UDC 621. 313. 3. 076. 7-531 : 621. 314. 58 : 621. 333

COMMUTATORLESS MOTOR FOR ROLLING STOCK

Hiroshi Sato
Kunihiko Sawa
Yoshitaka Fujiwara
Kazuhisa Okamoto

I. INTRODUCTION

As traction motor for driving rolling stock, the DC series motor with its easy control and excellent performance is widely used in Japan. With the progress in insulation materials, welding techniques, etc., compact, light weight traction motors with large capacities and high performance have came into use.

However, because DC motors are mechanically commutated with commutators and brushes, there is a danger of flashover depending on operating and surrounding conditions and much maintenance is needed due to breakdown of the commutator surface, brush wear, etc. The commutators are also limited in respect to maximum number of rotations because of mechanical strength and at present, the limit has been almost reached for increasing the output by means of increasing the number or rotations.

The application of semiconductor equipment to rolling stock can lead to many advantages such as the improvement of the control and adhesion performances and reducing maintenance, but recently the use of semiconductors in rolling stock is not limited to control devices and the development of commutatorless traction motors in order to improve traction motor performance, increase output and eliminate maintenance has become a major topic.

The commutatorless motors are synchronous motors or induction motors. Speed control can be achieved by controlling the applied voltage and the frequency and there are several systems which can be considered. The following sections will give the basic items in rolling stock drive and also give an outline of the 110kW self-controlled thyristor motor for rolling stock which showed excellent results in site tests and was delivered to the Japanese National Railways in 1972.

II. MAKING ROLLING STOCK DRIVE MOTORS COMMUTATORLESS

1. Performance Required of Traction Motor

The traction motor must satisfy the characteristics of a DC series motor and new problems must be solved which arise since the motor is commutatorless. The functions of a DC series motor are as follows:

(1) During starting and upgrades, a large torque can be provided and the input power does not increase at the same time.
(2) Easy wide-range speed control is possible, high speed operation at level can be achieved and high efficiency use is possible.
(3) Load unbalance during parallel operation is small and there is stability against rapid changes in source voltage and load changes.

The items required of a commutatorless motor are as follows:

(4) Maintenance, inspection and adjustments must be easy.
(5) There must be high efficiency and a high power factor.
(6) Torque vibrations must not injure the rolling stock or the drive system.
(7) High harmonic currents must not obstruct communication lines, etc.
(8) The equipment must be small and lightweight.
(9) Cost must be low.

2. Main Circuit System

There are various types of commutatorless motors but the typical types are shown in *Table 1*.

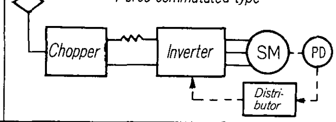
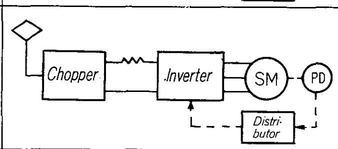
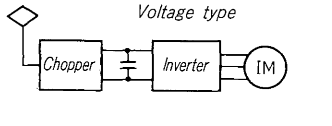
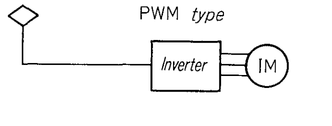
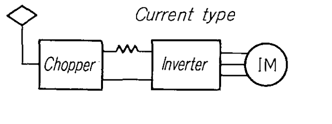
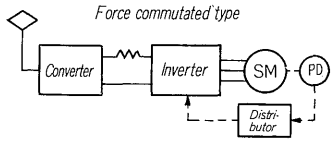
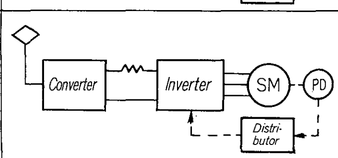
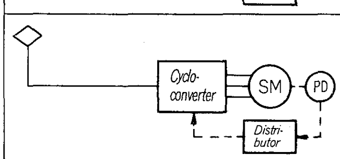
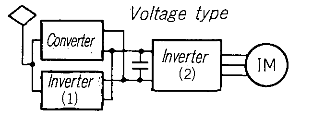
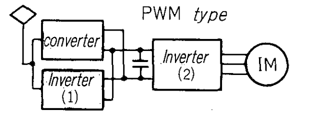
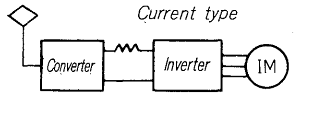
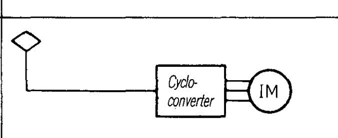
There are various merits and demerits for each type but considering regenerative braking, the DC source system has shown rather few merit of commutatorless because of the problems of compactness and weight. The externally controlled induction motor requires careful structure of the control system in order to ensure the output compensating the reaction magnetomotive force, and to obtain as well as DC series motor.

(1) Maintenance and inspection

From the maintenance and inspection free standpoints, types (7) and (8) (independent operation) and (10) and (12) (group operation) are convenient because of their simple structure and a minimum of attached devices such as line breakers and changeover switches.

(2) Efficiency and power factor

Table 1 System of commutatorless motor for rolling stock

Type	Power supply	Frequency	Commutation	Main circuit construction		Control			Features: Merits	Features: Demerits
1	DC	Self control	Self commutation	Force commutated type 	Chopper + self-commutating inverter + synchronous motor	Powering	Chopper	Voltage control	No need to consider commutation during starting	Main circuit switchover for powering / braking necessary, large size and weight
							Inverter	Inversion		
						Braking	Chopper	Voltage control		
							Inverter	Conversion		
2	DC	Self control	External commutation		Chopper + external commutating inverter + synchronous motor	Powering	Chopper	Voltage control	Arrangement most simple in DC rolling stock	Must consider commutation during starting, main circuit switchover for powering / braking necessary
							Inverter	Inversion		
						Braking	Chopper	Voltage control		
							Inverter	Conversion		
3	DC	External control	Self commutation	Voltage type 	Chopper + voltage type self-commutating inverter + induction motor	Powering	Chopper	Voltage control	No need to consider commutation during starting, suitable for operation of a group of motors	Main circuit switchover for powering / braking necessary, large size and weight
							Inverter	Frequency control Inversion		
						Braking	Chopper	Voltage control		
							Inverter	Frequency control Diode feedback		
4	DC	External control	Self commutation	PWM type 	PWM inverter + induction motor	Powering	Inverter	Voltage control Frequency control Inversion	No need to consider commutation during starting, motor current is sinusoidal, operation of a group of motors possible	Rather large size and weight
						Braking	Inverter	Voltage control Frequency control Diode feedback		
5	DC	External control	Self commutation	Current type 	Chopper + current type self-commutating inverter + induction motor	Powering	Chopper	Voltage control	No need to consider commutation during starting, suitable for operation of independent motors	Main circuit switchover for powering / braking necessary, large size and weight
							Inverter	Frequency control Inversion		
						Braking	Chopper	Voltage control		
							Inverter	Frequency control Inversion		
6	AC	Self control	Self commutation	Force commutated type 	Converter + self-commutating inverter + induction motor	Powering	Conversion	Voltage control Conversion	No need to consider commutation during starting, main circuit switchover for powering / braking unnecessary	Large size and weight, control rather complex
							Inverter	Inversion		
						Braking	Conversion	Voltage control Inversion		
							Inverter	Conversion		
7	AC	Self control	External commutation		Converter + external commutating inverter + synchronous motor	Powering	Conversion	Voltage control Conversion	Main circuit switchover for powering / braking unnecessary, simple structure, wide application	Must consider commutation during starting, control rather complex
							Inverter	Inversion		
						Braking	Conversion	Voltage control Inversion		
							Inverter	Conversion		
8	AC	Self control	External commutation		Cycloconverter + synchronous motor	Powering	Cyclo-converter	Voltage control Inversion and conversion	No need to consider commutation during starting, main circuit switchover for powering / braking, easy control, simple structure, wide application	
						Braking	Cyclo-converter	Voltage control Inversion and conversion		
9	AC	External control	Self commutation	Voltage type 	Converter + external commutating inverter + self-commutating inverter + induction motor	Powering	Conversion	Voltage control Conversion	No need to consider commutation during starting, suitable for operation of a group of motors	Large size and weight, control complex
							Inverter	Frequency control Inversion		
						Braking	Inverter (1)	Voltage control Inversion		
							Inverter (2)	Frequency control Diode feedback		
10	AC	External control	Self commutation	PWM type 	Commutator + external commutating inverter + PWM inverter + induction motor	Powering	Conversion	Conversion	No need to consider commutation during starting, operation of a group of motors possible	Large size and weight, control complex
							Inverter (2)	Voltage control Frequency control Inversion		
						Braking	Inverter (1)	Voltage control Inversion		
							Inverter (2)	Frequency control Diode feedback		
11	AC	External control	Self commutation	Current type 	Converter + self-commutating inverter + induction motor	Powering	Conversion	Voltage control Conversion	No need to consider commutation during starting, main circuit switchover for powering / braking unnecessary, suitable for operation of an independent motor	Rather large size and weight, control complex
							Inverter	Frequency control Inversion		
						Braking	Conversion	Voltage control Inversion		
							Inverter	Frequency control Conversion		
12	AC	External control	External commutation		Cycloconverter + induction motor	Powering	Cyclo-converter	Voltage control Frequency control	No need to consider commutation during starting, main circuit switchover for powering / braking unnecessary, easy control, suitable for high frequency power supply, operation of a group of motors possible	Limits on frequency
						Braking	Cyclo-converter	Voltage control Frequency control		

Since the use of thyristor equipment requires a large initial expenses, it is necessary to decrease operating costs including both maintenance costs and power costs, then efficiency and the power factor are very important. In the case of natural commutation, the power factor of the so-called fixed control angle thyristor motor is bad in the low current range. When high power factor operation is required, phase angle control is effective.

(3) Control characteristics

Various investigations are required in order to ensure performance better than that of DC machine. Particularly response and stability against external disturbances, stability while series field characteristics control and readhesion control and braking control, accuracy and stability of the current limiting control system, etc. are important. These can be achieved with any system but when induction motors are used, the considerations previously given must be taken and the control system might become complex.

(4) Torque ripple

When the output torque ripples, it is not only possible for unwanted vibrations and vibration noise to be occurred because of resonance between the truck and car-body but there are cases when the equipment is damaged. Generally, it is necessary to suppress torque ripple at an operating frequency near the inherent vibration frequencies of the truck and car-body but rather easy suppression is possible by the control system construction.

(5) Harmonics

High and fractional harmonic components differ depending on the main circuit and control system but basically, high harmonic suppression methods such as filters and multiphasing as are used in conventional chopper and Leonard controlled cars are effective.

(6) Suitable types of rolling stock

The synchronous motor type which is suitable for independent operation can be employed in stock with centralized drive power such as locomotives and the induction motor type which is suitable for group operation can be used in stock with scattered drive power such as electric cars.

III. AC THYRISTOR MOTOR

As was described previously, various conditions must be fulfilled in the adaptation of commutatorless motors to rolling stock drive, but at present, type (8), the AC thyristor motor, has been delivered to the Japanese National Railways and since the results of site tests have been excellent, it will be outlined here.

1. Specifications and Performance of the MT971 AC Thyristor Motor

Table 2 shows the specifications of the MT 971

Table 2 **Specifications of MT971 AC thyristor motor**

Item		Specifications
Wire voltage		1ϕ AC 20 kV 60 Hz
Performance	Output	2×110 kW (1 hour)
	Tractive effort	2×625 kg (〃)
	Speed	63 km/h
	Maximum operation speed	95 km/h
Main motor	Type	MT971
	Formula	Revolving field type self-ventilating
	Output	110 kW
	Rated voltage	320 V
	Rated current	326 A
	Rated rotational speed	2,280 rpm
Main transformer	Formula	Core type forced oil air cooled type
	Capacity	600/540/60 kVA
	Rated voltage	20,000/2×420/210 V
	Rated current	30/476/286 A
Main silicon controlled rectifier	Type	RS810
	Formula	1ϕ-3ϕ thyristor converter type
	Element	CS1400-25 (Fuji type EGP05-25)
	Element construction	1S1P12A
	Rated output	110 kW
	Rated output current	326A (continuous) 140% (10 minutes)
	Frequency	76 Hz (rated) 120 Hz (max.)

Note: Main transformer already exists

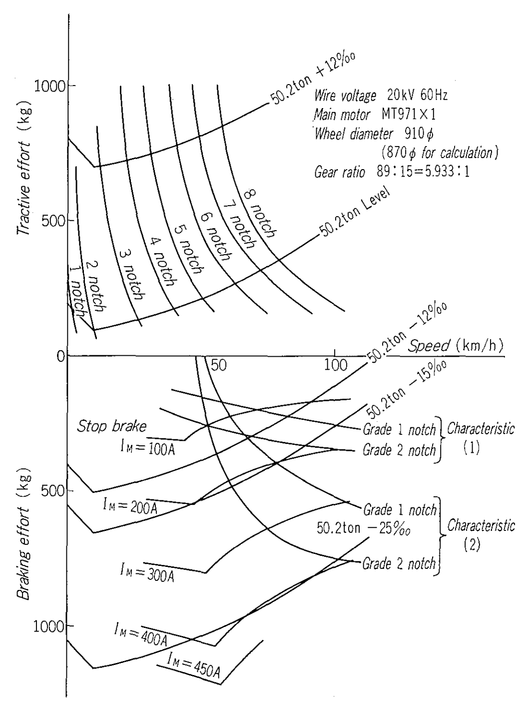


Fig. 1 Performance curve of powering and regenerative braking (stop•grade)

AC thyristor motor accomodated in the Kumoya 791 AC electric car and *Fig. 1* shows the performance curve for powering and regenerative braking (stop/down grade). The basic ratings are the same as those of the Kumoya 791 AC electric car (AC commutator motor drive).

2. Main Circuit and Control

1) Main circuit

Fig. 2 shows the main circuit connection. The main circuit consists of the main transformer, circuit breakers, the main smoothing reactor, the main converter, the main motor and the NFB for protection of the main motor. The converter for field control is connected to the main transformer.

This type of circuit can be considered as equivalent to that shown in *Fig. 3 (a)* and only by switching over the operating ranges of the firing angle control signals of the source thyristor and the commutating thyristor as shown in *Fig. 3 (b)*, forward and reverse powering and braking control are possible. Therefore, the AC breaker is closed except at notch-off.

2) Control

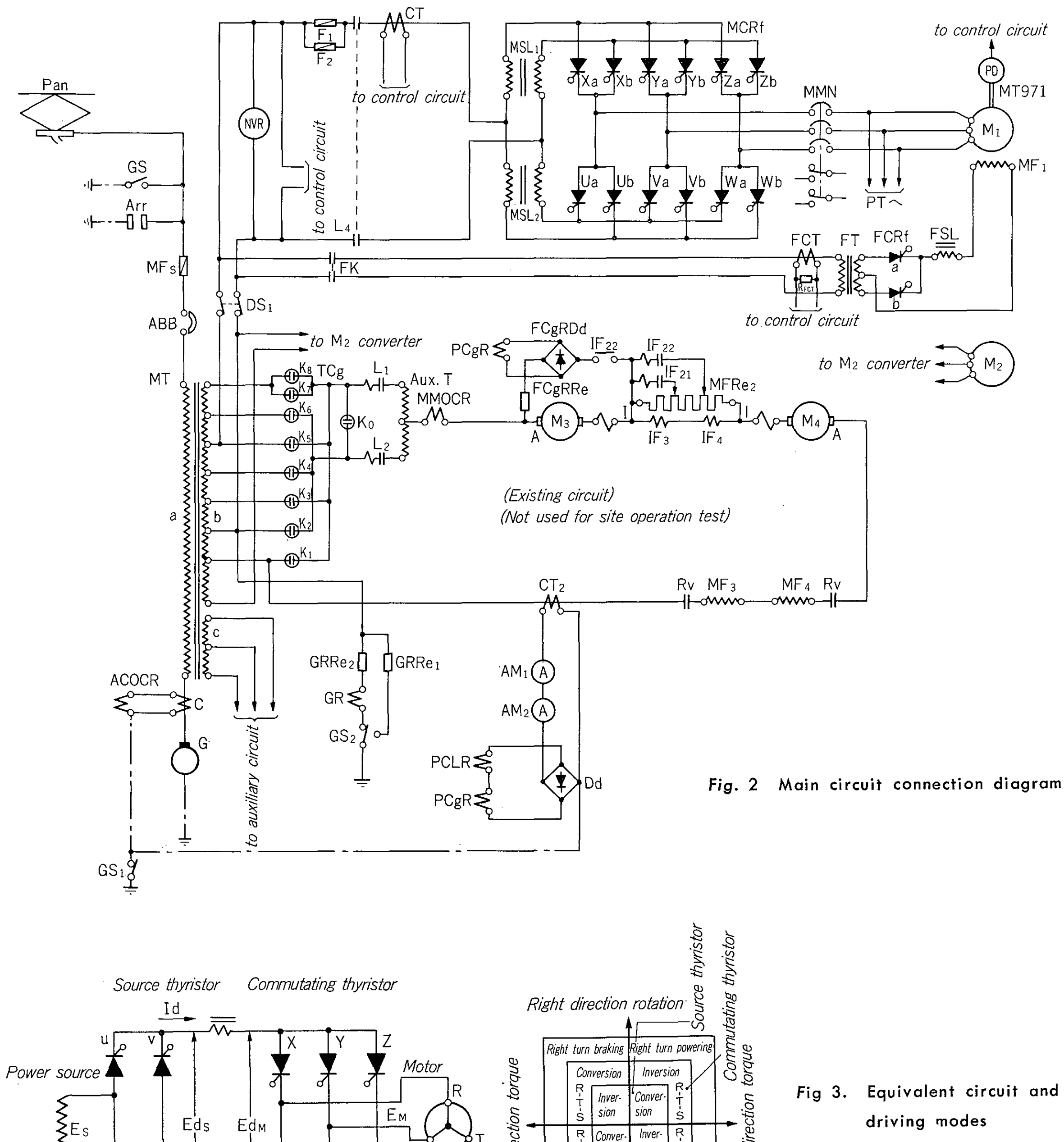
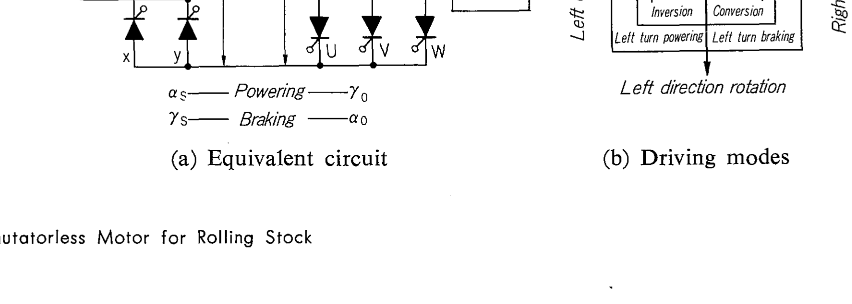


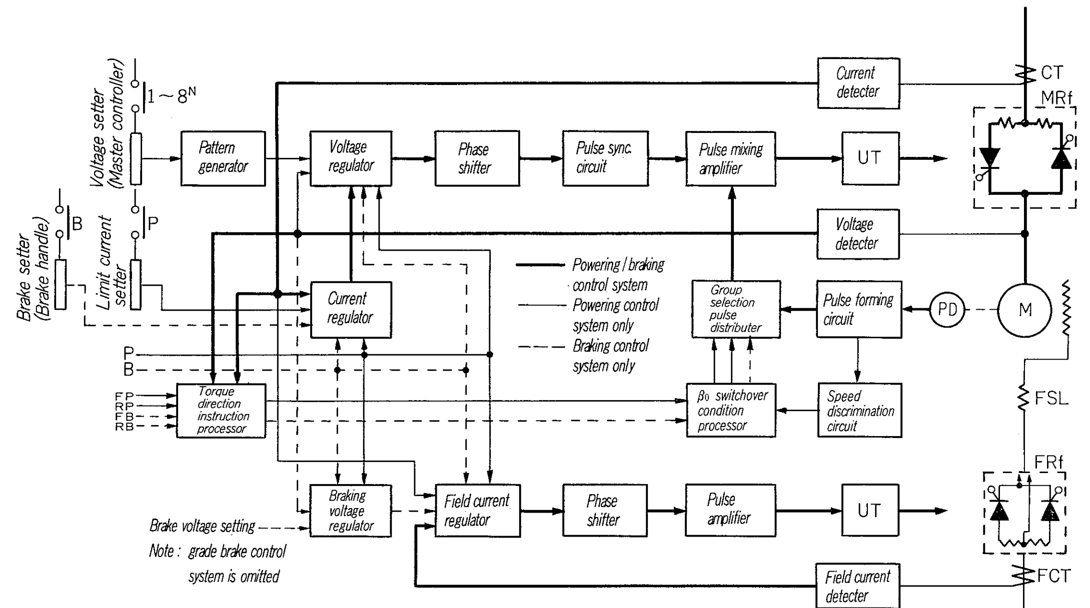
Fig. 2 Main circuit connection diagram



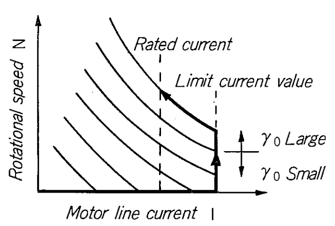
(a) Equivalent circuit

(b) Driving modes

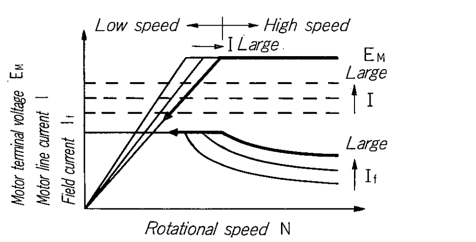
Fig 3. Equivalent circuit and driving modes



(a) Control block diagram

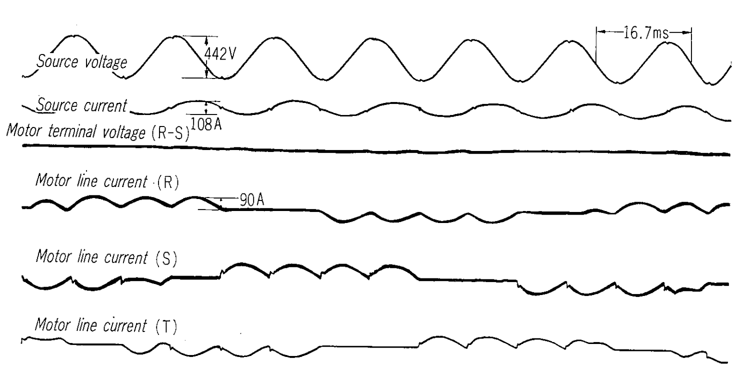


(b) Powering control operation

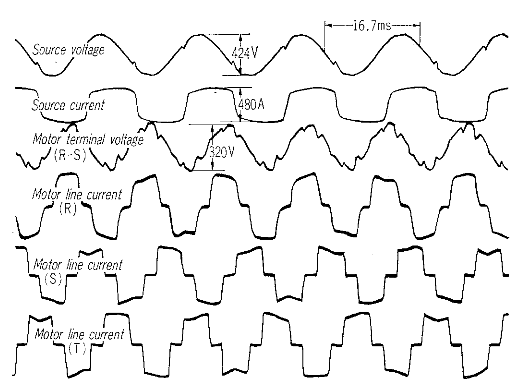


(c) Regenerative stop brake control operation

Fig. 4 Block diagram of automatic control



(a) At starting (γ_0=30deg)



(b) At high speeds(γ_0=70deg)

Fig. 5 Waveforms of motor terminal voltage and line current at powering

As is shown in *Fig. 3*, the main converter has exactly the same functions as the converter for voltage control in the thyristor-Leonard system and the commutators of DC machine. Therefore, the same concepts can be applied for the speed control method. With these characteristics, it is also possible to achieve all the features of a DC series motor. The equipment employs a series field characteristics separately excited control system so that a large degree of freedom is possible concerning main motor characteristics and the field is of low voltage and small current so that insulation to ground can be reduced.

Fig. 4 shows a block diagram of the control system.

(1) Powering control

The main motor rotational speed can be expressed as follows from *Fig. 3* (*a*) without considering circuit voltage drop and lap angle :

$$N=\frac{0.9E_S}{k\phi\cos(\gamma_0-\delta_M)}\cos\alpha_S$$

where : E_S : source voltage
α_S : source thyristor control angle
γ_0 : commutating thyristor control angle

k : proportional constant
ϕ : effective field flux
δ_M : armature reaction angle

From the above equation, control during powering is possible by control angle α_S of the source thyristor.

The powering control system consists of a master controller and a torque direction instruction processor. In regions where the counter elecromotive force is low because of low motor speeds, the current control system is given priority over the voltage control system and there is control at a constant limit current. When there is acceleration up to a motor voltage equal to the set voltage, the voltage control system has priority and the motor voltage is controlled at a constant value. At this time, the field current is controlled so that it is always proportional to the armature current and series field characteristics are achieved. The control leading angle of the commutating thyristor is switched over between high and low speeds. This is to increase output torque, minimize torque ripple, improve the power factor, etc.

Fig. 5 shows the motor voltage and current waveforms during powering.

(2) Armature reaction angle and lap angle

The commutating limit of the commutating thyristor during powering is assured by γ_0 but when the armature current changes in accordance with operating conditions, there are changes in the armature reaction angle δ_M and the lap angle u_M so that the converter circuit turn-off time γ also changes:

$$\gamma=\gamma_0-(u_M+\delta_M) \qquad (\gamma_0 \text{ is constant})$$

Generally when the armature current is increased, u_M and δ_M increase so that the thyristor turn-off time can not be assured and there is commutation failure. At that time, the behavior of the lap angle and armature reaction angle differ depending on field system. According to *Fig. 6*, when there is a separately excited shunt field, γ decreases in the high speed, large current range and when there is a separately excited series field, there is almost no change. In the case of the series field, the field current (flux) also increases in respect to the armature current and therefore, the change in δ_M is suppressed. Since the induced voltage also increases in respect to the flux, the commutating voltage also increases and the change in u_M becomes small.

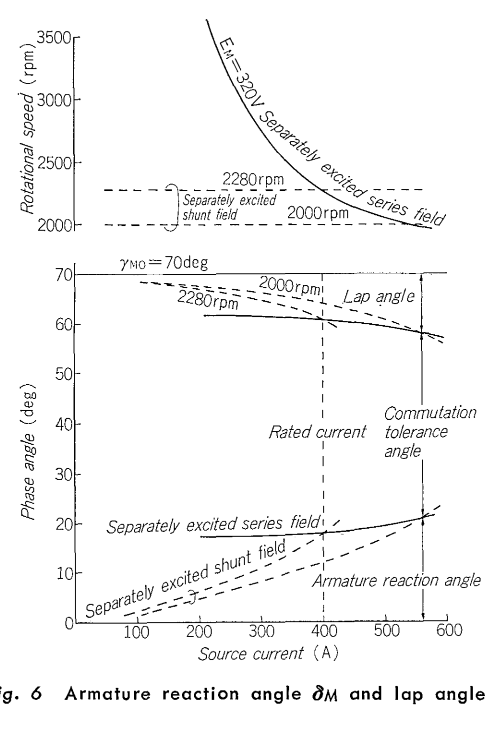


Fig. 6 Armature reaction angle δ_M and lap angle u_M

In other words, expansion of the output limits is required for series field characteristics in a thyristor motor.

(3) Regenerative braking control (stop)

For the stop brake, it is desirable that there be constant brake power characteristics proportional to the brake handle angle. The characteristics during braking can be expressed as follows without considering the circuit voltage drop and the lap angle:

Average motor torque: $\tau_{ave}=k_1\phi I\cos(\alpha_0-\delta_M)$

Supposed average armature current:

$$I=\frac{E_{dM}-E_{dS}}{|Z|}$$

Possible regeneration range:

$$E_{dS}\geqq E_{dM}=k_2N\phi\cos(\alpha_0-\delta_M)$$

where k_1 and k_2 : proportional constants
α_0 : commutating thyristor control angle
Z : circuit impedance

From the above equation, it is evident that controlling the armature current is sufficient for continuous torque control with good response. For stable control in all speed ranges, it is necessary to control the weak field flux in the high speed range.

The stop braking system consists of a brake handle and a torque direction instruction processor. In regenerative braking control, it is difficult to obtain stable characteristics with series field characteristics. Therefore, the field is separately excited and in the high speed range, the field control system keeps the motor voltage constant and the armature current control system controls the armature current in accordance with the brake setting value. In the low speed range, the field current becomes a maximum and is controlled at a constant value. The armature current is kept at a constant value only by the armature current control system.

(4) Regenerative braking control (down grade)

The down grade brake control system consists of a master controller and a torque direction instruction processor. As in the case of the stop brake, the field is externally excited and when the filed current is controlled at a constant value in accordance with the grade notch, the armature current is simultaneously controlled at a value proportional

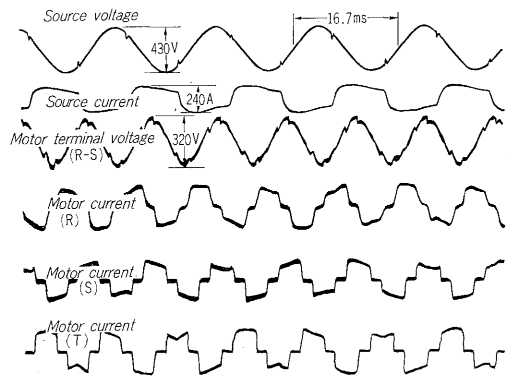


Fig. 7 Waveform of motor terminal voltage and line current at regenerative braking

to the motor voltage. This is equivalent to the grade characteristics (1) shown in *Fig. 1*. When the motor voltage is kept constant, the field control system ensured characteristics with large grading effects as in grade characteristics (2). *Fig.* 7 shows the waveforms of the motor voltage and current during regenerative braking.

For the regulation of the above powering and regenerative braking control systems, Fuji Electric has already established a method. The control constants are decided by the optimum regulation methods of control systems applied in various automatic control fields.

3) Protection

The protection of the thyristor motor requires consideration of the facts that measures must be taken based on the same concepts as for conventional rolling stock systems and that the thyristor motor has its own special characteristics. Typical examples are given below.

(1) Field zero current

Since this motor is of the separately excited series field type, the appearance of zero current due to faults in the filed circuit must be considered. During powering, the counter electromotive force becomes zero and the motor current is rapidly increased. In this case, the source thyristor control angle α_S is rapidly shifted to the γ region, the motor current is dampened and damage to the converter and other devices is prevented. During braking, the brake power is reduced but this is safe from the standpoint of the equipment.

(2) Dewiring and section

Under the no-voltage condition during several tens of mili-seconds to several seconds at the time of pantograph dewiring or when passing a section, a surge current will flow at the time of reapplication during powering. In this case, the no-voltage state is detected quickly, the master controller signal is off, the commutating thysistor control angle γ_0 becomes minimum, the motor current is rapidly dampened and at the time of reapplication, there is repowering in accordance with the starting pattern. At the time of braking, after the same detection as above is made, the commutating thyristor control angle α_S is shifted to the γ range, the motor current is dampened and at the same time, the elements of the same group are all fired and the current duty of the thyristor is reduced to 1/2. At the time of reapplications, braking resumes according to the control starting pattern.

In additions, various other types of protection for devices and systems such as the protection against drops in the pantograph voltage during regenerative braking have been developed and are in use.

IV. EQUIPMENT CONSTRUCTION

1. Main Motor

Main motors for rolling stock are limited in size and they must be as light as possible but still satisfy the required functions.

In the motor type, it is necessary to consider everything including output, constituents, winding systems, type of field, compensation for armature reaction, converters and their control systems.

The fields include the cylindrical type, salient pole type and claw-pole type. In the thyristor motor, the commutation reactance is very important in deciding the output and therefore, the revolving cylindrical pole type separately excited series field system with its low commutation reactance and low current is most suitable to rolling stock.

The thyristor rectifier control angle influences all characteristics but it is controlled by the armature reaction angle δ_M, i.e. the reactance angle u_m of the direct and quadrature axes x_d and x_q, i.e. the transient reactance x_d'' and x_q''. When x_d, x_q, x_d'' and x_q'' are large, δ_M and u_m increase and the output decreases but with a small electric loading, x_d becomes small and by providing a damper winding, the transient reactance can be minimized.

A compensation winding is also used to directly eliminate armature reactance and make δ_M small. The direct axis reaction magnetomotive force changes from the center of the brush axis and the distri-

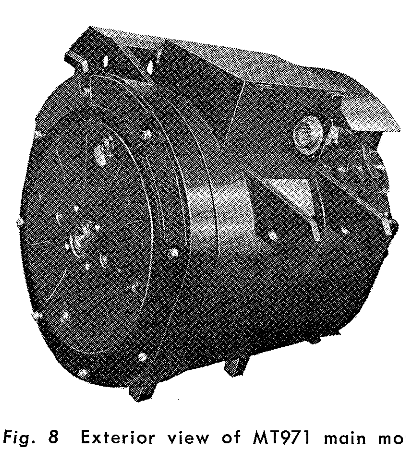


Fig. 8 Exterior view of MT971 main motor

bution is also changed by the effects of the lap angle so that compensation becomes difficult. Therefore, generally only the quadrature axis reaction is compensated but in the rotating field type, it is necessary to use a slip ring for the compensation winding and it is not so good for rolling stock.

As was described previously, the MT971 main motor has a large electric loading considering the effect of expanding the commutating limits of the series field and on the whole, the motor is compact and light. *Fig. 8* shows the exterior view.

2. Main Converter

The converter is a self controlled single phase/3 phase cycloconverter. The voltage normally applied to each arm is the sum of the source voltage and the motor terminal voltage. The current duty changes in relation to the source frequency and motor frequency as well as the phase relation. Especially when the frequency ratio of the motor and source is an integer or 1 by integer the conducting arm is fixed so that care must be taken with the cooling design. The exterior view is shown in *Fig. 9*.

3. Gate Control Device

This device mixes the pole position signal and the motor armature voltage control signal and controls the converter. The exterior view is shown in *Fig. 10*. The device consists of a requlator, phase shifter, digital circuits, etc., all arranged on functional block printed circuit boards which are used IC and are compact and of high reliability. The gate firing circuit employs a high frequency modulation system so that the gate peripheral circuits are small and performance is high.

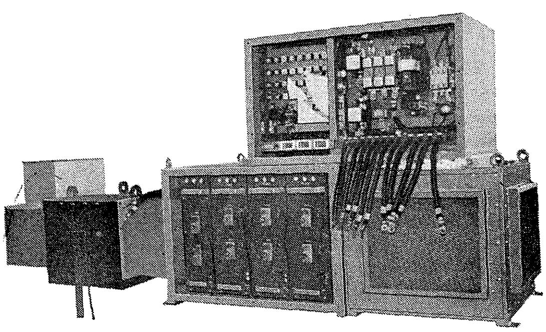


Fig. 9 Exterior view of RS910 main converter

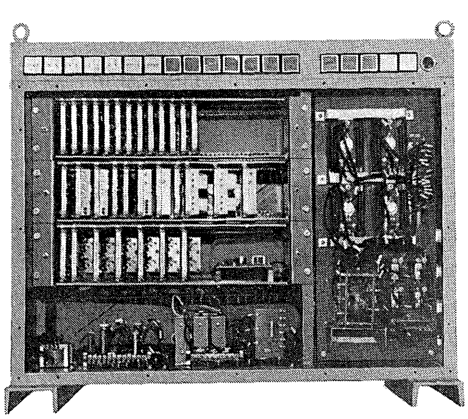


Fig. 10 Exterior view of gate control device

4. Main Smoothing Reactor

The main smoothing reactor suppresses main circuit current ripples and ensures correct commutation. It also prevents current interruptions and stabilizes the control systems. As can be seen in *Fig. 2*, the winding is divided into two parts to decrease the lap angle during source commutation and the inductance is eliminated during commutation.

5. Pole Position Detector

There are mechanical and electrical means to detect the relative position relation between the motor stator and rotor. The angles u_M and δ_M are increased by armature current. Therefore, the required γ_0 is decided by u_M and δ_M at the maximum current considering operation but since the power factor deteriorates in the low current range, it is necessary to compensate γ_0 ideally to correspond to the current. However, since the change of u_M and δ_M in the series field system is still several degrees (electrical degrees), it is possible to switch over γ_0 between the high and low speed ranges. In the mechanical system, since γ_0 is fixed, a detector is necessary to correspond to the switching of γ_0 but γ_0 can be set at any arbitrary angle. The γ_0 of the electrical system was compensated in respect to the changes in the armature reaction angle δ_M since the terminal voltage is set as standard but since it is only possible in a simple system to set γ_0 at 30°, operation at low factors can be considered more than in the mechanical case depending on the conditions. During the time when the motor voltage is low at low speeds, it is necessary to use the mechanical system also or use a special detecting method. In the electrical method, it is also possible to obtain any optional value of γ_0 but this presents a disadvantage since the equipment becomes rather complex. In this equipment, a double switching mechanical pole position detector is used.

V. SITE TESTS

The following is an outline of the site tests conducted by the Japanese National Railways on 12～16 December, 1972.

1) Aim of tests

These tests were meant to check the driving of the rolling stock by the AC thyristor motor and confirm the starting, powering and power regenerative braking functions. They were also meant to determine if there were any problems such as mutual interference when the motors were operated in parallel, as well as to analyze the source current harmonics and collect data for future designs.

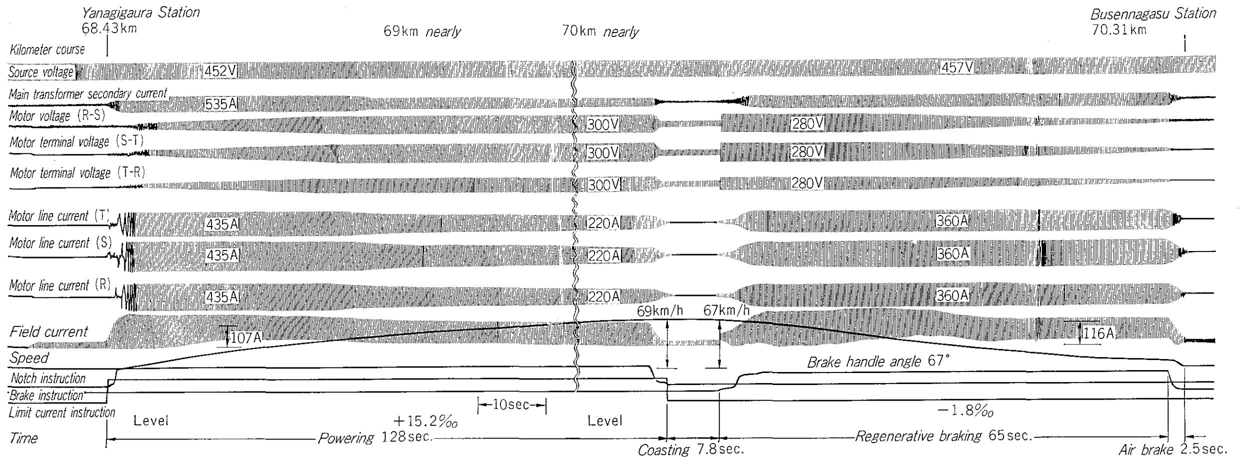


Fig. 11 Trial run oscillogram by Kumoya 791 EC

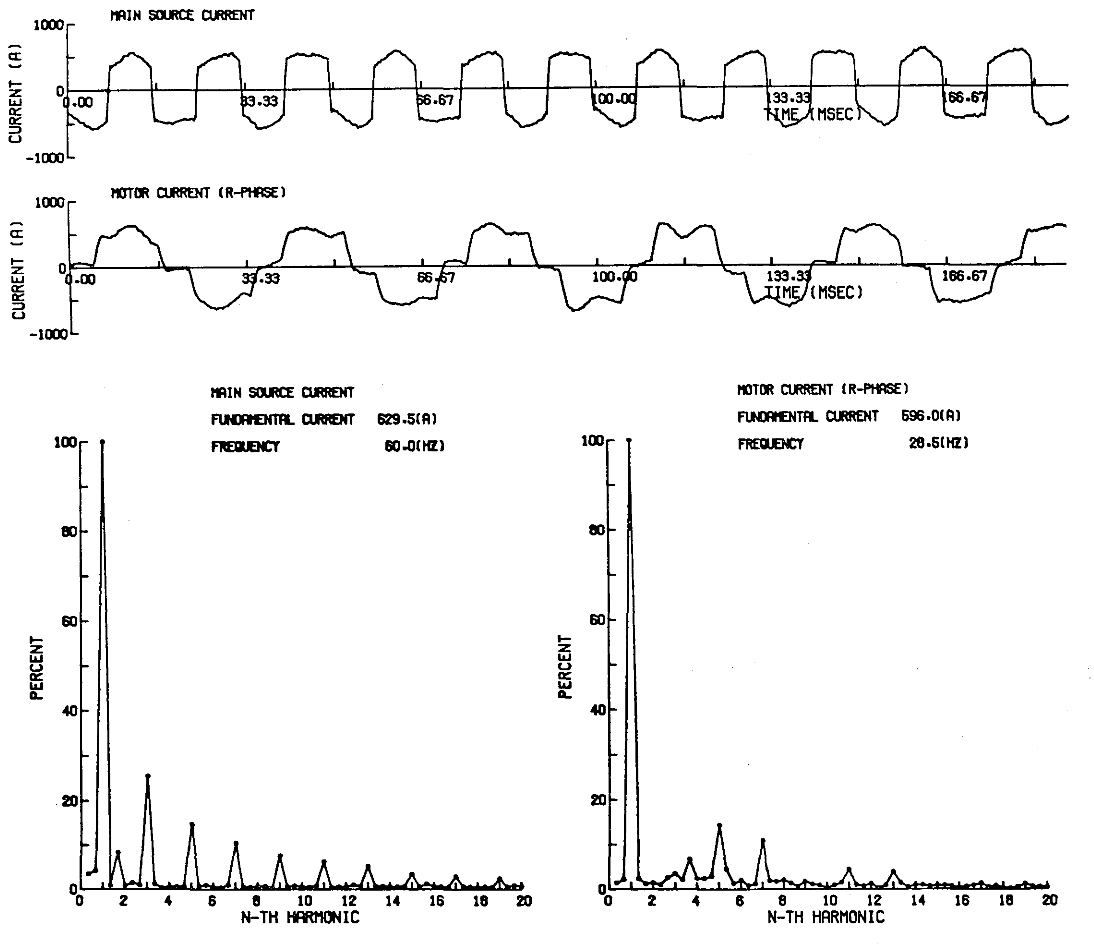


Fig. 12 Harmonics analysis

2) Test line

The tests were conducted between Yanagaura and Kitsuki on the Nippo line. (The upgrade was a maximum of 15‰ and the downgrade a maximum of 25‰, about 30km).

3) Assembly

The MT971 AC thyristor motor was installed on the base of the Kumoya 791 AC car and the converter, reactor, control devices, etc., were attached temporarily on the floor of the passenger compartment.

4) Test items

During parallel operation of two motors and single motor operation, starting, powering, stop regenerative braking, grade regenerative braking and continuous operation were performed and various functions and characteristics were measured.

5) Test results

The typical test results on main line are as follows:

(1) Operation of the MT971 AC thyristor motor was stable in both single and parallel operation. There was no current peak or hunting because of control system delays during starting and the operating characteristics of the separately excited series field characteristics were also stable. The effectivness of the equipment was confirmed.

(2) Performance of rolling stock were almost fulfilled as planned and maximum speeds of 65km/h with single operation and 80 km/h with parallel operation were recorded.

(3) Control and protective operations against power supply interruptions during powering and regenerative braking were reliable and stable.

(4) The source current harmonics were distributed at about $n^{1/1.5}$ and there were no basic differences with the conventional rectifier cars.

Fig. 11 and *Fig. 12* show the oscillographs for each part operation during powering and a harmonics analysis for the source and motor sides respectively.

VI. Future

As a result of research and development and site tests, the anticipated aims concerning technical problems of thyristor motor can be considered to have been achieved and in the future, research will naturally be conducted concerning raising the performance levels of various types of motors, making them more compact and lightweight, eliminating maintenance, etc. in order to develop a rolling stock system with the electrical parts and the control system balanced. However, it will also be necessary to investigate measures to improve expected adhesion coefficients, measures to eliminate harmonics and short-time non-cyclic harmonics evaluation methods, expansion in the main motor output limits, etc. from both the hardware and software aspects.

VII. CONCLUSION

This article has dealt mainly with the MT971 AC thyristor motor as a commutatorless motor for rolling stock. In the application of thyristor motors to rolling stock, planetary gear system and torque converter system etc. have been investigated but the research and development of a commutatorless motor applying semiconductor techniques to their fullest can be expected to be both technically and economically feasible as can be seen from the results of prototype tests.

Finally, the authors wish to thank sincerely all of those who aiding in the design, manufacture and testing of this equipment and especially those concerning in the Japanese National Railways.

References:

(1) Namba, Yamamoto and Tsukahara: Thyristor type commutatorless motors and their control: Fuji Journal, **44**, (3) (1971)

(2) Sasaki: Commutatorless motors for rolling stock, Railway Science, **26**, (2), (1972)

(3) Takada, Takahashi, Sawa and Naganuma: 110kW series wound thysistor motor, All Japan Conference of Electrical Engineering Society, (1973)

(4) Sasaki: Site tests of a prototype commutatorless motor Railway Science, **26**, (3), (1973)