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POWER ELECTRONICS APPLIED EQUIPMENT FOR TRACTION POWER SUPPLY SYSTEM

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1. FOREWORD

As power electronics applied equipment for traction power supply system of electric railways of recent years, we can cite thyristor rectifiers and thyristor inverters for braking power regeneration on one hand, as external commutated converters while on the other, as forced commutated converters, there are various equipment using Gate Turn Off thyristor, which is the typical self turn-off type semiconductor device, and the big features in these are that these equipment are put into practical use and made objects of studies.

That GTOs are widely used in the sector of electric railways beginning from traction motor control system, is that these equipment can fully utilize the fruits of their remarkable development of recent years in high withstand voltage and high current techniques.

This paper introduces the outline of the following equipment which are the GTO-applied equipment to traction power supply system of electric railways.

(1) GTO circuit breaker

They are static type circuit breakers that replace the conventional mechanical type DC high speed circuit breakers (hereinafter abbreviated as mechanical HSCB) at DC traction substation; they have excellent characteristics in their maintainability and safety of operation. They have been operating for more than one and half year without trouble at substation of Keio Teito Electric Railway Co., Ltd., large private railway in Japan.

(2) Regenerative power absorbing equipment

They are chopper equipment having resistor as load, and are efficient as simple regenerative braking failure preventing equipment having a record of satisfactory operation for about two years at Keihan Electric Railway Co., Ltd. another large private railway in Japan.

2. GTO CIRCUIT BREAKER

2.1 Background

Technological innovations for non-inflammability, reduction in size and noise, non-vibration, and non-emission of pollutants of the equipment applied to traction substation are much advanced with the background of their being of public utility, and the newest and the most innovative equipment are used for the purpose. However, from the point of view of traction power feeding and protection of the feeding system, the mechanical HSCB considered to have the biggest importance are, principally, the air circuit breakers, so that they are prone to wears in their contacts and mechanically mobile parts, stains of arc chute, etc. and bound to require troublesome maintenance. Also they generate a big arc and explosion at large current interruption.

With this background, the static type HSCBs were much sought for in Japan, and from several years ago on, those utilizing thyristors were manufactured in trial and in parts, such products were put into practical use. Since the development of GTOs, with high withstand voltage and current ratings, development of GTO circuit breakers has come to be accelerated.

(1) It was made possible to eliminate the turn-off capacitor that was indispensable for thyristor circuit breakers, and that, in turn, made smaller also.

(2) As there is a merit that those for DC 1,500V circuit can be composed with one-series connected GTO element.

2.2 Outlines of the equipment

(1) Composition

Fig. 1 shows the outer view, while *Figs. 2* and *3*, composition and structure, respectively. GTO circuit breakers, as they have no turn-off capacitors, have simpler circuit configuration when compared with that of thyristor circuit breakers. The detection of main circuit current is by DCCT (DC current transformer) having a good response and linearity. DCCT is composed of two parallel-connected units and by monitoring their current balance, utilizes it for detecting failures in GTO elements. For processing energy of fault current, non-linear resistor element or Zinc oxide (hereinafter abbreviated as ZnO) element is used and for cooling of GTO itself, a natural cooling system using heat pipe is adopted.

The important parts as control unit and power supply unit are made dual and for fault current calculator unit, micro-processor applied system with self diagnosis function

Fig. 1 GTO circuit breaker

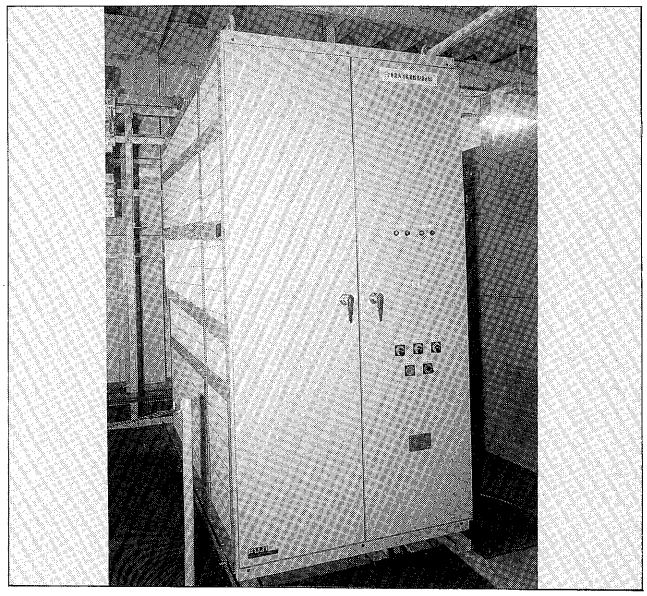

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Fig. 2 Composition

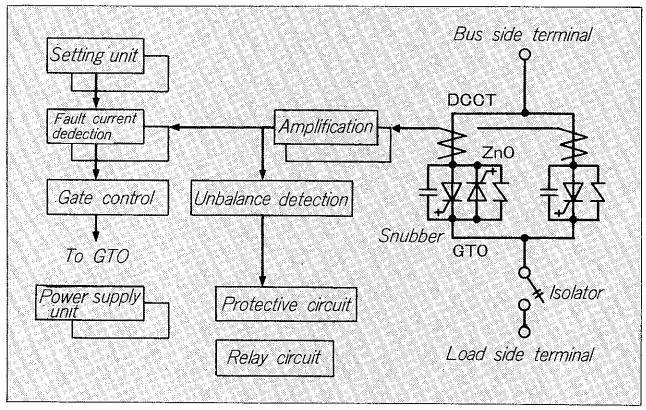
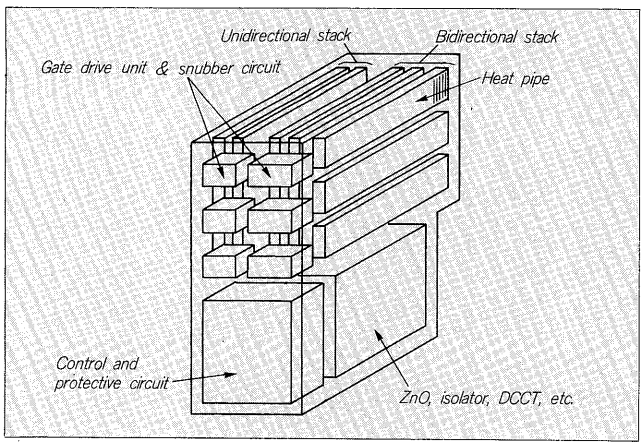


Fig. 3 Structure



is adopted.

(2) Specifications

Table 1 shows main specifications; *Fig. 4*, outer view of the adopted GTO and *Table 2*, characteristics. Reverse blocking type GTO whose off-state and reverse peak voltage

Fig. 4 GTO thyristor

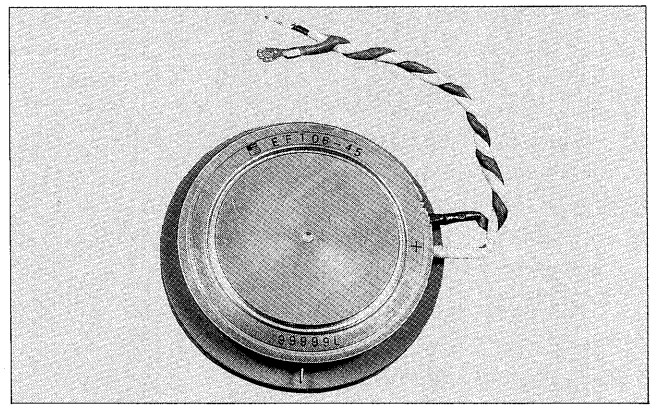


Table 1 Specifications

Item	Specifications
Rated voltage	DC 1,500V
Rated current	Forward DC 3,000A/Reverse DC 1,500A
Rated breaking capacity	50 kA (prospective short-circuit current)
Operating duty	0–10 sec. - CO
Setting current	8 kA (5~8 kA, changeable)
Cooling system	Heat pipe self cooled
GTO element used	EFT06-45
Element configuration	Forward 6 parallel/Reverse 3 parallel

Table 2 GTO characteristics

Item	Characteristics
Model	EFT06-45
Type	Reverse blocking type
Repetitive peak off-state voltage	4,500 V
On-state voltage	2.5 V
Controllable on-state current	3,000 A
RMS On-state current	1,500 A

is as high as 4,500 V, which is about the largest in the world in the capacity, is made up of one series connection.

Rating for each item is determined in due consideration of compatibility with HSCB. Current application is both current directional with GTO elements reverse paralleled.

(3) Principle of operation

Fig. 5 shows operating characteristics. Main circuit current detected by DCCT is calculated moment by moment, and when the current absolute value and di/dt enter the operating area, the equipment will issue the breaking command.

As it is used together with mechanical HSCB, in due consideration of cooperation with rectifier HSCB, the equipment is endowed with fault selectivity characteristics.

Fig. 6 illustrates the operation at the time of fault

current interruption, and the current value shows the results of electronic computer simulation. The following are the description of the operation on basis of the process shown in the illustration.,

(Mode 1) Turn on condition

- A turn on signal is given to GTO and it is under current conducting condition.

(Mode 2) Detection of Fault Current and Breaking

- A short-circuit accident ocurrs on the load side, and the current is increased.
- Calculating unit detects the fault current and applies a turn off signal to GTO which will be extinguished at once.

(Mode 3) Commutation of fault current to snubber circuit

- When GTO is turned off, the fault current will be commutated to the snubber circuit, charging the

Fig. 5 Operating characteristic

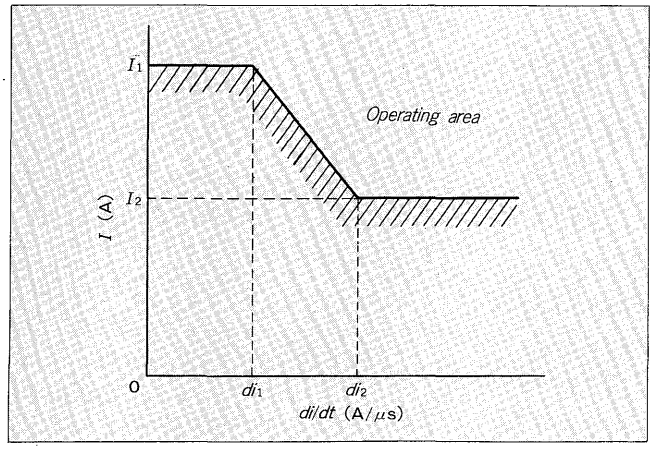


Fig. 6 Operation at the time of fault current interruption

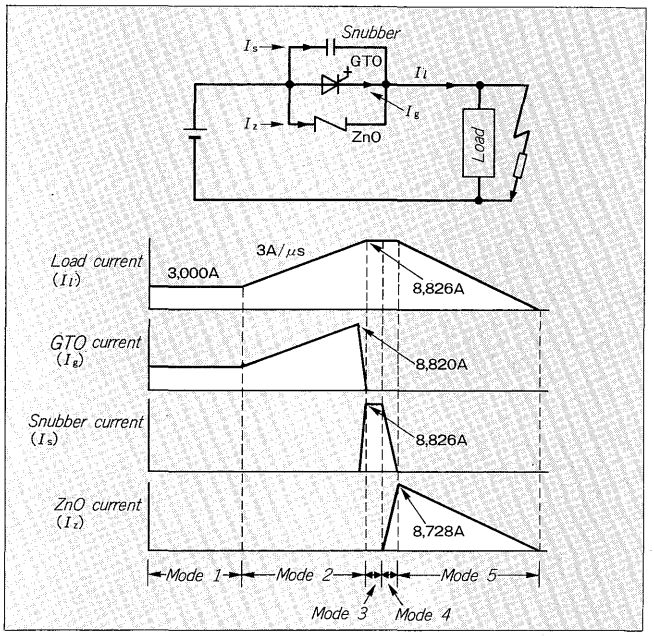
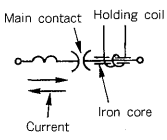
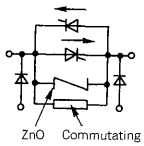
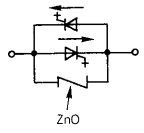


Table 3 Comparison of various types of DC circuit breakers

Items of comparison		Mechanical type	thyristor type	GTO type
Circuit configuration				
Main component	Current conduction	Contact	Thyristor, Commutating circuit	GTO thyristor
	Breaking energy extinction	Arc chute	Zinc oxide element	
Breaking capacity at di/dt = 3A/μs	Fault interruption time	About 20 ms	About 20 ms	About 5 ms
	Breaking capacity	50,000A	*50,000A or more	50,000A or more
	Current limiting value	25,000A	About 1.1 times more than the set value	
	Arc & noise during fault current interruption	Arc and explosion generated	No arc nor noise generated.	
Reliability		Mobile parts, arc chute, contact wears evident. When maintenance is properly effectuated, a high reliability may be obtained.	High reliability because there are no mobile parts.	As this has fewer componsnts, the reliability is high.
Operating characteristics		Operation current error generated due to mechanical wears and tears.	No operation current error essentially.	
Operation-ability	Load closing capacity	There is certain limit of load closing	Load closable under operation range.	
	Operation characteristic setting	The selectivity is determined by the characteristics of inductive shunt.	Selectivity adjustable at will.	
Maintainability		After several fault current interruptions maintenance is necessary on besides the ordinary maintenance items, contact and arc chute.	Ordinary maintenance items only	

* Determined by the capacity of commutation capacitor

snubber capacitor whose voltage will rise linearly. Almost no current will run to ZnO until when this voltage attains the ZnO operation voltage.

(Mode 4) Commutation of fault current from snubber circuit to ZnO

- When ZnO voltage attains the operation voltage, the current in conformity with the ZnO characteristics will start running. By this, the fault current will be commutated from snubber circuit to ZnO.

(Mode 5) Attenuation of ZnO current

- As the residual voltage of ZnO is higher than that of DC bus voltage, ZnO current will be attenuated.
- When ZnO current becomes zero, a series of breaking operation will be completed.

2.3 Comparison of various types of DC circuit breakers

Table 3 shows the comparison of various types of DC circuit breakers and the main features of GTO circuit breakers are as follows:

(1) Because it is of static type, maintenance is dispensable with less work, and the reliability is higher.

(2) As breaking is carried out with high speed according to the characteristics, even during the fault current with large di/dt value, the peak let-through current is low so that the damage due to the failure can be minimized.

(3) No arc nor noise is generated and operational safety is guaranteed.

(4) By setting properly the breaking characteristics, the equipment can be imposed with heavy load closing characteristics and series tripping coordination between circuit breakers can also be obtained.

(5) Even for system with heavy fault energy, by increasing the parallel number of ZnO elements, the energy to be processed can easily by increased.

As the breaker units are made of semiconductors, during the catenary system maintenance period, it is necessary to potentially isolate the equipment by meand of an isolator or other similar device.

2.4 Test results

The equipment was delivered after having effectuated the type tests at shop on the fault current interruption, load closing, electrical noise with-standability.

Further, at site, the equipment was commissioned after having effectuated tests on the effective system of short-circuit breaking, overcurrent tripping by heavy traction current, and mal-operation test across the track section.

Fig. 7 shows the short-circuit breaking test system and *Table 4*, its results.

Fig. 8 and *Fig. 9* shows the oscillogram.

In all the case, the equipment breaks correctly with the set value. And it was given to know that the track impedance was 0.0368 ohms/km, 1.05 mH/km from the count back from the test results.

Table 4 Results of fault current interruption tests

Test No.	Breaking characteristic setting value				Test data		
	I_1 (A)	I_2 (A)	di_1 (A/μs)	di_2 (A/μs)	Breaking current (A)	di/dt (A/μs)	Total breaking time (ms)
1	1,000	500	0.1	0.5	925	0.20	8.5
2	3,000	1,500	0.1	0.5	2,940	0.22	26.4
3	5,000	2,500	0.1	0.5	4,400	0.28	40.1

Fig. 7 Fault current interruption test system

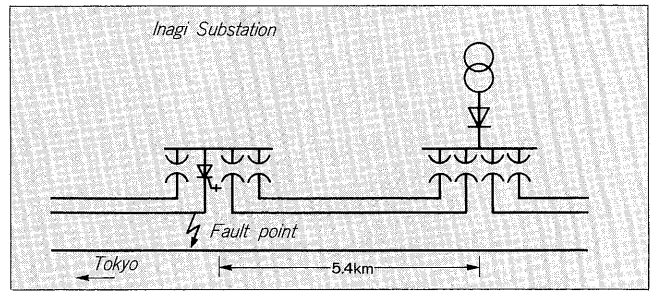


Fig. 8 Site fault current interruption test oscillogram (Test No. 3)

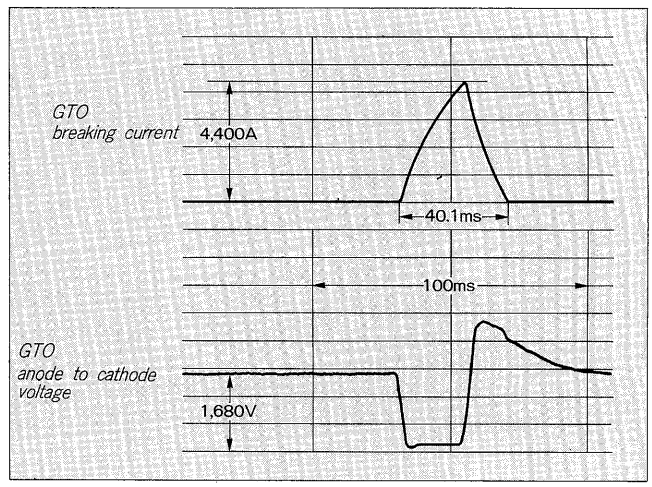
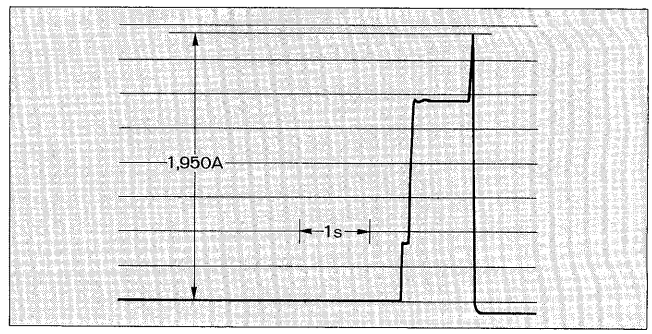


Fig. 9 Local overcurrent breaking test oscillogram (Setting value: 2,000A)



3. REGENERATIVE POWER ABSORBING EQUIPMENT

3.1 Background

With the tendency of adopting more and more electric

vehicles with regenerative braking system as chopper controlled cars or VVVF inverter controlled cars, it is sometimes necessary to provide measures for preventing regenerative braking failure in case there are no motoring trans. Keihan Electric Railway Co., Ltd. Ohtsu Line (DC600 V, feeding system, 25.2 km) is a line well known for its sharp gradient in its mountainous section, attaining the maximum $66.7^{0}/_{00}$, for which vehicles having the speed suppress regenerative braking system were used since long time ago as the first line to do so in Japan. However, when their is no motoring train during braking, the regenerative braking would be lost, so was it with riding comfort and maneuverability.

As means to resolve this problem, in the vicinity of Hama Ohtsu Station, for the first time in Japan, a resistor chopper type regenerative power absorbing equipment using GTO was employed.

3.2 Outline of the equipment

(1) Composition

Fig. 10 shows the outer view; *Fig. 11*, the main circuit diagram; *Fig. 12*, GTO chopper unit outer view, and *Fig. 13*, layout. The equipment is installed in a long slender space of 11.5 m x 2.6 m in the vicinity of Hama Ohtsu Station, being composed of GTO chopper unit, HSCB, and resistor, and remote-supervised and controlled. The equipment is naturally cooled and GTO is of unit plug-in construction so that its replacement is easy.

(2) Specification

Table 5 shows the main specifications. GTO works on peak-off-state voltage of 2,500V and controllable anode

Fig. 10 Regenerative power absorbing equipment

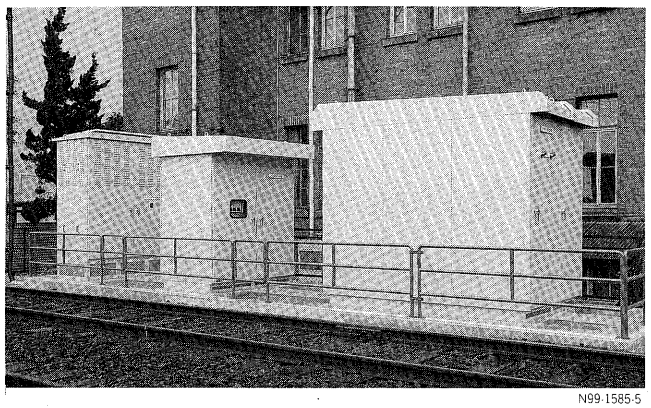


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Fig. 11 Main circuit diagram

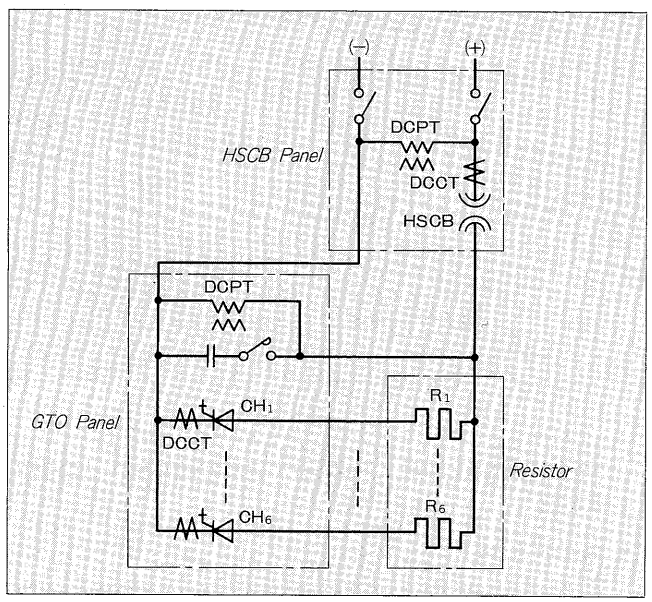

Fig. 12 GTO chopper unit

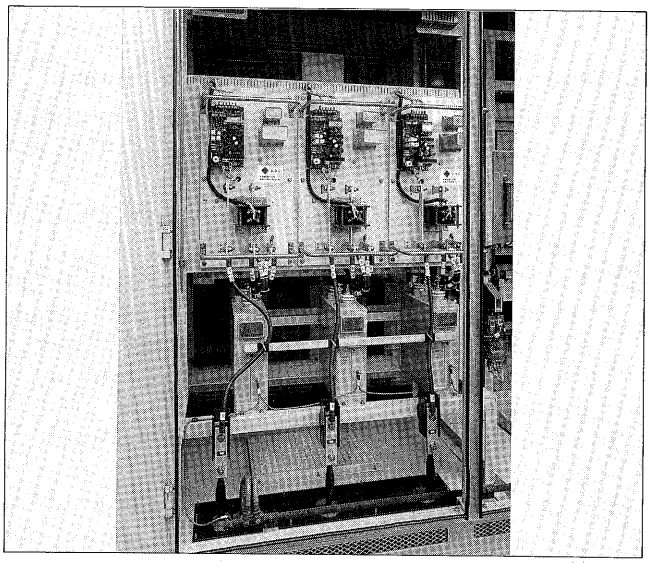

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Fig. 13 Layout

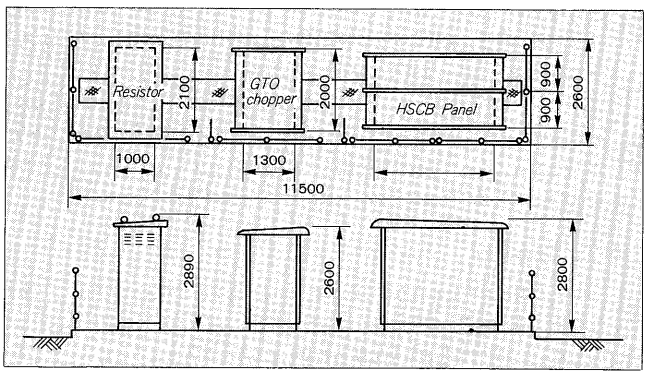


Table 5 Specifications

Item	Specifications
Rated voltage	DC 750V
Rated current	DC 2,600A, 30 sec. (8-min. interval)
Operation ripple frequency	360 Hz
AVR set voltage	675-700-725-750-775-800V
Installation	Outdoors installation
Cooling system	Natural cooling
Control power supply	DC 100V
Fault indication	Displayed per unit.

Fig. 14 Principle of operation

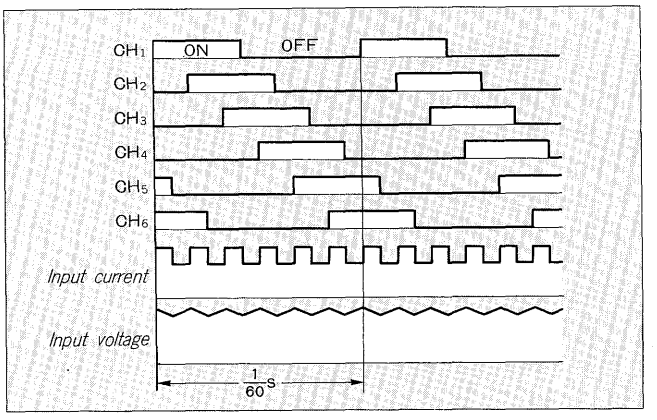
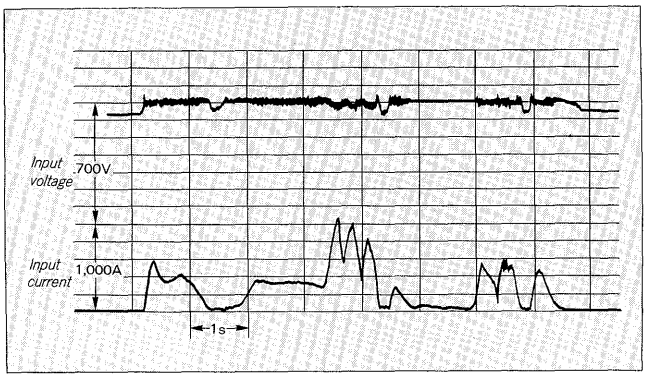


Fig. 15 Oscillogram at operation



current of 1,000A, anode short type.

(3) Principle of operation

Fig. 14 shows the principle of operation. *Fig. 15* shows the oscillogram at the time of operation with the operation set value of 700V. The equipment consists of 6 GTO chopper unit, and each one of the chopper carries out the phase difference operation with the difference of 1/6 chopping cycle, so that as the equipment as a whole works on the ripple frequency of 360 Hz. Purpose of this phase difference operation is to minimize the chopper switching loss, and the reason why the ripple is set to 360 Hz is to prevent the harmonic trouble by making it equivalent to the six-phase double bridge rectifier of the substation.

Control characteristics are those of AVR with load current compensation shown in *Fig. 16*. The aim of load current compensation is to facilitate the absorption of regenerative power from as far as possible by reducing the voltage in proportion of current intensity.

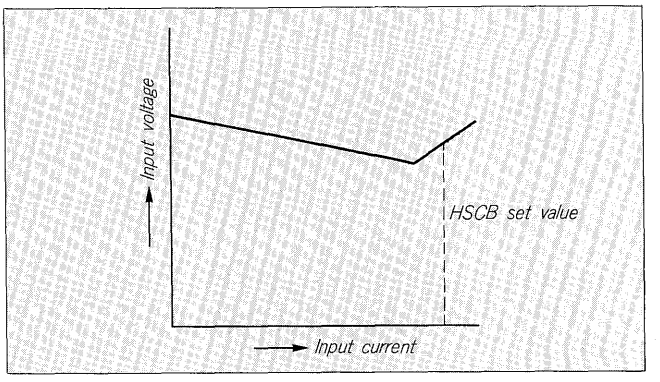
The equipment is provided with measures against generation of failure in any chopper unit of one phase. If this failure takes place, the chopping cycle is switched over to 5/6 one, and with the five normal units, the capacity-reduced operation with 360 Hz ripple frequency can be kept going on.

3.3 Features of the equipment

As this equipment functions on the principle of consuming the regenerative energy as heat, though it may not be the energy-saving type equipment, it has many superb features as follows.

(1) Equipment configuration is simple, and its installation cost is low.
(2) Installation site is not restricted to substations, but any narrow space along the rail, and no housing is necessary.
(3) The necessary power supply is only for control purpose.
(4) No harmonic troubles.
(5) As no transformers are required, there is no iron loss during the machine non operation, so that as a whole the total loss is low.
(6) No commutation failure.
(7) The equipment does not include any heavy component, so that the work on the equipment is extremely easy.
(8) As this equipment carries out a continuous control, no shocks are exerted on vehicles when the equipment operates.

Fig. 16 Control characteristics



3.4 Operation records

The operation record of this equipment for last one and half year (from July, 1986 to December, 1987, operation set value: 725V) is as follows.

(1) Regenerative braking failure

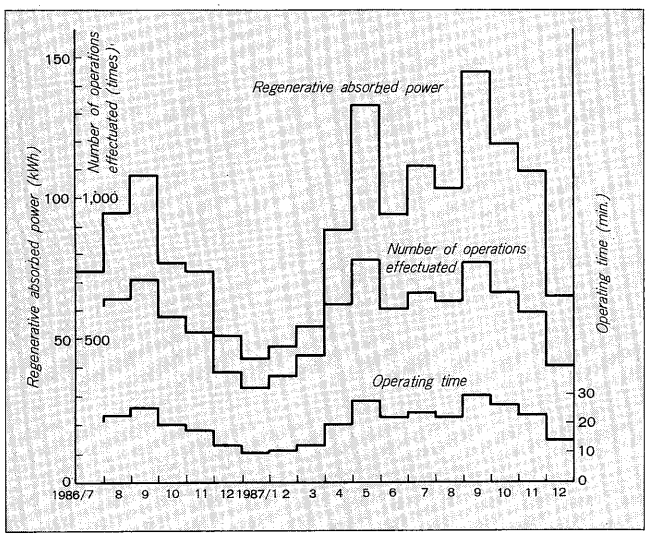
It was confirmed that the regenerative braking failure within the projected range (radius of 4 km) was completely eliminated as planned, and the regenerative braking failure in the peripheries well beyond the projected range was also largely suppressed.

(2) Data on operating record

Fig. 17 shows the quantity of regenerative power absorbed, number of operations effectuated and operating time per day. Summing up the figures, they are as follows:

- Average power absorbed per day: 90 kWh
- Average number of operations effectuated per day: 570 times
- Average duration of operation per day: 20 minutes
- Maximum power absorbed per day: 200 kWh
- Minimum power absorbed per day: 40 kWh
- Maximum current: 2,500A
- Average current during the operation: 370A

Fig 17 Absorbed power, number of operations effectuated, and operating time.



- Most common operation time: about 3 seconds

The absorbed power is unexpectedly small, and it is comparatively large during the intermediate season when no air conditioners nor heaters are used.

4. CONCLUSION

Among the power electronics applied equipment for traction power supply system, the authors introduced the outline of 2 GTO-applied equipment in this paper.

As for GTO circuit breaker, the future problem we face for applying the further development of GTO element-applied technology and lowering of loss, is as to how we should establish a rational method of defining the current rating and, on the basis of which, miniaturization thanks to the reduction of tolerance. We believe that GTO chopper type regenerative power absorbing equipment will be effective, as the measures for preventing simply the generation of regenerative braking failure prone to occur with the use of vehicles with regenerative braking system in the existing lines, so that the studies on their use utilizing their merits will be further developed. And with this as a foothold, use of the power electronics applied equipment for traction power supply system will be further diffused from now on.