full range of voltage can be adjusted without the use of the NVTC. When the circuit breaker is going to be closed, the lowest tap is set. Thus, the magnetizing inrush current was reduced substantially.

3.2 Ideal twelve (12) pulse rectification

When large capacity rectifier equipment is used, 12-pulse rectification per unit is commonly applied. To minimize the harmonic current which flows into the power supply system, 4 to 5 units are connected together to configure a 48 to 60 pulse rectifying system per pot. In this case, if an unbalance (difference in no-load DC voltage and difference in short-circuit impedance) exists among the 6 pulse groups that comprise the 12-pulse rectification, the system will not be an ideal 12-pulse rectification system, and therefore, 5th and 7th harmonic current may flow into the power supply system. To prevent such unbalance, we adopted a two-tier core construction with an intermediate yoke.

Figure 3 shows a sketch of the core and winding configuration. The upper stage DC winding is connected in star configuration and in the lower stage DC winding is connected in delta configuration. Twelve-pulse rectification was realized with the single core construction. Naturally, there are an integer number of turns of the winding. Therefore, only an integer number of turns can be selected. For the rectifier transformer with high secondary current, a large number of turns cannot be selected. Therefore,

Fig.2 Simplified diagram of transformer-rectifier package

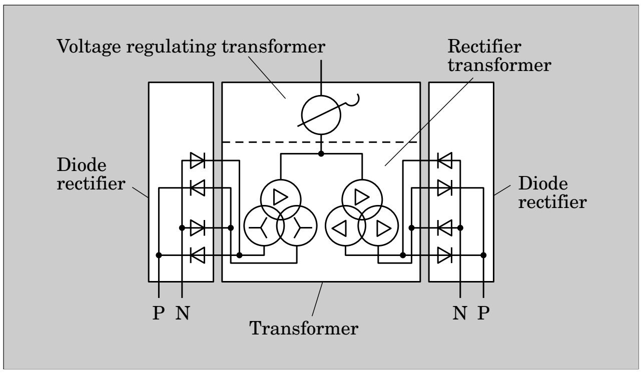
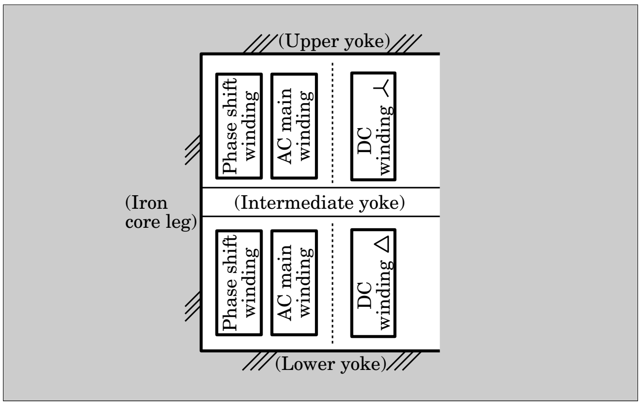


Fig.3 Cross section of the winding of a rectifier transformer



without an intermediate yoke, it is not possible to balance the no-load voltage between upper and lower stage windings. The ideal number of turns of the delta winding is $\sqrt{3}$ times that of the star winding. But, this is not possible for the high current winding. For example, if we select 5 turns for the star winding, 9 turns would be the optimum number of turns for the delta winding. In this case, the no-load unbalance between both windings will be:

$$(\frac{9}{\sqrt{3} \times 5} - 1) \times 100 = 3.9\ \%$$

Because the output DC circuit of both windings is common, this unbalance will be absorbed by VCR control. As a result of the unbalance, ideal 12-pulse rectification cannot be achieved. In the above case, 5th and 7th harmonic current which would be cancelled by real 12-pulse rectification will remain about 1 % of the fundamental current. In addition, the unbalance of the short-circuit impedance may increase the residual 5th and 7th harmonic current.

Our rectifier transformer is provided with an intermediate yoke and the differential flux between upper and lower windings can be bypassed. Therefore, the magnetic flux density of both winding can be selected individually. This means that the optimum number of turns can be selected for both DC windings. As a result, it is possible to limit the unbalance no-load voltage to within 0.2 %. In addition, because the dimensions of each winding stage can be selected individually, the short-circuit impedance of both windings can be balanced. Thus, we were able to realize a single core, space saving rectifier transformer with ideal 12-pulse rectification. By connecting 4 to 5 rectifier units, the merits of multiple rectification can be most efficiently utilized.

3.3 Internal construction of transformer

The main circuit configuration of the high capacity transformer for aluminum smelting usually comprises a voltage regulating transformer (single-winding transformer with full-range on-load tap changer) and a rectifier transformer for 12-pulse rectification (two-tier construction with intermediate yoke and VCR). Because the rated secondary voltage of the voltage regulating transformer is the input voltage to the rectifier transformer, the manufacturer can select the secondary voltage arbitrarily and independent of the customer's requirements. If we select to increase the voltage, the current through the on-load tap changer may decrease, but the insulation level would be higher. We have to select the most suitable voltage considering these factors. The selection of the rated secondary voltage of the voltage regulating transformer is a key factor when planning the transformer design. Two factors were taken into consideration. First, the maximum voltage of the intermediate circuit during the tap changing process should not exceed the IEC specification of 72.5 kV. And secondly, the current through the on-load tap changer should be a value at which reliability of the on-load tap changer can be guaranteed. After due consideration, we selected 66 kV as the rated secondary voltage of the voltage regulating transformer.

When designing a high capacity transformer, transportation restrictions must also be considered. In our design, the voltage regulating transformer and the rectifier transformer are housed in separate tanks so that each transformer can be transported separately. In this case, both transformers will be installed side-by-side at the site and connected by an oil-filled duct. The insulation oil of the duct is completely separated from the oil of both transformers. The oil-filled duct is provided with its own conservator, pressure relief device, oil gauge, etc., to facilitate the maintenance work.

4. Diode Rectifier

In the design of a high capacity rectifier, the following issues have to be resolved.

(1) Measures to prevent local heating due to the high current
(2) Awareness of the actual current unbalance between parallel connected elements
(3) Application of technology to high capacity elements and their protection fuses
(4) Measure to prevent the deterioration of high capacity fuses due to vibration

4.1 Measures to cope with local heating due to high current

Steel parts near the leads or terminals will become locally overheated due to the magnetic flux generated by the high AC current of the rectifier. Fuji Electric has for many years utilized an in-phase contra-polarity connection, which is very effective in preventing local heating due to a high current rectifier. The in-phase contra-polarity connection is a circuit configuration in which two groups of rectifier circuits with the same design are arranged so that the current of each group

Fig.4 Principle of in-phase contra-polarity connection

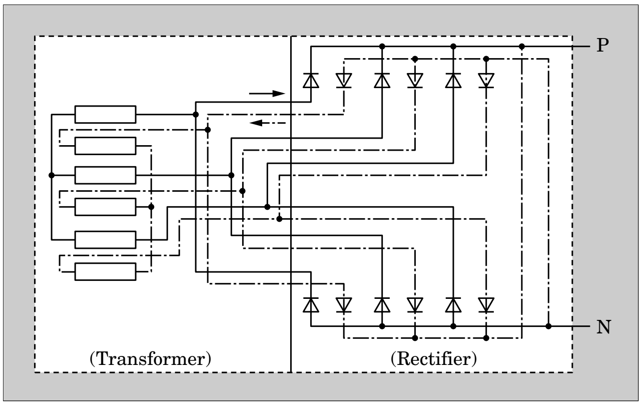
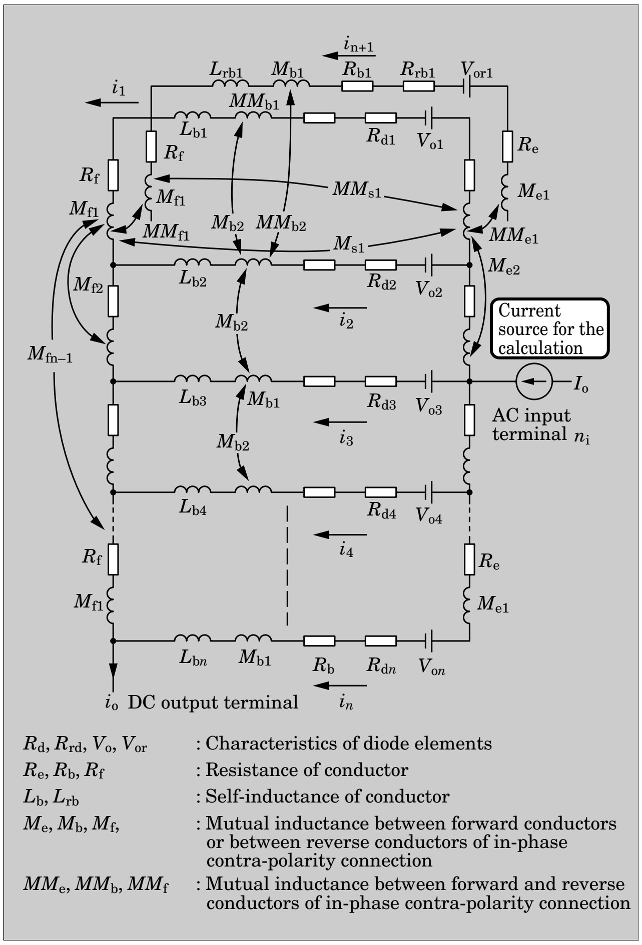


Fig.5 Simulation circuit of current unbalance



flows in opposite directions as shown in Fig. 4. Because the magnetic flux generated by one group will cancel the other, the parts or casing of the rectifier equipment will not overheat locally, even if those parts are made of steel. In addition, the in-phase contra-polarity connection exhibits the following advantageous characteristics for the design of rectifier equipment.

(1) Because the inductance of transformer-rectifier connection leads and rectifier circuits can be greatly reduced, the voltage drop during the operation will be reduced and the power factor of the circuit will be improved.
(2) Because the inductance of rectifier circuits can be greatly reduced, the current unbalance between elements will be improved.

4.2 Current unbalance between diode elements

When several diode elements are connected in parallel, the current among each of the elements will not be uniform due to the different characteristics of the elements and the inductance of the conductor for each element. The required number of parallel elements will be determined based on consideration of the current unbalance. Reliability and economical efficiency will also be considered for this decision. Theoretically, the number of parallel elements can be calculated by the following formula, when one parallel redundancy is to be applied.

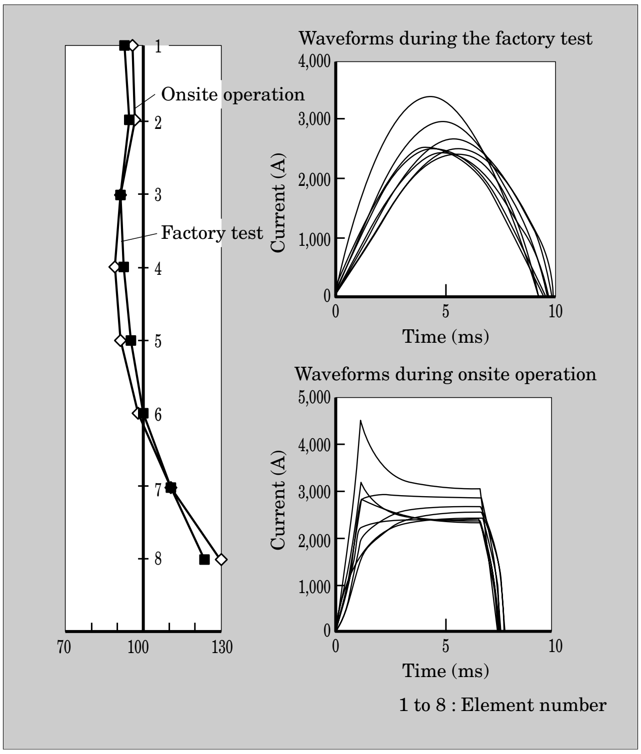
$$P = \frac{I_d \cdot \alpha}{K \cdot G \cdot I_s} + 1$$

where, I_d: Rated output of the rectifier equipment
α: Current unbalance rate between the elements
G: Number of sets of rectifier equipment
I_s: Maximum available current per element
K: 3 (for bridge connection)

The number of parallel elements is dependent on the current unbalance and the current unbalance is dependent on the inductance of the conductor for each circuit and on the waveform of the current. At the factory, the current unbalance is measured by using the short-circuit method. Because the waveform of the current during the factory test is different from that during actual operation at the rated current, the actual current unbalance cannot be measured at the factory. But, it is important to know the actual current unbalance for the purpose of maintaining equipment reliability for long-term operation. Actual current unbalance can be measured by the simulation circuit shown in Fig. 5. By comparing the test data at the factory and the simulation circuit data, we are able to estimate the actual current unbalance at the rated current.

Figure 5 shows an example of the equivalent circuit for simulating the parallel element peripheral circuitry. Because two groups of rectifiers are connected in an in-phase contra-polarity connection, two groups of rectifier have to be simulated at the same time. Also, mutual inductance between several conductors must be simulated in detail. The current through each path can be calculated using general-purpose circuit analysis software. Figure 6 is an example of the results of simulation, and shows the current waveforms of each current path under factory test conditions and during actual operation at the rated output and also shows

Fig.6 Example of the result of current unbalance simulation



the current unbalance at that time. This example simulation is for the case of 8 parallel elements. The horizontal axis of the graph shows the percentage of current flowing through each element, assuming that the average current is 100 %. Because the factory test is performed by the short-circuit method, the waveform of current flowing through each path will be almost sinusoidal. However, the waveform of the current during actual operation will be almost a square wave. Because the current unbalance is affected by the inductance, it may also be affected by the difference in waveforms of the current. From the results of the simulation, we can estimate the difference of the unbalance quantitatively.

4.3 Technology applied to high capacity diode elements and protection fuses

The high-withstand-voltage/high-current flat-type diode was developed to realize high capacity rectifier equipment. Table 2 lists the major characteristics of the developed diode and Fig. 7 shows its appearance.

The newly developed diode has a pole diameter of 80 mm, a pellet diameter of 89 mm, and its rated voltage and current are 4,500 V and 3,000 A, respectively. In addition, Fuji Electric also provides a series of diodes rated at 5,000 V. For the development of the new diode, several modern technologies were adopted. Below, some of those new technologies are introduced.

(1) Establishment of uniform diffusion technology

To ensure the uniform diffusion layer and surface density of large diameter silicone plates, we developed a custom silicone wafer in collaboration with a silicone wafer manufacturer. Utilizing this new silicone wafer, we succeeded in reducing the non-uniformity of diode characteristics to 50 % of the conventional type.

(2) Realization of higher voltage diode

To improve the withstand-voltage of the diode, it is essential that the voltage distribution in the diode be understood in order to determine its internal construction and insulation material. We simulated the voltage distribution in the diode and verified how the voltage distribution would be affected by changing the shape of internal parts. Based on the results of simulation, we designed the package internal construction for high reliability. In addition, tetra fluoride ethylene resin insulation parts made by a mechanical cutting process were replaced by polyimide resin molded insulation parts. This contributed to the reduced cost of the diode.

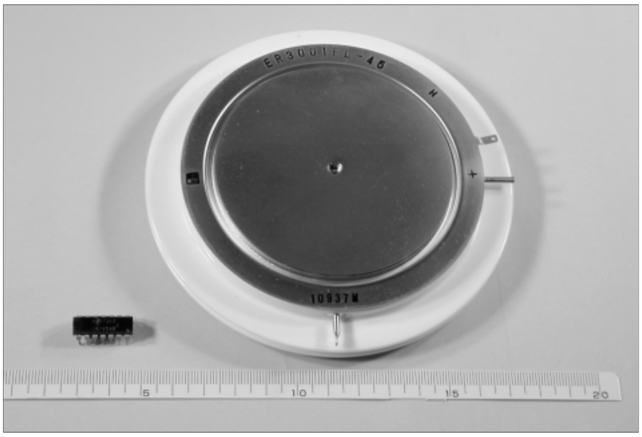
To select fuses for equipment and semiconductor protection, we need to know the exact rating of the surge forward current of diode. We verified the diode endurance by causing an actual current to flow with reverse voltage using the short-circuit generator (2,000 MVA) at our high-voltage and high-power testing laboratory.

With the increasing current ratings of diodes, higher current semiconductor protection fuses are

Table 2 Summary of the high-voltage high-current flat-type diode

Description	Symbol	Type of diode	Unit
		ER3001FL-45	
Repetitive reverse voltage	V_{RRM}	4,500	V
Non-repetitive reverse voltage	V_{RSM}	4,700	V
Mean forward current	$I_{F(AV)}$	3,000 (T_f = 80°C)	A
Surge forward current (with reverse voltage)	I_{FSM}	58,000	A
Junction temperature	T_j	– 40 to +160	°C
Forward voltage	V_{FM}	1.65	V
Reverse current	I_{RRM}	300	mA
Heat resistance	$R_{th(j-f)}$	0.013	k/W

Fig.7 New flat-type diode element (ER3001FL-45)



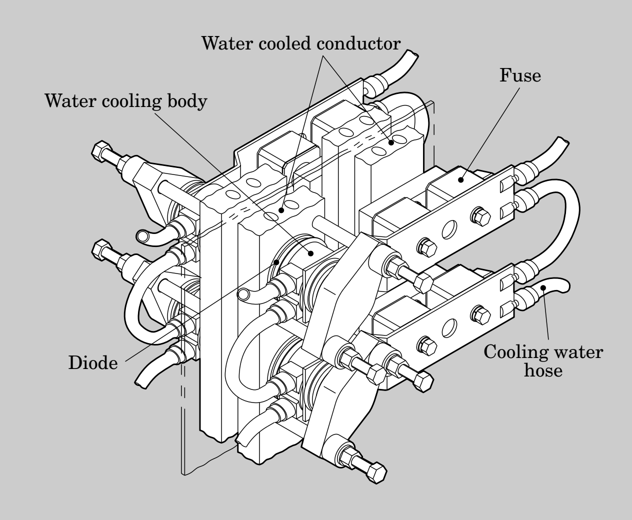


Fig.8 Sketch of the stack

required. Fuses used for MOZAL were rated at 4,000 A and 1,350 V. Those fuses were a twin-type consisting of two parallel fuses with external dimensions of 105 mm-by-105 mm and total weight of about 9 kg. Recently, a press-pack design in which a fuse and a diode are pressed together is adopted in some applications for high current diode/fuse combinations. In such a design, if the fuse is blown, both the fuse and diode must be disassembled, and thus this design is undesirable for maintenance work. Therefore, Fuji Electric decided to follow the traditional method of fuse and diode installation. However, we had to resolve a problem regarding the rigidity of the conductor that connects the fuse and diode.

When a fuse and diode are installed separately, a conductor to connect them is required. To limit the mechanical force applied to the fuse, the thickness of the conductor has to be limited. But, this means that current carrying capacity of the conductor would be limited and would be insufficient for a high current diode and fuse.

To solve this problem, we developed a conductor having a thickness of 5 mm and provided with a path for cooling water. Thus, a high-current connecting conductor with low rigidity was made possible. Fuses can be cooled from both sides by water and sufficient current capacity is achieved. Figure 8 shows a sketch of this stack.

5. Conclusion

The demand for aluminum is increasing from year to year. Therefore, investment in aluminum smelting equipment will definitely continue. Fuji Electric has supplied 34 units (including units currently being manufactured) of rectifier equipment to seven plants in the past five years. We will continue to make an effort to realize more economical and more reliable rectifier equipment, and hope to be able to contribute to the aluminum industry.

Custom-Waveform Power Supply for Metal Surface Treatment

Tetsuhiro Maruo

1. Introduction

Thyristor rectifiers have been used conventionally for metal surface treatments such as the color anodizing of aluminum window sashes and electroplating of various kinds of metals. However, such treatments using direct current from thyristor rectifiers have limitations on the extent to which they can improve yield rate, color tone, uniform coloring, etc. Meanwhile, due to recent technological progress in power electronics, it has become possible to generate specialized waveforms unobtainable by thyristor rectifiers and to pursue conditions optimum for each process according to the waveform of the power supply.

In this paper, we introduce principles of the color anodizing of aluminum window sashes and examples of power supplies delivered by Fuji Electric for that application. Moreover, as an example of the expanding scope of applications, the copper plating of printed circuit boards is introduced.

Table 1 General specifications for custom-waveform power supply

Item	Description
Input	Three phase, 50/60 Hz, 200 V, 440 V, 3.3 kV, 6.6 kV (able to correspond to requirements)
Output range	Current : up to 10 kA (peak) Voltage : up to 300 V (peak)
Control method	Automatic current control, automatic voltage control, automatic power control
Accuracy of control	Standard : ±2 % (non-standard unit can be produced)
Specification for inverter	Element used : IGBT
Cooling system	Transformer : ONAN or AN Diode rectifier : WF or AF Inverter : WF or AF
Examples of approximate outer dimensions	80 V, 300 A unit : 800 width×1,000 depth ×1,950 height (in mm) 50 V, 4.5 kA unit : 5,200 width×2,000 depth ×2,350 height (in mm)

2. General Specifications for Custom-Waveform Power Supply

A custom-waveform power supply can generate specialized waveforms suited for each process and Fuji Electric has a proven track record of delivering custom-waveform power supplies mainly for the color anodizing of aluminum window sashes. General specifications, a simplified diagram of the main circuit and example waveforms of a custom-waveform power supply are given in Table 1, Fig. 1 and Fig. 2, respectively. This power supply is an inverter that uses single-phase pulse width modulation (PWM). High frequency, high capacity operation is supported through the use of insulated gate bipolar transistors (IGBTs). Although the output waveform may be set arbitrarily, in many cases, the waveform is fixed to a suitable degree for use in actual production.

Fig.1 Simplified diagram of main circuit of a custom-waveform power supply

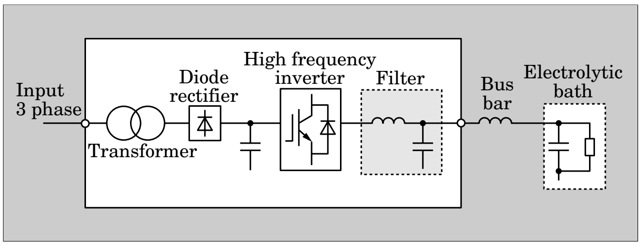
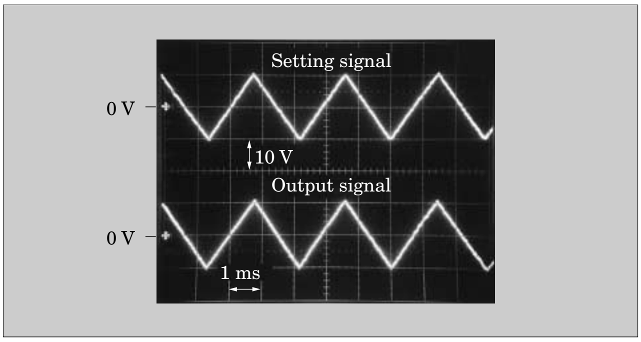


Fig.2 Example of waveform of output voltage



3. Power Supply for Color Anodizing of Aluminum Sashes

3.1 Principles and process of aluminum surface color anodizing

As shown in Fig. 3, the surface treatment of aluminum consists of anodic oxidation treatment to form oxide film on the aluminum surface, followed by color anodizing.

In the first process of anodic oxidation, oxide film is formed on the surface by flowing a DC current with the aluminum material as the positive pole. The chemical reactions are given by the following equations.

$Al \rightarrow Al^{3+} + 3e$, $H_2O \rightarrow O^{2-} + 2H^+$

$2Al^{3+} + 3O^{2-} \rightarrow Al_2O_3$ (aluminum oxide)

As shown in Fig. 4, the oxide film consists of a nonporous film called the barrier layer and a porous oxide film called the porous layer. The shape of pores in the porous layer can be altered according to the type of solution and electrolytic conditions (waveform of the power supply etc.). Recently, development of special functional applications (optical, photoelectric, magnetic etc.) using this porous layer is being pursued.

In the color anodizing process, current is flowed with aluminum as the negative pole and metal is electro-deposited in pores in this porous layer as below:

$M^{n+} + ne^- \rightarrow M$ (M^{n+}: metal ion)

The processing sequence of electro-deposition is shown in Fig. 3.

Color tone of the aluminum material subjected to color anodizing will change according to the degree of deposition in the pores. Although the mechanism in which metal is electro-deposited by the flow of electric current through the barrier layer, an insulator material, is not completely understood, it is known that yield rate, color tone and color uniformity can be controlled by using different waveforms such as DC, AC or specialized waveforms. Those methods of control represent the expertise of the manufacturer.

The metal to deposit is usually nickel and the colors obtained have been mostly blackish brown. Recently, however, it has become possible to achieve a grayish-blue color by a method known as third electrolytic coloring. In this method, as tolerances of the required electrolytic conditions for coloring are narrow, the role of the power supply becomes more important and consequently requirements for the waveform setting function and accuracy of the output waveform are more stringent.

3.2 Custom-waveform power supply

In the color anodizing of aluminum sashes, the type and temperature of electrolytic solution, and shape and arrangement of electrodes influence the quality of coloring. Electric current and voltage that are output by the power supply are also important factors. By accurately controlling the current and voltage waveforms, improvement in the yield rate and coloring of specialized colors is realized.

In this paper, a power supply unit recently delivered to Toyama Light Metal Industry Co., Ltd. is described as an example. Its specifications, appearance and simplified circuit diagram of the unit are given in Table 2, Fig. 5 and Fig. 6, respectively.

Output voltage waveforms consist of DC waveforms and AC square waves, having asymmetric positive and negative components with soft start. Color anodizing of brownish colors is performed by using DC output with soft start and that of blackish colors is performed by using a square wave with soft start. Further, a similar power supply unit delivered to the Pilot Center uses an AC square wave to perform grayish-blue color anodizing by the third electrolytic coloring method, in addition to brownish and blackish coloring. In the DC electrolytic coloring method to obtain brownish colors, error in output voltage during the soft start has a significantly harmful influence on color evenness. Also, in the third electrolytic coloring process in which a square wave AC voltage is applied

Fig.3 Typical processing sequence of aluminum surface treatment

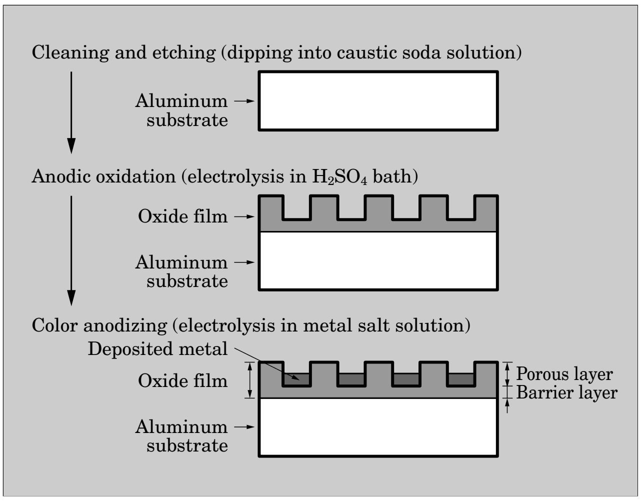


Fig.4 Surface condition of aluminum

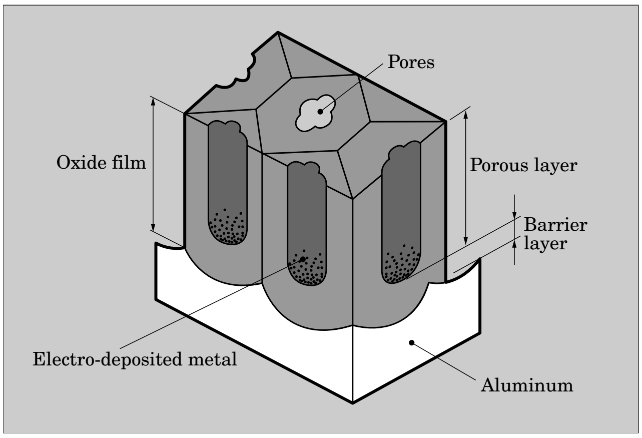


Table 2 Specifications of a ±50 V, 10 kA unit delivered to Toyama Light Metal Industry Co., Ltd.

Item	Description
Input	Three phase, 60 Hz, 6.6 kV
Output	DC: 50 V, 10 kA
	AC: 50 V (peak), 10 kA (peak)
Output waveform	DC and square wave Specification for square wave : frequency: 10 to 100 Hz, ratio of current duration positive/negative : 0.1 to 10
Control method	Automatic voltage control
Accuracy of control	±0.2 %
Main circuit components	Step-down transformer, diode rectifier, inverter
Specification for inverter	Composed of 6 IGBTs in parallel/stack×28 stacks Type of IGBT : 2MBI400N-060 Carrier frequency : 7.5 kHz
Cooling system	Transformer : ONAN Diode rectifier : WF Inverter : WF
External dimensions	5,500 width×1,960 depth ×3,200 height (in mm)
Mass	9,400 kg

to aluminum materials to obtain grayish-green colors, a highly accurate value is required for peak amperage of the AC square wave, over the entire range from low voltage to rated voltage.

In order to achieve the requirement for highly accurate control, the following items were taken into consideration to obtain an accuracy of 0.2 %.

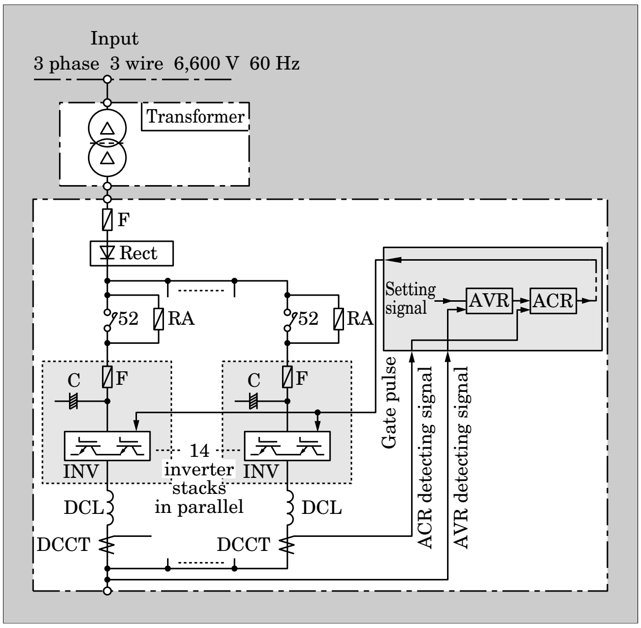
(1) Adoption of components with low drift for use in the controller
(2) Adoption of output voltage detector with high accuracy
(3) Adoption of isolation amplifier for setting command signals with high accuracy
(4) Elimination of noise infiltration into control line

On the other hand, high-speed response is required of the square wave rise-time of the output voltage. This is because a delay in rise-time becomes dead time during an AC square wave color anodizing process. By accelerating the rise-time, electrolytic deposition time can be shortened and productivity improved.

In applications for coloring aluminum sashes, the capacitance is largely due to the load, that is, the conditions of oxide film on the aluminum sash surface (thickness of barrier layer and structure of porous layer), the type of electrolytic solution and the arrangement of electrodes. Moreover, inductance due to the bus bar connecting the power supply to the load is significant because of the high current that flows there. Since the equivalent circuit, as shown in Fig. 1, contains capacitance and inductance in the load side, it is difficult to achieve control that is both high-speed and stable. Furthermore, capacitance is not constant, but varies largely depending on the quantity of aluminum material, stage of current flow (beginning or final) and waveform (DC or square wave AC). Accordingly, the magnitude of these variations should be taken into account by the control.

Fig.5 Appearance of a ±50 V, 10 kA unit delivered to Toyama Light Metal Industry Co., Ltd.

Fig.6 Simplified diagram of main circuit of a ±50 V, 10 kA unit delivered to Toyama Light Metal Industry Co., Ltd.



To resolve these problems, high-speed response is improved by adopting a design to give sufficient voltage allowance. And to improve stability, automatic voltage control with an automatic current control minor loop is provided and is used together with current limit control to suppress current overshoot at the rising edge of the waveform. Furthermore, it is possible to changeover control constants according to whether the operation is DC or AC.

To handle the high current output of 10 kA, the inverter part of the unit is configured as a single-phase inverter consisting of 28 water-cooled stacks, 14 in parallel, with each 600 V and 400 A rated unit consisting of 6 IGBT modules in parallel with upper and lower arms. Figure 7 shows the appearance of one of

Fig.7 Appearance of an IGBT inverter stack

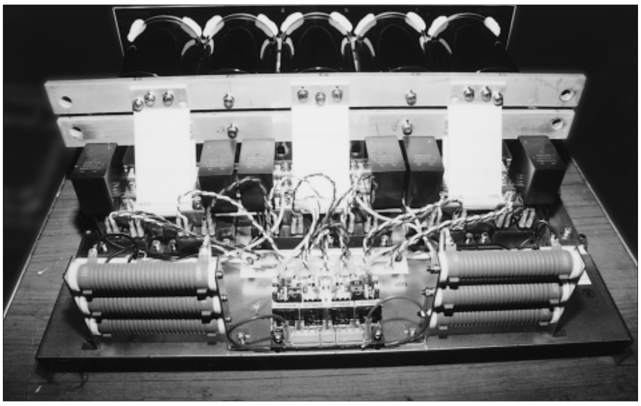
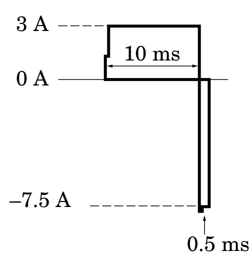


Table 3 Experimental conditions

Area to be electroplated	673.3 cm^2
Duration of electroplating	60 min.
Pulsed waveform (Amperage is per 100 cm^2)	10.5 ms/cycle 

the stacks. The current flow among the stacks in this multi-parallel connection is made uniform by performing automatic current control for each inverter unit. Additionally, a DC reactor is added to the output of each inverter unit to suppress cross-current among inverter units. Also, the bus bar inverter unit is positioned so that magnetic flux can be canceled to prevent local heating in the unit.

To optimize onsite maneuverability and monitoring ease, load side (aluminum sash) expertise is incorporated into the control hardware and software. This directly leads to improved productivity. By utilizing this unit, the inferiority rate of color difference is reduced to 1/3 compared to that of the former system using a thyristor rectifier and induction voltage regulator.

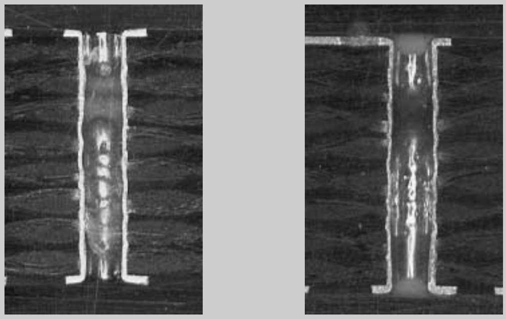
4. Custom Wave-Form Power Supply for Copper Plating of Printed Circuit Boards

In addition to use for the surface treatment of aluminum, this power supply can be applied to various kinds of electroplating where specialized waveforms are useful. The application of a custom waveform power supply for the copper electroplating of printed circuit boards is described below.

4.1 Process of copper plating printed circuit boards and recent trends

In the process of copper plating circuit boards, electroplating is performed after electroless plating. Until now, a rectifier has been used for the process of electroplating. Recently, as printed circuit boards become more dense, plating technology for manufacturing and processing minute parts such as minute through-holes, minivias, fine bumps, built-up circuit boards, etc., has become more important. However, DC electroplating has the problem of non-uniform film. That is, at corners and projecting points, plating thickness increases due to the electric field concentrated there, while on the other hand, plating thickness is reduced in areas where the electric field is weak such as the middle of through-holes. These problems must be resolved for the sake of future progress of fine processing.

Fig.8 Photos showing cross-section of through-hole



(a) Electroplating using special waveform (Throwing power : 105 %)

(b) Electroplating using DC (Throwing power : 49 %)

4.2 Results of applying the custom-waveform power supply

The results of applying a specialized current waveform generated by a custom-waveform power supply are described below. The plating thickness distribution on the interior surface of a through-hole deposited by a square wave output current is compared to that from a DC current.

The experimental conditions are given in Table 3. The output current waveform is a square wave having asymmetric positive and negative components as shown in this Table. The waveform on the positive side deposits the metal plating, as in the case of usual DC electroplating. The short term pulsed wave on the negative side re-dissolves into the electrolytic solution the electroplating deposited on areas such as the edges of through-holes, where metal is usually excessively deposited and also equalizes ion concentrations near the surface of the aluminum. Thus, the combination of positive and negative waveforms aims to achieve uniform plating thickness.

The command signal for a square wave with asymmetric positive and negative components is somewhat compensated to suppress overshoot of the output

Table 4 Comparison of physical properties of through-hole

Item \ Waveform		Electroplating using pulsed waveform	Electroplating using DC
Expansion (%)	Sample 1	27.3	22.0
	Sample 2	27.0	21.4
	Average	27.2	21.7
Tension (kN/cm^2)	Sample 1	38	35.9
	Sample 2	37.8	36.2
	Average	37.9	36.1
Throwing power (%)	Sample 1	105	49
	Sample 2	104	50
	Average	104.5	49.5
Heat cycle (number of cycles)		20	20

Expansion : Evaluation for flexibility. (The larger, the better)
Tension : Evaluation for peeling resistance of wiring pattern. (The larger, the better)
Throwing power : Ratio of plating thickness at entrance of through-hole to that at middle of through-hole. (The nearer to 100 %, the better)
Heat cycle : The number of heat cycles before occurrence of an abnormality. (The more, the better)

current and to realize rapid rise-time. Automatic current control is used as the control method to output the current within a definite time.

The distribution of plating thickness on the interior surface of a through-hole is as shown in Fig. 8. Comparison with DC plating is given Table 4. The distribution of plating thickness (throwing power) is remarkably improved compared with that of DC electroplating.

Other physical properties are also better than or equal to those of DC electroplating.

5. Conclusion

In this paper, the color anodizing of aluminum sashes and copper plating of printed circuit boards are introduced as example applications of the custom-waveform power supply for metal surface treatment. As for aluminum, special functional anodic oxide film, anodizing for special colors, etc., are possible applications. Further advantages are expected in applications of surface treating other metals such as magnesium, where the range of application is expected to grow in the future. Utilizing these advantages, Fuji Electric intends to develop further applications for this type of power supply.

MOSFET Inverter Type High-Frequency Power Supply

Toshie Miura
Kiyokazu Nakamura

1. Introduction

Induction heating is a typical application field for high-frequency power supplies whose operating frequencies range from one to several hundred kilohertz. Induction heating applies an alternating magnetic field generated from the current flow in a coil to the conductive matter to be heated. This induces eddy currents on the conductive matter, those currents generate joule loss due to the matter's resistance and thus cause the matter to be heated. Steel sheet heating, hardening, and seam welding are some examples of the industrial applications of induction heating, and still now, there is much demand for the high-frequency power supplies used in these examples.

In the past, vacuum tube oscillators were used for the high-frequency power supplies from one to several hundreds of kilohertz. In recent years, with the emergence of inverters using MOSFET (metal-oxide-semiconductor field effect transistor) devices suitable for high-speed switching, the volume of power supplies has been reduced to about 1/4, resulting in space savings. Also, efficiency has significantly increased to 96 % (during rated operation) from about 75 % previously, resulting in enhanced energy savings and productivity.

Fuji Electric has previously commercialized flat-packaged 500 V, 240 A MOSFETs and high-frequency power supplies using 20 to 100 kW stacks which incorporated those MOSFETs.

This paper will report the newly developed and commercialized flat-packaged large-power 500 V, 500 A MOSFET and the 125 kW stack containing those MOSFETs, both of which were applied to a 1,000 kW, 150 kHz high-frequency power supply for steel sheet heating in a steel production process.

In addition, recent seam welding power supplies, application of high-frequency power supply for plasma heating, and surface treatment for metalizing film using high-frequency discharge, will also be introduced.

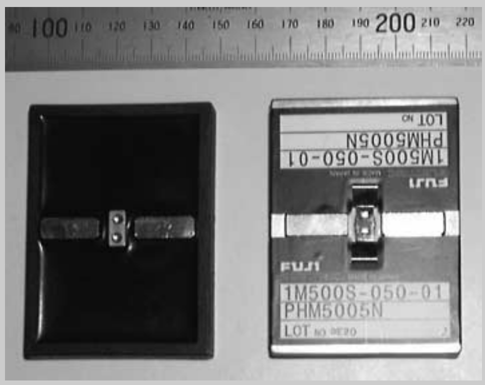
2. 1,000 kW, 150 kHz High-Frequency Power Supply

2.1 Large-power flat-packaged 500 V, 500 A MOSFET (1)

Figure 1 shows external views of an existent 500 V, 240 A MOSFET and large-power 500 V, 500 A MOSFET, and Table 1 lists their specifications. As with the existent MOSFET, the large-power MOSFET has Fuji Electric's unique low-inductance-type slim shape suitable for high-frequency use. Both of the MOSFETs have the same external dimensions. But, compared with the existent MOSFET, the large-power MOSFET's performance is extensively improved.

Advantages of the large-power flat-packaged MOSFET are as described below.

Fig.1 External views of existent and large-power MOSFETs



Existent MOSFET (500 V, 240 A) Large-power MOSFET (500 V, 500 A)

Table 1 Specifications of existent and large-power MOSFETs

Item \ Classification	Existent MOSFET	Large-power MOSFET
Rated current	240 A	500 A
Rated voltage	500 V	
On-resistance ratio	1	1/2
Thermal resistance ratio (between channel and case)	1	1/3
External dimensions	13 thick × 71 long × 52 wide (mm)	

(1) Double the rated current

The MOSFET chip has been redesigned to reduce its on-resistance to 1/2 and the thermal resistance between the chip channel and the case to 1/3 of prior values. This allows the on-state loss to be reduced and the cooling performance to be improved. As a result, the rated current is increased by more than twice, from 240 A to 500 A, despite having the same dimensions.

(2) Low inductance

The structure of the MOSFET device is changed to realize reduced wiring inductance, an important factor in high-frequency use. This change is implemented in consideration of applications up to 500 kHz, the same as the existent MOSFET.

(3) Backward compatibility with conventional components

Because of the external dimensions are maintained the same as the existent MOSFET, conventional stack components can be used for the 125 kW stacks. This makes it possible to cut the lead-time and reduce the cost for all 125 kW stacks.

2.2 125 kW stack

Figure 2 shows an external view of the stack with a unit capacity of 125 kW, and Table 2 lists specifications of an existent 100 kW stack and of the 125 kW stack. The 125 kW stack inherits its shape from the existent 100 kW stack, but its cooling structure, gate drive unit (GDU), intermediate DC capacitor, hose connectors for cooling water, and the like are substantially changed.

Advantages of the stack are as described below:

(1) 25 % increase in output power

The design to reduce thermal resistance at cooling parts of the MOSFET devices is implemented in the stack, as well as within the device itself. As a result, the thermal resistance per MOSFET device between the channel and the cooling water is decreased to 1/3, compared with the existent 100 kW stack. This increases the output current and increases the output power by 25 % despite a reduction in the number of parallel devices per arm.

(2) Reduction in size and weight

Changing the GDU mounting locations, the hose connectors, and redesigning the stack interior such as high-density mounting of the intermediate DC capacitor, has achieved the following reduction in size and weight. Compared with the existent 100 kW stack, dimensions have been reduced by 10 mm in width and by 100 mm in depth, and thus to 80 % in volume. Mass has been decreased to 60 %, from 56 kg to 34 kg.

(3) Improved reliability

The stack structure is designed to reduce its inductance, resulting in less switching oscillation of the stack together with the MOSFET device. This allows the noise and surge levels to be decreased and the device characteristics to be improved.

2.3 1,000 kW, 150 kHz inverter

Figure 3 shows an external view of a 1,000 kW, 150 kHz inverter panel. The panel contains eight of the newly developed 125 kW stacks connected in parallel and has an output capacity of 1,000 kW. This is used for a steel sheet heating power supply.

Figure 4 illustrates a schematic diagram of the 1,000 kW, 150 kHz high-frequency power supply main circuit. The rectifier uses a diode bridge; each 125 kW stack in the high-frequency output section has a voltage source type full-bridge connection with a single phase output, and the body diode of the MOSFET device is used as a free wheeling diode of the voltage source inverter.Each stack output is connected to a high-frequency current transformer (HFCT) that serves both as a current sensor and a current balancer for each stack.

To reduce the load impedance and to improve the load power factor, a series or parallel resonance circuit

Fig.2 External view of 125 kW stack

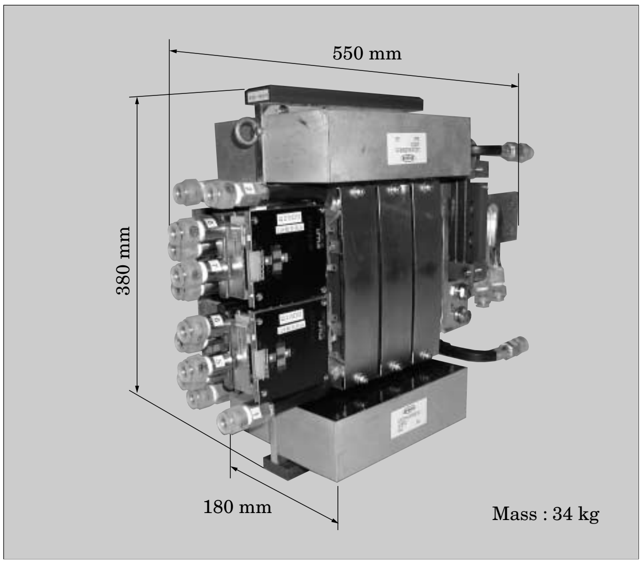


Table 2 Specifications of existent 100 kW stack and 125 kW stack

Item \ Classification		Existent 100 kW stack	125 kW stack
Input (three phase)		220 V, 50/60 Hz	
Rated output (single phase)	Power	100 kW	125 kW
	Voltage	300 $V_{p\text{-}p}$ (square wave)	
	Frequency	up to 500 kHz	up to 150 kHz
Cooling	Method	Water cooling (ionized water circulating system)	
	Thermal resistance ratio per device (between channel and cooling water)	1	1/3
Dimensions [width × height × depth] (mm) (Volume ratio)		190 × 380 × 650 (100 %)	180 × 380 × 550 (80 %)
Mass (Ratio)		56 kg (100 %)	34 kg (60 %)

Fig.3 External view of 1,000 kW, 150 kHz inverter panel

Fig.4 Schematic diagram of 1,000 kW, 150 kHz high-frequency power supply main circuit

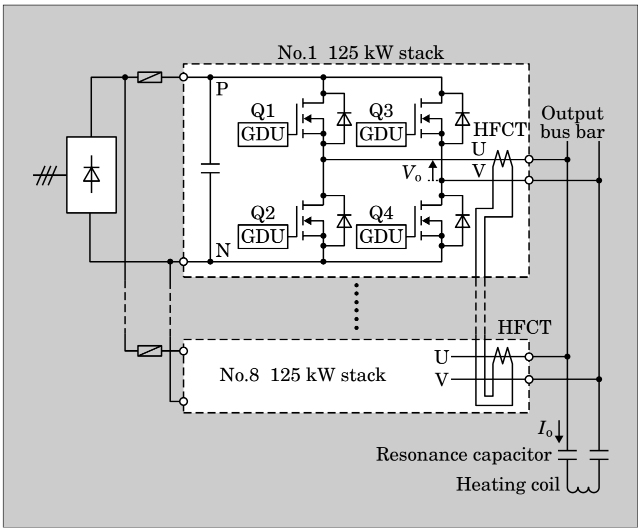


Fig.5 Example of each stack's current waveform, both in and out of operation

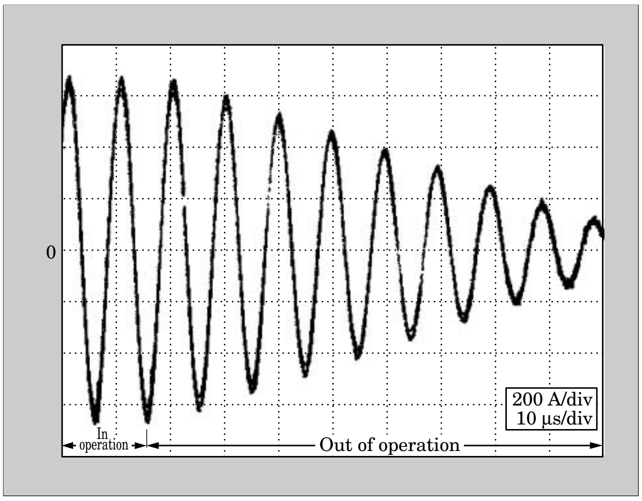
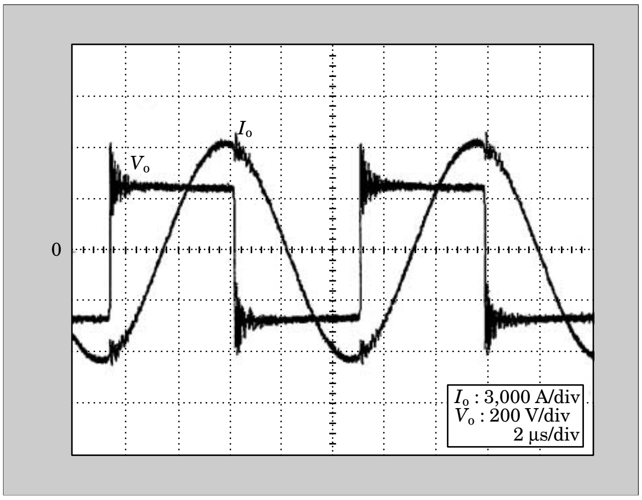


Fig.6 Waveform examples of 1,000 kW, 150 kHz inverter's output voltage and current



is used in load circuits where a high-frequency large current flows. For MOSFET inverter type high-frequency power supplies, Fuji Electric generally uses series resonance circuits in which a resonance capacitor of the load circuit is connect in series to a heating coil.

Figure 5 shows examples of each stack's current waveform, both in and out of operation. The stack currents are each superimposed over one another to appear as a single waveform. It can be verified that each stack current is balanced with the current balancing function of the HFCT.

Figure 6 shows waveform examples of a 1,000 kW, 150 kHz inverter's output voltage and current. The voltage waveform with low surge voltages and rapid oscillation attenuation and the current waveform with little distortion are both favorable and are obtained due to the reduced inductance of the MOSFET devices and the stacks.

Fuji Electric is further studying how to enhance the output capacity, and has capability to build inverters up to 2,000 kW and 200 kHz by combining multiple configurations of the above-mentioned circuits.

3. A Recent MOSFET Inverter Type High-Frequency Power Supply and Examples of its Application

Table 3 shows the standard lineup and specifications of existing MOSFET inverters.

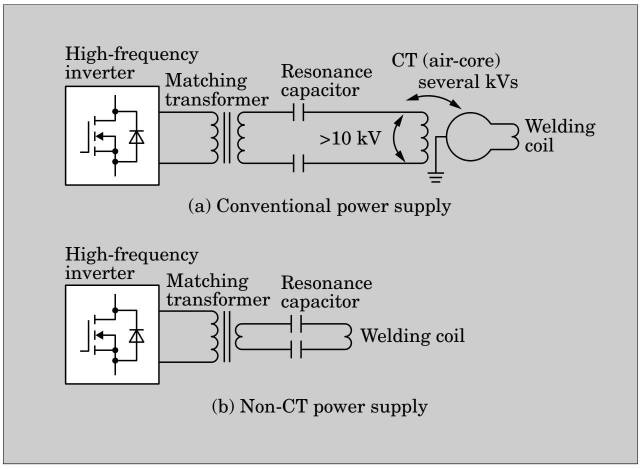
3.1 Non-CT power supply for seam welding

Because a welding coil requires a large current, as shown in Fig. 7 (a), a current transformer (CT) is connected behind the resonance capacitors in the conventional power supply for seam welding. Recently, the non-CT power supply, in which the CT has been

Table 3 Standard lineup and specifications of MOSFET inverter

Item		Specification		
Input (three phase)		220 V±5 % (insulated source)		
Output (single phase)	Inverter system	Voltage source inverter		
	Load circuit	Series resonance circuit		
	Power	20 kW	100 kW	500 kW
		30 kW	200 kW	600 kW
		50 kW	300 kW	800 kW
		75 kW	400 kW	1,000 kW
	Voltage	±150 $V_{p\text{-}p}$ (square wave)	±300 $V_{p\text{-}p}$ (square wave)	
	Frequency	10 to 500 kHz		
	Control system	Power control		
	Adjusting range	10 to 100 %		
Cooling	System	Water cooling (ionized water circulating system)		
	Cooling water temperature	5 to 35°C		

Fig.7 Conventional and non-CT power supplies for seam welding



omitted as shown in Fig. 7 (b), has become typical. Figure 8 shows an external view of this compact power supply.

Advantages of the non-CT power supply are as described below:

(1) Low withstand voltage design and easy maintenance

Insulation having a high withstand voltage rating is unnecessary since no section in the primary side of the CT has a high voltage of more than 10 kV. Moreover, the power supply seldom causes a dielectric breakdown and is easy to maintain. Surge voltages during a dielectric breakdown do not adversely effect other equipment.

(2) Improved efficiency and reduced size

Because there is no use of a lossy air-core CT (having a large power loss of about 30 %), it is possible to improve the efficiency by about 20 % and to reduce the size.

Fig.8 External view of non-CT power supply for seam welding

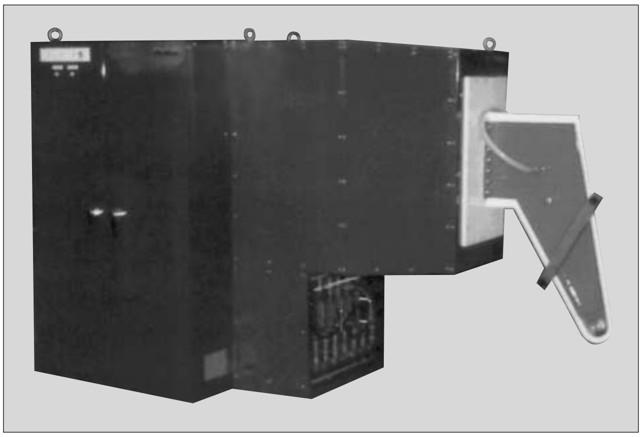
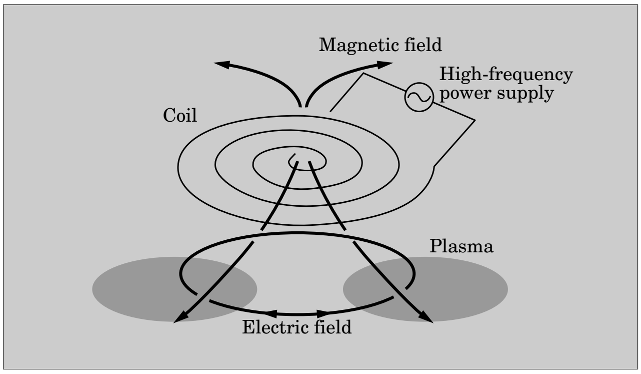


Fig.9 Principle of plasma generation in ICP spent resin volume reduction system



3.2 ICP spent resin volume reduction system

Figure 9 illustrates the principle of plasma generation in the ICP (Inductively Coupled Plasma) spent resin volume reduction system. An inverter with an output frequency of 450 kHz is used for the power supply. The current flow in a coil gives rise to a magnetic field and an interlinked electric field, which generates plasma. Figure 10 shows an external view of the plasma generating section (during plasma generation).

This system decomposes radioactive ion-exchange resin, which has been used in water-based cleaning systems at atomic power-plants, through oxidation using oxygen heated and activated by plasma, and thus reduces its volume. A large volume reduction ratio of 20:1 is possible in this system. The decomposed matter is treated as waste and then buried underground. (This system is currently undergoing verifying tests.)

3.3 Surface treatment for metalizing films

The surface of a metalizing film must be roughened by silent discharge treatment to enhance metalizing. Figure 11 is a diagram showing the principle of surface treatment for a metalizing film. Fuji Electric's high-frequency power supply is also used in this

Fig.10 External view of plasma generating section (during plasma generation)

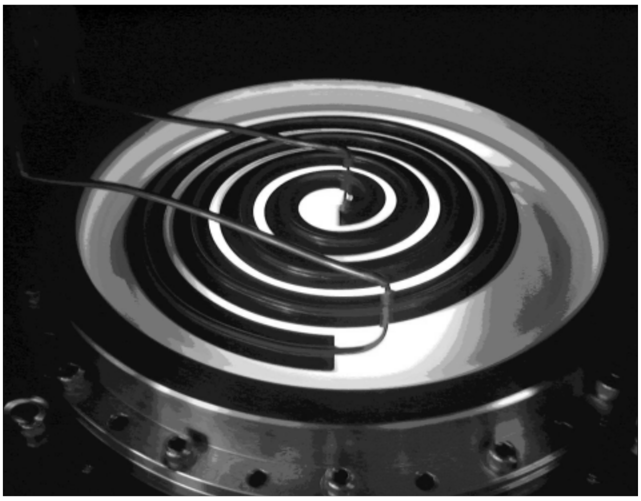
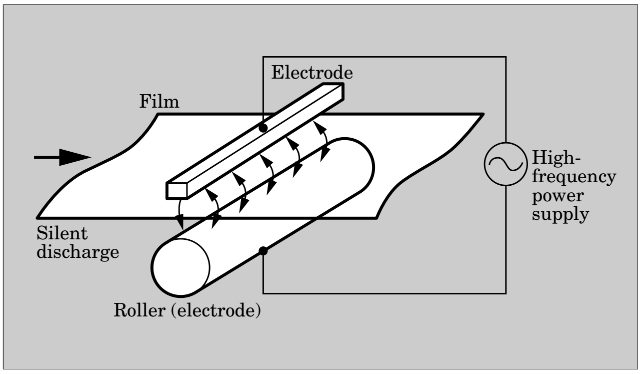


Fig.11 Principle of surface treatment for metalizing film



system, wherein electrodes are placed at both sides of a film that is moved by a roller, and the power supply generates silent discharges between the electrodes.

The surface-treated plastic film with metalized zinc or aluminum is used in capacitor electrodes and food packaging materials such as for snacks, as a high-performance film providing both the air-tightness of aluminum foil and strength of plastic.

This surface treatment is also utilized to enhance the ease of ink printing on films.

4. Conclusion

Fuji Electric has previously developed high-frequency power supplies with MOSFET devices from several tens of kilohertz to five hundred kilohertz and has commercialized them for various application fields. Fuji Electric is now promoting the development and production of large-power flat-packaged 500 V, 500 A MOSFETs, the 125 kW stacks containing them, the applicability of new type high-frequency power supply systems, and expansion of the high-frequency power supply application range including environmental use.

In the future, Fuji Electric will make every effort to supply products with advanced performance and higher reliability by improving the 125 kW stacks to achieve higher output frequencies and to support a wider range of loads. In addition, Fuji Electric hopes to contribute to the progress of high frequency circuits and their application fields through further development of power supplies with larger power and higher output frequency.

Reference

(1) Miura, T. et al. Prototype of 500 kHz, 250 kW MOSFET Stack for High Frequency Power Supply. IPEC-Tokyo 2000, vol. 2, 2000, p. 899-904.

Water Vaporization-Cooling Silicon Rectifiers for Traction Substations

Shingo Tsuda
Toyotada Nakamura
Shuji Odaki

1. Introduction

The 21st century is the age of ecology. Therefore the theme of environmental conservation for the earth is an important theme concerning our daily life.

Electrical railway transportation is extremely high energy efficiency in the fields of transportation for travelers and freight, and moreover is the transportation mode having the lowest volume of carbon dioxide exhaust, which is directly linked to global warming. About 2,500 silicon rectifier units for substations have been operating in Japan. These silicon rectifier units play an important role in the DC-powered urban railway substation, and the installed base has a total capacity of about 8,000 MW. For the last 20 years, Freon vaporization-cooling has been utilized as the standard cooling system in these units. Although the Freon vaporization-cooling system has many advantages, at the Montreal Congress in 1987, restrictions were imposed on the production of chlorofluorocarbon (CFC), a specific Freon that had been used as the original cooling media, because its chlorine component is harmful to the ozone layer. Therefore per-fluorocarbon (PFC), which has no chlorine component, was subsequently adopted instead of CFC after the Montreal Congress. However, as a result of the Kyoto Congress in 1997, PFC together with SF_6 gas is headed toward regulation as a substance that causes global warming.

Fig.1 External view of water vaporization-cooling silicon rectifier

For the new problem of changing the cooling media of the silicon rectifier, Fuji Electric has successfully manufactured water vaporization-cooling silicon rectifiers and begun to deliver them. These rectifiers use pure water as the cooling media and do not burden the earth's environment. The authors introduce here the new type of silicon rectifier as follows. Its external appearance is shown in Fig. 1.

2. Transition of Silicon Rectifiers for Traction Substations

Electrical railway transportation has a very high public profile, and consequently its power supply equipment is required to have high reliability, long life, reduced maintenance, high efficiency, be non-flammable, and have small size and light weight, and adaptable to the environment. Fuji Electric has delivered a total of 800 units of silicon rectifiers so far, having delivered the first forced air-cooling type in 1960, and the total capacity of this installed base is over 2,500 MW (including foreign markets). Over time, along with the development of high capacity diodes, cooling technology has also undergone dramatic progress and the performance, quality and maintenance of the cooling system has also been enhanced. Figure 2 shows the transition of the cooling system, cooling media and capacity of silicon diode.

2.1 Cooling system and cooling media

The cooling system has changed from the early forced air-cooling type to the oil-immersed type, which is based on the high reliability of diodes and immerses all components in oil. Together with the realization of high capacity diodes, the cooling system has progressed from the heat conducting type, based on the flow of air and oil, to the vaporization-condensation-cooling (vaporization-cooling) type which has some

Fig.2 Transition of cooling method, cooling media and capacity of silicon diode

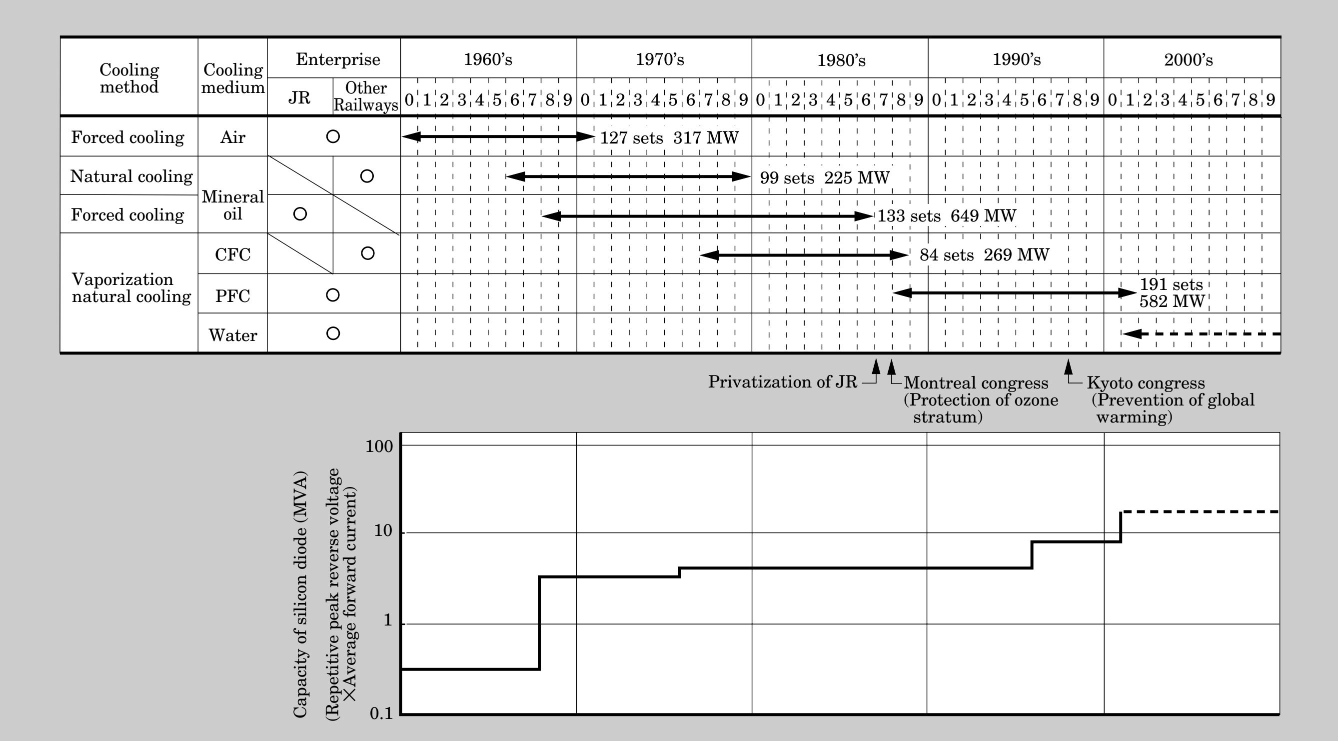


Fig.3 Large-capacity silicon diode

Type	ER3211FL-50
Repetitive peak reverse voltage (V_{RRM})	5,000 V
Non-repetitive peak reverse voltage (V_{RSM})	5,500 V
Average forward current ($I_{F(AV)}$)	3,200 A
Surge current (50 Hz, 1 cycle) (I_{FSM})	58,000 A
Diameter	125 mm

advantages such as effective cooling, non-flammability, reduced maintenance, and smaller size and lighter weight.

The cooling media have changed from air to mineral oil and then to CFC, a synthetic substance with high heat conducting characteristics in vaporized and condensed states and with high electrical insulating ability. Following CFC, the cooling media were changed to PFC, and now has finally returned to a natural substance, water.

2.2 Silicon diode

The silicon diode has been improved in voltage and capacity from an initial-stage 1,000 V, 200 A class stud-type, to a 3,000 V, 3,200 A flat packaged type, and now to a 5,000 V, 3,200 A flat packaged type diode, the highest level in Japan. This diode was developed for the new type rectifier based on our long experience and proprietary power diode technology. The external view and ratings of this large-capacity silicon diode are shown in Fig. 3.

3. New Type Silicon Rectifier

3.1 Concept and special features of the product

Figure 4 shows the concepts and special features of the new type silicon rectifier. The special features and means in which they are achieved are described below:

(1) Prevention of global warming

Natural water is used as cooling media and therefore this rectifier is unrelated to the problem of global warming. Further, the utilization of a 5,000 V diode enables the 1,500 V DC silicon rectifier to be constructed with a single series diode connection. Consequently, the number of parts and power loss could be reduced greatly. As a result, compared to the conventional vaporization-cooling system, generated loss was decreased by 40 % (6,000 kW, comparison to a Fuji Electric product), and this decrease in loss also contributes to the prevention of global warming.

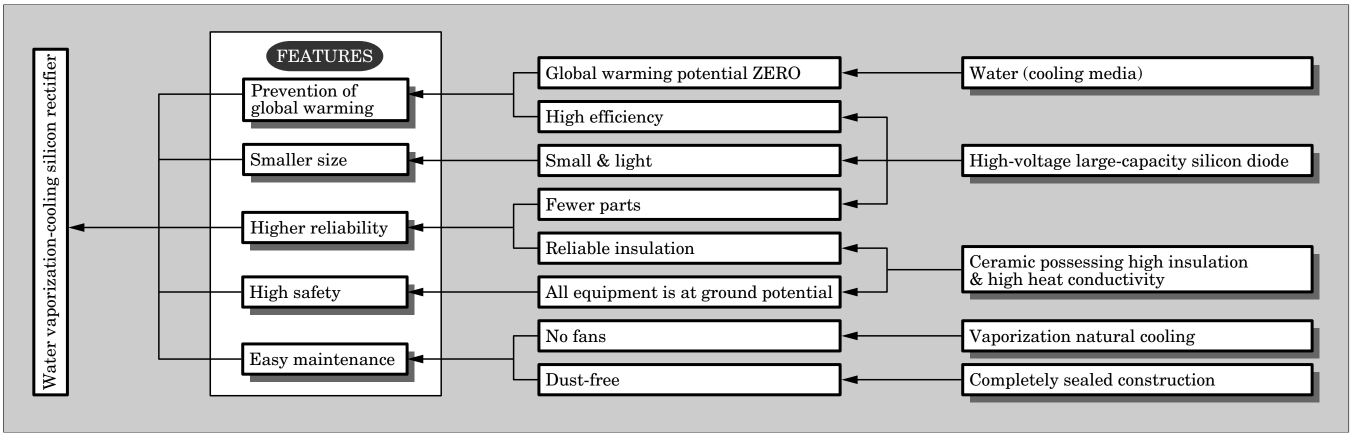
(2) Smaller size

The large reduction in the number of parts contributes to the smaller size and lighter weight. Consequently, compared with our conventional model type, the volume and required installation space were reduced by 40 % and 30 % , respectively.

(3) High safety

Since CFC and PFC have insulating properties, by immersing the rectifying stack composed of the silicon diode, electrodes and heat sink in the cooling media, the enclosure can be set to ground potential. However, since the water is electrically conductive, some insula-

Fig.4 Concepts and special features of the new type silicon rectifier



tion shall be necessary. To accomplish this purpose, a ceramic plate with high mechanical strength, high heat conductivity and high isolating ability is placed between the silicon diode or main conductor and heat sink to establish electrical isolation. In this manner, all the equipment, including the condenser, can be set to ground potential and high reliability can be achieved.

(4) Higher reliability and easy maintenance

This rectifier realizes extremely higher reliability through assuring sufficient insulating ability by means of decreasing the number of parts and using a ceramic insulating plate.

Furthermore, this rectifier utilizes a new system in which the snubber and resister for surge-absorber are cooled by vaporization, in the same manner as the silicon diode. The purpose of this system is to realize a completely enclosed construction specialized for compactness and dust proof ability. This system prevents contamination due to dust collection and assures long-term reliability, easy maintenance and cleaning. Of course, it contains no fans as in the convention type.

3.2 Selection of cooling media

Assuming that new cooling media will preserve and inherit many advantages which the conventional cooling system possessed, in selecting new cooling media, Fuji Electric conducted much research and made many assumptions based on the following requirements.

(1) No adverse effect on the environment

The new media shall neither destroy the ozone stratum nor contribute to global warming and endocrine disrupting chemicals. Consequently it can be used hereafter without anxiety.

(2) The new media shall operate in an adequate temperature range and have excellent cooling characteristics.

In order to cool the silicon diode effectively, it is expected that vaporization and condensation of the media be performed at a suitable temperature range (below 95°C). Also, it is desired that the cooling media have a high latent heat of vaporization and good heat conducting characteristics for vaporization and condensation. Table 1 lists the characteristics of some cooling media and Fig. 5 shows the characteristics of saturated vapor pressure.

(3) Excellent long-term reliability

The combination of cooling media and enclosure material must have excellent stability so that no corrosion shall occur and non-condensable gases such as hydrogen shall not be generated by chemical reaction. Corrosion causes leakage and non-condensable gas causes the effective cooling area of the condenser to decrease and depreciates its cooling ability. These are the important considerations in order to maintain stable operation of the rectifier throughout its expected life.

Based on these requirements, Fuji Electric reached the conclusion that the combination of water and copper is optimal, and that additives (such as an anti-freezing agent) shall not be used. Consequently, we employ an anti-freezing method in which an electrical heater operates automatically to heat the heat sink and condenser.

Further, we performed an accelerating test and verified that water in the enclosure does not change in quality during a long time interval. Of course, changing or replenishing the water shall be unnecessary.

3.3 Cooling principle and structure

This system is based on the principle that silicon diodes are cooled by the latent heat of vaporization, as in the case of the conventional-type vaporization-cooling silicon rectifier.

3.3.1 Cooling principle

Figure 6 shows the principles of the cooling mechanism.

(1) Construction

An individual heat sink insulated by ceramic insulator is connected to a common condenser by connecting pipes, and the cooling fin of the condenser is cooled naturally.

Table 1 Characteristics of various cooling media

Type of cooling medium		Water	PFC	CFC	HFE
Product name			FX-3300	R-113	7200
Chemical formula		H_2O	$C_8F_{16}0$	$C_2CL_3F_3$	$C_4F_9OC_2H_5$
Boiling point (at 1 atg)	°C	100	101	47.6	78.5
Freezing point (at 1 atg)	°C	0	–65	–35	–138
Specific heat	kJ/kgK	4.19	1.05	0.92	1.21
Latent heat of vaporization	kJ/kg	2,260	92	147	133
Insulation strength (2.54 mm gap)	kV	—	41	30	30
Coefficient of ozone depletion potential (ODP)		0	0	0.8	0
Global warming potential (GWP)		0	5,000 to 6,000	5,000	90

ODP : Ozone depletion potential : Relative value (CFC-11 = 1.0)
GWP : Global warming potential : Relative value (CO_2 = 1.0)

Fig.5 Saturated vapor pressure of various cooling media

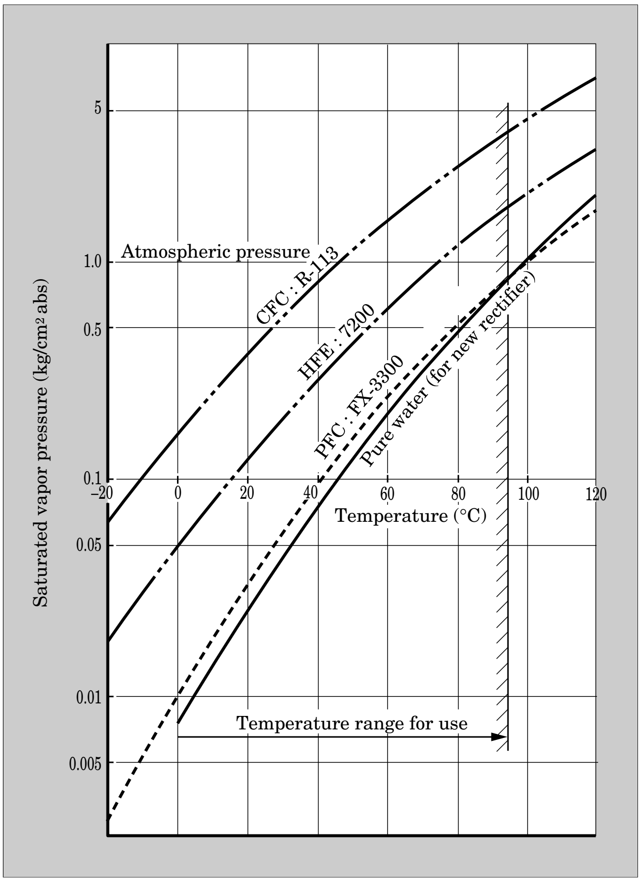
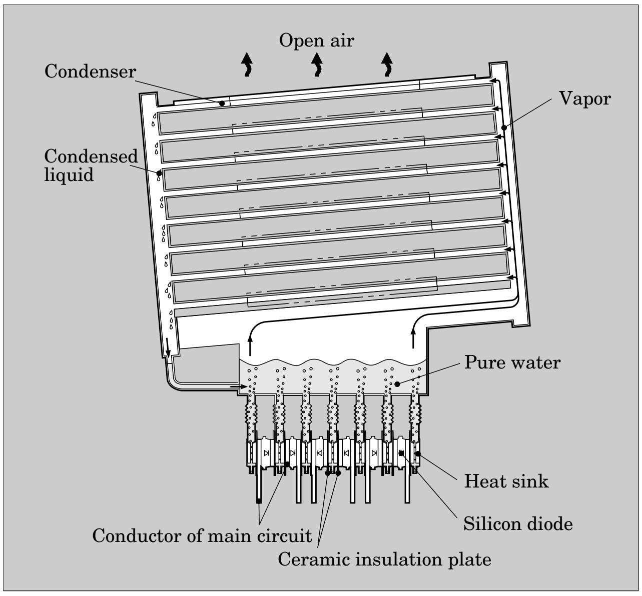


Fig.6 Cooling principle



(2) Cooling

Heat generated by the silicon diode is conducted to a heat sink where it vaporizes water that has been decompressed and injected into the heat sink for the purpose of vaporizing at low temperature, thereby causing the vapor pressure to increase. The vapor rises toward the upper space where the temperature and pressure are comparatively low. There it is cooled and condensed, and then finally returns to the heat sink. By repeating this cycle, generated heat is radiated to the air efficiently and with low thermal resistance. The heat generated by the snubber and resister for surge absorber is radiated similarly.

3.3.2 Construction

Figure 7 shows the internal structure.

The rectifier consists of a rectifier-stack, condenser and circuit holder. A heat sink is connected to the bottom of the condenser through a flexible pipe. The lower part of the pipes and the reservoir are enclosed in the main circuit box. The purpose of the reservoir is to realize smooth circulation of the vaporization-cooling.

3.4 Specifications dimensions

Standard specifications of the new type silicon rectifier are listed in Table 2.

3.5 Protection schemes

Protection schemes for external trouble such as over current, short circuit and ground fault, and for internal trouble in an emergency are shown in Fig. 8. The new type of vaporization-cooling system differs

Fig.7 Internal structure

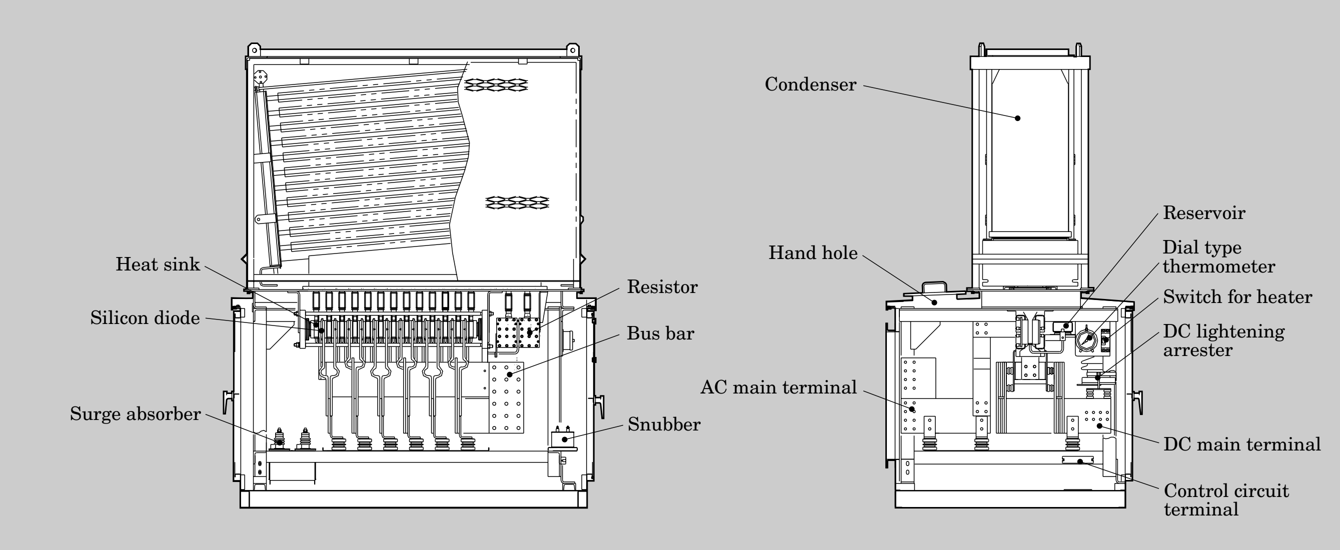
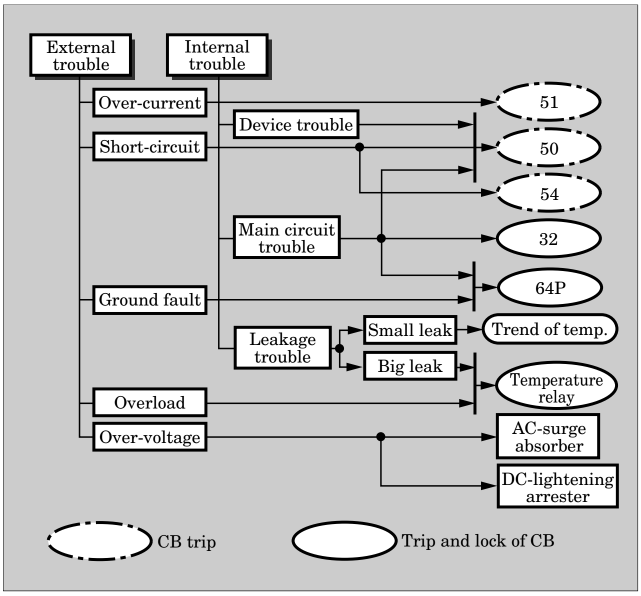


Table 2 Standard specifications

Name	Water vaporization-cooling silicon rectifier			
Installed location	Indoor or outdoor			
Ambient temperature	Indoor : 0 to +40°C Outdoor : –5 to +40°C Outdoor (cold district) : –10 to +40°C			
Cooling method	Vaporization natural cooling			
Applicable standard	JEC-2410 (1998)			
Frequency	50 Hz or 60 Hz			
Rated class	D or E			
Type of connection	Three-phase bridge (6 pulse), or double three-phase bridge (parallel 12 pulse)			
Rated DC output voltage	1,500 V, 750 V, 600 V			
Rated capacity	Rated capacity (kW)	DC volt (V)		
		1,500	750	600
	1,500		○	○
	2,000		○	○
	3,000	○		
	4,000	○		
	6,000	○		
Fluctuation rate of DC-V	6 % or 8 %			
Auxiliary power source	Control cct.: 100/110 V DC Space heater cct.: single phase 200 V AC			
Color	Munsell 5Y7/1			

Fig.8 Protection scheme



from the conventional type in that the new type does not require protection for abnormal internal gas pressure because no live part exists inside the enclosure. Small, emergent air leaks can be detected by temperature trends during a maintenance inspection.

4. Conclusion

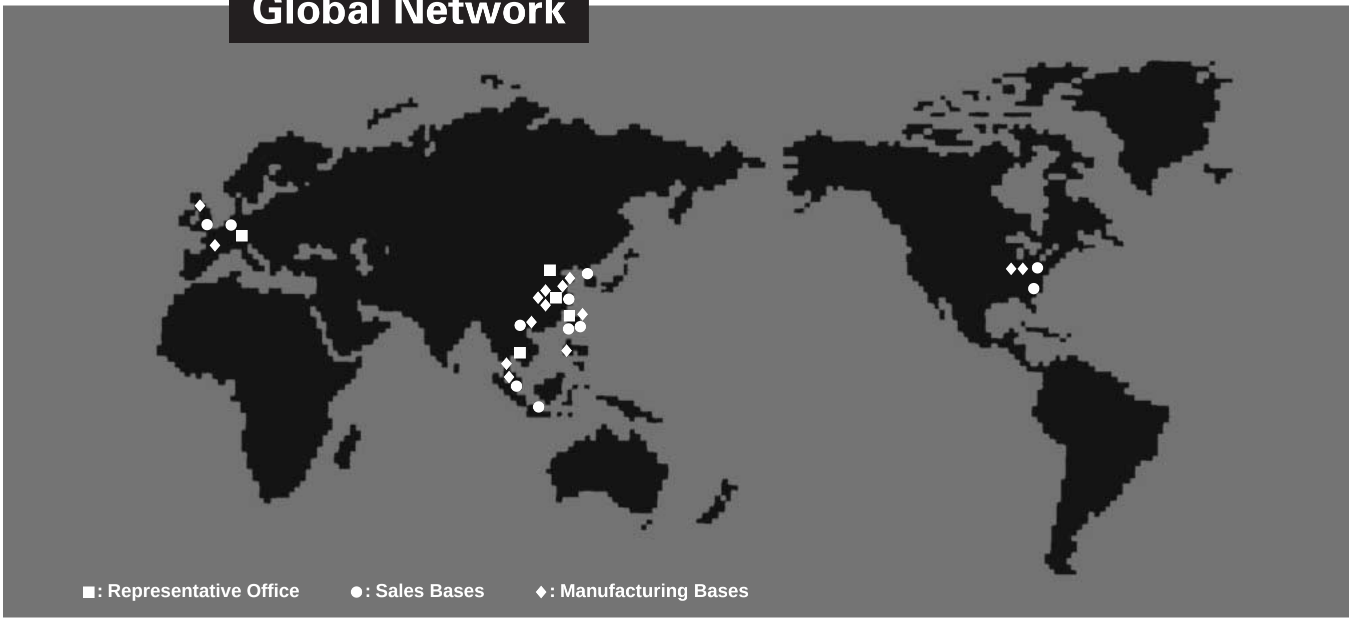
The new rectifier is a product that essentially does not influence the earth's environment, and as the result of gathering our original ideas, satisfies all requirements for the main equipment of a traction substation.

Fuji Electric will promote the development of products suited to the global environment in the future, and intends to deliver those products to many users.

Business Outline of the Each Internal Company

Company	Business Areas	Major Products
Energy & Electric Systems Company	Providing optimal solutions from information control systems to substations to meet the individual needs and demands of each customer	Water treatments systems; information, telecommunications and control systems; measuring and instrumentation systems; power systems; environmental equipment and systems; industrial power supplies; electrical equipment for rolling stock; substation systems; thermal, hydraulic and nuclear power plant equipment; and others
ED & C · Drive Systems Company	Delivering broad FA system components, individually or as integrated small-scale systems	Small-scale systems combined with PLCs, inverters and actuators; FA control equipment; low-voltage circuit breakers; molded transformers; drive control and power electronics; and others
Electronics Company	Providing distinctive electronic devices, based on our world-leading technologies	Power semiconductors; ICs; magnetic disks; photoconductive drums and peripherals; and others
Retail Support Equipment & Systems Company	Promoting consumer convenience and comfort, through machinery and systems focused on vending machines	Vending machines; beverage dispensers; food machines; freezing and refrigerated showcases; coin mechanisms and bill validators; leisure-related systems; and others

Global Network



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