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DC SUBSTATION EQUIPMENT FOR RAILWAY SERVICE

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I. FOREWORD

Mercury-arc rectifiers and rotary converters have been used as dc power converters for almost all railway service. Several years ago, however, the high voltage large capacity silicon rectifier element was developed, and since then has been proven to meet the requirements for use in railway service. Silicon element utilization in the railway service has been remarkably developed and, at present, it is no exaggeration to say that the silicon rectifier is used in all dc substations for railway service. The ease of control and maintenance of the silicon rectifier simplifies remote supervisory control and completely automatic control; thus, the reliability of unmanned substations has been raised. It has become mandatory to build dc substations, which are built along the railroad as the unmanned type. The dc substation silicon rectifier devices introduced herein are installed in the Nakatsu Substation. This substation was built for the No. 1 subway line of the Osaka City Communication Bureau which links the New Osaka Station of JNR's New Tokaido Line and Osaka.

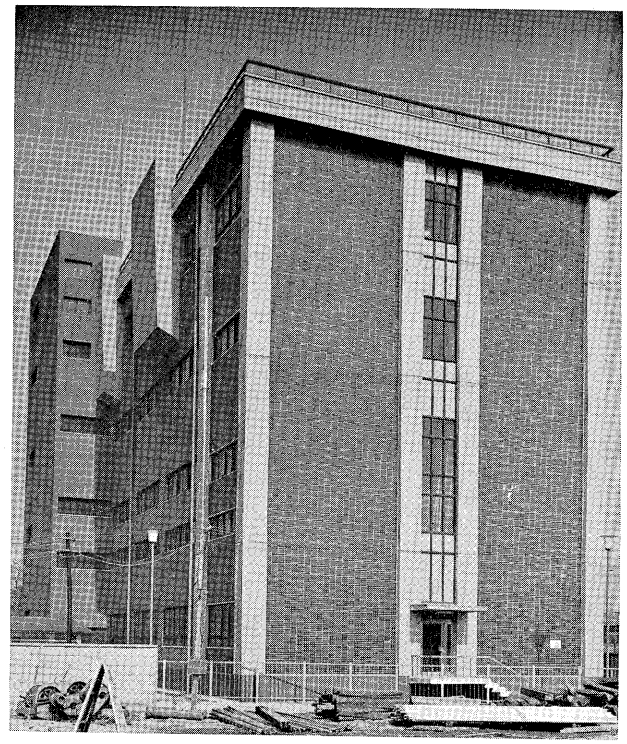

Fig. 1 External view of Nakatsu Substation

II. OUTLINE OF EQUIPMENT IN SUBSTATION

As the Nakatsu Substation of Osaka City Communication Bureau was built in the city area, building construction restrictions necessitated building a reinforced concrete structure of four stories. The first floor is an office area where general administrative activities of the Communication Bureau are performed, and the substation equipment is installed on the 2nd and 3rd floors. On the 4th floor, the telephone and signalling installations and concentrated supervisory control equipment (which perform the remote control of the substation devices located on the 2nd and 3rd floors and remote supervisory control of the Minamikata Substation) have been installed. *Fig. 1* shows an external view of the Nakatsu Substation.

The equipment for this substation was designed to be unmanned, and particular consideration was given to increasing reliability, simplifying maintenance, improving non-inflammability, and reducing noise, while minimizing the dimensions, and lightening the weight.

This is a large substation. It has been provided with three 20 kv power receiving lines, four sets of 750 v, 2000 kw rectifiers (two of the four are to be installed in the future), four feeders for 750 v dc supply with one reserved feeder, and five feeders for the 3 kv ac supply. As the rectifiers and transformers (which are the major devices in this substation) are air-cooled, noise countermeasures required for the cooling system posed considerable problems. The installation has been revised to discharge the internal noise directly to the city area by extending a concrete duct onto the roof of the building so that the discharged cooling air (and noise) is exhausted upward. *Fig. 2* shows a skeleton diagram of this substation.

1. Equipment on the 2nd Floor

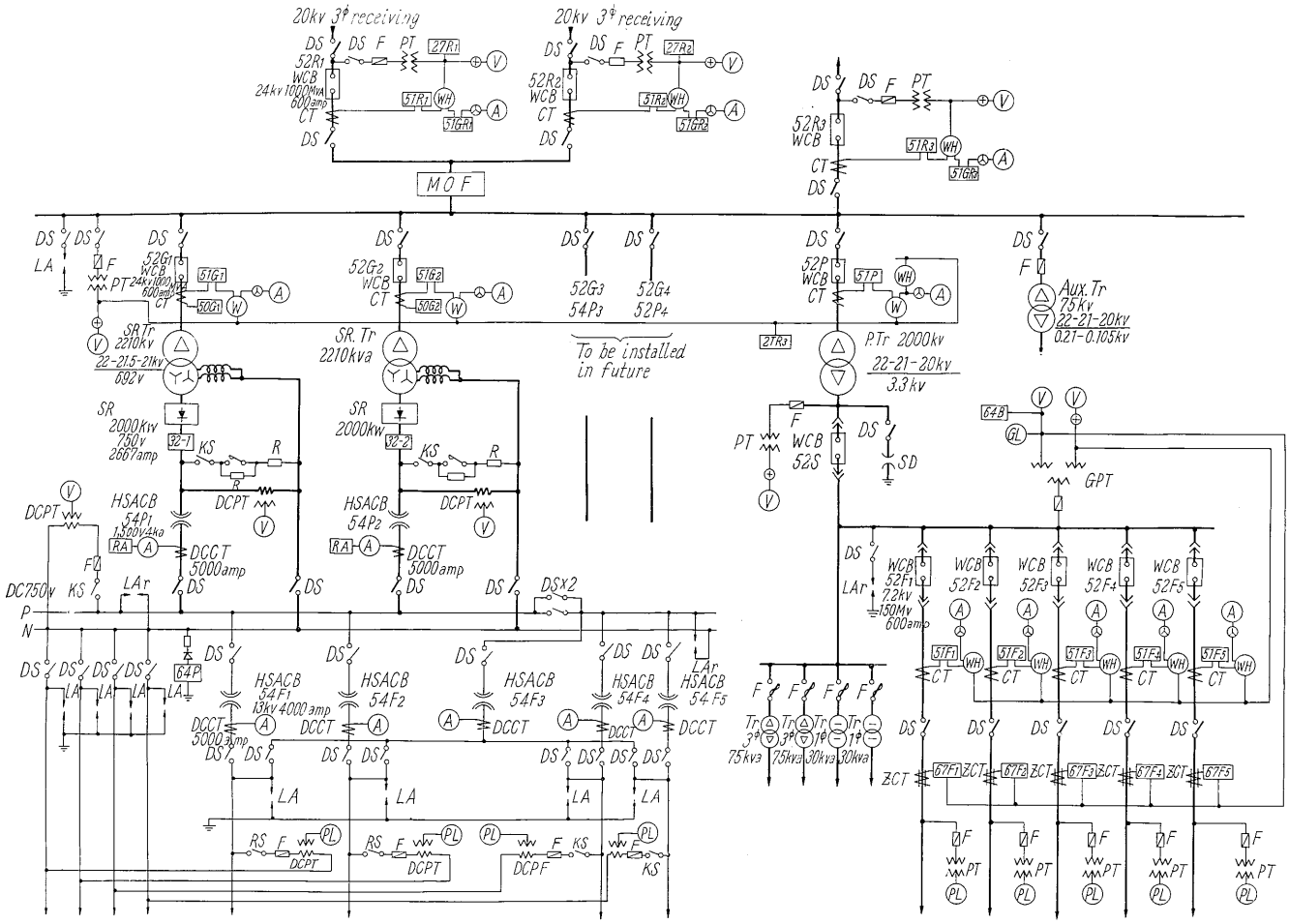

Fig. 2 Skeleton diagram of Nakatsu Substation

13 × Metal-clad type 20 kv switchgear
24 kv 600 amp 1000 Mva
2 × Class "H" insulated, dry type, forced air-cooled rectifier transformers
22 kv/692 v 2210 kva Class "D" rating
1 × Class "H" insulated dry type forced air-cooled power transformer
22 kv/3.3 kv 2000 kva
8 × Metal-clad type 3 kv switchgear
7.2 kv 600 amp 150 Mva
1 set of accessory devices

Two of the intake cables receive power from the Kansai Electric Power Co. through an underground cable. The other is used to contact the Minamikata Substation and also receives its power through the underground cable.

2. Equipment on the 3rd Floor

2 × Indoor use, forced air-cooled, cubicle type silicon rectifiers.
750 v dc 2000 kw Class "D" rating
2 sets of dc high speed air circuit breakers and operation panels (54 P)
1500 v dc 4000 amp
5 sets of dc high speed air circuit breakers and operation panels (54 F).
1500 v dc 4000 amp
1 set of control switchboards (for receiving equipment and 3 kv ac feeders)
1 set of control switchboards (for dc converting plant and 750 v dc feeders)

Other devices, such as an ΔI device, storage batteries, etc., are installed.

III. MAJOR DEVICES IN SUBSTATION

1. Air-cooled, Cubicle Type Silicon Rectifier for Indoor Use

Specifications :

Type :	S 150–120 BL
Rating :	750 v 2000 kw 2667 amp 60 cps Class "D" raiting (100% continuous, 150% 2 hr, and 300% 1 min)
Connection :	Double star connection
Balancing :	Condenser type voltage dividing
Break down detection of silicon element :	Double alarm system, a breakdown detecting unit consist of 20, each of silicon elements (5 S. 4 P)
Element structure :	5 S · 8 P · 6 A (240 elements)

Cooling system: Intake type, using 8 double propeller fans
Rating of Silicon Rectifier Element
Type: Si 150 F
Rated voltage: 380 v ac (effective value)
Rated current: 200 amp dc (mean value)
Peak inverse voltage: 1200 v
Surge breakdown voltage: over 1500 v
Instantaneous thermal capacity 72,000 A^2S

As this rectifier is used at an unattended substation, it was designed to ease the inspection and maintenance requirements together with improvement of reliability. More specifically:

(1) Cooling system

An air filter has been provided for the cooling air; thus, virtually all dust is eliminated. The cooling air is exhausted through the filter, element fin, and cooling fan, which are separated from the elements themselves and other accessories. As a result, the cooling efficiency is high and the elements are not affected by dust. In addition, a passage has been provided in the silicon rectifier cubicle to allow inspection and cleaning.

(2) Inspection of elements and accessories

The elements are of the mesh connection screw-in type, and are installed uniformly on the front and rear sides of the cubicle. The passage mentioned above is provided between these element panels. When the door is opened, the element-fins and the accessories are visible; thus, inspection and maintenance can be easily performed.

(3) Breakdown detection and replacement of the elements

The element breakdown detecting device is the double alarm type. If one element in a series has broken down or has seriously deteriorated, an alarm is given but the operation is continued. The replacement of the element may be performed when the operation is at rest. However, if two elements in a series are broken down, the circuit breakers opens and an alarm is given to report the breakdown. The replacement of the elements can be performed (after detecting the broken elements by using a simple reverse characteristic tester) with a torque wrench. The replacement can be accomplished by one man within about ten minutes.

Fig. 3 shows an external view of the silicon rectifier cubicle.

1) Overcurrent fault protection

In rectifiers for railway service, fuse protection is not generally employed because of the high voltage dc requirements and the large short-circuit capacity needed. Protection from dc overcurrent and dc short-circuit faults is performed by a forward overcurrent trip type high-speed circuit breaker (54 P). Protection from ac overload and ac overcurrent faults is performed by an induction disc type and moving iron type overcurrent relay. *Fig. 4* illustrates the coordinated relay protection. The number of silicon elements connected in parallel is determined to satisfy the following two conditions.

(1) It is to be selected so that the charge current per element, out of a number of elements connected in parallel, for an output current of 300% of the rectifier output equals the element rated current. More specifically:

$$8000\ \text{amp} \Big/ \frac{200\ \text{amp} \times 6}{1.2} = 8\ \text{each}$$

(2) The first cycle current value of short-circuit current in the maximum loaded phase when the dc

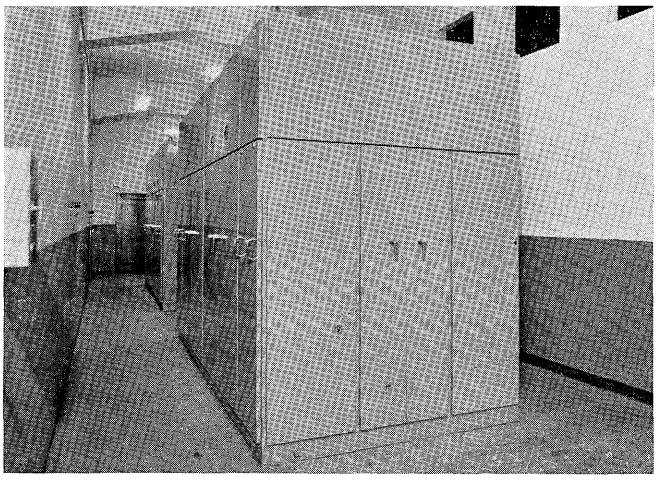

Fig. 3 External view of silicon rectifier cubicle

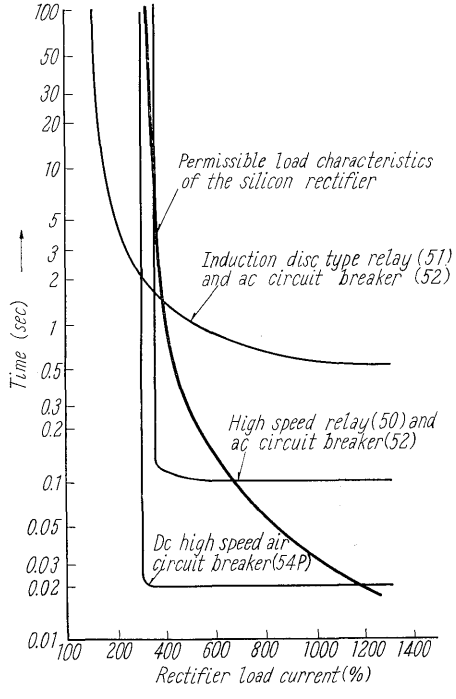

Fig. 4 Overload protecting characteristics for silicon rectifier

side is short-circuited should not exceed the instantaneous thermal capacity of the element. The impedance of the transformer has been selected so that dc voltage regulation is 7% (10% tolerance is included). In order that the high speed circuit breaker completes interruption within approximately 20 ms, consideration need be given to only the first cycle of the short-circuit current.

2) Overvoltage protection

For rectifiers in railway service, the elements are connected in series because of the high dc output voltage. To equalize the voltage per element, condensers are connected in parallel. This also absorbs surge voltages. Dc arrester and ac arrester are provided so that surge voltages will be discharged entering from the dc feeder lines and power receiving lines. Accordingly, the number of the elements connected in series must be able to withstand voltage greater than the voltage limit of these arresters. For example :

(1) Number of elements connected in series against dc side surges.

The voltage limit of the dc arrester is 4800 v at 3 ka :

$$\text{therefore ; } \frac{692\times\sqrt{2}+4800}{1500}=3.8 \rightarrow 4 \text{ each}$$

(2) Number of Elements connected in series against ac side surges.

The volage limit of the ac arrester is 100 kv at 5 ka ;

$$\text{therefore ; } 100 \text{ kv}\times\frac{692 \text{ v}}{22 \text{ kv}}\times\frac{\sqrt{3}\times 0.8}{1500 \text{ v}}=2.8\rightarrow 3 \text{ each}$$

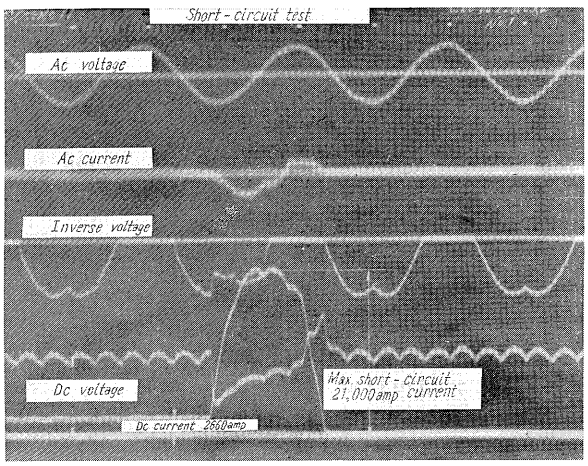

Fig. 5 Oscillogram of simulated short-circuit test

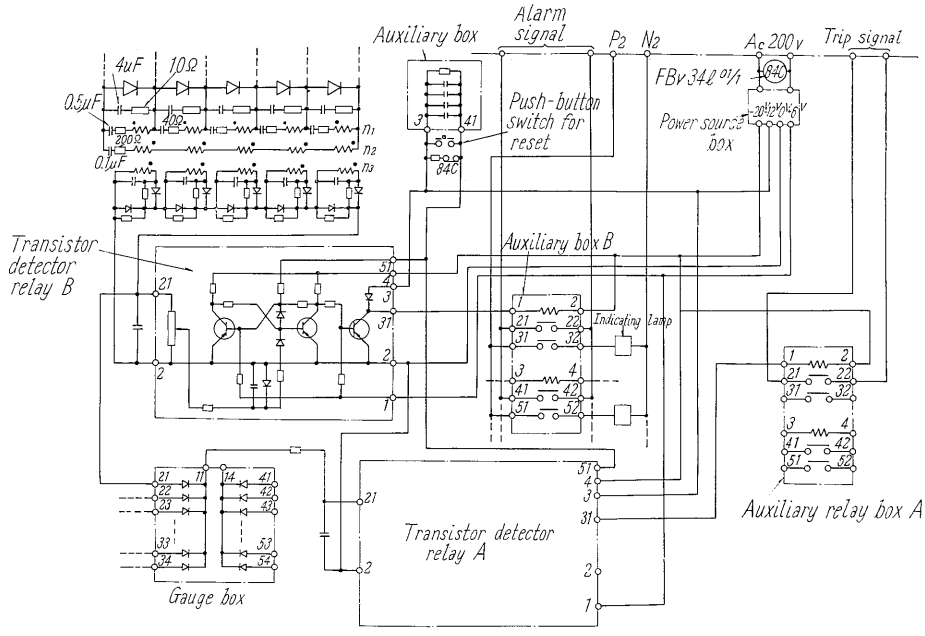

Fig. 6 Transistor circuit for detection of silicon element breakdown

Accordingly, four elements connected in series are sufficient. The use of five has been determined, thereby providing one spare.

In addition, for the positive and negative feeders, a dc arrester is provided and the ac side power receiving is performed by cable, the protection system is sufficient.

(3) Silicon element breakdown detector

Breakdown of the elements is detected by classifying the 240 elements of 5 S · 8 P · 6 A into 12 sets of 20 each 5 S · 4 P, with the individual sets indicated by a lamp. The alarm signal is taken to the outside by the auxiliary relay. *Fig.* 6 shows the fundamental circuit. The device consists of five 3-winding current transformers for detection per each parallel, load resistance, selenium rectifiers, and a transistor relay for the output signal. The current transformers consist of a detecting coil n_1, a standard coil n_2 and an output winding n_3. Normally, the ampere turns of n_1 and n_2 are equal and the magnetic flux within the current transformer is cancelled. If a rectifier element is short-circuited or its inverse characteristics deteriorate, a difference occurs in the magnetic flux within the current transformer and voltage is generated in the output coil n_3 ; this signal is transmitted to the transistor relay. If two or more elements break down or deteriorate, the individual output coil voltage overlaps and is provided to the large signal transistor to become the major breakdown signal. The transistor relay is a self-holding type in which a flip-flop circuit is used ; thus, once it is operated, it holds and the lamp indication remains. To release this condition, the reset push-button is operated.

2. Main Transformer

For the main transformer, as it is installed on the 2nd floor, a Class "H" insulated dry type forced air-cooled transformer (which is light and non-inflammable) is employed.

1) Specifications of the rectifier transformer.

Type: Indoor use Class "H" insulated, dry type air-cooled cubicle type ALTD 162826/20

Rating: 2210 kva Class "D" rating (100% continuous, 150% 2 hr, 300% 1 min) 60 cps

Voltage: Primary: 22 R–21, 5 F–21 F kv
Secondary: 692 v

Current: Primary: 58 amp
Secondary: 751 amp

Connections: Primary: 3-phase delta connection
Secondary; Two 3-phase double star connection, with interphase reactor.

2) Specifications of the power Tansformer

Type: Indoor use Class "H" insulated dry type air-cooled cubicle type ALTD 1429/20

Rating: 2000 kva 60 cps 22 R–21 F–20 F/3.3 kv 52.5/350 amp 3-phase delta/delta connection

The interphase reactor for the rectifier transformer is provided on the upper portion of the main transformer core and is contained in the same cubicle. *Fig. 7* shows an external view of the transformer for the rectifier. *Fig. 8* is an internal view of the same. The cooling system is installed in an independent room in the left-hand portion of the cubicle and is perfectly blocked from the high voltage unit. The specification of both cooling devices is the same in order to permit interchange.

3) Cooling device specifications

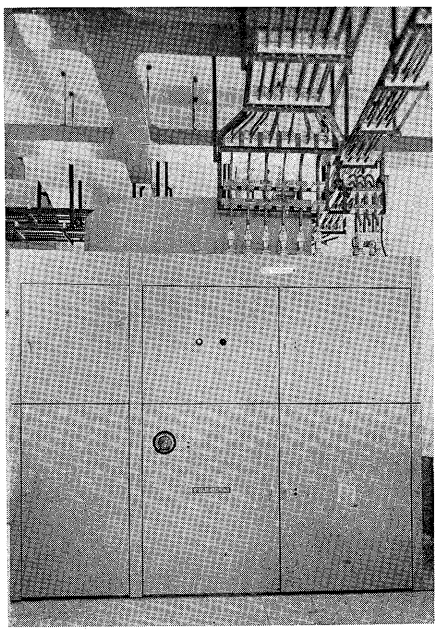

Fig. 7 Transformer cubicle for rectifier

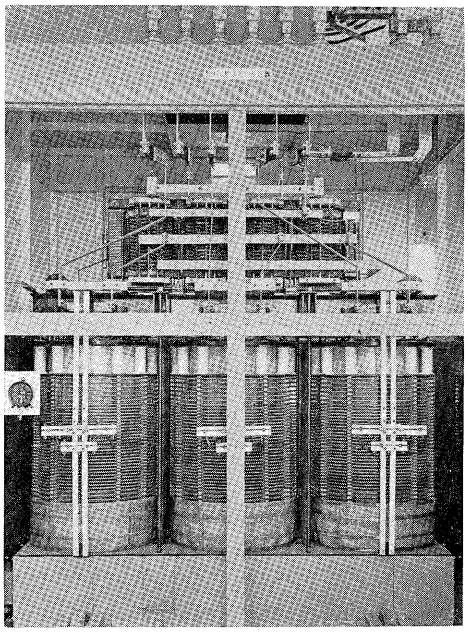

Fig. 8 Internal view of transformer cubicle

Cooling turbo-fan: VN 52.5 2 cu. m/s
70 mm Aq 1140 rpm

Induction motor: ORC 581–6, 6 pole, 3.7 kw
200 v, 60 cps, 3-phase, 1140 rpm

The cooling air is drawn in through the filter installed on the cubicle and exhausted through the cubicle duct and a concrete duct provided on the building. By this system, greater cooling efficiency has been effected and the noise has been eliminated. This Class "H" transformer has been manufactured under very strict specifications, such as the customer specifications [in which the temperature rise is 120°C or below after 150% 2-hour operation (resisting method), and the impulse testing is 120 kv or greater] which are more severe than the JEM 1156 specifications. The cubicle has been installed and fixed in the building and, for maintenance or replacement of the transformer, only the transformer body is pulled out. A comparison of weight and external dimensions between this transformer and a non-inflammable oil immersed transformer of 2210 kva (which was delivered to the Showacho Substation of the Osaka City Communication Bureau in 1961, under the same specifications) is shown in *Table 1*.

Table 1 **Comparison of "H" Insulation Transformer and Non-Inflammable Oil Transformer**

	"H" Insulation Transformer	Non-Inflammable Oil Transformer
Width (mm)	4400	4060
Depth (mm)	2300	3200
Height (mm)	3600	4300
Weight (kg)	9900 (Main body only)	19,300

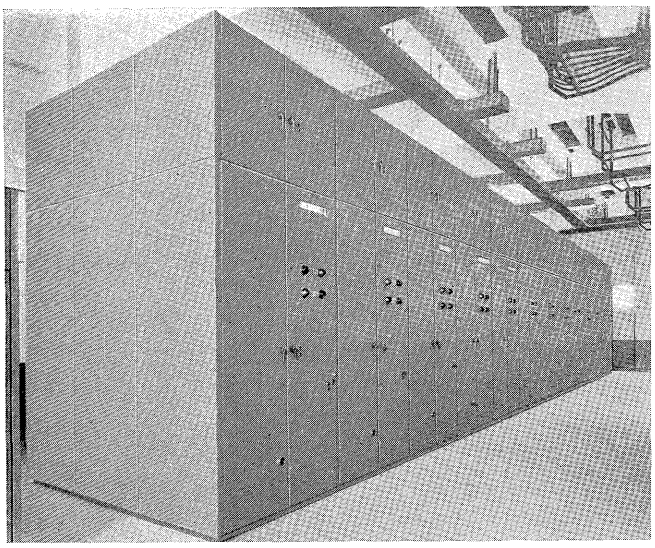

Fig. 9 20 kv metal-clad switchgear

3. Indoor 20 kv Switchgear

The 20 kv switchgear is very efficient from the point of maintenance, safety in operation, and prevention of breakdown extension. This switchgear has a simple but beautiful appearance not seen in other substations. Fuji Electric's own water circuit breaker has been employed in order to provide non-inflammability and eliminate noise. The switchgear consists of 13 metal-clad panels, the structure of which corresponds to JEM 1114 Specification (Class F). Individual internal devices are all non-inflammable. An external view shown in *Fig. 9*.

Major devices contained in the cubicle:

6 × pull-out type water circuit breakers,
24 kv, 600 amp, 1000 Mva

1 × non-inflammable oil immersed self-cooled transformer for auxiliary power source
75 kva, 22 R/0.21–0.105 kv, 60 cps, 3-phase

4 × non-inflammable oil immersed self-cooled transformers for metering.
22,000 v/110 v 2 × 200va, 60 cps

10 × molded type current transformers
23 kv, 40 va, 400–200/5 amp

As an explanation of the water circuit breaker used in this system was reported previously in detail, an outline only is given in the following. This circuit breaker uses distilled water to which ethylene glycol is added for its arc suppressing liquid. As there is no danger of fire and the noise generated is very small, this circuit breaker is very suitable for substations in city areas. The circuit breaker is the pull-out type, in which a plug-in type circuit-disconnecting switch is provided, and is built so that it can be removed and relocated with a specially designed mobile cart. The plug-in type connection terminal is also provided in the auxiliary circuit; thus, inspection and testing can be easily performed by pulling out the circuit breaker. Disconnecting switches can be operated from the outside of the cubicle without opening the doors. Full interlocking of the door, circuit disconnecting switch and the circuit breaker is performed to eliminate the possibility of erroneous operation. In addition, in the 75 kva transformer and the metering transformer circuits a new Fuji-developed load interrupting device has been used that always makes release possible.

4. Dc High Speed Circuit Breaker

A dc high speed air circuit breaker is used to protect the silicon rectifiers and dc feeders. As protection of the silicon rectifiers from overcurrent faults is provided mainly by this circuit breaker, this breaker is very important. This is an excellent and new type circuit breaker (provided with various new devices) which perfectly satisfies the Electric Specification Investigating Committee Standard Specification JEC-152. The major units of this circuit breaker are the same as for the air operated type which was developed in 1963 for the Japanese National Railway. This new circuit breaker was especially developed in response to demands for simple structure magnetic operating circuit breakers from non-government railway companies. For the circuit breakers delivered, the load current is so large at this substation that the rated operating current of the breakers becomes 8–10–12 ka. This rating is not covered by the JEC-152 specification. *Fig. 10* shown an external view of the circuit breaker.

Specifications of the new type magnetic operating dc high speed circuit breaker.

Type: RP 250 1/4000 H
Rating: Dc 1.5 kv 4 ka
Directivity: Positive direction
Rated operating current: 8–10–12 ka
Rated interrupting capacity:

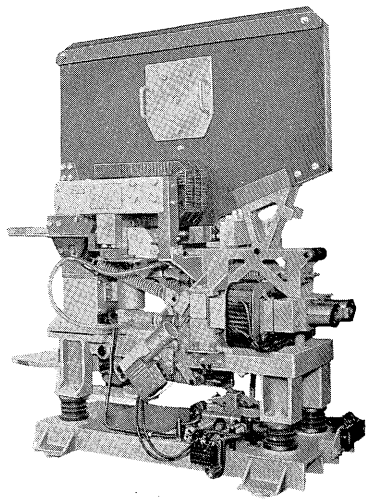

Fig. 10 Dc high speed circuit breaker

Estimated short-circuit current 50 ka at dc 1.5 kv, rushing factor 3×10^6 amp/s

Briefly given, the main features of this circuit breaker are :

1) Superior current limiting characteristics and very stable interrupting capacity resulting from the light-weight switching mechanism unit. The holding mechnism (provided with high speed tripping capacity) and the logically arranged arc blasting mechanism are both compactly arranged.
2) Even with an inverse current of more than 10 ka it will not self-hold ; thus, it can be operated safely.
3) The operating current setting can be changed easily (by changing the position of an adjusting core which is inserted in the magnetic path of the holder magnet), handling is easy, the holding current is less than 0.7 amp and the control panel is simple and compact.
4) The operating system is magnetic. The closing control current is about 50 amp and closing time is approximately 1 second, both of which are smaller than those of old types.
5) To secure small current interruption, this circuit breaker is provided with an air blasting device. The compressed air used in this device provides high compressed air used at the time of circuit breaker releasing, and supply from the outside is not required.
6) The structures of the units where inspection and adjustment are required (such as replacement of the arc contactor, removal of the arc suppression chamber, etc.) have been simplified ; thus, inspection and maintenance are easily made.

Fig. 11 shows an oscillogram of a breaking test.

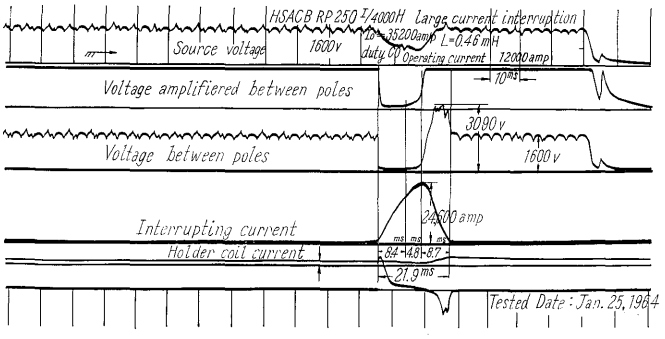

Fig. 11 Oscillogram of a breaking test for dc high speed circuit breaker

5. Switchboard

The composition of the dc substation can be briefly classified into a receiving system, a rectifier system, a dc feeder system, a power signal system, and an internal power source system (Refer to *Fig. 1.*). In a substation where remote control is performed, the control element of the individual systems (mainly

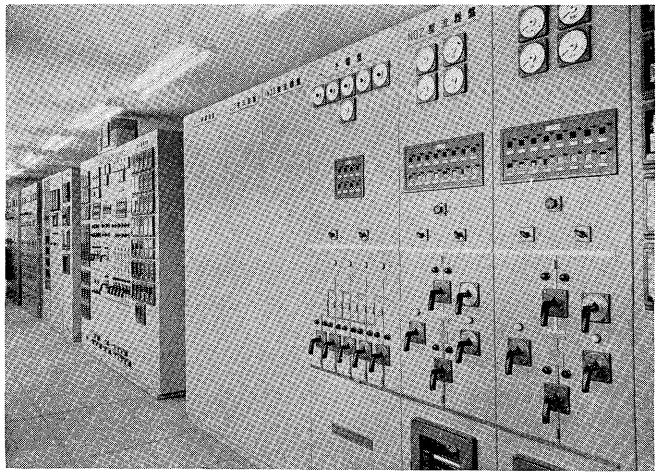

Fig. 12 Switchboard

***Table 2* List of Protection and Interlock Device Conditions**

Circuit	Type of Breakdown	Symbol	Circuit Breaker Opening	Lock	Alarm
Receiving Circuit	Overcurrent fault	51 R	52R	No	Bell
	Ground	51 RG	52R	No	Bell
	Low voltage and missing phase	27 R		No	Buzzer
Rectifier Circuit	Overload on ac side	51G	52G 54P	No	Bell
	Overcurrent fault on ac side	50G	52G 54P	Yes	Bell
	Control power source abnormal	47G	52G 54P	No	Bell
	Rectifier temperature rise	26G	52G 54P	Yes	Bell
	Cooling air off	69G	52G 54P	Yes	Bell
	Reverse flow on dc side	32	52G 54P	Yes	Bell
	Overcurrent fault on dc side	54 P	52G 54P	No	Bell
	Does not start smoothly	48G	52G 54P	No	Bell
	Transformer temperature rise	26 T	52G 54P	Yes	Bell
	Breakdown of fan for transformer cooling	$69T_2$	52G 54P	Yes	Bell
	Rectifier element is unsatisfactory (light)	$71E_1$		No	Buzzer
	Rectifier element is unsatisfactory (heavy)	$71E_2$	52G 54P	Yes	Bell
	Breakdown of fan for ventilation of transformer	$69T_1$		No	Buzzer
Dc Feeder Circuit	Overcurrent fault	54 F	54 F	No	Bell
	Dc frame grounded	64 P	54 F	No	Bell
Power Transformer Circuit	Overcurrent fault	51 P	52P 52S	No	Bell
	Temperature rise	26 P	52P 52S	Yes	Bell
	Breadown of cooling fan	$69P_2$	52P 52S	Yes	Bell
	Breakdown of ventilator fan	$69P_1$		No	Bell
High Voltage power Supply Circuit	Overcurrent fault	52 F	52 F	No	Bell
	Power line ground	67 F		No	Buzzer
	Bus bar ground	64 B		No	Buzzer

control of the circuit breaker) is constructed so that control can be made independently. By considering the rectifier system as one unit to be one controlling element, control is accomplished from 52 G to 54 P in linked action in case of remote control. For direct control, the controlling system is divided into automatic and manual. In the automatic system. control is made in a linked motion from 52G to 54P and, in the manual system, it is individually and independently controlled. Further, in the rectifier system, the operating sequence has been established for all controlling systems so that operation is from starting of the rectifier cooling fan to 52 G, and from closing to 52 P closing for safety of operation. Operation can not be obtained if this sequence is not followed. *Fig. 12* shows an external view of the switchboard. *Table 2* is a list of protection and interlock device conditions.

IV. CONCLUSION

With the recent concentration of urban population, the traffic situation has become more and more critical, and the planning and construction of additional means of transportation and traffic routes has become an urgent necessity. Construction of new subways, and the substations to provide them with power, is a vital part of this new transportation build-up.

The Nakatsu Substation, a typical large capacity city area substation, is an important part of the Osaka City Communication Bureau's efforts to cope with the traffic facility expansion necessities. They have already received one set of 750 v, 750 kw, and two sets of 750 v, 2000 kw rectifier equipment, which are providing satisfactory service at the Asashiobashi and Showacho Substations, respectively. The equipment delivered to the Nakatsu Substation will soon be in operation and is confidently expected to provide excellent performance.

The continuous improvement and development of silicon rectifier elements during the past several years has resulted in large rectifier elements with the capacity to withstand very high overloads. Use of this newly developed rectifier element will make future equipment far smaller. Equipment of 1.5 kv 2 Mw is being manufactured for the Kurosuna Substation of Keisei Electric Railways Co. (utilizing this new element) and will be described in the near future.