UDC 621. 335: 621. 314. 63. 07

APPLICATION OF THYRISTORS IN ELECTRIC ROLLING STOCK

Yukio Miyakami
Railway Application Engineering Dept.

I. INTRODUCTION

The Japanese National Railways (JNR) commenced ac electrification in 1955 on its Senzan Line and it has been continuing steadily ever since. However, the development of semiconductor rectifier elements, especially silicon elements, of larger capacities and higher reverse voltages has lead to greater reliability and capability in ac/dc electric rolling stock and has provided an impetus to further ac electrification. From the initially developed stud type silicon rectifier element with soldered connections, the next step was the pressure-contact type using plate springs. This type was developed because of the thermal stress on the soldered junction parts due to the highly intermittent load characteristics of electric rolling stock. Subsequently a disk-type elements was developed so that both surfaces could be cooled by a gas or liquid such as oil. With all this remarkable progress, it has been possible to not only increase the capacity and reverse voltage of the elements themselves, but also raise the capacity of the equipment as a whole, as well as making it more compact and lightweight. Thyristors are finding a wide range of applications in the field of electric rolling stock because of the above-mentioned advantages of silicon rectifier elements and also because of their rapid switching performance. The Japanese National Railways has already started to use them for several applications. This practical application of large capacity thyristor elements with high blocking voltages has given rise to many advantages. For example, by combining the previous tap-changers and silicon rectifier elements, it is possible to change the traction motor voltage control system to thyristor phase control. Also since stepless continuous control of the electric coaches can be effected with thyristors, it is possible to improve ride comfort and track adhesion. Because of the contactless construction used in the main circuit switches, maintenance and inspection costs can be greatly reduced. Due to the increases in capacities and blocking voltages of thyristors, tests are now being conducted aiming at the practical application of stepless continuous thyristor control and contactless construction by means of thyristor choppers etc. in dc electric rolling stock. As the capacities, blocking voltages and speeds of the thyristor elements increase, several problems arise concerning their application in electric rolling stock. These include the elimination of commutators from traction motors and making the equipment more compact and lightweight by the use of new cooling systems etc.

II. LARGE CAPACITY SEMICONDUCTOR ELEMENTS FOR ROLLING STOCK

Semiconductor elements for traction motors in rolling stock must operate stably over long periods coping with the highly intermittent loads characteristics of rolling stock. Since they are to be inserted in the coaches, the equipment must be compact and lightweight but the elements used must have high capacites and reverse voltages. For some time Fuji Electric has been developing semi- conductor elements with large capacities and reverse voltages and at present are mass producing a series of large capacity power semiconductor elements. As the elements increased in capacity, the soldered connections between the junction part and the outer part used in ordinary small and medium capacity elements proved to be too weak especially in rolling stock where the repeated thermal stress arising due to the highly intermittent loads can cause element breakdown. The large capacity elements manufactured by Fuji Electric employ a pressure contact construction with plate springs etc.[1] in place of the soldered connections and this problem is therefore eliminated. This effectiveness of this contact method has been proven by the good results obtained over long periods of practical application in various fields. Also with the large capacities of the elements the cooling effects obtained with usual screw-in cooling system are insufficient to handle the heat losses which occur at the junctions and thermal limitations arise. To solve this problem, Fuji Electric has developed a disk type construction for the element based on the pressure contact principles. As was

Table 1 **Fuji Silicon Diode and Thyristor Elements Corresponding to JNR Standards**

JNR Type	SI 300	CSI 250	CSI 400	CSI 400 x	SI 800
Fuji Type	SIN 01	GTN 01	KGP 03-25	KGP 21-13	KSP 03-25
Main Characteristics	1200 v 280 amp	1200 v 250 amp	2500 v 400 amp	1300 v 400 amp	2500 v 800 amp
Remarks	Stud-type diode	Stud-type thyristor	Flat-packaged disk type thyristor	Flat-packaged disk type thyristor (high speed type)	Flat-packaged disk type diode

described previously, cooling of both the anode and cathode surfaces is possible with this type of construction and it has made possible great increases in element capacity[(2)]. From some time before the Japanese National Railways have issued standards for large capacity semiconductor elements for rolling stock because of uniformity required in parts for mass produced rolling stock and also to make semiconductor elements more applicable for use in rolling stock. *Table 1* shows a selection of the standard series of large capacity semiconductor elements manufactured by Fuji Electric in accordance with the standards set by the Japanese National Railways, along with their main properties.

III. COOLING SYSTEMS FOR LARGE CAPACITY SEMICONDUCTOR ELEMENTS USED IN ROLLING STOCK

There have been several cooling systems developed for use with power semiconductors, but in the majority of cases, the air cooling system is generally employed at present. However, as the capacity of rectifier elements increase, it becomes necessary to reconsider the ordinary air cooling system and also to make the cooling equipment larger, which runs counter to the compact equipment demanded for rolling stock. When the air cooling system is used, it is necessary to obtain the cooling air from the exterior and it is also necessary to expose high voltage parts to the cooling air. This means that the surrounding atomsphere can have a great influence and considerable precautions are needed to prevent insulation deterioration due to snow, mois ture, dirt, etc. To solve this problem, Fuji Electric developed a disk type form for the element in which the coolers are sandwiched on both surfaces of the element and held in place by pressure contacts. Therefore, the heat resistance between the elements and the coolers is greatly reduced. When this element/cooler structure is arranged in the form of a stack, immersed in oil, and hermetically sealed, the high voltage parts do not come into contact with the atmosphere. This new type of equipment represents a revolutionary breakthrough over former rolling stock rectifier equipment. Since all the high voltage parts are immersed in oil in this type, the insulation distances are short, the equipment is much more compact than air cooling systems of the

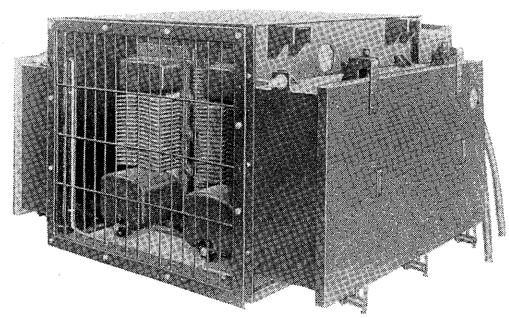


Fig. 1 Oil-cooled silicon rectifier set for electric rolling stock

sameacity, cap there is no need to worry about insulation deterioration and maintenance is not required. *Fig. 1* is an outer view of equipment employing this system. This equipment has been used for long time by the Japanese National Railways with good results.

IV. APPLICATION OF THYRISTORS IN AC ELECTRIC ROLLING STOCK

The major applications of thyristors in ac rolling stock are as follows:

1. Thyristors Used as Switch Elements

1) Arcless tap-changer[(3)]

The previous voltage control system for ac rolling stock traction motors was tap changing of the voltage transformer windings, but an air-circuit breaker was usually used for load current switching. Since the number of such switching is very high in rolling

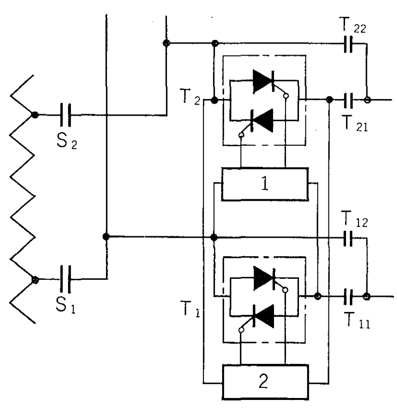


Fig. 2 Arcless tap-changing circuit

stock, these breakers required considerable maintenance. However, the great progress made in power thyristors in the last few years has made it possible to replace these circuit breakers with completely arcless switching, and in Europe, this new system has become standard in several hundred mass-produced ac locomotives. The operating principles of these systems will be outlined below.

In *Fig. 2,* T_1 and T_2 are thyristor switch elements each containing thyristors connected in anti-parallel. Gate control equipment 1 and 2 provide control signals to the respective thyristors. S_1 and S_2 are selector switches for choosing the transformer tap winding. When the current flowing between S_1 and T_1 is switched up one step to tap S_2, the gate of thyristor switch T_2 is in the no-singal state so that S_2 is closed. When the gate signal of thyristor switch T_1 is cut off, the current flowing in S_1–T_1 is out off after a half-cycle delay. If a signal is applied to the gate of thyristor switch T_2 immediately after this, the main motor circuit is switched to tap S_2 with almost no time delay. After this S_1 is open to complete the switching of all circuits.

T_{11}–T_{22} are switches provided as a means of minimizing the current load of the thyristor elements. Because of these switches, it is possible to use thyristors with short-time current ratings.

2) Arcless tap-changing with phase shifting

As can be seen from *Fig. 3*, the operating principles of this system are basically the same as those of the system outlined in 1). However, since phase shifting is also provided, it is possible to continuously vary the voltage between the taps so that the voltage between the taps can be continuously controlled simultaneously with arcless changing.

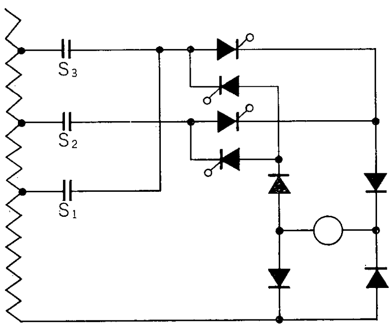


Fig. 3 Arcless tap-changing circuit with phase shifting

2. Contactless Continuous Control Using Thyristor Phase Control

Fig. 4 shows the operating principles of the system. The (a) part of the figure is the case when the thyristors are connected in antiparallel and used as an ac switch. Continuous control is possible by performing thyristor phase control. Part (b) shows a circuit which operates the same as that in (a), but the thyristors which are phase controlled also serve as part of the arm of a rectifier bridge. This hybrid bridge differs from the previous type. In both (a) and (b), all the circuits can be contactless, except for the breaker used for protection on the primary side and this circuit is therefore superior to those described in IV. 1. in respect to maintenance and inspection.

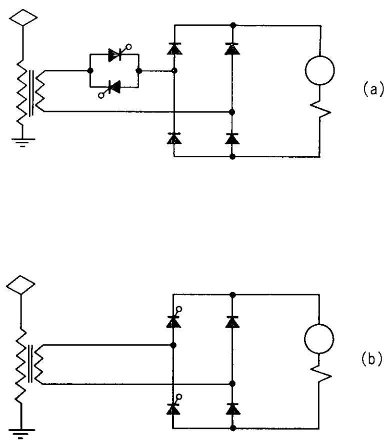


Fig. 4 Stepless control circuit with phase shifting

3. Regenerative Brake Using Thyristors

Fig. 5 shows a circuit which employs thyristors for powering and regenerative braking. The thyristor switch is connected as a pure bridge. During powering, it operates as a rectifier which is also used for phase control. During regenerative braking, it operates as a natural commutated inverter which is commutated by the source voltage and recirculates regenerative power to the power source. Because of its characteristics, the field winding of the motor is used as a series winding during normal powering and as a shunt winding (shown in the diagram) during braking. However, since both relaible and rapid control are possible because of the development of automatic control systems with electronics, it is also possible to make a permanent shunt field motor so that there are series winding characteristics for powering and shunt winding characteristics for braking. This system has already been put to practical use[4]. As this system is operated as a natural com-

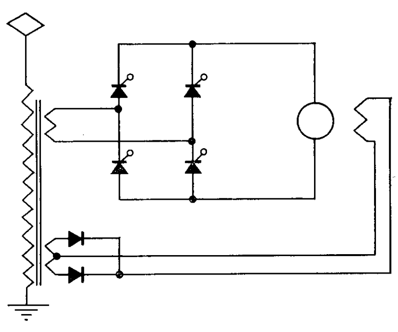


Fig. 5 Regenerative brake with thyristor bridge

mutated converter when braking, if a commutation failure is occured, overcurrents will occur on the dc side due to the short-circuit condition and therefore a high-speed circuit breaker is normally employed for protection. However, this breaker can now be eliminated since an overcurrent supression method by which the main motor field undergoes rapids reverse excitation during commutation failures has been developed and put into practice[4].

V. APPLICATIONS IN DC ELECTRIC ROLLING STOCK

1. Application in Dc Rolling Stock Supplied by Trolly Wires

For many years, dc series wound motors have been used in electric rolling stock driven by a dc power supply because their characteristics are ideal for rolling stock operation. However, the use of thyristors has made it practical for the first time to use systems in which large variable dc voltages can be obtained from a constant voltage source without series resistors etc. When thyristor choppers are used, the elements must not only have large capacities and high blocking voltages, but also must be of the high speed type since the thyristors must serve as switch elements for high-speed circuit switching. At present Fuji Electric is mass producing the high-speed type thyristor listed in *Table 1*, and this elements fulfills all the requirements for switching elements. The following will explain the problems which occured when the thyristor chopper was adapted for use in chopper equipment for dc electric rolling stock equipment now manufactured by Fuji Electric.

1) Main circuit connections

Fig. 6 shows the main circuit of the dc chopper. As is clear from this connection, the equipment can perform both powering and regenerative braking by means of the chopper.

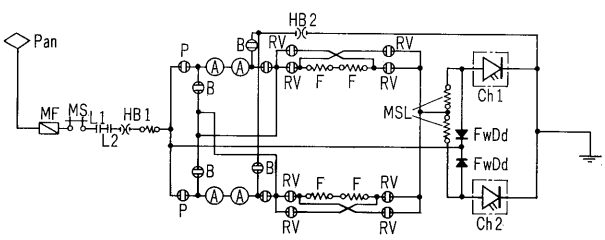
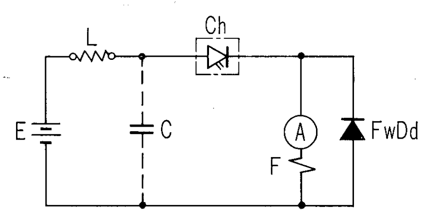


Fig. 6 Main circuit for dc chopper

Simultaneous control of 4 main motors with ratings of 90 kw 375 v is performed in two groups of two circuits in series. Each single phase chopper consists of a main thyristor, auxiliary thyristor, commutating capacitor and reactor. A commutating circuit is thus formed which provides sufficient commutation even during voltage and current variations, especially low current variations. There are 2 single phase choppers connected in parallel and they are operated with a phase difference of 180° in order to minimize the amount of pulse current in the main motor as well as the capacity of the power source filter.

2) Power source filter[5]

When chopper equipment is adapted to dc electric rolling stock supplied with power from trolly wires, the inductance of the source side including the wires presents a problem. As is well known, the chopper operates, on the basis of high speed switching by a thyristor switch in respect to a dc power supply. By varying the switching period and switching time ratio, any dc voltage lower than the source voltage can be supplied in respect to the average values of the load. Therefore, a current with an approximately square waveform will flow in the source only when the thyristor switch is closed. If this current waveform is in the vicinity of signals with harmonic components or communication lines, there is a chance of various disturbances due to induced voltage. However when a capacitor as shown by the broken line in *Fig. 7* is included, this approximately square wave current becomes a direct current including a small ac component. As can be seen from the figure, when the inductance of the trolly wires etc. is present on the source side, resonance can occur between the dc circuit and the capacitor. This is especially dangerous when the chopper operating frequency and the resonance frequency are very near since the capacitor voltage and current could increase remarkably.



Ch:	Chopper	*L*:	Reacter
C:	Capacitor	*E*:	Power source
A, *F*:	Motor	*FwDd*:	Flywheel diode

Fig. 7 L-C filter circuit

The inductance in trolly wires changes according to the position of the train and therefore the resonance frequency also changes. If a comparatively large reactance is connected in series with the trolly wire inductance to avoid resonance, and if the resonance frequencies of the capacitor and reactor are set at a small fraction of the operating frequency of the chopper, the inductance from the overhead lines can be minimized and there will be no chance of the filter resonance frequency being near the chopper operating frequency. For example, in order to keep the equivalent disturbance current in respect to communication line inductance to about 0.3 amp for an trolly wire current of 100 amp the resonance frequency of the filter is kept low, about 1/10th that of the chopper operating frequency.

3) Control and protection systems

There are various well know methods for voltage control using choppers. However, when the power is supplied from trolly wires as mentioned above, and a filter is provided to prevent wave form distortions, it is desirable that the chopper operating frequency be as far away as possible from that of the filter, and therefore a method in which the time the chopper is closed can be varied at a constant frequency is the most suitable. Fuji Electric therefore uses this type of system for voltage control. To make chopper equipment practical, not only must the thyristors used in the main circuits have high capacities, speeds and reverse voltages, but the thyristors used in the control and protective circuits must also be highly reliable, quick acting, and stable in respect to noise, as well as compact and lightweight. The chopper equipment manufactured by Fuji Electric consists of DCPT and DCCT units employing magnetic resistance elements[6] with rapid-acting characteristics for detectors used in current limit control and protection against overvoltages and overcurrents. The amplifiers and logic decision elements all contain TRANSIDYNE and F-MATIC[7] elements based on silicon transistors. With these components, Fuji choppers fulfill the standards of reliability, rapid-action and stability against noise required in rolling stock.

2. Application in Electric Cars with Batteries

The large increases in the number of automobiles in recent years have served to emphasize the public hazards such as exhaust gases and noise which automobiles cause in urban areas. At the same time, as investigations were begun to find effective countermeasures, the development of large capacity thyristors made highly efficient control possible and more attention was paid to equipment using electric drive systems. Fuji Electric developed experimentally electric devices for use in automobiles and industrial vehicles powered by batteries. At present, this equipment is operating satisfactorily.

1) Electric automobile

An electric automobile employing a thyristor chopper control system was developed experimentally in cooperation with Furukawa Battery Co., Ltd.

(1) Outline of experimental car

The experimental car is a reconstructed compact gasoline passenger car. The engine and related parts were removed. In the front engine compartment were placed a 9 kw dc motor, a thyristor chopper and a controller. A special compact, lightweight lead storage battery was placed in the trunk compartment.

Since the car is operated by a no-cluth system, forward/reverse changing is effected by an electric switch, and speed control is performed solely by the accelerator, operation is very easy. If the accelerator is released during driving, the regenerative brake (equivalent to the engine brake) is automatically engaged to insure driving safety, and the control energy is reabsorbed by the battery so that the car can travel long distances without recharging.

(2) Drive motor

This motor differs from ordinary dc series wound motors in that regenerative control, field suppression and forward/reverse changing are easy, fast and accurate. This is because the field winding consists of a specially devised 2-winding type construction. When the speed exceeds a certain value, the field is automatically suppressed by means of a simple speed detector attached to the motor. The motor has high speed characteristics and special consideration has been given to reducing power consumption during acceleration at low speeds.

(3) Control equipment

The main part of the control equipment is the thyristor chopper which employs an oscillation type double swing system and operates stably even when there are load current variations.

The control system commands the voltage to be applied to the motor in accordance with the angle through which accelerator is pressed. Motor current variations are supressed during starting by a variable frequency system and in the high speed range, the voltage utilization factor is improved and efficiency increased by means of control frequency reduction.

The protection equipment insures that there will be no commutation loss by stopping the chopper within one cycle when the rapid current

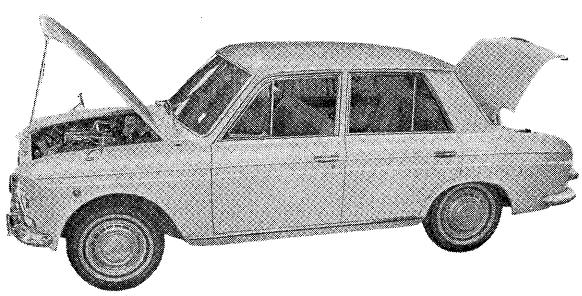


Fig. 8 Electric automobile with battery

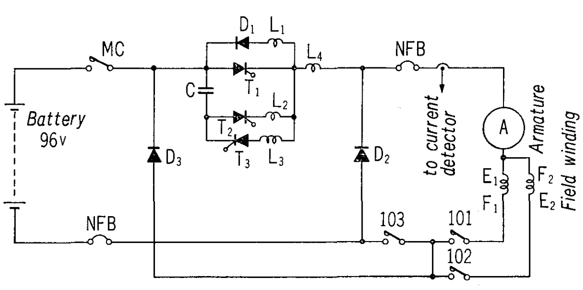


Fig. 9 Main circuit of electric automobile with regenerative brake

change occurs just befor commutation loss. This protective system guarantees complete safety. *Fig. 9* shows the circuit connections used in this equipment.

(4) Governor

The governor operated by the accelerator is a contactless, non-slip type which utilizes a magnetic resistor. The service life is long since there is absolutely no breakdowns due to mechanical vibrations or wear.

(5) Capabilities of the experimental car

Maximum speed :	70 km/hr
Economy speed :	40 km/hr
Gradeability :	10 km/hr when 25% gradient 35 km/hr when 5% gradient
Battery :	150 amp-hr 96 v
Occupancy :	5 persons (max.)
Driving distance/battery charging :	70 km
Dc motor :	9 kw 85 v 2000 rpm

2) Industrial forklift

The forklift is subjected to severe operating conditions such as very low speeds during starting and quick turns during both forward and reverse operation. To fulfill all these conditions, and also to simplify the equipment and maintenance the electrical equipment is arranged in units and a completely contactless control circuit is employed. The equipment is also in a molded casing so that it will be resistant to moisture and vibrations and thus more reliable. At present, electrical equipment is being manufactured for 1 ton and 1.5 ton forklifts.

3) Other systems

Battery driven motors with no brushes and commutators are now being developed to replace dc series wound motors.

VI. APPLICATION OF THYRISTORS IN AUXILIARY AND CONTROL CIRCUITS

1. Thyristor Inverters for Auxiliary Circuits

Static type high voltage thyristor inverters have now become practical as power sources in auxiliary and control circuits for dc electric railways because of the recent development of high speed elements with high blocking voltages.

The conditions required of these inverters are as follows :

(1) Input voltage variations are large.
(2) Surge voltages from the power source side are high.
(3) Line jumping on current collector of pantographs etc., section transit, and short-time power source interruptions due to above phenomena occur rather frequently.
(4) It must be compact and lightweight
(5) There must be stability in respect to noise both inside and outside to rolling stock and there must also be no wave generated to cause faults in other equipment.

Naturally, in addition to stable operation in respect to the above conditions, economy can not be overlooked when considering thyristors.

A typical high tension thyristor inverter of single phase 9 kva for rolling stock which was recently manufactured by Fuji Electric will be introduced below. The ratings of this inverter are as shown in *Table 2.*

In consideration of the previously mentioned conditions, various new systems are employed in the control and protective circuits. *Fig. 10* is an external view of this inverter.

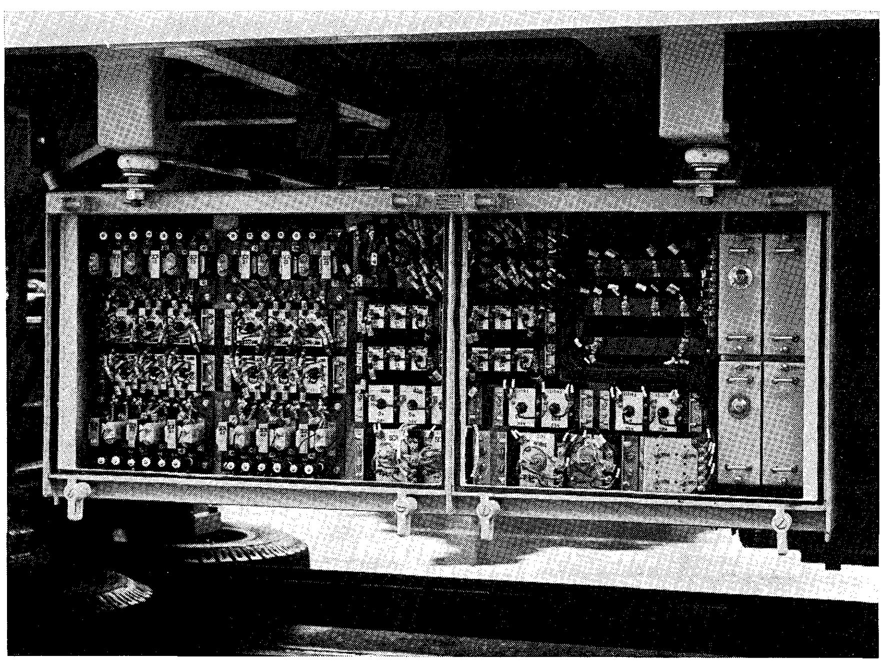


Fig. 10 High tension thyristor inverter for electric rolling stock

Table 2 **Ratings of High Tension Thyristor Converter**

System :	Thyristor bridge type		
Ratings :	Capacity	9 kva	
	Input voltage	Dc 750 v	
	Output	Ac 100 v	50 Hz

2. Contactless Control Circuits Using Thyristors

Several types of circuits have been developed for making control circuits contactless. These include the use of semiconductor elements such as transistors and saturable reactors. This article, however, will introduce only contactless control circuits employing thyristors.

In accordance with the present level of semiconductor technology, medium and low capacity elements have sufficient reverse voltages and capacities for use in control circuits. Therefore, the points to be considered when constructing constactless control circuits are as follows:

(1) Economy (manufacturing costs, maintenance costs, etc.)
(2) Stability in respect to overvoltages, noise, etc.
(3) Compactness and lightweight.

Table 3 **Ratings of Control Circuit for Pilot Motor**

System :	Field switching type forward/reverse drive control
Power source :	Dc 100 v
Load motor :	120 w dc 100 v with double field
Control circuit :	Dc 100 v

Fuji Electric has been manufacturing contactless control systems for some time. An example of a short-circuit relay employing thyristors for a cam motor which requires almost no maintenance when compared with the former dc rolling stock systems will be introduced here.

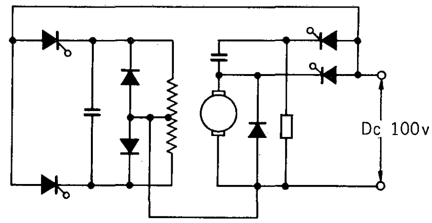


Fig. 11 Circuit diagram for controlling pilot motor with thyristor

The ratings of this control circuit are shown in *Table 3*. This equipment was incorporated in test cars used on the Japanese National Railway's New Tokaido Line (B-type) in 1962 and has operated well for seven years. The previous thyristors used as switching elements in dc power source circuits, had no self extinction characteristics and therefore erroneous operation was a frequent occurence. However, the long years of practical experience with this equipment has indicated that no problems arise concerning the thyristors used as switching elements in the dc circuits.

References :

(1) Mori, Kato: Pressure contact type silicon rectifiers, Fuji Electric Journal, Vol. 38, No. 3
(2) Tahara: 800 amp flat packged type reverse voltage silicon rectifiers, Fuji Electric Journal, Vol. 41, No. 9
(3) Warner Stein: Stufenschalter mit Thyristorlastum-schalter fuer Wechselstrom-Triebfahrzeuge Siemens-Z, 39 (1965), H. 4, S. 269
(4) Robert Fischer und Gerhard Scholtis: Die Thyristorgesteuerte Nutzbremse im Triebwagen ET 45.01 der Deutshen Bundesbahn Elektrische Bahnen 1968 H. 6/7, S. 136/154
(5) Konard Heintze und Rudolf Wagner: Elektronischer Gleichstromsteller zur Geschwindigkeits-steuerung von aus Fahrleitungen gespeisten Gleichstrom Triebfahrzeugen ETZ-A Bd 87 1966 H. 5, S. 165
(6) Namba: InSb-NiSb crystals used in magnetic resistance elements Fuji Electric Journal 39, No. 6
(7) Sakuragi, Takemura, Kaneda: Fuji standard F-MATIC series of transistor digital control elements, Fuji Electric Journal 41, No. 7 and 8.