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# FORCED-OIL SELF-COOLED SILICON RECTIFIER FOR RAILWAY USE

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## I. INTRODUCTION

Until recently, silicon rectifiers for use on electric railways were usually of the forced air-cooled type employing stud-type rectifier diodes. The forced air cooling system has several advantages such as simple construction and easy maintenance and replacement of the rectifier diodes, but there are also many problems such as contamination of the cooling air in salty atmospheres and industrial areas, obstruction of the air filter by rain, snow etc., decreases in main circuit insulation, regulations against cooling blower noise in urban areas etc. To offset these problems, it was necessary to employ an oil cooling system.

Oil cooling systems can roughly be classified into two general types: the cooling bus type which has a cooling oil path and uses stud-type rectifier diodes, and the oil-immersed type in which the rectifier diode and cooling fins are immersed in an oil tank. For several years, Fuji Electric has been developing a flat-packaged silicon rectifier diode and now that this is completed, it is being employed in a series of oil-immersed self-cooled silicon rectifiers for railway use. Eighteen units (about 40,000 kw in total) have already been manufactured for private railway companies. The flat packaged type silicon rectifier diode has already surpassed $10^8$ operations (number of operations × time) with no accidents.

The Japanese National Railways now use standardized liquid cooled type silicon rectifiers for electric railways instead of the former forced air cooled types, after conducting investigations at the end of last year. This standardization is based on the following policy: the main circuit is oil immersed and sealed, the forced oil system is used so that the equipment will be as small as possible and maintenance will be simple, and the system is used in accordance with noise regulations. The rectifier and radiator are separate so as to provide the most rational distribution under all installation conditions.

Fuji Electric has produced three 1500 v, 4000 kw units and 1500 v, 3000 kw units based on the JNR standard system for the West Bosso Line of the Japanese National Railways. All of these are now operating satisfactorily. This article will introduce the construction and functions of this equipment.

## II. ARRANGEMENT OF FLAT-PACKAGED SILICON RECTIFIER DIODES

### 1. Silicon Rectifier Diodes

The flat-packaged silicon rectifier diode is of the both-side dissipated-type which is completely different from the former stud-type diode both in shape and

*Table 1.* **Ratings and Characteristics of KSPO3-30 (for railway use)**

| | | |
|---|---|---|
| Rated mean forward current | Continuous ($T_F$=100°C) | 800 amp mean |
| Allowable mean forward current | Continuous ($T_F$=100°C) | 750 amp mean |
| (three-phase bridge connection) | Continuous (a) Oil temp. 75°C | 640 amp mean |
| | (b) Cooling fin 12×100×100 (Cu) | 2 pieces per diode |
| Repetitive peak reverse voltage | | 3000 v peak |
| Non-repetitive peak reverse voltage | | 3300 v peak |
| Rated junction temperature | | 160°C |
| Peak surge forward current | 1 cycle | 12,500 amp peak |
| 50 Hz sine half wave | 5 cycles | 9500 amp peak |
| | 15 cycles | 7500 amp peak |
| Reverse current | | 8 ma peak |
| | | 50 ma peak |
| Forward voltage drop | | 25°C 2500 amp≤1.55 v |
| Thermal resistance (between junction and cooling fin base) | | ≤0.044 deg/w |
| Weight | | about 120 g |
| Storage temperature | | −40°C～+160°C |
| Compression pressure | | 1000±100 kg |

construction as can be seen from the data givin in Vol. 14, No. 5 of the Fuji Electric Review. Because the rectifier diode has been enlarged and the generated loss increased to about 1 kw, this both side dissipated construction is indispensiable for high power silicon rectifier equipment.

For both high efficiency and compactness, Fuji Electric employed a 3000 v-class high power flat-packaged silicon rectifier diode. The specifications for the flat-packaged rectifier diode, KSPO3-30 (for electric railways), are given in *Table 1* and an external view is shown in *Fig. 1*.

These specifications differ from the usual rectifier diode specifications in respect to the permissible mean forward current for three phase bridge connection which means that they can be used directly for electric railways as specified in JNR Standard JRS 23303–3A. This rated forward current value is determined by the temperature of the cooling fin but, as shown in *Fig. 2,* this value can be made larger as the cooling fin temperature decreases. When the cooling fin temperature is 110°C (oil temperature used: 75°C), the mean forward current is 640 amp.

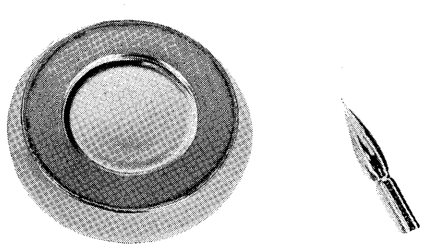

*Fig. 1* External view of flat-packaged silicon rectifier diode

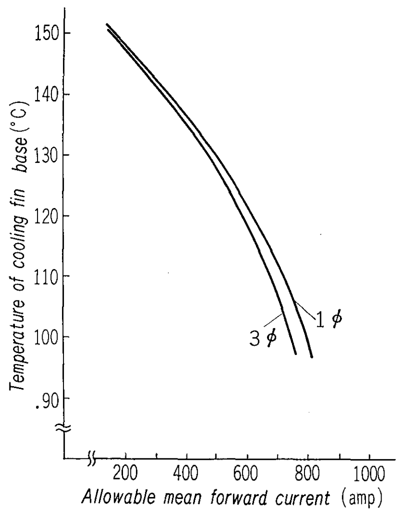


*Fig. 2* Allowable forward current to temperature of cooling fin

### 2. Rectifier Diode Arrangement

1) Number of parallel diodes

The required number of parallel diodes in rectifier equipment for railway use must be determined in accordance with the relation between the max. dc current and the permissible mean forward current as well as the relation between the short circuit current at the dc terminal and the peak surge forward current. These relations are as follows:

$$N_p \geqq I_S a / I_p \quad \cdots\cdots (1)$$

$$N_p \geqq I_d a \cdot b / I_{th} \quad \cdots\cdots (2)$$

where

- $N_p$: Number of parallel diodes
- $I_p$: Peak surge forward current
- $I_d$: Max. dc load current (load current which shows maximum temperature rise. With E class rating, 300% of load)
- $I_{th}$: Mean forward current for 3-phase bridge connection
- $I_S$: Max. peak value of the short-circuit current which flows in the rectifying arm when there is a short circuit between the dc output terminals)
- $a$: Rate of forward current unbalance between each diode; generally 1.2
- $b$: Coefficient determined according to the connection system cooling conditions (1/3 for the 3-phase bridge connection)

In accordance with the above equations, for a 1500 v E class 3-phase bridge connection, there will be 4 parallel diodes with 3000 kw and 6 parallel diodes with 4000 kw.

2) Number of series diodes

The number of series diodes is the sum of the number of stand-by series diodes and the number of diodes which will be able to withstand the surge overvoltage from the dc or ac sides as well as the rated 2 ry voltage. However, the number of series diodes $N_S$ is determined according to the following equation since the abnormal voltage on the dc side is generally much greater.

$$N_S \geqq E_a \cdot \alpha / E_p + \beta \quad \cdots\cdots (3)$$

where

- $N_S$: Number of series diodes
- $E_a$: Abnormal voltage in each arm; 5.5 kv with a 1500 vdc 3-phase bridge connection.
- $\alpha$: Coefficient of voltage supplied between the series diodes = 1.1
- $E_p$: Rectifier diode non-repetitive peak reverse voltage
- $\beta$: Number of stand-by diodes; generally $\beta = 1$

When the KSPO3-30 is used, there are 3 series diodes with the 3-phase bridge connection, including one stand-by diode. Therefore, the standard diode arrangements are 3S 4P 6A for 3000 kw and 3S 6P 6A for 4000 kw.

## III. CONSTRUCTION OF THE FORCED-OIL SELF-COOLED SILICON RECTIFIER

### 1. Specifications

| | |
|---|---|
| Rated output voltage: | 1500 vdc |
| Rated output: | 3000 kw/4000 kw |

Type of rating:

| | |
|---|---|
| E class | 100% load continuous<br>120% overload: 2 hr; 300% over load 1 minute |
| Type of rectifier: | KSPO3-72 TBHC/KSPO3-108 TBHC |
| Rectifier connection: | 3-phase bridge |
| Diode connetion in each arm | Mesh connection |
| Voltage divider system | Condenser divider system |
| Cooling system | Forced oil self-cooled (radiator separate from rectifier cubicle) |
| Applied standard | JRS 23303-3A (JNR) |

According to the JNR standards, there is no distinction between indoor and outdoor use because of the liquid cooled type, but as a principle, this rectifier is for outdoor use.

## 2. Rectifier Stack

An external view is shown in *Fig. 3*. The stack used in this equipment consists of 6 flat-packaged rectifier diodes with 2 cooling fins for each diode. The diodes and cooling fins are pressure-connected under a pressure of 1000 kg into a single unit using 4 insulated iron bolts. The cooling fins which also serve as the diode electrodes are made of copper since the maximum cooling effect is possible with the smallest area. The 6 diodes are connected in series and the end terminals are dc, while the middle terminals are ac. Each stack consists of 2 arms, each with 3 series diodes. The 4 clamping bolts employ disc springs stacked in series to absorb the thermal expansion of the stack. The contact pressure is always maintained at a standard value of 1000± 100 kg to compensate for temperature variations and changes with time. Steel balls are employed at both sides of the stack and make uniform contact with the silicon diodes.

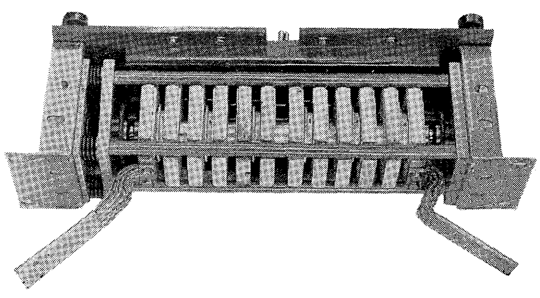

Fig. 3 External view of flat-packeged silicon rectifier stack

## 3. Rectifier Tank Construction

1) Inner construction

The inner construction of the 3000 kw rectifier tank is shown in *Fig. 4*. The 3000 kw rectifier consists of 12 stacks and as shown in *Fig. 4*, each stack consists of 6 levels arranged back-to-back in the support with epoxy resin insulators between. The stacks are of two levels, i.e. 4 stacks are connected in parallel and there are three groups of these 4 stacks, in one rectifier. Both ends of the cooling fins of each stack are connected to the supports which also serve as dc bus bars. The ac side is extracted through the space between the stacks connected in parallel. A voltage dividing condenser is fixed via insulation to the stack front surface. A C-R surge absorber is attached to the lower part of the side surface and a dc side discharge registor is located on the upper part of the stacks. The diodes are connected by means of the standard mesh connection and an unbalance rate between each diode of less than 20% can be expected because of the use of diodes with uniform characteristics and the rationalization of bus bar construction. The oil flows from the bottom to the top and it is arranged so that the oil flows effectively in the stacks. The main circuit bus bar contains oil and is locked in position with tightening bolts since daily maintenance inspections are not possible.

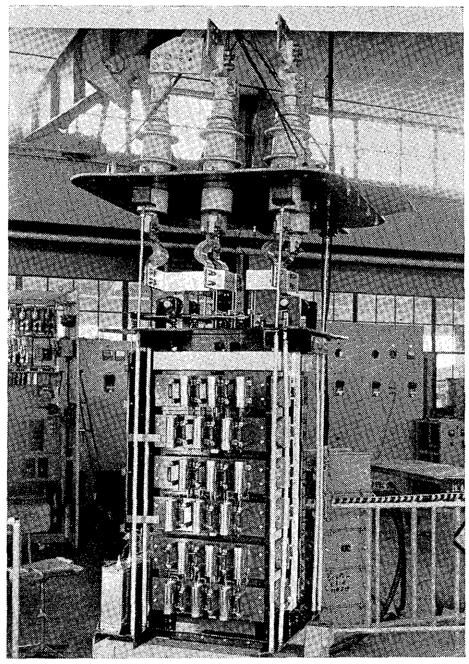

Fig. 4 Inner view of silicon rectifier

2) Oil tank construction

The oil tank which acommodated the rectifier unit contains an oil pump for cooling, a discharger, a reverse current relay, a dial thermometer and an auxiliary circuit terminal box. The cover plate has input, and output terminals and a bursting tube. This cover plate is larger than the oil tank flange and in this part which a 15 mm dia. holes are made every 200 mm. These holes are utilized for attaching the discharger and reverse current relay and it is also possible to attach the cable support fixtures etc. The oil is injected from the lower flange and drawn out via the upper flange. The oil inlet and outlet flanges are attached to the square surface of the oil tank, which is a good arrangement no matter which is used.

The oil injected through the lower flange enters the lower part of the tank through a duct, which also serves as reinforcement for the tank, and is jetted into the stack section. At the outlet side, the oil enters another duct attached to the upper flange and is conveyed to the exterior via the outlet flange.

### 4. Radiator

The radiator is a self-cooled type plate radiator. The plates are made of iron sheets and are light weight. Other advantages include easy repairs and comparative freedom in the choice of the cooling surface. The radiator is attached to the oil duct via the radiator valve. A conservator is attached to the upper part of the radiator and the oil makes contact with the exterior via a silica gel breather. The oil flows from top to bottom and the oil ducts are arranged so that oil flows uniformly in all the radiators.

### 5. Connection of the Rectifier and Radiators

An example of the connection of the rectifier and radiators is shown in *Fig. 5*. *Fig. 6* shows the main circuit connections and *Fig. 7* is a diagram of the cooling system. The rectifier and radiators are separated so that they can be arranged as desired at the site. For example, it is possible to arrange the radiators out of doors and the rectifier indoors.

A steel pipe with a diameter of 100 mm is used to connect the rectifier and the radiators. An expansion joint is used in this pipe in order to compensate for basic errors during operation and expansion due to oil temperature changes. The oil pump, oil flow relay etc. can be replaced without removing any oil from the tank by closing the butterfly valve in the middle of the pipe. Since it is possible for air to remain in the pipe for long periods, ventillation holes are provided in the intake side of the oil pump pipe and the upper cover of the rectifier.

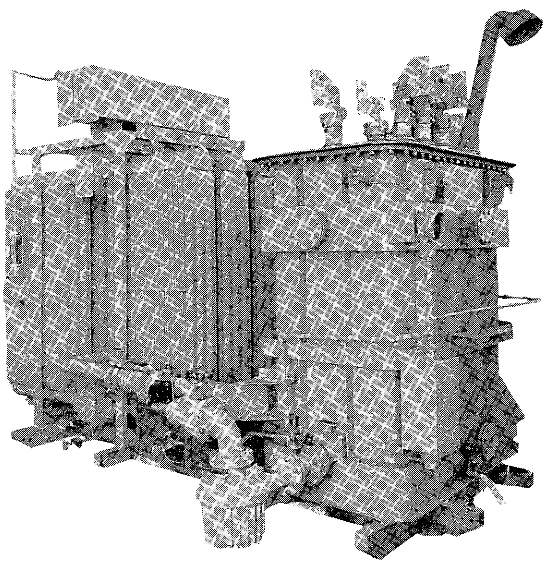

*Fig. 5* External view of forced oil self-cooled silicon rectifier

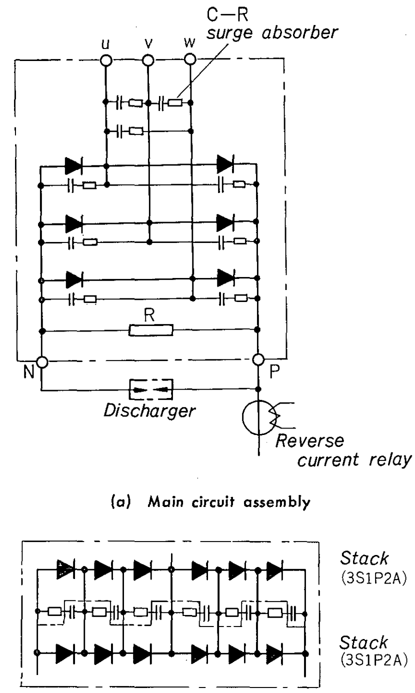


*Fig. 6* Connection diagram of main circuit

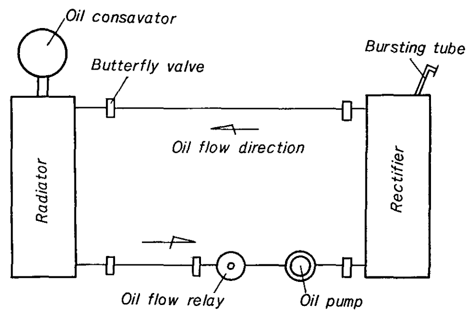


*Fig. 7* Connection diagram of cooling system

### 6. Protective Devices

1) Surge overvoltage absorber

The following two devices are provided to absorb abnormal voltages in this equipment:

Ac side···C-R surge absorber

Dc side···Discharger (JNR standard JRS 29102–3C)

As mentioned in section II, the number of series diodes is selected so as to agree with the surge overvoltage absorber ratings and there is one spare, as in the forced air cooled type.

2) Oil flow relay

When the oil pump stops pumping oil, the auxiliary contacts open and the power source is cut off. Since the oil viscosity increases during the winter, the amount of oil decreases which may prove a hindrance to operation and therefore the oil flow relay contact operation points are set at half the rated amount of oil flow.

3) Oil pump circuit protective NFB (No-fuse breaker)

This NFB protects the auxiliary circuit against short-circuit faults in the pump motor.

If the power supply for the oil pump does not satisfy the specified supply voltage range, the pump stops momentarily and the oil flow relay then operates. In this way, open phase protection by the NFB (no-fuse circuit breaker) is not provided.

4) Bursting tube

When short-circuit faults arise within the rectifier, a buffer plate bursts so as to prevent damage to the oil tank. The bursting pressure is about 0.6 kg/cm$^2$ which is the same as for the transformer.

5) Reverse current relay

6) Dial thermometer

This thermometer has contacts which close at an oil temperature of 75°C.

7) Diode fault detection device

If there is no fault detection device and the rectifier contains oil, there is no way to tell if a fault develops in the diodes.

Since the diodes undergo strict tests at the factory, there is no chance of initial failures and therefore only accidental failures during operation present any problem. Experience with recent silicon diodes has shown that the rate of accidental failure is over $10^{-8}$ and therefore reliability can be improved by omitting an internal fault detection circuit. However, it is essential to check the diode condition during periodic inspections without removing the inner parts and for this purpose, Fuji Electric has standardized a portable type diode fault detection device which operates on low voltage as shown in *Fig. 8* and *Fig. 9*. With this device, the diode reverse characteristics can easily be checked via the main circuit terminals.

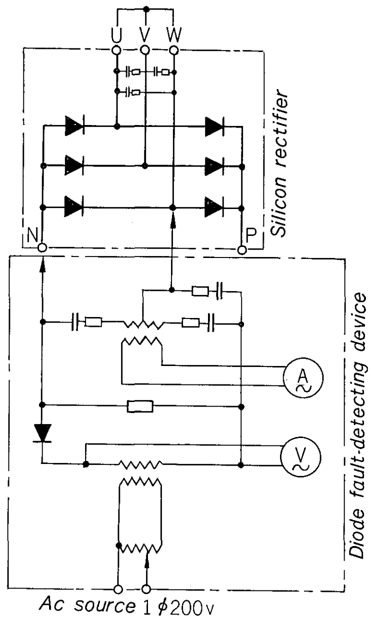


*Fig. 8* Connection diagram of diode fault detecting device

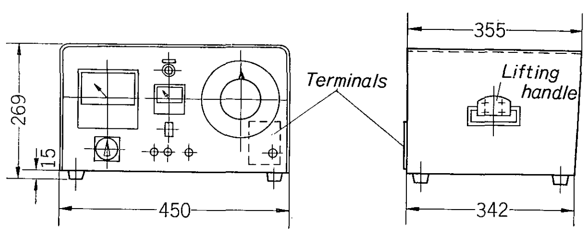


*Fig. 9* Outline drawings of diode fault detecting device

## IV. TEST RESULTS

### 1. Insulation Tests

This equipment is of the oil-immersed type and maintenance checks are not required in principle since the creeping distance is maintained constant in respect to the internal parts. However, the following insulation tests were performed and satisfactory results obtained.

(1) Insulation test with commercial frequency

| | |
|---|---|
| Main circuit-ground | Ac 60 Hz 5.5 kv eff. for 1 minute |
| Auxiliary circuit-ground | Ac 60 Hz 1.5 kv eff. for 1 minute |

(2) Impulse voltage test

| | |
|---|---|
| Main circuit-ground | $1 \times 40\ \mu s$ 20 kv peak applied |

### 2. Temperature Tests

A short-circuit was created at the rectifier dc output terminal and the temperatures of all portions of the cooling oil and stacks were measured at low voltage loads. The temperature differences between the oil inlets and various positions in the stack were very small; only 1～2°C which can be neglected in practice. Results of the temperature tests are shown in *Fig. 10*. The oil temperature is the actual measured value at the outlet and the cooling fin temperature is the value measured at the base of the cooling fin in the center of the stack nearest the outlet. The maximum temperature is shown for a 300% load for 1 minute. The oil temperature rise is 30°C while that of the cooling fin is 42.5°C. Tests confirmed these values and also indicated that there were sufficient margins in all cases. The temperature rise

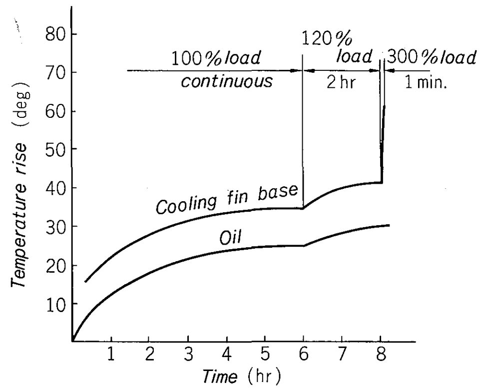


*Fig. 10* Temperature rise characteristic of the rectifier

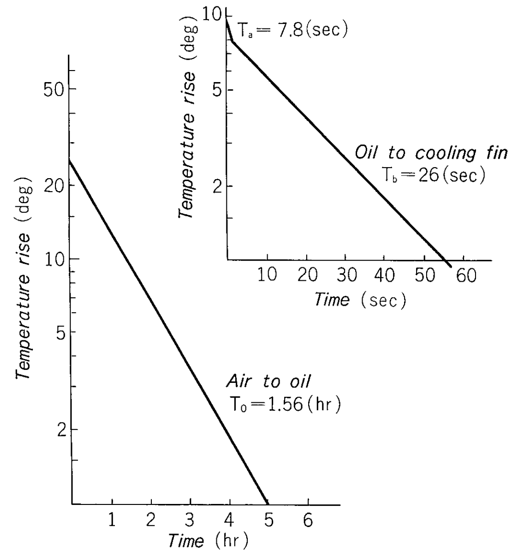


*Fig. 11* **Time constant for the temperature rise**

time constant is shown in *Fig. 11.* The figure shows that the air-oil value of 1.56 hours is slightly smaller than the forced oil self cooling value of about 2.3 hours and also that the cooling fin-oil value is about 26 sec.

## 3. No-load Voltage Test (Test of Voltage Distribution Between Series Diodes)

110% of the rated voltage was applied with the dc side disconnected. After measuring the ac input current to see whether it was abnormal or not, the inside of the rectifier was raised and voltage distribution was measured as indicated in the following sections. However, low values of 1.02 were shown in respect to a specified unbalance rate of 1.1 or above.

(1) Surge analyzer test

Voltages of 100 v and 200 v in impulse waves of $1 \times 40 \mu s$ positive polarity were applied to each arm and the voltage distribution between series diodes was measured.

(2) Test for the rated input voltage

The rated input voltage was applied and the voltage distribution at each diode was measured.

Voltage distribution under rated load conditions was omitted because a condenser divider system is used.

## 4. Test of Current Distribution Between Parallel Diodes

Because flat-packaged diodes and the oil immersed construction are used in this rectifier, it is not possible to measure current distribution as easily as with the forced air cooling system. In this equipment, current distribution measurements were omitted since the forward characteristics of the diodes used were regulated. The Fuji KSPO3 diode is regulated according to class for a voltage drop of 50 mv at a current of 2500 amp. Therefore, there are 2 adjacent classes in the same rectifier so that a range of only 100 mv is employed. From previous experience with diodes regulated at these values, it was confirmed that the current distribution lies within a specified unbalance rate of 1.2, no matter where they are located or what they are connected to.

## 5. Equivalent Short-Circuit Test

The short circuit current tests were not conducted on the rectifier as a whole, but equivalent tests were conducted for the diodes only. First, the diodes with the largest, medium and smallest forward characteristics were chosen and their forward characteristic curves were measured up to the over-current range. It was then confirmed that the unbalance rate in respect to short circuit currents was within 1.2. An example of these characteristics is shown in *Fig. 12.* Next, the same cooling fin used in the rectifier was connected to a stack so that the cooling conditions were the same, and the test given in the next section was performed. By measuring the reverse characteristics before and after this test, it was confirmed that there were no abnormalities.

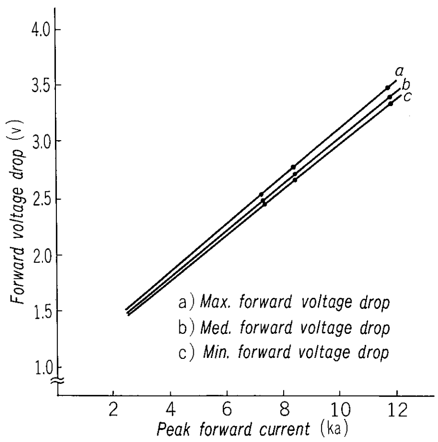


*Fig. 12* **Forward characteristic curves of the overcurrent range**

(1) Short circuit hypothetical test at the rectifying arm

When there is a short circuit in one arm of

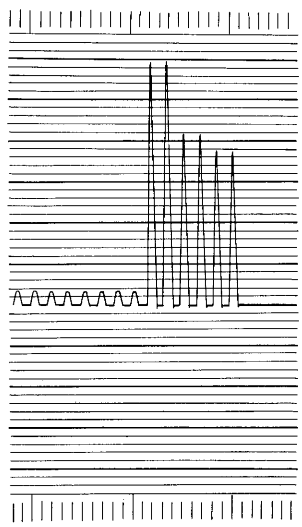

*Fig. 13*
**Oscillogram of the equivalent short-circuit test assuming a shorted rectifier arm**

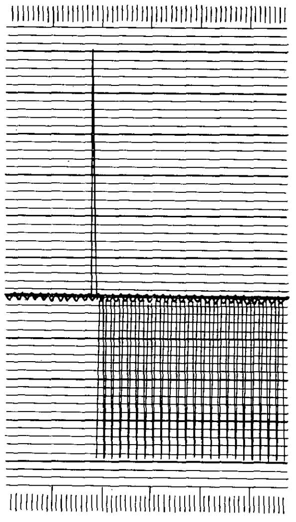

*Fig. 14*
Oscillogram of the equivalent short-circuit test assuming a shorted dc terminal

the rectifier, this test confirms that the short circuit current can be withstood. After the rated current flowed at the specified oil temperature, a damped wave, calculated as shown in *Fig 13*, flowed and the test was performed.

(2) Short circuit hypothetical test at the dc terminal

As shown in *Fig. 14,* after one wave of the rated dc current flowed in the oil at normal temperature, the rated reverse voltage was soon applied. This test was repeated 10 times at suitable intervals and it was confirmed that there were no irregularities.

(3) Force life test

Diodes which had undergone the test in (2), were tested 100 times under the same conditions and their durability was confirmed.

## 6. Sequence Tests for the Protective Device

1) Hypothetical fault test for the cooling system

After the pump was operated with the normal flow amount at the usual pressure, the motor input was cut off and it was confirmed that the oil flow relay operated.

2) Dc reverse current

Since the reverse current relay is located in a separate box outside the oil tank, it was tested separately for specified operation at the rated reverse current as well as undergoing temperature and insulation tests.

3) Hypothetical single phase operation test for cooling pump motor.

During oil pump operation, the pump was manually put in the open phase condition. The motor soon stopped and it was confirmed that the line relay operated.

4) Thermal relay operation test.

The dial thermometer set point was short-circuited by hand and an operation test for the temperature rise detection circuit was carried out.

# V. CONCLUSION

This article has described the construction and given test results concerning newly developed forced oil self-cooled silicon rectifier equipment for railway use. Features of this equipment are:

(1) Because the equipment is completely oil immersed, it can be installed anywhere with no limitations as to salty atmospheres, wind, snow etc.
(2) Daily checking is unnecessary so that maintenance staff is not required.
(3) The equipment generates no noise.
(4) Because the radiator is divided and the forced oil system is used, a rational arrangement is possible during installation.
(5) The equipment is compact due to the use of 3000 v class large capacity flat-packaged type rectifier diodes.
(6) Reliability is also much improved throughout the equipment because of simplification which has allowed for omission of the previously used diode fault detection circuit etc.

The greatest disadvantage of forced oil cooling type equipment is that it is difficult to change the diodes easily at the site when there is a diode fault. However, most of faults in previous rectifiers were caused by external conditions such as insulation damage etc. rather than by deterioration of the actual circuit elements in the rectifier diodes. Considering this point, rectifier diodes are manufactured of the highest quality materials and assembled in keeping with the latest techniques so that they are more reliable than previously.

As was described above, this equipment is based on JNR standards and is a forced-oil self-cooled silicon rectifier with high power flat-packaged type rectifier diodes immersed in oil. It is felt that this equipment will be widely used from now on in place of forced air silicon rectifiers using stud-type diodes.

The cooling efficiency of the oil-immersed self cooling systems for railway use is less than that of forced oil systems, but it's features are that it is a complete self cooling system with no auxiliary equipment, maintenance is simple, and unconditional starting is possible. Fuji Electric have two standard series for railway use employing the forced oil self-cooled system; use the one which is the most advantageous under the particular operating conditions.

From now on, better cooling systems will be investigated and more rational uses found for the flat-packaged rectifier diodes.