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POWER EQUIPMENT FOR ROLLING STOCK AIR CONDITIONERS

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I. INTRODUCTION

The astounding rise in the standard of living in recent years has been accompanied by a remarkable increase in the popularity of air conditioners which are now almost indispensable. This is especially true in countries such as Japan where hot, humid weather is normal during the summer. This trend is also evident in the transportation field where air conditoiners are used not only in long distance buses but also even in taxicabs. In the field of rolling stock, air conditioners were first employed for the dining car of the limited express "Tsubame" in 1936. Ever since, air conditioners have been primarily employed in dining cars and 1st class sleeping cars. However, since the compressor and evaporator of these air conditioners were installed to the underframe of car and mechanically driven from the wheel axle, the cooling system itself had the drawback of lack of cooling capacity during the train was stopped. The first power car equipped with a diesel generator for supplying air conditioning power was developed in 1958. This centralized power system was first used for the limited express " Asakaze " and enabled air conditioning of all cars while the train was stopped. Since then, all limited express trains have been equipped with air conditioning facilities. At the present time, express trains are also being equipped with air conditioning equipment.

The first power generator used for the limited express " Asakaze " was supplied by Fuji Electric. Since then, the diesel generator equipment for many Japanese National Railways passenger and diesel cars, as well as motor-generator equipment for motor cars, has been supplied by Fuji Electric. Recently we supplied diesel generator equipment to the Korean National Railways for use in centralized power systems. The outline of our power supply equipment will be described in the following.

II. TREND IN ROLLING STOCK AIR CONDITIONER POWER EQUIPMENT

(1) Generally, the formation of limited express train is fixed and it is more advantageous to adopt a centralized power supply system with enough capacity to feed electric power to a number of cars.

In cases of fixed formation limited express trains, two units of 250 kva diesel generators are installed in the power car and supply electric power for air conditioning, illuminating and other purposes.

No special power car is provided in the case of diesel limited expresses and motor cars. Instead, two or three large capacity diesel or motor-generators are installed to the underframe in order to supply all the power requirement of the train.

(2) In the case of luxury car " green car " of other than limited express train, a 20 to 25 kva diesel generator is installed to each car for the one formation convenience for separation and recombination of train.

(3) A 3-year project for the installation of air conditioners in all express cars has recently been initiated. The planned power supply system has enough capacity to feed one group of cars consisting of 5, 3 or 4 cars in cases of passenger, diesel and motor cars respectively in order to meet the actual practices in separating and reassembling of cars. *Table 1* shows the major particulars of power equipment for air conditioning to the Japanese National Reilways made by Fuji Electric.

At present, three types of diesel generators having capacities of 180 kva, 70 kva and 110 kva are being manufactured as standard sets for passenger, diesel and motor cars respectively.

III. DIESEL GENERATOR EQUIPMENT

Considering the particular situations of diesel generator equipment for rolling stock, the following requirements must be satisfied :

(1) As installation space is limited, the unit must be compact in size and light in weight. In particular, the unit must be designed to effectively utilize the narrow space under the frame of the car.

(2) The unit must withstand vibration and should be of dust and drip-proof construction. The insulation of the generator shall be of high quality since

Table 1 Power Equipment for Air Conditioning

	Type of Car	Generator				Diesel Engine (Motor)		Cooler		
		Model	Output (kva)	Voltage (v)	Freq. (Hz)	Model	Particulars	Model	Cooling capacity kcal/hr	System
Passenger Car	Limited express	PAG-1	250	600	60	DMF31 S-G (Diesel engine)	340 ps 1200 rpm	AU 21/22	12,800×2	Under frame mount
	1st class sleeping car	PAG-2	20	200	60	3 PK-9 A (Diesel engine)	25.2 ps 180 rpm	AU 31	19,000×1	Under frame mount
	1st class reserved seat car 2nd class sleeping car	PAG-8	20	440	60	4 PK-9 A (Diesel engine)	35 ps 1800 rpm	AU 13 AU 14	5500×5 2700×9	Roof mount Roof mount
	2nd class reserved seat car	DM-82-A	180	440	60	DMF 15H-G (Diesel engine)	220 hp 1800 rmp	AU 13	5500×6	Roof mount
Diesel Car	Limited express	DM-63	125	440	60	DMF 17H-G (Diesel engine)	160 ps 1200 rpm	AU 12	4000×6	Roof mount
	1st class reserved seat car	DM-72	25	400	50	4 DQ-11 P (Diesel engine)	43 ps 3000 rpm	AU 13	5000×6	Roof mount
	New model limited express {1st classs 2nd class	DM-82-A	180	400	60	DMF 15H-G (Diesel engine)	220 hp 1800 rpm	AU 13 A	5500×5 5500×5	Roof mount
	2nd class reserved seat car	DM-83	70	400	50	AUK-88 (Diesel engine)	90 ps 3000 rpm	13 AU	5000×7	Roof mount
Motor Car	1st class reserved seat car	DM-76-A	20	440	60	MH 122 A (Motor)	Dc 1500 v 20 kw 3600 rpm	AU 12	4000×6	Roof mount
	1st class reserved seat car	DM-84	90	440	60	MH 127 (Motor)	Dc 1500 v 85 kw 1800 rpm	AU 13	5500×5	Roof mount Roof mount
	2nd class reserved seat car	DM-85	110	440	60	MH 128 (Motor)	Dc 1500 v 104kw 1800rpm	AU 13 E AU 72	5500×5 33,000×1	Roof mount

its ambient temperature is high and environmental conditions are not favorable due to the exhaust from the engine.

(3) A remote control system is required to start and stop the engine and to monitor the engine operating conditions.

1. Diesel Generator

An integrated diesel generator consisting of an engine and generator coupled by flanges is installed to the underframe of the car through resilient rubber. An automobile engine easily available in the market is employed as the prime mover for supplying the air conditioner of " green car " for the convenience of procurement of spare parts.

A large capacity engine of horizontal cylinder type is preferred because of limited vertical underframe space. In the cases of 125 kva and 180 kva diesel generators for express diesel cars, the engine used to drive the diesel car is partly modified to drive the generator. A high-speed (3000 rpm) engine for use with 70 kva generator has been especially developed for air conditioning.

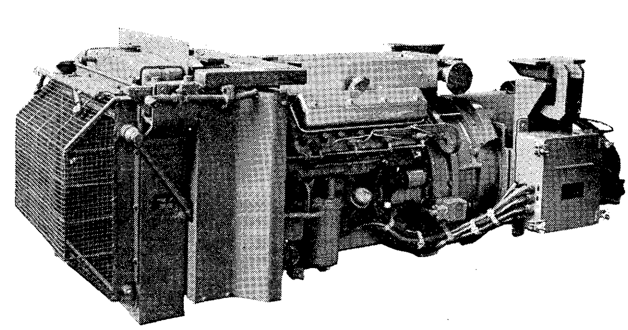


Fig. 1 70 kva brushless diesel generator for the air conditioning of the diesel express

The peak load of a generator is extremely large during the starting period since all the compressors are turned on simultaneously. In addition, since the load is constantly being turned on and off during operation, load fluctuations are extremely high. Therefore, the generator must quickly respond to the load fluctuation. A compound type self-exciter featuring quick response and comparatively simple maintenance has been used for voltage regulation for many years. However, a brushless generator, which requires less maintenance, has recently taken over the position as the main generator for rolling stock.

Fig. 2 shows a static exciter consisting of a saturable reactor, potential current transformer and silicon rectifier. A constant dc excitation is fed to the saturable reactor whose output winding is connected in series with the potential winding of the potential current transformer. Thus, the field current required to generate the rated voltage generation under no-load is supplied by the line voltage. In order to compensate the influence of load variation, the line current is supplied to the current coil of the potential current transformer. The magnetic flux created by the current and potential windings is vectorically summed and the generator voltage is kept nearly constant irrespective of changes in load current and

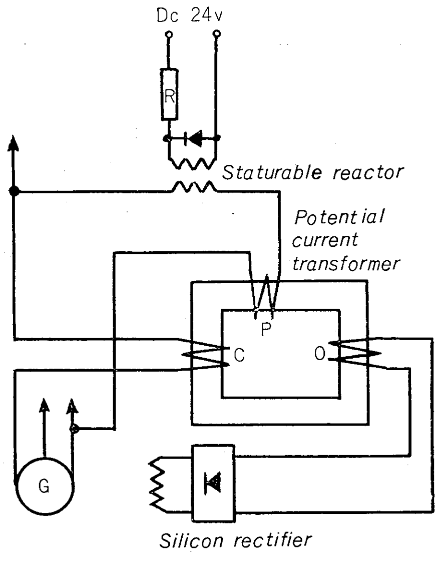


Fig. 2 Simplified schematic diagram of static exciter

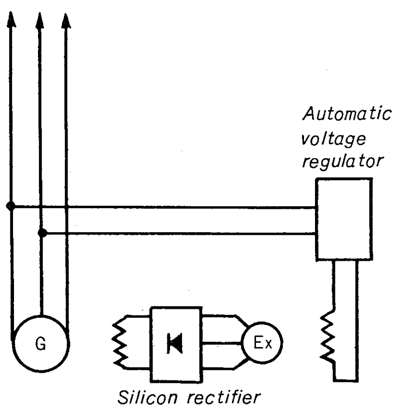


Fig. 3 Simplified schematic diagram of brushless generator

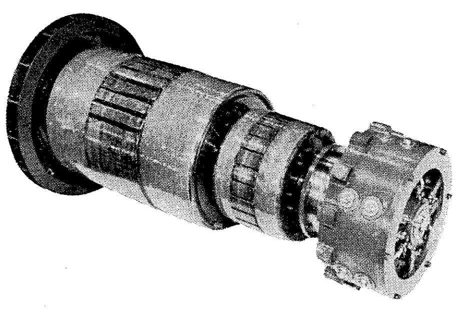


Fig. 4 Rotor of 70 kva brushless diesel generator

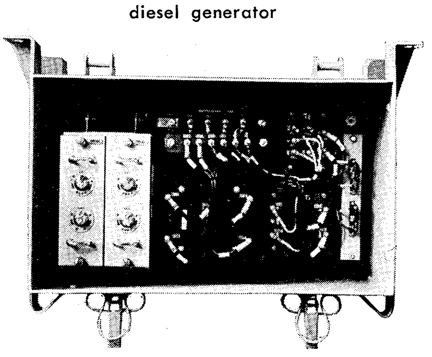


Fig. 5 Static exciter for 70 kva generator

power factor.

Fig. 3 shows a schematic diagram of a brushless generator. The 3-phase output from the ac exciter is converted to dc current by 6 silicon diodes mounted on the rotor shaft. This dc current is then applied to the generator field. Therefore, the generator voltage can be controlled without using mechanical contacts such as brushes by adjusting the separate field current of the exciter.

Since the voltage regulator only controls the exciter field, it can be a small capacity thyristor type voltage regulator.

2. Control System

When air conditioning was employed only for fixed formation limited expresses and certain luxury cars and maintenance engineer always attended, simple manual control systems were widely used. However, the wide spread use of rolling stock air conditioning coupled with personnel reduction program being pursued by the Japanese National Railways have led to the gradual employment of automatic control and safety measures.

(1) Controller construction

A car with power equipment is also equipped with all the devices required for engine control, generator voltage adjustment, power distribution and protection. The output of the generator is supplied from the controller to the 3-phase train wires running through all the cars. A switchboard is provided in each car to supply the power received from the train wires to the air conditioner of the car. A molded case circuit breaker is provided at the end of the train wires of each car to permit breaking of the train wires for the proper number of cars to be combined and to establish the distribution range for each power equipment.

(2) Automation of operation

All operations including starting of the engine and air conditioning, are automatically performed by push button switch. A series of these operations is se-

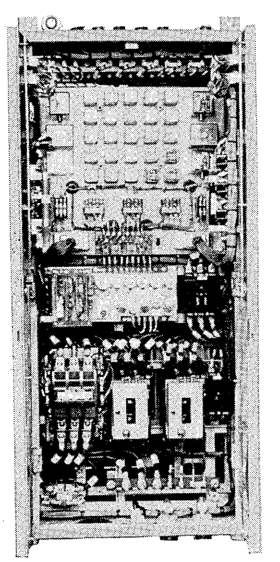


Fig. 6 Control panel of 70 kva brushless diesel generator

Table 2 **Major Particulars of 70 kva Diesel Generator**

Engine	
Model	4VK
Type	90° Vee, single acting, 4 stroke cycle, water cooled type
No. of cylinders	8
Bore×stroke	88×100 mm
Brake horse power	90 ps
Speed	3000 rpm

	Generator	Exciter
System	3-phase ac, revolving field type	3-phase, ac, revolving armature type
Type	Open, self-cooled type	Open, self-cooled type
No. of poles	2	4
Output	70 kva	18 kva
Voltage	400 v	72 v
Current	101 amp	145 amp
Speed	3000 rpm	3000 rpm
Frequency	50 Hz	100 Hz
Power factor	80%	
Insulation class	F	B

quentially performed in the order of a) preheating of engine, b) starting of engine, c) building up of generator voltage, d) sequential starting of air conditioners.

(3) Multiple control

Several sets of power equipment are normally installed in a train. Therefore, in order to control these power equipment, control train wires are run through all the cars.

(4) Protection

Interlock contacts are provided in each breaker connected to the train wires in order to avoid parallel operation of generators as a result of separation and recombination of the cars, and a control train wire circuit is provided to protect the generators against parallel operation. Engagement or disengagement of the couplers while high voltage is being applied to the couplers is prevented by means of the control train wires and the auxiliary contacts of the power coupler.

As a typical example, the major particulars of a 70 kva brushless generator are given in *Table 2*.

IV. MOTOR-GENERATOR EQUIPMENT

1. Motor-Generator Requirements

Since motor-generators are used under the most severe conditions among any rotary machine for rolling stocks, consideration must be given to the following items:

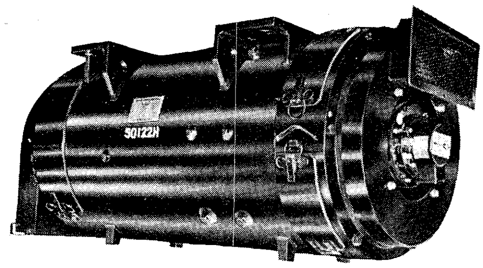


Fig. 7 110 kva motor-generator

1) Constant speed and output characteristics must be obtained over a wide range (900 v to 2000 v) for both ac and dc catenary.
2) Stable commutation must be maintained under extremely severe transient voltoge variations caused by changes in the line voltage and momentary power interruptions and re-application during pantograph jump and section passage.
3) The unit should be compact, light weight, vibration-proof and water-proof.

In order to meet these requirements, Fuji Electric has developed an all new ripple voltage motor with a single series winding, unique commutation compensation and special thyristors excitation control.

2. Improvement of Commutation

The most important point required for motors for traction use is stable commutation over a wide range of voltage variations. To achieve this objective, it is necessary to keep an rush current as low as possible. However, since the conventional compound motor-generator employs several field windings, it is almost impossible to improve the follow-up of field flux and the response of the induced electromotive force of the armature during the transient period. For this reason, resistors are normally connected in series with the armature to limit the rush current.

However, the resistance value of series resistors is limited since armature current considerably increases as the line voltage drops in the case of motor-generator which requires constant speed and output characteristics. So it is almost impossible to limit the rush current for a large capacity generator by this method. Therefore, a compensating winding has been provided in the motor and a laminated magnetic circuit has been employed to improve the response of the magnetic flux of the interpole and to obtain good commutation.

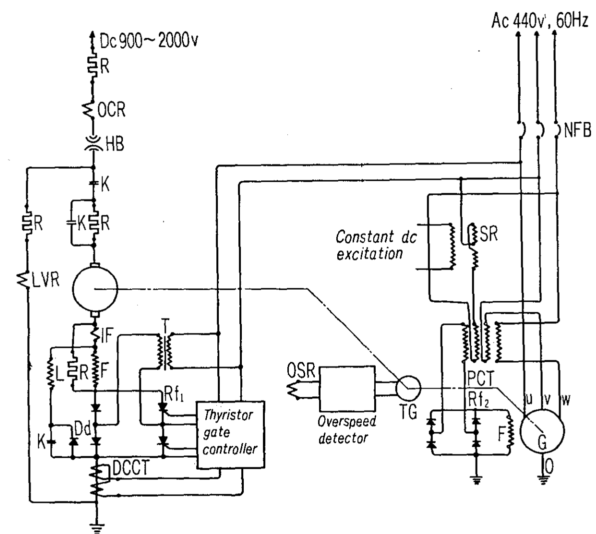
However, the series motor-generator developed by Fuji Electric is completely different from conventional motor-generators, in that the rush current is suppressed by increasing the induced electromotive force of the armature in proportion to the amount of rush current entering the field winding. Since the action of the electromotive force induced in the armature is equivalent to that of series resistors, the series resistors are unnecessary and the rush current can be reduced to less than one-half that of conventional type equipment. Therefore a compensating winding is not required.

A laminated magnetic circuit is also employed to improve the follow-up of the magnetic flux of the field.

3. Constant Speed Characteristic

Another requirement for motor-generator, constant speed characteristic, is fulfilled by conventional compound type motor-generator which is specially designed to obtain good speed characteristic.

In contrast to conventional type equipment, our series motor-generator does not have a separate regulating winding since this winding often causes poor follow-up characteristics of the magnetic flux of the field. Instead, as shown in *Fig. 8*, a hybrid bridge type rectifier consisting of thyristors and diodes is connected in series with the field winding and a reactor is connected in parallel with the said rectifier as a current passage to superpose the current from the external power source onto the field.



DCCT:	Dc current transformer	OCR;	Over current relay
Dd:	Silicon diode	OSR:	Over speed relay
F:	Field winding	PCT:	Potential current transformer
G:	Generator	R:	Resistor
HB:	High speed breaker	Rf_1:	Thyristor
IF:	Interpole winding	Rf:	Diode stack
K;	Magnetic contactor	SR:	Saturable reactor
L:	Reactor	T:	Auxiliary transformer
LVR:	Low voltage relay	TG:	Tachometer generator
NFB:	Molded case circuit breaker		

Fig. 8 Basic connection diagram of ripple voltage type series motor-generator

4. Compactness and Light Weight

As previously described, the Fuji Electric motor-generator is equipped with a single series winding and requires no compensating winding and thus provides a considerable savings in space. A compact, lightweight construction is also possible since the current capacity of the motor can be reduced through the elimination of the series resistors.

The current increase due to a drop in the line voltage is considerably smaller than that of compound motors.

5. Commutation Compensation during Ripple Current Operation

The following methods have been conventionally used when a dc motor is operated on ripple current in order to improve commutation:

(1) Large smoothing reactor is connected in series with the armature circuit to limit the ripple factor 10~15% or less to reduce the effect of the transformer emf to a minimum. Although all conventional motor-generators utilize this method, it requires a large smoothing reactor.

(2) Either magnetic circuit is laminated or field winding is shunted by a resistor which by-passes the ac component included in the field current and helps reducing the transformer emf.

Since an rush current flows during the transition period in this type of motor, it cannot be used for rotary machines such as motor-generators which must withstand severe commutation conditions during the transition period.

(3) In contrast to the above methods, since the ripple voltage motor has excellent field flux follow-up characteristics, an ac magnetic flux is generated by the ac component passing through the field and the field winding acts as an inductance and suppresses the ac component entering from power source side.

However, in this case, compensation of the transformer emf generated by the alternating magnetic flux of the field becomes the key point. In order to solve this compensation problem, a new commutation compensation method has been developed in which both the interpole and field windings are shunted by a high resistance.

A transformer emf and reactance voltage vectorically out of phase are present in the armature coil under commutation. Therefore, in order to obtain perfect commutation compensation, it is necessary to cancel these two resultant spark emf by means of the commutation emf.

When a high shunt resistance is employed, the phase of the current passing through the interpole and field winding lags behind that of the armature current. By suitable selection of this resistance, sparkless commutation can be realized over the whole range.

In contrast to conventional motor-generators, the Fuji Electric motor-generator permits operation on high ripple current and utilization of the field inductance. This makes reduction of the size of the smoothing reactor to less than one-half that required for the conventional motor-generators as well as the size of the other equipment, possible.

6. Motor-Generator Control Equipment

Motor-generator control equipment consists of starting equipment, frequency regulating, voltage control equipment.

1) Starting

The starting system is 3-step starting combined with time limit starting and speed detection under full field and special consideration given to improve commutation during the starting period.

The field shunt circuit is opened by the contactor prior to starting and starting is performed under full field conditions. The voltage of the tachometer generator attached to the shaft end of the motor-generator builds up and the starting resistor is short-circuited after confirming that the speed has reached approximately one-half of rated speed. When the motor speed increases, the generator voltage rises accordingly. Regulating current is gradually superimposed on the field and the motor speed approaches the final value without overshooting. Ample time limit is allowed to elapse after the 2nd stage contactor is opened and the contactor of the field shunt circuit is closed after the motor reaches normal speed.

The major features of this starting method are that strong starting torque, quick acceleration and good commutation are obtained since full field series motor starting is employed.

2) Frequency regulator

Since Fuji Electric's ripple voltage motor employs a single series winding, a unique control method differing from conventional one was adopted.

The thyristor rectifier circuit is connected in series with the series field of the motor and a reactor is connected in parallel with the above combination.

The current flowing through the field is the resultant of the following components.

(1) Part of the armature current (self-excitation component). This current changes in accordance with the motor armature current.

(2) Regulating current supplied by the generator through the transformer, rectifier and reactor (separate excitation).

This current can be adjusted by controlling the firing angle of thyristors.

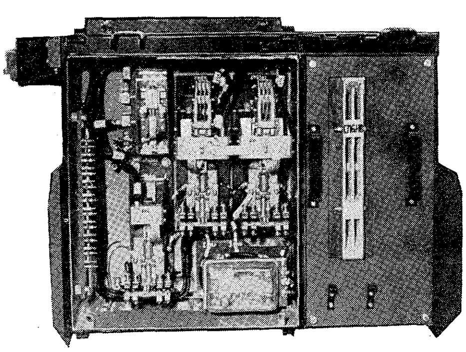


Fig. 9 Starting equipment for 110 kva motor-generator

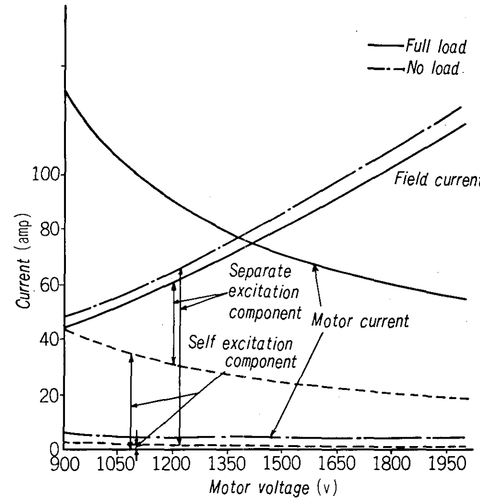


Fig. 10 Relation between field currents and motor voltage

In order to maintain a constant generator frequency, that is, motor speed, independent of changes in line voltage and load, it is necessary to control the motor field current as shown in *Fig. 10.* As the line voltage increases, the self-excitation component decreases and the separate excitation component increases.

In order to detect frequency, an LC series resonant circuit is used, the output of which is compared with a reference value, converted to a phase shift signal in accordance with the magnitude of frequency deviation by means of a magnetic amplifier or a unijunction transistor type phase shifter, and then supplied to the thyristor as a pulse signal through a gate transformer to control the field current.

(3) Voltage control equipment

Self-excited compound type static exciter similar to that used for diesel generators is used.

(4) Protection

A high-speed circuit breaker combined with a current relay trip system is used to protect the motor against flashover. In this system the circuit breaker proper and highly sensitive current relay are separated. This combination can eliminate mis-operation due to dust and dirt when installed to the underframe of a car. So as to protect the motor-generator set against over speed, a tachometer generator and static detector are used instead of a conventional centrifugal switch. This makes the equipment much smaller and simplifies maintenance.

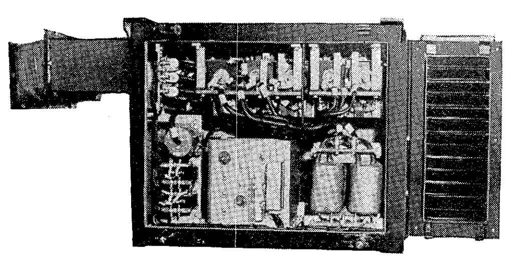


Fig. 11 Regulator box for 110 kva motor-generator

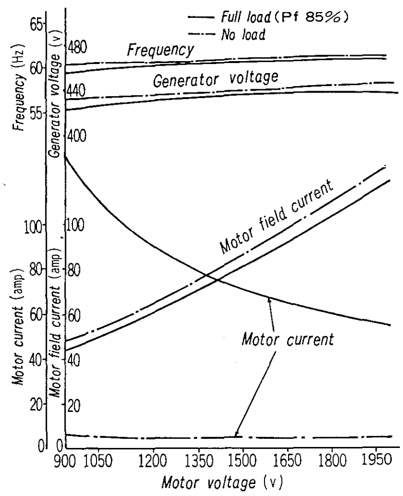


Fig. 12 Voltage change characteristic curves for 110 kva motor-generator

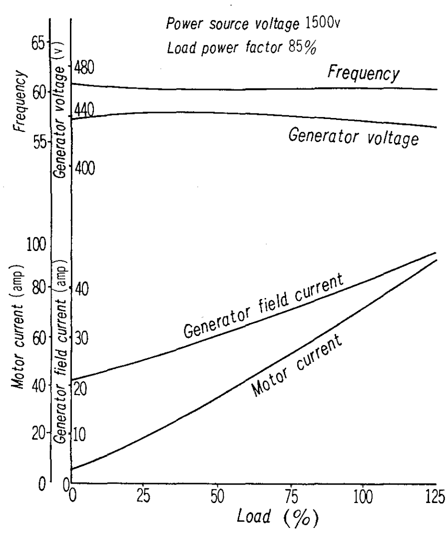


Fig. 13 Load characteristic curves for 110 kva motor-generator

(5) Characteristics

The voltage change characteristics, load characteristics and major particulars of a 110 kva motor-generator are given in *Figs. 12*, *13* and *Table 3* respectively as a typical example.

Table 3 Major particulars of 110 kva Motor-Generator

	Motor	Generator
Model	MH125	DM85
System	Dc and ripple voltage motor with interpole	Revolving cylindrical field type
Type	Open, self-cooled type	
No. of poles	4	4
No. of phase	—	3-phase, 4-wire
Output	104 kw	110 kva
Voltage	1500 v	440 v
Current	78 amp	144 amp
Speed	1800 rpm	
Efficiency	80%	
Frequency	—	60 Hz
Power factor	—	85%
Ripple frequency	50 Hz×2 60 Hz×2	—
Insulation class	F	F
Dielectric test voltage	5400 V	1900 v
Maximum test speed	2400 rpm	
Voltage regulation		400～480 v
Frequency regulation		54～66 Hz
Weight	Approx. 1700 kg	
Characteristics	Voltage change characteristics (See *Fig. 12*)	
	Load characteristics (See *Fig. 13*)	

V. CONCLUSION

Popularization of rolling stock air conditioning systems in the future is apparent. Studies on air conditioning for commuter cars have already been started and such systems should be actually realized in the near future.

In commuter car air conditioning, the required capacity per car is estimated at 40,000 to 45,000 kcal/hr. This is considerably large compared to the 25,000 kcal/hr required for express cars. Also, since a large number of commuter cars are in actual operation, economical air conditioners and power equipment are required.

This makes a centralized power source system having the largest possible capacity and suspendable from the underframe of the car necessary.

It is also anticipated that all new cars for privately-owned railways will be equipped with air conditioners. In this case, the power source system will supply power not only to the air conditioners but also to the low voltage equipment of each car in consideration of overall economy. This means that highly reliable power equipment must be available for this purpose.

In view of the facts described above, the demand for power equipment will increase considerably in the near future. We are ready to put maximum effort into the development of highly reliable and economic power equipment requiring simple maintenance.

We would like to express our gratitude to the staff of the rolling stock design of the Japanese National Railways for their guidance in the design and manufacture of this air conditioner power equipment.

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