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CHOPPER CONTROL EQUIPMENT FOR DC CARS

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I. INTRODUCTION

The direct current electrification systems of railways has long been practiced because of the excellent features of DC systems for railway transportation. The recent advances in power type semiconductors and the application of electronic control equipment to the power field have made modernization of DC rolling stock possible by the use of such things as contactless and stepless control systems.

The DC voltage converter of the so-called thyristor chopper type, which is constructed of large capacity power thyristors and highly reliable and rapid response electronic control devices containg silicon transistors, have made the main circuit almost completely contactless. This means that maintenance of contacts which formed such a large percentage of the maintenance work formerly required for rolling stock is not necessary. The stageless rapid response control insures greater comfort and large acceleration and deceleration. There is also no resistance loss during starting, power comsumption is lower due to the use of regenerative braking and operating efficiency is higher. These are only some of the many features of this system.

This article will describe recent thyristor chopper equipment manufactured by Fuji Electric for use in rolling stock. It will also outline some problem points encountered in the application of the equipment to DC cars supplied from overhead lines as well as in increasing the capacity of the thyristor chopper equipment. These will be discussed mainly in respect to the results of actual site tests conducted through the kindness of the Traffic Department of the city of Sapporo in Hokkaido.

II. CONSTRUCTION OF MAIN CIRCUITS AND CONTROL SYSTEM

1. Main Circuit Construction

The application of chopper control to DC cars is highly effective, but there are several points which must be considered in practice since the chopper is such that a interrupted current flows from supply to the load. Therefore the main circuits must be constructed so that the advantages of the chopper are not lost because of this point.

Table 1 **Principal rating of DC chopper for electric rolling stock**

Composition	M+M′
Main motor capacity	85kW(375 V×227 A)×4 units
Car line voltage	750 V (450 V∼825 V)
Maximum acceleration current	486 A/motor (α=3.5)
Maximum brake current	325 A/motor (β=3.5)
Motor connection	2S • 2P permanent
Chopper connection	2-phase double
Chopper frequency	200 Hz (total 400 Hz)
Main motor current pulsation factor	10%
Control system	Average current value control, set frequency phase angle control system
Chopper circuit system	Special double reversing system
Element construction	
Main thyristors	2S×2P×2G
Commutating thyristors	2S×1P×2G
Flywheel diodes	2S×1P×2G
Commutating diodes	1S×1P×2G
By-pass diodes	1S×1P×2G
Element types	
Main and commutating thyristors	KGP21-13
Flywheel, commutating and bypass diodes	KSP03-30
Cooling system	Oil immerced air cooling (ambient temperature −30°C∼+40°C)
Commutating capacitor capacity	165 μF
Smooth reactor inductance	5 mH
Filter reactor inductance	7 mH
Filter capacitor capacity	1,800 μF
Filter resonance frequeucy	45 Hz

(1) The protective high speed breaker, unit switch for circuit breaking, P–B changeover cam switch, reversing cam switch etc., all should have a simple circuit construction which only the most essential contacts are kept and the operating requirements are minimized. Therefore the chopper should contactless and maintenance free.

(2) The current flowing the motor circuits has an adverse influence on the main motor, since it includes a pulse component with a relatively high frequency. Therefore, a smoothing reactor is used to minimize this pulse. In addition, however, it is a advisable that countermeasures such as using a motor with a high pulse current factor or making the chopper multi-phase. If the chopper is two phase, there is sufficient protection against pulsating currents, and a solid yoke main motor can be used without the pulsating current countermeasure.

(3) When a current which includes a pulsating component flows in the overhead line, a disturbance can arise in communication lines or signalling systems depending on the frequency and magnitude of this current. This pulsating component can be minimized by using a filter and also in this case it is effective to make the chopper multi-phase. If the number of phases increased, the filter can be made smaller, but a filter capacitor is required in order to suppress abnormal voltage which occur due to interruption of the main current. It is also necessary to design the filter so that there will not be any resonance due to the pulsating voltage from the substation as well as that from the chopper.

(4) Regenerative breaking of the series motor with the chopper operates effectively down to low speeds. However, when the voltage arising in the motor during regenerative braking becomes larger than the car line voltage, the regenerating current is despersed, control becomes impossible and stable operation can not be maintained. A countermeasure against this is therefore necessary.

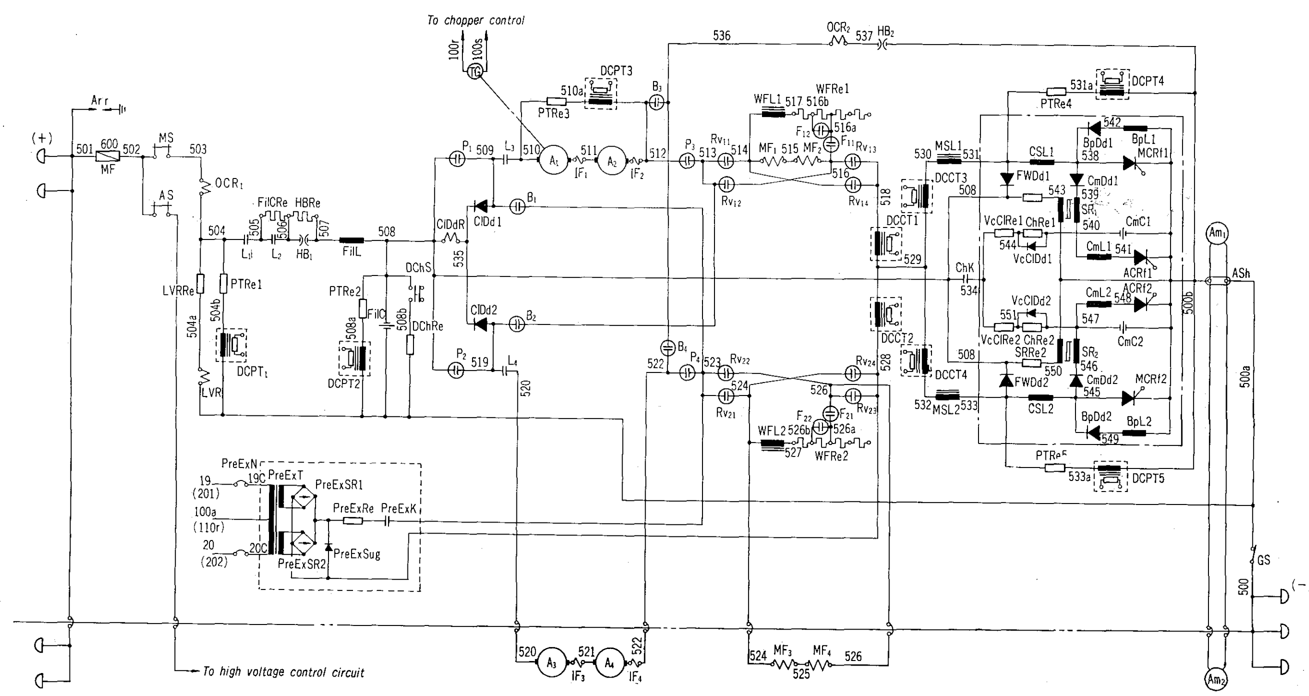
Table 1 shows the principal items of DC car chopper control euquipment manufactured under trial.

2. Connection of the Circuits

The main circuit connections of chopper control equipment manufactured in accordance with the above points are shown in *Fig. 1*.

1) Main circuits during powering

Fig. 2 is a shematic diagram of the main powering circuit. The main motors of series type are connected in two series and two parallel. In chopper control, it is not necessary to convert the motor connections between series and parallel, since the control loss is low. As can be seen from the drawing, there are two groups of choppers. Each chopper operates at



Arr: Lightning arrestor
MF: Main fuse
MS: Main switch
OCR: Overcurrent relay
LVR: Low voltage relay
DCPT: DC potential transformer
L: Unit switch
HB: High-speed circuit breaker
FilL: Filter reactor
FilC: Filter capacitor
P: Changeover switch (powering)
B: Changeover switch (regenerating brake)
A: Main motor armature
MF: Main motor main field
IF: Main motor interpole field
RV: Reverser
WFL: Induction coil
WFRe: Shunt resistor
F: Field contactor
DCCT: DC current transformer
MSL: Main smoothing reactor
CIDdR: Current relay
MCRf: Main thyristor
ACRf: Commutating thyristor
CmDd: Commutating diode
BpDd: By pass diode
FwDd: Flywheel diode
ClDd: Clamping diode
CmC: Commutating capacitor
CmL: Commutating reactor
SR: Saturable reactor

Fig. 1 Main circuit diagram of DC chopper

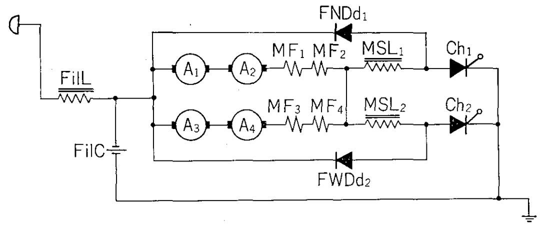


Fig. 2 Schematic powering circuit

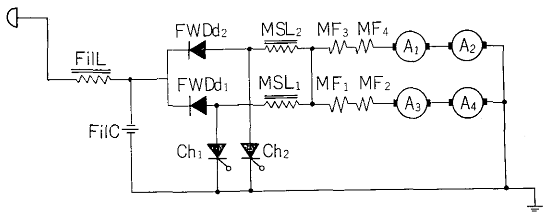


Fig. 3 Schematic regenerating circuit

a fixed frequency and controls the motor current by means of an average value control system which controls the current flow-through time. The two choppers operate at a phase difference of 180°. For high speed powering, weak field control is performed. This weak field control can be performed in one stage with chopper control, but two stages are actually used in order to effectively utilize the torque.

2) Main circuits during regenerative braking

Fig. 3 is a shematic diagram of the regenerative braking circuits. The main motor connections are the same as in the case of powering: two series and two parallel, but in order to balance the brake current, the fields are made reciprocal. In order to build up the braking current at low speed, a pre-exciter is provided. A high speed circuit breaker is also inserted in motor circuit for protection during regenerative braking. In order to stabilize regenerative braking, weak field control is performed and the chopper current flow rate is automatically controlled so that the motor voltage does not become higher than the car line voltage. When an unstable region is entered because of a sudden drop in the line voltage, etc., there is regeneration from the armature directly to the power source which leads to attenuation of the field current which in turn causes voltage drops. Therefore, a diode (C1Dd) is provided so that a stable region can be attained again.

3. Filter

As is well-known, the chopper operating principle is that the thyristor is switched at high speeds in respect to the DC voltage supply and an arbitrary DC voltage which is lower than the power supply voltage (average value). In this way, a current with a rectangular wave flows in the power source only when the thyristor switch is closed. The waveform of this current includes many harmonic components and can cause disturbances in nearby communication or signal lines by inducing a voltage into the lines by means of electromagnetic induction. A current with a wave form like this can be smoothed out in theory by connecting a capacitive impedance in parallel but in practice, a series impedance which serves as a socalled reverse L-type filter is used to avoid influencing the impedance in the power supply line. When the chopper frequency is near the resonance frequency of this reverse L-type filter, there is a danger that the capacitor voltage and current will increase abnormally. In order to prevent this resonance, the resonance frequency of the capacitor and impedance are selected to be only a fraction of the chopper operating frequency and the chopper operating frequency is fixed so as not to come near the filter resonance frequency. There are various method concerning voltage control by the chopper, but ordinarily a set frequency control system is used in cars where the power is supplied from an overhead line for the reasons given above.

There are two type of induced disturbances which cause a problem in this equipment disturbances induced in communication lines by frequencies within the voice range and disturbances induced in signal circuits such at ATC and track circuits. The former are multiplied by a noise evaluation coefficient in respect to each harmonic current. The product is squared and a value is obtained which is about the same as the level of disturbance in an equivalent telephone line. The latter are different from the former and the harmonic current of a fixed frequency presents a problem. Since the level of the disturbance differs in accordance with the conditions on the induced side (the frequency used, circuit impedance etc.), it is very difficult in practice to estimate the degree of influence using only the values for the inducing side.

When the inductance of the filters which make up the reverse L-type is L and the capacitance of the capacitor is C, the terminal voltage of this capacitor repeats the pulse in accordance with the chopper switching of the load side. The maximum value of this variable component $\Delta E_{c\,\max}$ can be shown by the following eqation in a 2-phase chopper where the control factor $\alpha=1/4$ and $3/4$.

$$\Delta E_{c\,\max}=\frac{1}{\omega_0 C}\;\frac{1}{2}\;\tan\left(\frac{1}{2}\pi f_0/2f\right)\;\cdots\cdots\cdots\;(1)$$

where I: Main motor circuit current

$f_0=\frac{1}{2\pi\sqrt{LC}}$: filter resonance frequency

$\omega_0=2\pi f_0$

f : operating frequency for each phase of the chopper equipment

The maximum value of the pulse amplitude of the pulse current which flows in the power supply side in this case can be expressed as follows:

$$\Delta I=\frac{I}{2}\left[\frac{1}{\cos\,\pi f_0/2f}\right]\;\cdots\cdots\cdots\cdots\cdots\cdots\;(2)$$

In practice, the overvoltage withstand of the chopper equipment is decided from the lightning surge which is determined by the arrestor. In order to prevent induced disturbances, it is necessary to keep the pulse current which flows in the overhead line as low as possible and therefore since the filter constants must be selected with this in mind, ΔE_c is not an important factor in deciding the withstand voltages of the elements.

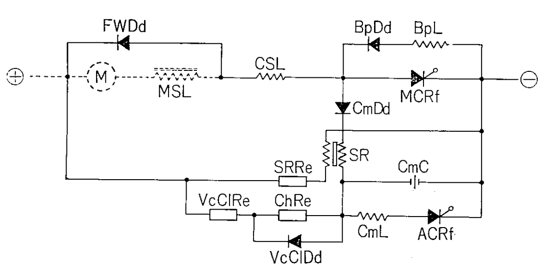
In this equipment, a single reverse L-type filter was constructed by considering the above-mentioned conditions and its constants are maximum impedance $L=7$ mH, and $C=1{,}800\ \mu F$ (resonance frequency of 45 Hz).

4. Commutating Circuits

Fig. 4 shows a schematic of the Fuji Electric thyristor chopper commutating circuit. In this figure, MCRf is the main thyristor which operates when the chopper is ON and ACRf is an auxiliary thyristor used for extinction of MCRf when the chopper is switched to the OFF condition. *C* and *L* are various types of commutating capacitors and reactors. These are the main circuit components. *Fig. 5* shows the oscillograms for each voltage and current during commutation. An explanation of the commutating operation follows.

When the main circuit is formed, the commutating capacitor is charged at a polarity as shown in the figure by the power supply before operation begins. In this state, when MCRf is ignited, the load current takes the following path: power supply→M→MSL→CSL→MCRf.

Then when ACRf is ignited, the capacitor voltage is first reversed by the CmC→CmL→ACRf resonance circuit. After this reversal is finished, saturable reactor SR is saturated, and MCRf is switched to OFF by the CmC→MCRf→CmDd→SR resonance circuit. After MCRf is OFF, resonance occurs in the CmC→BpL→BpDd→CmDd→SR closed circuit and the capacitor is again charged with the original polarity. The reverse voltage time of the main thyristor is



MCRf: Main thyristor
ACRf: Commutating thyristor
FWDd: Flywheel diode
CMDd: Commutating diode
BpDd: Bypass diode
VcClDd: Commutating condenser voltage clamping diode
CmL: Commutatiog reactor
BpL: By pass reactor
SR: Saturable reactor
CSL: Main thyristor di/dt suppression reactor
SRRe: Saturable reactor reset resistor
ChRe: Auxiliary charging resistor
VcClRe: Discharge resistor

Fig. 4 DC chopper circuit

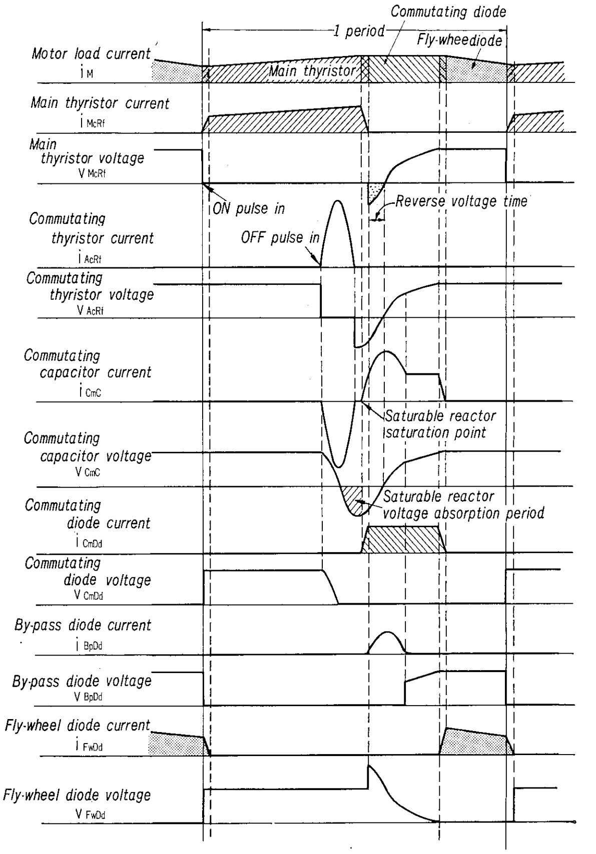


Fig. 5 Oscillograms of each voltage and current

given by the period until the capacitor voltage becomes zero after MCRf is OFF. Therefore, the smaller the effective turn-off time of the thyristor, the smaller CmC and BpL can be. After this resonance is finished, the capacitor is again charged via CmDd by the operation of MSL and CSL. Since this is not equal to the power source voltage at this time, the load current circulates in the closed circuit MSL→free-wheeling diode FWDd→M. Then when MCRf is again ignited, the load current flows from FWDd into MCRf.

This chopper is repeatedly switched ON and OFF, but this repetition frequency is related to disturbances induced to the exterior, the size of the input filter, the permissible thyristor current, the turn-on time, the voltage control range of the chopper equipment, the permissible current pulse factor of the motor, the size of the smoothing reactor etc. In this equipment, a frequency of 200 Hz per chopper is used and in respect to a power supply and motor it is 400 Hz.

The circuit of the resistors ChRe and VcClRe is an auxiliary charging circuit and the resistor VcClRe and diode VcClDd prevent the commutating capacitor from charging above the power supply voltage due to the load current (Patent applied for).

The saturable reactor SR keeps the output voltage constant in respect to variations in the power supply voltage and the control equipment can be simpler

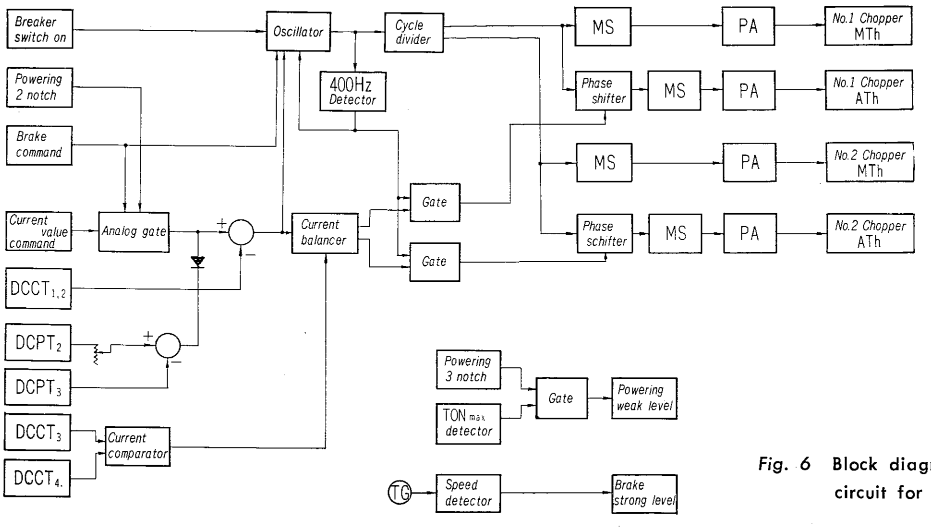


Fig. 6 Block diagram of control circuit for DC chopper

than when a thyristor is used instead.

The feature of this Fuji Electric thyristor chopper commutating circuit is that the reverse current of the commutating capacitor does not flow through the main thyristor and therefore the current capacity of the main thyristor need only that of the load current. Also when the power supply voltage is high as in a DC car, the voltage of the commutating capacitor is not raised more than is necessary so that the withstand voltages of the chopper circuit components do not increase.

5. Control System

Fig. 6 shows the control circuit.

1) Current control system

The chopper control system is a set frequency phase angle control system and because countermeasures against induced disturbances as well as increasing the chopper phases are both easy.

2) Control at start of powering

Since the chopper operating frequency was chosen as 200 Hz in order to avoid the frequencies of signal systems etc., frequency control of the constant chopper ON period is also used to supress the motor starting current. After the frequency reaches 200 Hz, the control is switched to shift phase angle control.

3) Regenerative brake control

In order to make it easy to build up the brake current momentary value control is performed only when the braking starts and control switches to phase control of a constant frequency when the braking current is maintained. In order to keep the regenerative braking stable, a voltage control loop is provided in addition to the current control.

4) Field level

During powering, starting is with the entire field and when the phase angle is a maximum, a weak field level is reached. When the phase angle is maximum at least weak field level, the chopper is short circuited since the loss produced in the chopper is small.

During braking, the braking current is achieved at the weakest field and a safe field is chosen by checking the motor speed.

III. MAIN ELECTRICAL DEVICES

1. Chopper Control Rectifier Equipment

Fig. 7 is an outer view of a chopper control rectifier, and *Fig. 8* shows the components inside the tank. *Tables 2* and *3* give the main ratings and characteristics of the main flat-packaged thyristor used in this equipment as well as the main diode. As can be seen from *Fig. 7* and *8*, this equipment consists of thyristors, diodes and gate transformers which are placed in an aluminum alloy tank with cooling fins on the outer surface. The tank is filled with insulation oil and sealed. There is also a cross-flow pump inside the tank and this provides cooling by force circulating the oil in the tank. With this system, heat loss which occurs at the semiconductor junctions is dispersed in the metal fins through the cooling fins at both ends. This is a feature of the flat-packaged type elements. This heat loss is then dispersed in the oil by the forced circulation and finally reaches the exterior through the fins on the outer surface of the tank. With this method, the dimensions and weight can be much smaller than those required with the ordinary air cooling or the

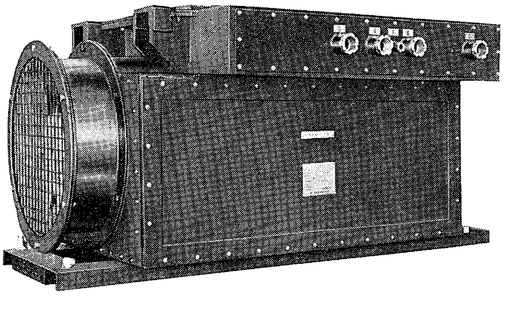


Fig. 7 Outer view of DC chopper

Table 2 Ratings and characteristics of main thyristor used in DC chopper

Type	KGP21-13
Rated average forward current	400 A (180° current flow angle)
Rated operating reverse voltage	1,300 V (peak value)
Rated non-repetitve reverse voltage	1,450 V (peak value)
Rated operating forward blocking voltage	1,300 V (peak value)
Rated gate current	10 A
Rated gate voltage	10 V (forward direction) 5 V (reverse direction)
Overcurrent withstand 1 cycle	8,000 A (180° current flow angle 60 Hz base)
Maximum reverse current	30 mA (peak value)
Maximum forward leakage current	30 mA (peak value)
Forward voltage drop	1.65~2.0 V (at 1,250 A)
Thermal resistance	0.04°C/W
Turn on time	1~6 μ sec
Rated critical forward current rise rate	100 A/μ sec
Peak turn on current	200 A
Turn off time	50 μ sec
Rate critical forward blocking voltage rise rate	300 V/μ sec (at PFV/1.5)
Rated junction temperature	115°C

Table 3 Ratings and characteristics of main diode used in DC chopper

Type	KSP 03-30
Rated average forward current	800 A
Rated operating reverse voltage	3,000 V (peak value)
Rated junction temperature	160°C
Overcurrent withstand 1 cycle	12,500 A (180° current flow angle 50 Hz base)
Maximum reverse current	50 mA (at 10°C)
Forward voltage drop	1.6 V (at 25°C 2,500 A peak value)
Thermal resistance	0.04°C/W

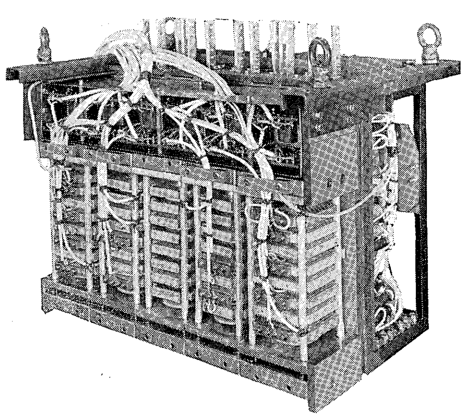


Fig. 8 Outer view of oil-immersed element in DC chopper

forced oil air recooler systems. The main circuit live parts are also not exposed to the exterior and therefore the insulation will never deteriorate due to external influences. These are some of the many features of this system.

2. Chopper Gate Control Equipment

An outer view of the chopper gate control equipment is shown in *Fig. 9*. The reliability of this circuit is high and it is made up of Fuji's standard F-MATIC N logic elements which are resistant to strong vibration. The circuits have also been especially designed to prevent noise.

3. Other Devices

The main devices of chopper control are listed in

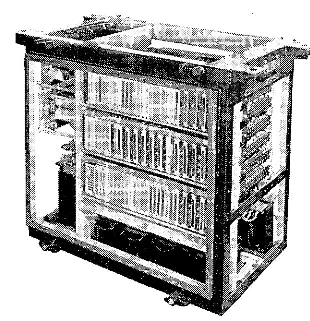


Fig. 9 Outer view of gate controlling unit for DC chopper

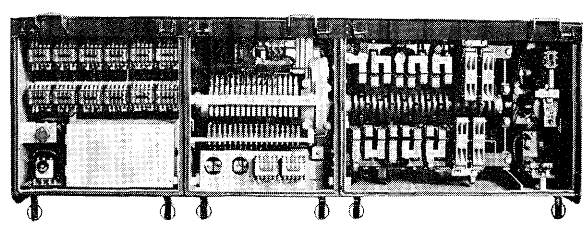


Fig. 10 Outer view of main controller

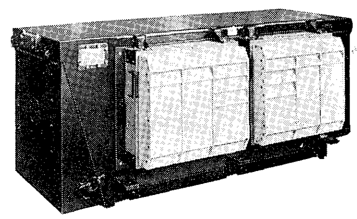


Fig. 11 Outer view of line breaker box

Table 4 Control equipment for dc chopper rolling stock

Name of device	Contents
Chopper control rectifier	Chopper circuit, cross-flow pump, motor blower
Chopper gate controller	Chopper gate circuit
Commutator box	Commutating capacitor, commutating reactor
Conversion controller	P-B change overswitch, reverser, field contactor, DC potential transformer
Line breaker	Unit switch, high speed circuit breaker
Filter reactor box	Filter capacitor
Filter capacitor box	Filter reactor
Main smoothing reactor box	Main smoothing reactor
Pre-excitation equipment	Pre-excitation circuit

Table 4. *Fig. 10* is an outer view of the main controller and *Fig. 11* shows the line breaker box.

IV. TEST RESULTS

The test car used for actual tests of this chopper control equipment is a guide track rubber tire car developed by the Traffic Department of the city of Sapporo, Kawasaki Heavy Industries and Fuji Electric as a noise countermeasure vehicle for use in urban areas or underground. It is equipped with resistor type control equipment and an outer view is shown in *Fig. 12*. Besides the high adhesion of the rubber tires, this type of car has many advantages of chopper control.

For tests, one set of the chopper equipment was placed on the car to replace the resistor type control equipment and the actual tests were conducted for two months from August 1969 using the guide rail system of the Sapporo Traffic Department. An outline of the tests results is given below.

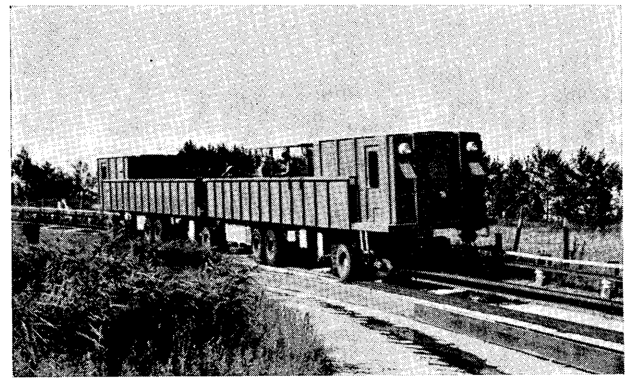
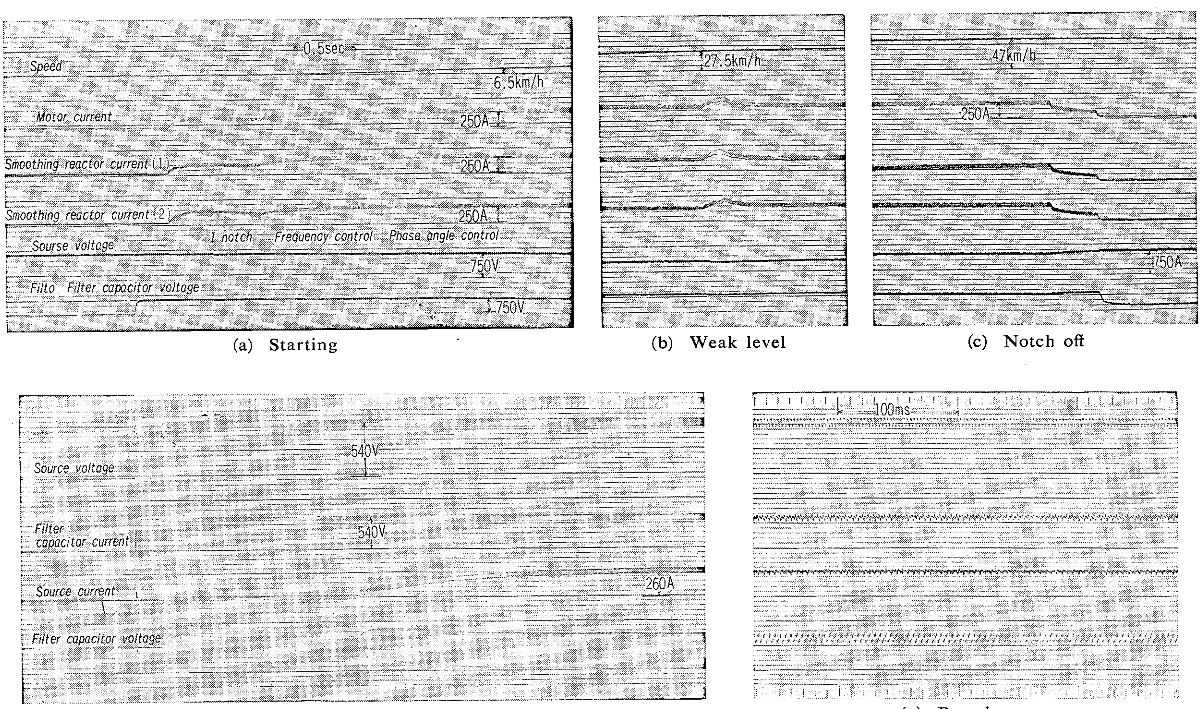


Fig. 12 Outer view of testing car

1. Powering and Braking Functions

Fig. 13 shows powering oscillograms. (*a*) is during starting, (*b*) is when the weak field level is reached, (*c*) is during notch off, (*d*) shows the power supply relations during starting and (*e*) is an amplification of the time axis in (*d*). *Fig. 14* shows the oscillo-



(a) Starting (b) Weak level (c) Notch off

(d) Starting (e) Running

Fig. 13 Oscillogram of powering

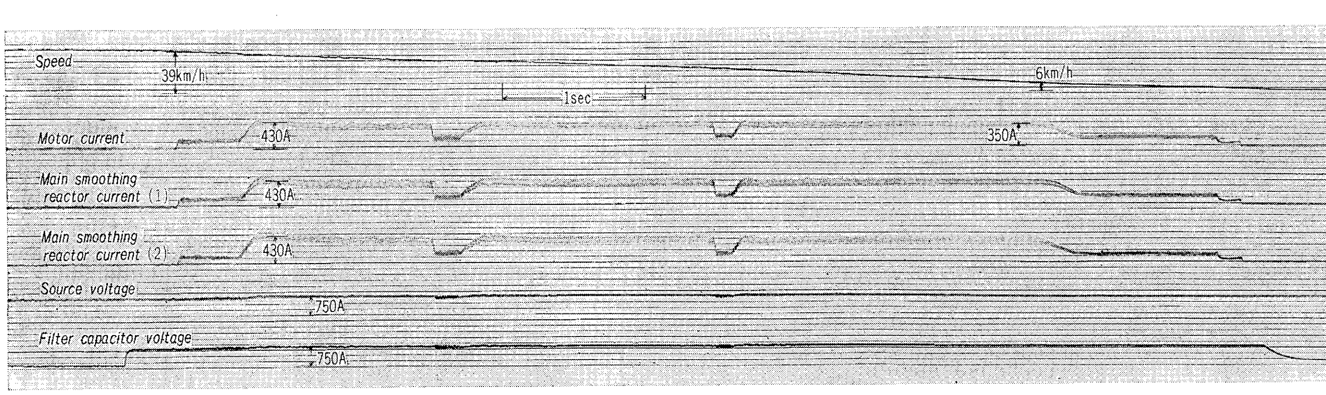
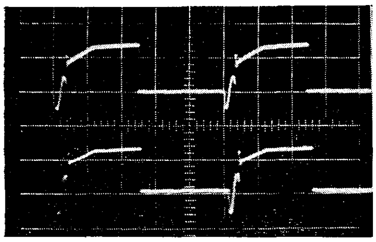
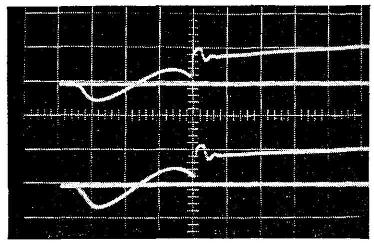


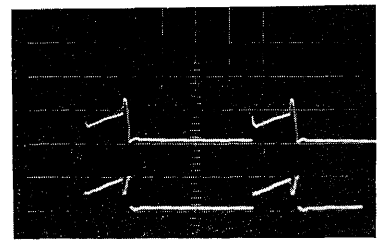
Fig. 14 Oscillograms of regenerative braking



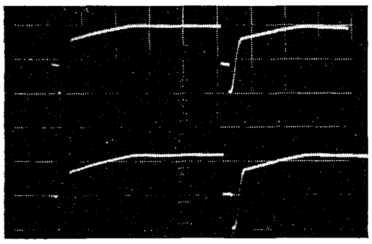
(a) Main thyristor voltage waveform
200 V/cm, 1 msec/cm



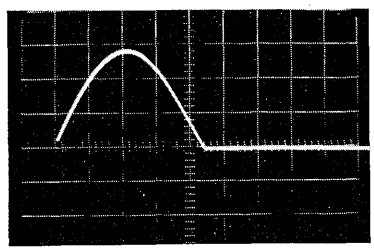
(b) Main thyristor voltage waveform during commutation
200 V/cm, 100 μsec/cm



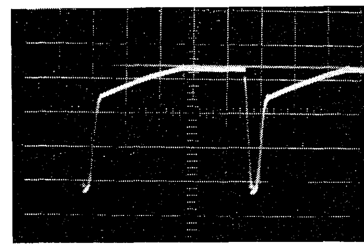
(c) Main thyristor current waveform
50 A/cm, 1 msec/cm



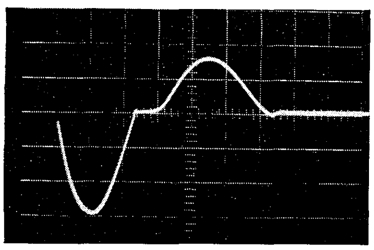
(d) Commutating thyristor voltage waveform 200 V/cm, 1 msec/cm



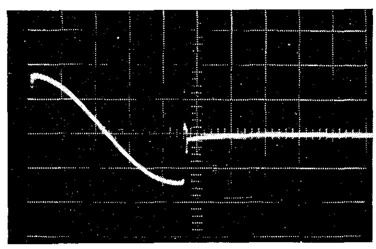
(e) Commutating thyristor current waveform 500 A/cm, 50 μsec/cm



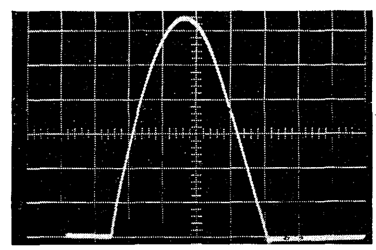
(f) Commutating capacitor voltage waveform 200 V/cm, 1 msec/cm



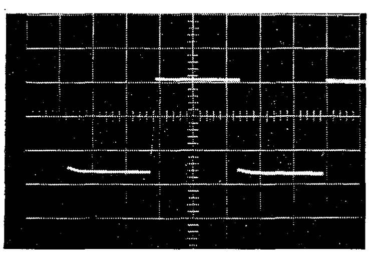
(g) Commutating capacitor current waveform 500 A/cm, 100 μsec/cm



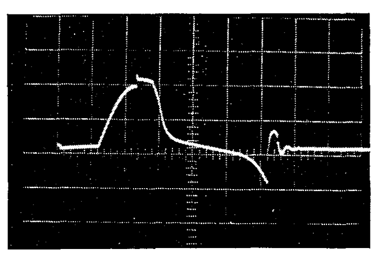
(h) Commutating reactor voltage waveform 200 V/cm, 50 μsec/cm



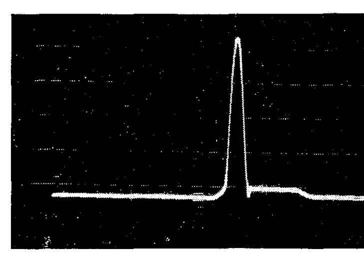
(i) Commutating reactor and diode current waveform 200 A/cm, 50 μsec/cm



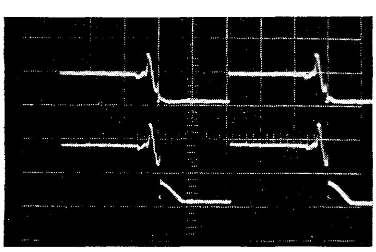
(j) Commutating diode voltage waveform
200 V/cm, 1 msec/cm



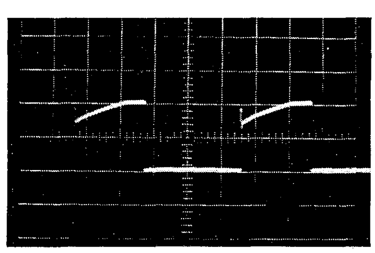
(k) Saturable reactor voltage waveform
200 V/cm, 100 μsec/cm



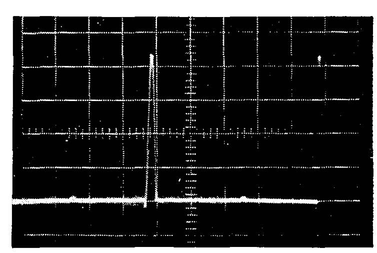
(l) Saturable reactor current waveform
200 A/cm, 0.5 msec/cm



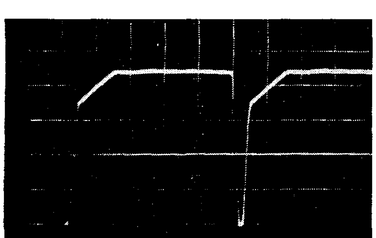
(m) Flywheel diode voltage waveform
200 V/cm, 1 msec/cm



(n) Bypass diode voltage waveform
250 V/cm, 1 msec/cm



(o) Bypass diode current waveform
200 A/cm, 1 msec/cm



(p) Clamp diode voltage waveform
250 V/cm, 1 msec/cm

Fig. 15 Oscillogram of each voltage and current

Table 5 **JP of souce current**

Speed	Supply current (A)	JP (A)
Powering 1 notch	30	0.005
Powering 2 notch	400	0.045
Powering 3 notch	400	0.055
Braking 1 notch	100	0.045
Braking 2 notch	140	0.043
Braking 3 notch	180	0.05
Braking 4 notch	200	0.05
Braking 5 notch	230	0.06
Braking 6 notch	230	0.063
Braking 7 notch	260	0.073
Powering 2 notch (chopper single phase)	200	0.05

grams during regenerative braking. The acceleration functions show almost no differences when compared with the resistor control (generative braking), but with chopper control, passenger comfort and brake response are much better.

2. Waveforms of Each Part of the Chopper Equipment

Fig. 15 (*a*) to (*p*) are photographs of measurements made with a synchroscope for the waveforms of each part as shown in *Fig. 5*. These agree well with *Fig. 5* and this shows that chopper operation and control both function well.

3. Analysis of Equivalent Disturbance Current and Power Source Current Harmonics

Table 5 lists the measured results of JP (maximum value during running). The value is about 1/10 of the planned value of 0.3 A/100 A. It is considered that the influence of mojor factors which have not been considered such as power source inductance, magnitude of back power and types of power source (use of rotational converter in actual tests) is great. Almost the same degree of JP is observed in the case of resistor control. There is absolutely no influence on television or radio nearby the lines and even though induced disturbances from the overhead line can not be judged simply because of the few examples, it appears that current countermeasures are sufficient. The wiring of the chopper equipment requires precautions when installing on the car because a high pulse current flows and this results in the danger of directly induced disturbances from the circuit wiring to broadcasting equipment in the car.

In the factory tests, the results of an analysis of harmonics included in the power supply current show that 60, 120, 360, 720 and 1,080 Hz are observed as harmonices caused by the power source (60 Hz, 3-phase full-wave rectification). Independent of the operating conditions on the chopper side, these are almost constant and the current which flows is decided by the JP filter constants. The harmonics which arise in the chopper equipment side are observed as f, $2f$, $3f\cdots\cdots nf$ when the single phase chopper operating frequency is f. These values vary according to the chopper operating conditions, but there are cases when attenuation is low up to about 25 steps. In the actual tests, the JP (flat) containing no auditory sensation was about six to eight times the JP (weight) and this is usually evident when the highest harmonic is included. The 60 Hz component presents a problem in respect to reducing the weight of the JP filter. Special tests concerning disturbances in signals were not conducted this time, but investigations are required since specific frequency components present a problem.

4. Measurement of Power Consumption

Powering was carried out under the same conditions as used with the resistor method and power consumption was measured. When the power consumption with resistor control is considered as 100%, the power consumption with chopper control not including regenerative braking was 91% and was about 70% when the regeneration power was subtracted.

V. CONCLUSION

The above has been a general outline of the thyristor chopper control equipment for use in DC cars. The applications of semiconductor elements are expected to rise sharply in the near future and efforts are now continuing which should leak to greater modernization and rationalization of rolling stock. The authors will be very pleased if they receive comments from many people. The authors also wish to take this opportunity to offer sincere thank to the persons in the Traffic Department of Sapporo City and Kawasaki Heavy Industries who cooperated so much in the tests on this equipment and gave so much advice concerning these tests.

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