Water Vaporization-Cooling Silicon Rectifiers for Traction Substations

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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

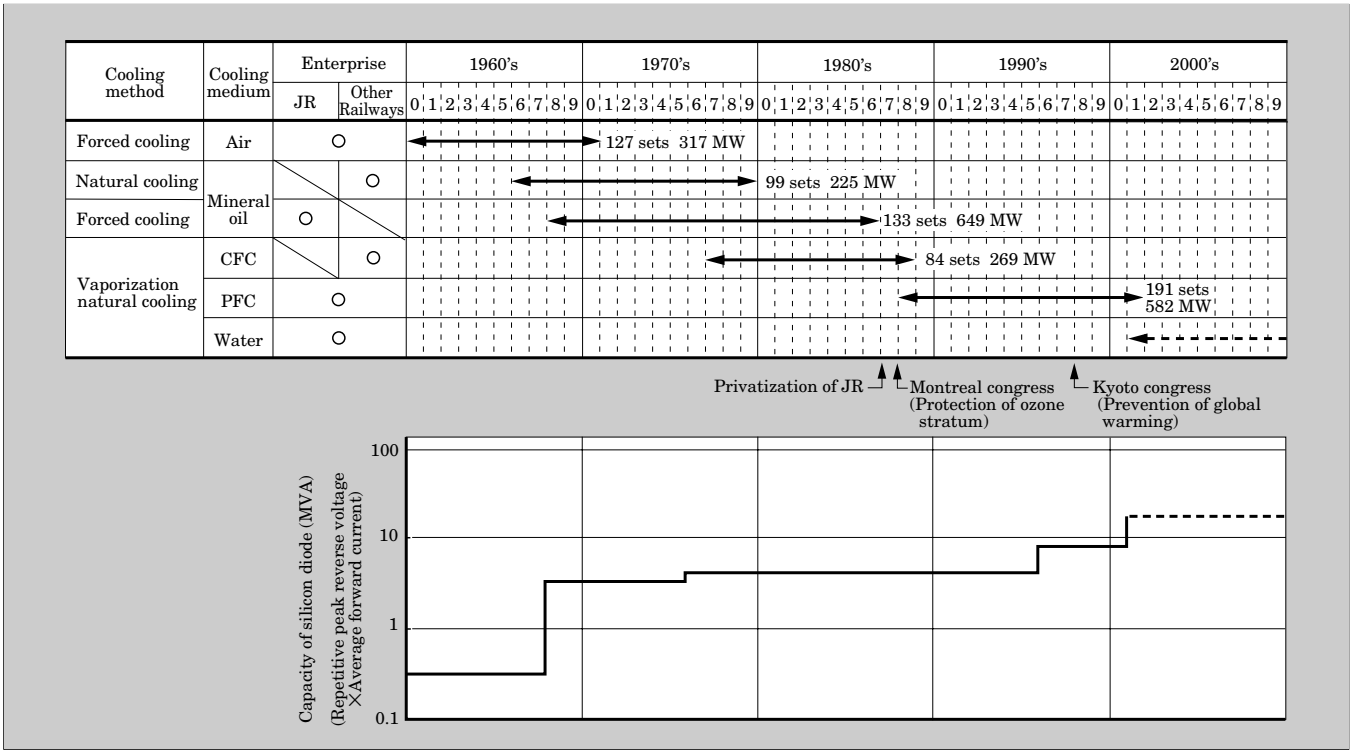


Fig.3 Large-capacity silicon diode

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.

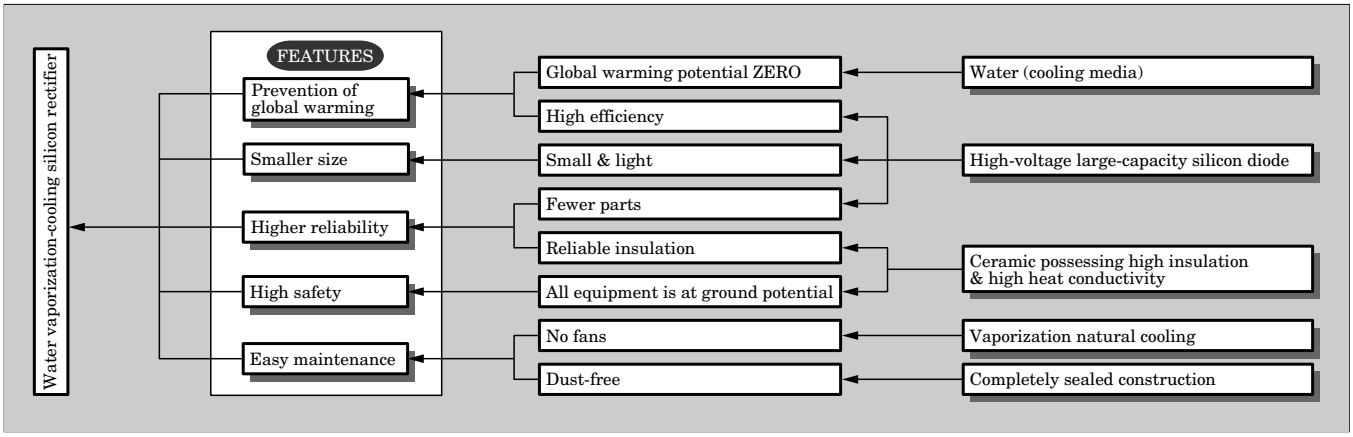
(2) Smaller size

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

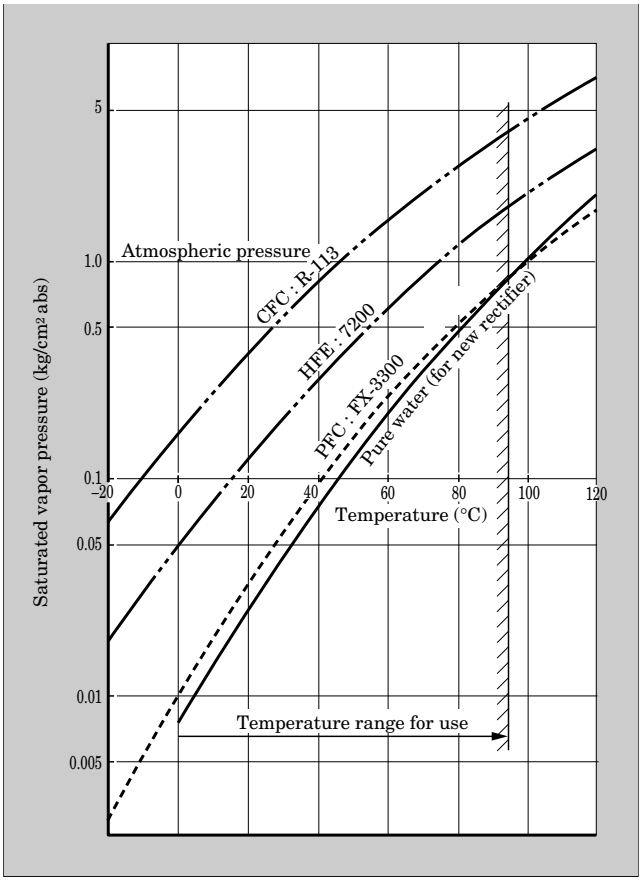
An individual heat sink insulated by ceramic insulator is connected to a common condenser by connecting pipes, and the cooling fin of the condenser is cooled naturally.

Table 1 Characteristics of various cooling media

Type of cooling medium / Product name		Water	PFC FX-3300	CFC R-113	HFE 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)

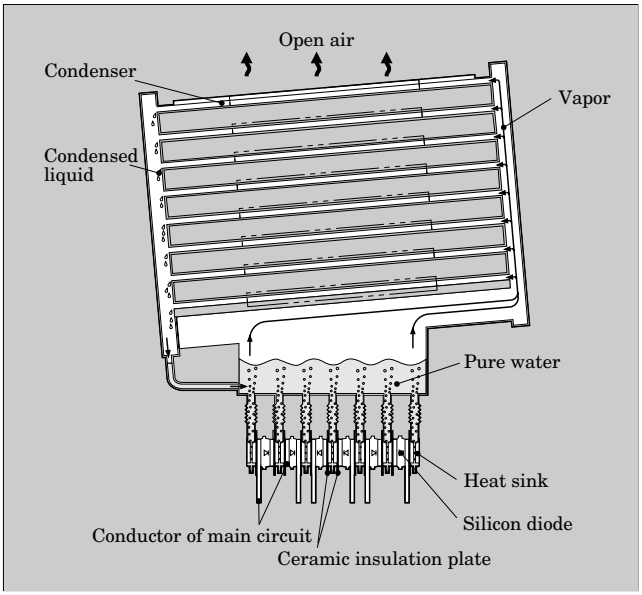
Fig.5 Saturated vapor pressure of various cooling media



(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.

Fig.6 Cooling principle



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

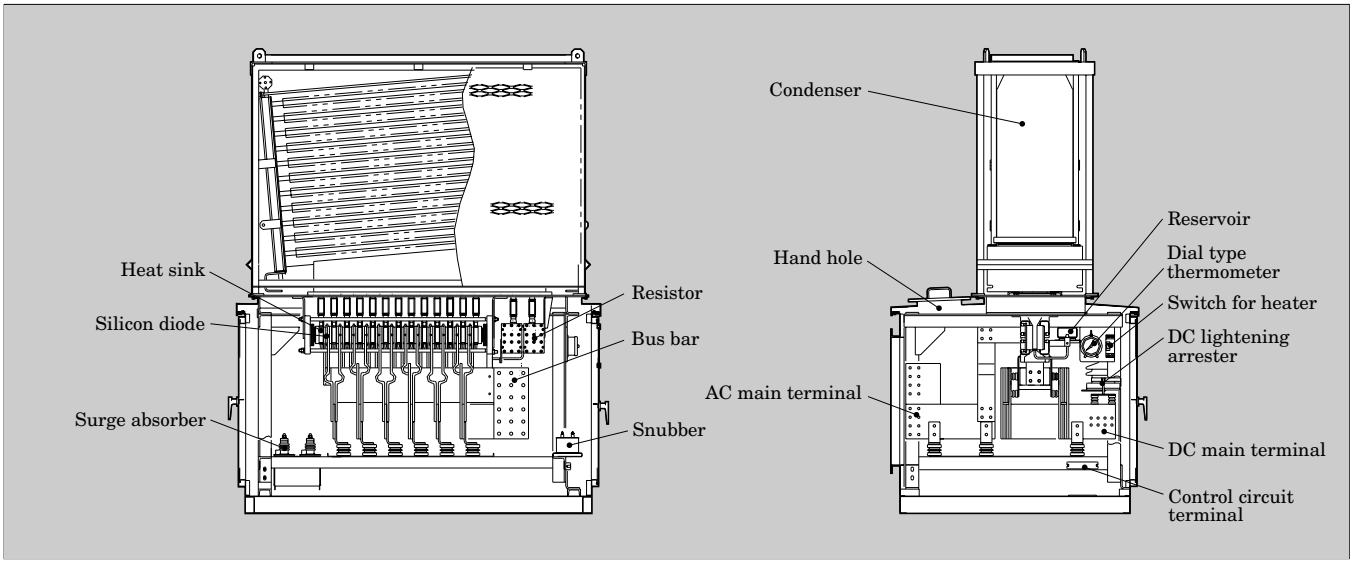
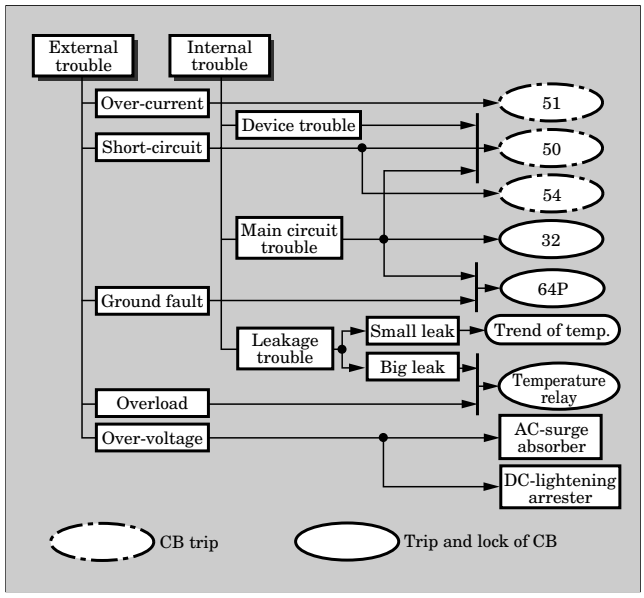


Table 2 Standard specifications

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			

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.

Fig.8 Protection scheme



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.