60 c/s COMMUTATOR TYPE TRACTION MOTOR FOR AC ELECTRIC CAR

By

Yoshio Adachi, Eiji Koyasu, Takeo Miyagawa

(1st Rotary Machine Div., Design Dep't) (2nd Rotary Machine Div., Design Dep't)

I. PREFACE

A few years have hardly passed after the Japan National Railway Corp. decided to adopt the AC system of a commercial frequency in electrification of the trunk lines; the AC locomotives have been in operation at the Senzan- and the Hokuriku-line, and the electrification of the Kagoshima-, the Tohoku- and the Jyoban-line will be soon completed. There have been used for these lines the so-called indirect type rolling-stocks employing the rectifiers, and the uses of them have been almost for goods trains. The indirect type rolling-stocks have so good adhesive characters that the greater parts of them manufactured in Japan are the mercury rectifier locomotives. When the utilization of an electric train car becomes a subject of discussion, however, the adhesive character wanders from the point, and weight of a car, simplicity in operation, cheapness of initial funds are important. Then the direct type electric rolling-stocks which have been scarecely utilized in spite of their good characteristics, attract the public attention as the medium distance attend-office train cars on the Kagoshima-line in North-Kyushu district.

Deciding the fundamental design of these cars, J.N.R. ordered an experimental car and several traction motors which were the most important parts for direct type electric cars of commercial frequency. Our Company cooperated to these plans, and manufactured two trial 60 c/s traction motors, which were the first ones ever made in the world. Early in this year, we tested them in our factory and on the railroad, and could get very good results. Then we give here an epitome of our single phase 60 c/s trial commutator motor and its test records.

II. OUTLINE OF THE PLAN

The defect of a single phase commutator motor, specially of a commercial frequency traction use, was the difficulty of design to get much starting torque. Designing and manufacturing difficulties increased furthermore with the commercial frequency, so that the maximum frequency of the single phase traction motors ever made in the world was only 50 c/s. Hence the specifications given to these trial motors were determined under careful considerations.

The technical developments of the general electric machines were lately so splendid and the researches about this sort of motors in our country for these years were so thoroughly treated, that the severest tractive characters were given to these trial motors under the convictions that any difficulties might be conquered.

The characters of the trial car were therefore planned that it might exceed those of the newest superior DC electric train-cars in Japan, and the car might be used not only on the Kagoshima-line but also might run as a standard AC car wherever on the AC regions in Japan.

The specifications of this trial car and the traction motor are as follows:

Gauge	1,067 mm
Wheel diameter (new)	910 ϕ
Average station intervals	3 km
Weight empty motor car (M)	45 t
Weight empty trailer car (T)	30 t
Max. load weight	each 15 t
Max. speed	95 km/h
Average speed	63 km/h
Fundamental composition	MTT
Max. acceleration (at full load)	1.5 km/h/sec.
Drive	Hollow shaft cardan drive
Gear ratio	85 : 15 = 5.933
Frequency	60 c/s
Rated output	150 kW
Rating	1 hour
Speed (max./rated)	3,420/2,280 rpm
Current per one motor	1,120 A
Ventilation	Forced ventilation, 40 m^3/min, 120 mmAg

The output of our trial motor was 150 kW, which was calculated on root-mean-square current when the fundamentally composed MTT train car rans with maximum load at the acceleration of 1.5 km/h/sec. As the capacity of this motor was comparatively large, then the number of motor cars decreased in one long composed train car, and the running cost of the train car reduced.

There have been discussed what percentage of rated speed to maximum speed was best concerning to the expression of the capacity, when the car could run at any speed by voltage control. It seems that this value may be taken about 70% in Europe, especially in the countries which utilize the $16\frac{2}{3}$ c/s electrification. But this time J.N.R. investigated the normal running conditions of DC train cars and the largest probability of efforting speed in total efforting time. The results of them showed that about 70% of maximum speed was the most probable, then the rated speed was selected the value of 63 km/h which corresponded to the 70% of the usually used maximum efforting speed 90 km/h.

The high speed and the light motor are the feature of the newest DC traction motor in Japan. In planning this AC motors also, its speed was chosen as high as possible in order to give the good character to the car by decreasing weight, and the motor was mounted on the truck using the hollow shaft parallel cardan drive.

Four motors were connected in series and despite of increase of motor current due to 60 c/s frequency, weight of controlling equipment was rather decreased. As the single phase series motor shows good commutation character at direct current running, DC dynamic braking was used as the braking system of the car. It was so designed that the maximum reterdation of a motor car only with full load might be gained about 4 km/h/sec, but this value was easy enough comparing with the commutation at accelerating. Fig. 1 shows the photograph of our 150 kW AC traction motor which was manufactured under the projection here we mentioned.

III. OUTLINES OF THE MOTOR DESIGN

We completed this trial motor with much efforts on designing and manufacturing which were based on the experience of 50 c/s single phase locomotive motor(1) made few years ago in our factory and showed good results, so that it might suit to 60 c/s electric train car. To design this motor, the points which we considered carefully were that the motor was the first 60 c/s one in the world, higher speed was employed as a commutator motor to decrease weight, and larger accelerating torque was required in order to get higher accelerating character of the car comparing with that of the motors in Europe.

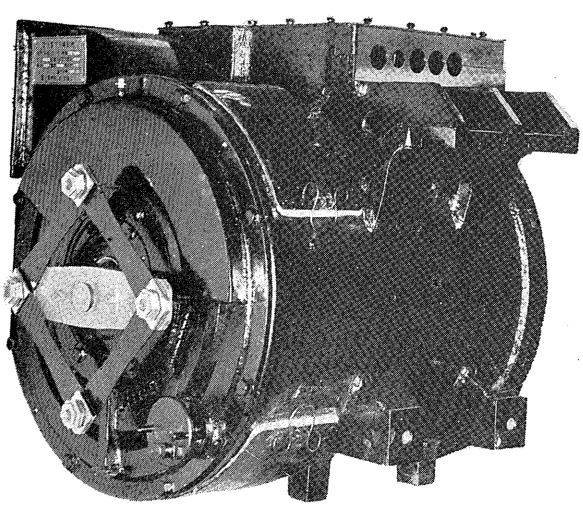

Fig. 1. 150 kW traction motor for AC electric car

1. Bases on electric design

Now taking P as shaft output in kW, p as number of pole-pairs, A as electric loading in A/cm, e_t as transformer voltage in Volt, D_a as armature diameter in cm, f as line frequency in c/s, n as speed in r.p.s., η_A as the ratio of mechanical output to armature electrical input, then the generally used formula of output is written as follows.

$$P = \frac{A}{1000} e_t p \frac{D_a}{f} n \eta_A \qquad (1)$$

This is the basic formula to design single phase series commutator motor. It shows that the higher the line frequency, the p fewer the number of pole-pairs and the lower the transformer voltage, the electric loading have to be taken larger in the same amount of shaft output. In case of a traction motor, the armature diameter is limited dimensionally and the speed is defined by the number of minimum pinion teeth and the diameter of gear wheel which is kept within bounds, so that the values of D_a, n, η_A can not be varied largely. How to select the values of A, e_t, and p, therefore, is the basic line to design.

Core weight and also total weight decrease with the number of pole-pairs. Hence we took 8 poles, which were supposed as the limited numbers, considering its frequency and output. The transformer voltage is the fundamental value to design this motor, and it is the latest tendency in Europe to take the value as lower as possible, considering its injuring effect to commutators and brushes(2)(3). We took then the lower value, about 2.8 V, than that of the 50 c/s motor which we had ever made for the locomotive on the Senzan-line. We believed also that the lower transformer voltage was better for the life of commutator and brushes, but accordingly the electric loading became higher and it was necessary to make efforts technically on design. The temperature rise of this motor was carefully schemed, and the cooling character was skilfully treated by three parallel paths method which we had heretofore recommended, together with the decreasing means of the stray-load losses. The transformer voltage was chosen safely refering to the results of our 50 c/s locomotive-motor in which the relation between transformer voltage, brush short-circuited current and the running commutations were fully investigated.

It is necessary, of course, to take enough care for the shape of interpole, so as to get better running commutations, also saturations of the main pole and magnetic paths are the most important factor to them[4][5]. So we designed them under particular investigations and limited the saturabilities of both poles in the grade that might not give much influences to the commutations.

2. Armature

To get light weight, the armature periferal speed was comparatively high, so the constructions of rotating parts were determined carefully, and at the same time, the mechanical strengthes about each details were checked by the experiments. After the coreplates were assembled, their internal surface was finished and shrink-fitted to the shaft. Along the contact part of shaft and core, and in armature yoke, many ventilating canals were settled, which played important roles about the cooling effects.

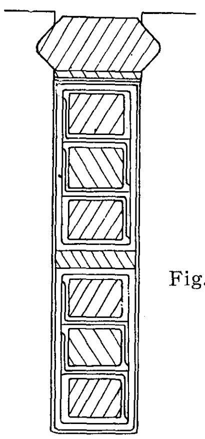

Fig. 2. Conductor arrangement in armature slot

The insulation of the armature winding was special B class, and as shown in Fig. 2 the armature coils were inserted into a little shallow open slots, and were six largers winding. Therefore it would protect to increase the stray load losses despite of the higher armature frequency. In order to settle the coils easily, we took short pitch lap winding not using the treppen winding, so the reliability of insulation was assured.

3. Commutator and brushes

The higher the commutator periferal speed, armature voltage becomes higher and current decreases. But there is danger of increasing the brush injuries, so it was determined to be about 38 m/s at rated speed and the commutator segment pitch was about 4 mm. Mechanical strength of the commutator posesses large safety factor at higher speed running and the internal diameter of it is large enough not to increase the ventilating resistance. The armature side outer ridge of the commutator was settled by a sustaining ring as shown in Fig. 4, and the commutator was pressed by nuts holding a ring spring. Of course the material of each commutator segment was the copper silver alloy, so that the local heat due to brush short-circuited current might not soften each segment.

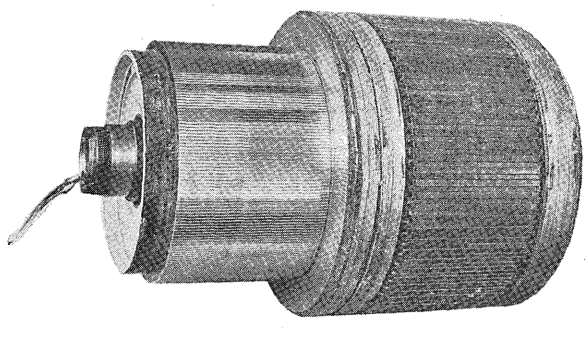

Fig. 3. Armature with thermo-couple leads

Damping the injurious vibration at high speed running and improving the collecting capacity, silicon gum dampers were sticked on the top of the brushes. The brush holder was designed and manufactured as lighter as possible, then the brushes might never jump by car vibration. At the same time, it discharged the duties of the air-guide for commutator cooling air. The brush-rocker was sustained by both end of the arm, and could be rotated or fixed by a handle attached at the side face of the motor to exchange the brushes.

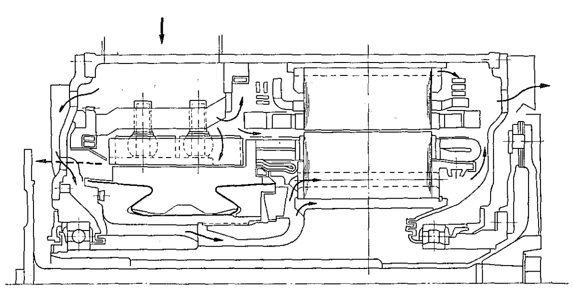

Fig. 4. Section of 150 kW traction motor

4. Stator

Sometimes the starting torque decreases by brush-short-circuited current at start, when the ratio of exciting ampere-turns to armature ampere-turns is smaller than some limited value[6]. Hence about the motor for locomotive, this ratio could not be taken

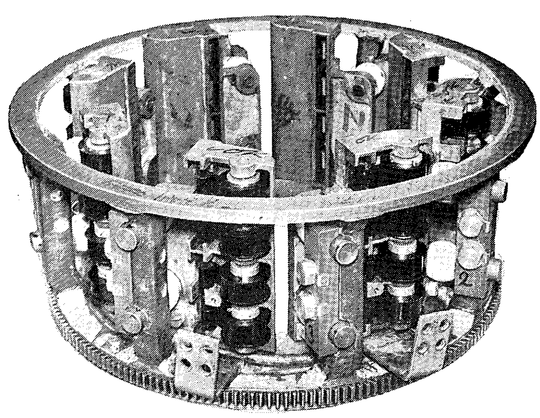

Fig. 5. Brush-locker

so smaller concerning the adhesion character, but when the motor was used for train cars, it could be taken the comparatively smaller value, as there were no chances that the motor would be locked or run at very low speed for a long time. On the other hand, the smaller value of this ratio meant the decreasing of exciting reactance and could give better characteristics, especially the higher power factor. Accordingly we considered this point of view and made efforts to get better characters.

The stator core plates were previously fixed with pressplates and, after the coils were settled, inserted into the stator frame of light weight welded construction. Insulation of stator coils was class H, and all the connecting parts were soldered. Of course it had better make the number of parallel circuits fewer, so all the stator windings had 2 parallel circuits and could be made as bar-winding. The stator of a single phase commutator motor, properly speaking, posesses complicated windings, so that it was

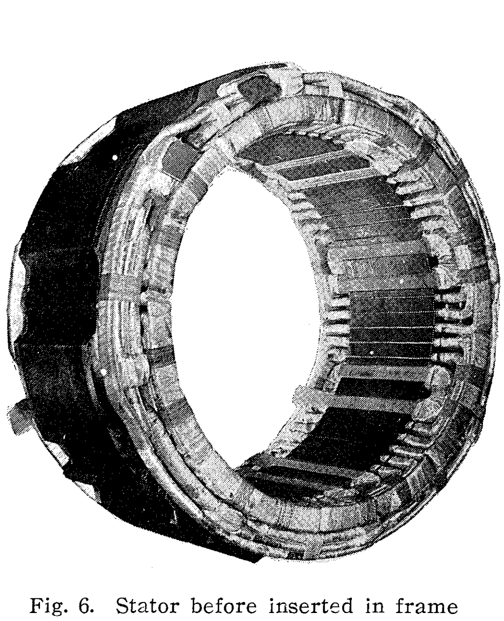

Fig. 6. Stator before inserted in frame

necessary to use the bar-windings which were never put in danger of layer-short and had permanently long life. Number of slots for compensating windings was taken 5 slots per pole, and the conductors of them were transposed. Then in spite of their relatively deep slots, the stray load loss decreased as if it might be neglected and moreover the strong magnetic saturation could be avoided. Fig. 6 shows the stator before it was inserted into the frame.

5. Cooling

The motor is forced to ventilate by separately mounted fan. As shown in Fig. 7, the fan is overhanged on the fan motor attached to the hanging frame, which is built across the end beam and the main motor. Both main motor and fan motor being mounted on the truck, there is a benefit that the strenuous force due to trembling of body and wheels cannot be imposed upon the attached parts. Flexible duct is set at the coupling part between main motor and fan outlet, and it is easy to exchange them.

The fan is the Sirocco type, the forms of its blades and case are ideally designed on our long experiences so as to get higher efficiency and lower noise. The air filter mounted on the air inlet, having good filtrating capasity and also little amount of loss head, can be removed easily by loosening only two bolts for the maintenance and inspections. Aiming at the good running character and easy maintenance, the fan motor is the totally enclosed form and the condenser-run type.

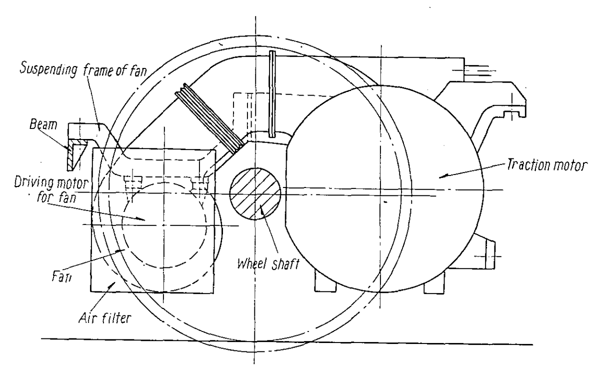

Fig. 7. Cooling fan mounted on the truck

The cooling method of the main motor is, as formerly mentioned, the three parallel paths system, in which system the cooling air comes in from commutator side upper duct, and be separated into three paths, that is, stator, armature and commutator, with necessary quantity corresponding to each losses. Cooling air for commutator is discharged from the B side shield, for armature and stator from opposite side shield. Accordingly the decrease of the necessary air head, improvement of cooling efficiency are able to be expected, and the carbon dusts are exhausted directly unless they are carried away to the windings, so that the electrical assurance of each winding becomes higher.

IV. TEST RESULTS

1. Test in factory

It was reported in details about the records of 50c/s 335 kW AC locomotive motor which we manufactured formerly, where we could find good testing method and measured results on the torque characters and the commutating affairs. Therefore we tested particularly the commutation and the characteristics of this motor with the methods enough experienced before, and also we measured in details about the temperature rise and cooling properties so as to get the fundamental data of the standard future design for AC truction motor.

1) Characteristic tests

Being designed this motor on the basis of our experiences, the measured values of the torque character and the general characteristics coincided with the designed. The characteristic curve of the trial AC electric motor-car calculated from these values are shown in Fig. 8. Though the current–speed characters shown in Fig. 8 contains the voltage regulation of the main transformer, their curves show that the torque decreases are very little comparing with the speed increases and the shock of the accelerating torque is rather little than that of the DC cars in spite of the fewer number of notches. Watching the torque character at running shown in the figure, it may be recogniezd that the torque increase becomes larger than the current increases in the most important accelerating region. This is the particularity of this motor. Though it has been suspected that the torque at start would decrease largely comparing with

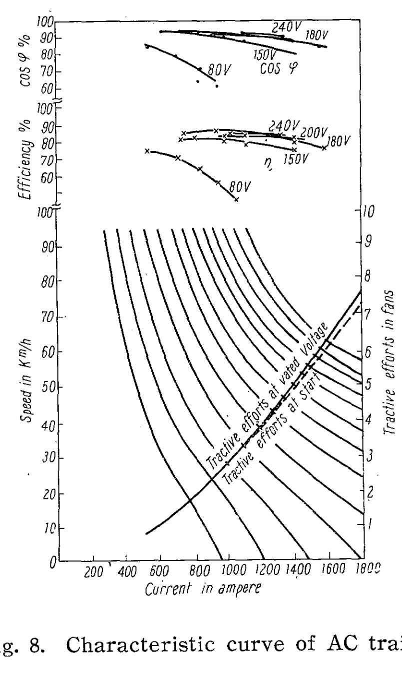

Fig. 8. Characteristic curve of AC train car

that at running, but the result has shown that both values have differed little despite of the weaker exciting-ampere-turn. This owes surely to the suitable value of the transformer voltage. The efficiency was about 84% and the power factor about 90% at the rated. We believed that our confidence on designing was right because of these higher value, considering the general sense that these values of 60 c/s machines are lower than that of 50 c/s.

2) Heat run test

This test was taken thoroughly as a type-test. Besides the measuring methods of the alcohol-thermometers and the resistance measurement, we added these of the Cu-Constantan thermo-couples, which were embedded in the slots of the motor. Especially the thermo-elements for the rotor were leaded out through the sliprings, so that they might be measured in running conditions.

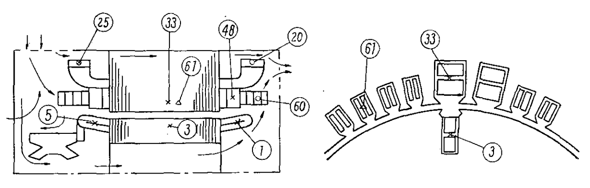

Fig. 9. Embedded position of the thermo-couples and its corresponding number

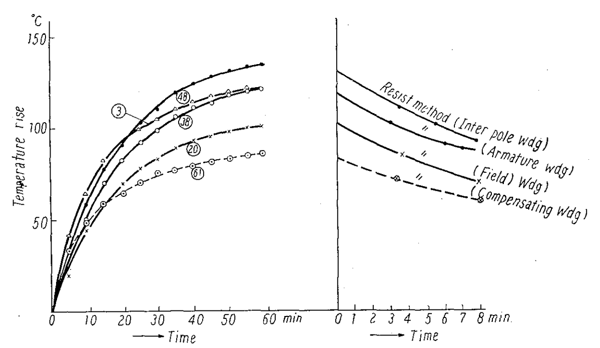

Fig. 10. Thermal characteristics at 1 hour rating test

Fig. 10 shows the tested results at one-hour rating with 100% current measured by these thermo-couples and the resistance method. The numbers in Fig. 9 correspond to that indicated in this figure, in which only the most representative data are written to avoid the complication. Though the temperature gradient of each winding were not shown in such a figure, but the results showed that the temperature near to the air outlet of either stator or rotor is the highest. All the measured values about the temperature proved that the motor could be utilized practically enough about the thermal character and our cooling method was the best.

Fig. 11 is the thermally allowable tractive effort shown in the speed—effort diagram of the car, where the parameters are the allowable time that may give equal temperature-rise to that of one hour rating test, which is calculated from the variable speed continous heat run test. Seeing Fig. 10, it may be recognized that the thermal time constant of this motor is far shorter than that of ordinary DC traction motors. This is the reason how the cooling effect of the motor is effective, and also it is feared that the motor may be overheated by starting overload. But Fig. 11 shows that the allowable time for normal 150% accelerating current is about 10 min. and the accelerating time is less than 1 min. even on the 10 $^{0}/_{00}$ ascent gradient, so that the capacity calculated from root-mean-square current is an enough one. Moreover, the motor is cooled quickly while coasting and stopping, then the motor of forced ventilat-

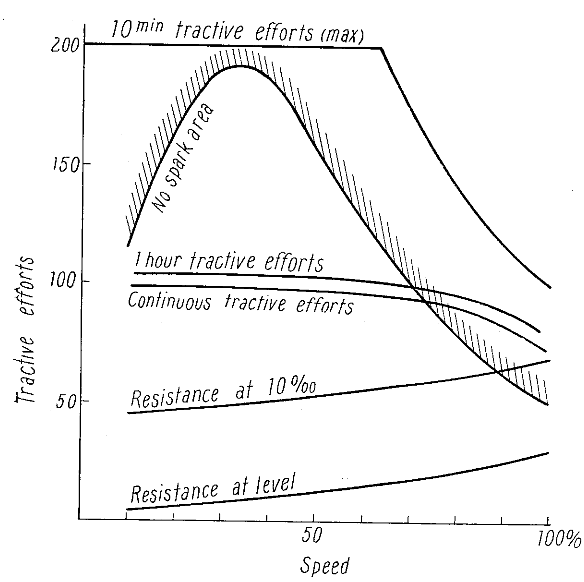

Fig. 11. Speed-tractive effort curve

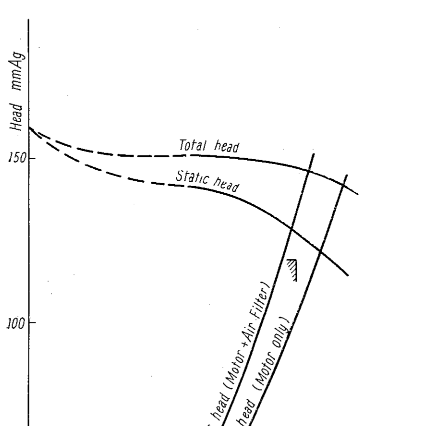

Fig. 12. Characteristics of cooling fan and resistance curve of motor

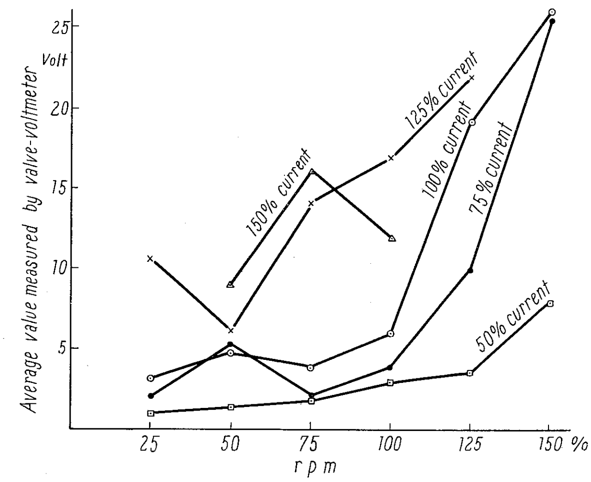

Fig. 13. Characteristics between rpm and spark voltage measured by valve voltmeter

ed type is the most desirable one for the use of the electric train car.

We showed the characteristics of the ventilating fan for the motor in Fig. 12. The measured values of the characteristics and ventilating head losses coincided with these of the designed. The noise level of the fan was very low comparing with that of the self-ventilated motor as the enough consideration was taken for the design of the fan.

3) Commutation test

The no-spark region of this motor observed by the human eyes is surrounded by hatching in the speed-effort diagram of Fig. 11. It seems that the speed at which the best commutation is obtained is a little lower than the rated speed, but the motor can ran with no-sparks at any speed in which it displays the balancing effort.

We observed the commutation by the method[7], by which the armature spark-voltage was measured directly with the high-pass filter connected to the armature terminals. As the accuracy of the method applied to the test of the commutator machine was already confirmed, the search coils for the commutation measurement were not provided in the test. Fig. 13 shows the result of the test. Combining the result of the spark observation and the above result, it is observed that the spark appears at the voltage more than 10V. This fact coincides with the previously reported test result of the 335 kW motor.

The effect of the magnetic saturation on commutation was so important as described Chapter III that a careful test was carried out. At the same time with commutation test, the wave forms of main current and induced voltage in the field winding were recorded and the higher harmonics were measured by the harmonics analyser. According to this test, the quantities of the higher harmonics were not dependent on the speed but the value of main current

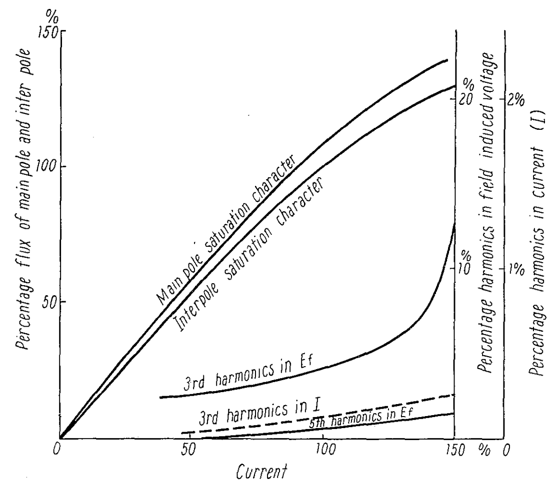

Fig. 14. Saturation curve and percentage harmonics contain

in the region of the speed from 25% to 150%. Fig. 14 shows the saturation curve of the main pole and the interpole of this motor and the percentage of each harmonic wave refered to the fundamental wave was measured in the above-mentioned test. Fig. 14 shows that the saturation gives more effect on the wave form of the field flux than on the current, and hardly effect upon the spark at the vicinity of the normal speed when the quantity of the higher harmonics of the field flux is less than 10%.

2. Practical test

After the above-mentioned home tests, the motors were mounted on the electric car, and a practical test was carried out between Tsuruga and Nagahama of the Hokuriku-line. Among the various test results, that of the temperature-rise test at the practical running is the new data to the AC electric car. Fig. 15 shows the result of a temperature-rise test at the practical running, in which the electric car of 45 ton trailed a load of 88 ton besides men and measuring instruments. Though the test range of the Hokuriku-line had a span of inclination 25‰ and the car trailed the load equal to a fully crowded condition, the value of the temperature-rise was about 70% of the factory test, and the value of the spark voltage was equal to or less than that measured at the factory test.

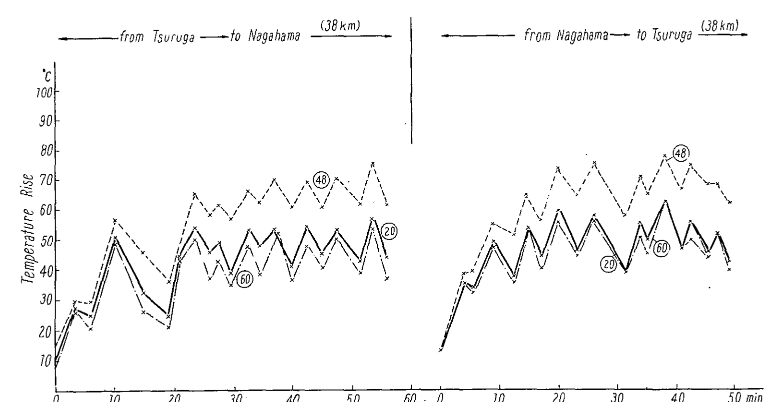

Fig. 15. Temperature rise when tested on the Hokuriku-line

V. CONCLUSION

Our single phase commutator motors of 150 kW for the railway electrified with 60 c/s AC power, were designed and manufactured with sufficient experience and precise consideration. Then they were tested carefully and showed much satisfactory results. Of course particularly thorough tests were carried out about the torque characteristics, temperature rise and commutation, which were the most important points for the single phase commutator motor. These tests were all successful, and through this success we have got belief that our motor will establish a standard system of the AC electric car and will also show our excellent designing and manufacturing technique at the long time practical tests scheduled in near future.

Ending this paper, we express our appreciation to the members of J.N.R. who decided to use direct type AC electric cars, and also to Dr. Yamamura and his assistants of Railway Technical Research Institute, J.N.R., who measured the temperature rise and the spark voltage of the motor at the test, and gave us permission to make public the data of the test.

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