Fig. 15 and 16 demonstrate its internal oscillation and neutral potential. The oscillations are quite irregular and the rises of neutral potential are between 120% and 140% even if the wave tail lengths are rather short (20 μs to 40 μs)

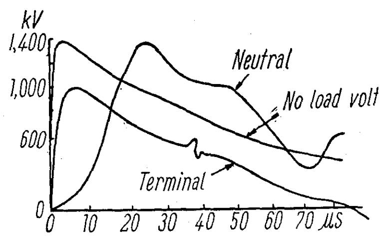

Fig. 16. Neutral oscillations of "Surge proof" transformer

V. CONCLUSIONS

For the cylindrical-layer-winding :—

1) The equivalent circuit for internal oscillation can be given by a simple circuit shown in Fig. 5. or Fig. 6.
2) The potential of non-earthed neutral point is to be calculated by equation (9).
3) The amplitude of oscillation will be small if C_N is small.
4) For incoming wave of short tail length, with increased value of C_N, the rise of neutral point potential will be decreased.
5) For $L=0.3$ H $K=1{,}460$ pF and standard wave tail length of 40μs., the rise of neutral point potential will be maximum at when $C_N=3{,}000$ pF.
6) The Oscillation of "surge proof" winding with its sandwich-like coil arrangement is quite different from those of the cylindrical layer winding.

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50 c/s MAIN MOTORS FOR A. C. LOCOMOTIVES

By

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I. INTRODUCTION

In view of the brilliant success in 50∿ a.c. electrification of railways in Europe, the Japan National Railways after preparation for a few years, materialized it in 1954 with the trial run of two units of 50∿ a.c. locomotives on the Sendai-Yamagata Line. One of them was of the mercury rectifier type, and the other was of the commutator motor type. Our company co-operated in the a.c. electrification project of the National Railways by designing and manufacturing the main electric motors for the commutator motor type locomotive.

The single phase series commutator motor used as the main motor of the a.c. locomotive was the first product manufactured in Japan. Furthermore, as the main electric motor is of cardinal importance for commutator motor type locomotives, the National Railways ordered two units each from three manufactures namely Fuji, Hitachi, and Toyo to test and compare their performance. Upon receiving the order, our company made a painstaking effort in designing and manufacturing, and completed them in August, 1955 with far better successful results of the factory tests than those expected.

The first test runs were completed successfully in the fall of the same year. The following brief report is then made for the reference to those who may find it interesting.

II. OUTLINE OF SPECIFICATION

Principal conditions specified by the National Railways for the main motor of the a.c. commutator motor type locomotive are as follows:

1) The maximum running speed (tractive running) 65 km/h, critical maximum speed 70 km/h.
2) To suit for operation on the Sendai-Yamagata Line, a capacity must be enough to start with 280 ton train on a 33‰ slope.
3) The performance must be equal to or exceed the d.c. ED type locomotive now in use.
4) The weight per tractive wheel must be under 15 tons.
5) The tractive wheel diameter must be 1,250 mm, the National Railway standard dimension.

In the case of type D locomotive, the total weight is maximum 60 tons. Then tractive effort required to start the 280 ton train on a 33‰ slope would be 14 tons, i.e. the starting resistance of 1.7 tons, slope resistance of 11.2 tons and accelerating resistance of 1.1 tons (the acceleration is taken as 0.1 km/h/sec), thus requiring each electric motor to possess a capacity of a starting tractive effort of 3.5 tons.

Assuming that the rated speed is 70% of the maximum running speed, it would be 45.5 km/h, and the tractive wheel rated revolution N would be 200 r.p.m. against the diameter of the worn out tractive wheel $D=1,210$ mm.

Assuming that the percentage of starting torque compared with running torque is 150% in consideration of the characteristics of a.c. commutator motors, and that the gear efficiency η is 0.975, the rated output P of the motor at rated speed is:

$$P=1,026\times N\times T\times\frac{D}{2}\times\frac{1}{\eta}\times\frac{1}{1.5}$$
$$=1,026\times200\times3.5\times\frac{1.21}{2}\times\frac{1}{0.975}\times\frac{1}{1.5}\doteqdot300\text{ kW}$$

In designing an electric motor to satisfy the above conditions, choosing the gear ratio between the electric motor and the tractive wheel becomes a problem. Compared with d.c. models, the dimensions of the a.c. commutator is inevitably large, and, therefore, in order to increase capacity with similar external dimensions to the d.c. machine, it is necessary to increase the gear ratio and the motor speed. Furthermore, as the commutator diameter increases when compared with that of a d.c. type, in the case of traction motors of limited dimensions, it is preferable to keep the rated speed above 1,000 r.p.m. On the other hand, in the case of plain gear one step reduction drive and nose suspension systems, considered from the viewpoint of gear wheel manufacturing, the transmission torque to this extent will be the allowable limit of Module 11. In the teeth number of pinion for a flat gear without transposition, 16 is the minimum. For the necessity of interchangeability, the National Railways and the three manufactures decided after discussions that the gear ratio should be 93 : 16 (Module 11), thus making the rated revolutions for the electric motor 1,160 r.p.m.

The temperature rise should be taken into consideration for the rated output of electric motors, and this was finally decided after factory test results. The specifications for this motor are as follows:

Number of Phase	Single Phase
Rated Frequency	50∿
Number of Poles	14
Rated Output for one hour	335 kW
Rated Number of Revolution	1,160 r.p.m. (Equivalent to 45.5 km/h)
Rated Voltage	200 V
Rated Current	2,350 A
Continuous Rated Output	300 kW
Ventilation System	Forced Ventilation (Wind Pressured 170mm WC, Wind Volume 90 m^3/min)

Two motors are connected in series and then connected to the secondary side of a main transformer of 1,310 kVA stepped down from the power obtained from a single phase 50 c/s 20 kV trolly wire. Speed control is made, as shown in Fig. 2, by secondary change-over voltage control of the main transformer, and the number of notches is 16. Braking is made by air brakes and manual brakes, no dynamic brake being adopted.

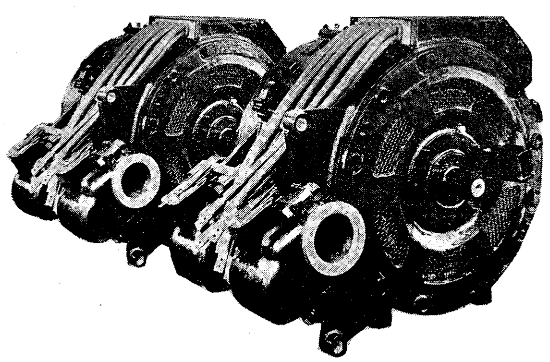

Fig. 1. 335 kW main motors for 50 c/s a.c. locomotive

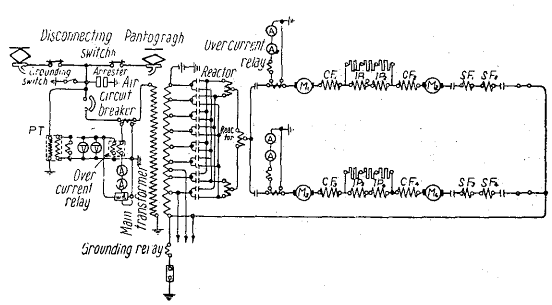

Fig. 2. Connection diagram of main circuit

III. CHARACTERISTIC FEATURES OF ELECTRICAL DESIGNING

Single phase series motors for 16⅔ cycles have been widely put into practice in Europe especially Germany, Sweden and Switzerland, and have a long history as a main electric motor for railways, but the 50∿ electric motor was put into use at the Höllental Line in 1937 and in France after the war. Particularly, in our country where the track gauge 1,067 mm is in use, the conditions required for motor are very severe.

1. Transformer e.m.f. and Number of Poles

In the case of commutator motors, besides the reactance voltage e_r induced at the commutation as in a d.c. motor, transformer e.m.f. e_t is induced by the alternation of the main magnetic flux. Therefore, to compensate these voltages having 90° phase angle to each other, interpole windings and interpole shunt resistor have been provided. In spite of this provision, residual voltage indicated in Fig. 3, will remain inevitably.

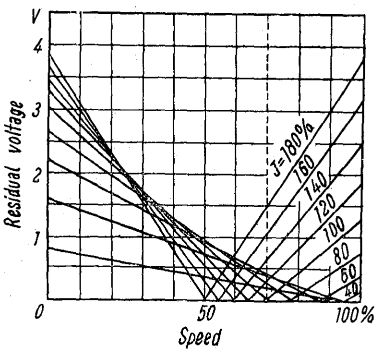

Fig. 3. The residual voltage-speed character, when interpole resistor is so adjusted as to give the best commutation at rated speed and rated current

As can be seen in the illustration, a large short-circuit current will flow through the brush circuit and cause sparks upon starting owing to the entire residual transformer e.m.f. Such being the case, it is desirable that the transformer e.m.f. be as low as possible. On the other hand, the flux per pole will be in ratio with the transformer e.m.f. and naturally any limitation on the transformer e.m.f. will means an increase in the number of poles. The greater the required capacity, the greater the necessary number of poles.

But it is mechanically difficult to reduce the space between brush holders more than necessary; and an increase of poles means the increase in weight. For the above reasons, the 14 pole system was adopted by the Company. In order to acquire greater capacity with 14 poles, the ampere loading must be increased. This brings about an increase in reactance voltage and temperature rise, but sufficient output was obtained by special consideration in designing the interpoles for the former, and by using the three divided flow cooling system mentioned later for the latter.

2. Commutator and Brushes

For simplicity of structure and easiness of control, it is desirable that the terminal voltage be obtained as high as possible. To accomplish this, the commutator peripheral speed must be increased and the segment pitch reduced. For this purpose, a special shrink ring was attached to the riser, inner side of the commutator. Without lengthening it particularly, and at a segment pitch of about 4 mm which is close to the limit within which high bar will not be caused, a commutator peripheral speed of about 60 m/s at the maximum speed was made available.

From much experience and research results obtained from the 16⅔ cycle, the brush covering is increased to 3 or more advanced from the old commutator motors. By this designing, it was possible to reduce the brush current density without increase in the commutator length despite a larger capacity.

A split brush of 12.5 mm width was used, assuring stable contact at high speeds and limiting short-circuit currents at the starting. The brush is interconnected at the top, the construction being such that for practical handling it is no different than a single unit brush.

3. Rotor Coils

The increase in the number of poles greatly heightens the armature frequency which in turn increase the rotor core loss and additional copper loss. These losses do not pose much of a problem as the motor is restricted by the saturation characterictics rather than the generated heat loss. But due consideration must be given to the saturation character. For the rotor coil, "treppen" coil with six conductors per slot which had achieved desirable commutating results with 16⅔ cycle motors was used, and fractional slots per pole were used. The conductors in the slot, as shown in Fig. 4, are of bar windings making the leakage flux of each conductor uniform. Furthermore in order to reduce the stray loss, the upper bar was specially arranged as shown in the illustration. The conductor 2 crosses at the coil end and is placed in the middle of conductors 1 and 3. Conductors 1, 3, and 1′, 2′, 3′ are crossed once at the top and bottom. By this, despite the fact that the stray loss is above the frequency of 130∿ at rated speed, a value near that at 16⅔ cycle motor is obtained.

With H class insulation, it is fully heat-resistant, and the electrically conducting parts have been silver soldered by a special welding process, enabling the structure to resist local overheating and mechanical vibrations at the starting.

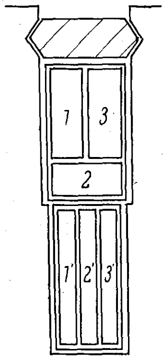

Fig. 4. Armature conductor arrangement

4. Stator Coils

a. Gompensating Coils and Interpole Coils

Fig. 5 shows the distribution of each ampere-turn, and Fig. 6 the vector diagram of each ampere-turn. In Fig. 6 AW_A is the armature back ampere-turn, AW_K the compensating ampere-turn and AW_W the interpole ampere-turn. As can be seen in the Fig. 6 OA is AW_A, and the compensating coil AD was selected to almost completely cancel the portion corresponding to the pole arc of OA at AW_A as shown in Fig. 5 and 6. In this case, to make the space flux distribution of the compensating coil agree with the armature flux distribution, it is preferable to make the number of compensating coil slot as many as possible. On the other hand, considering the limitation of mechanical dimensions and of increased production cost, 6 slots per pole were employed.

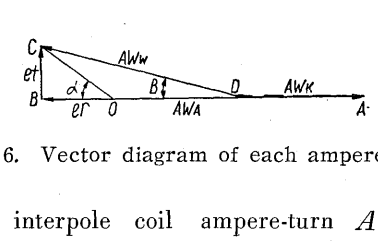

Fig. 5. Space distribution of each ampere turn

Fig. 6. Vector diagram of each ampere turn

The interpole coil ampere-turn AW_W must give the combined ampere-turn with ampere-turn OD equal to AW_A-AW_K and ampere-turn OC forming the interpole pole flux to cancel the e_t and e_r. Two parallel circuits were chosen for both coils to meet the above conditions and eliminate unbalance of each pole, and the crossing-in-the-slot method was used for bar windings of sufficient mechanical strength.

b. Magnetizing curves and Exciting Coils

It was thought in the past that by increasing the saturation of the main magnetic circuit, greater tractive force could be obtained, when the transformer e.m.f. is limited to a certain value. The degree of saturation is certainly high for d.c. traction motors but this is wrong conception in the case of a.c. traction motors. If saturation is high, the main current is no longer sinusoidal and contains a large amount of higher harmonics. This current flows through the armature, and as the parallel impedance is connected to the interpole, the impedance for this higher harmonics differs from that of the interpole circuit, thus the interpole field in ratio with the armature current can no longer be obtained.

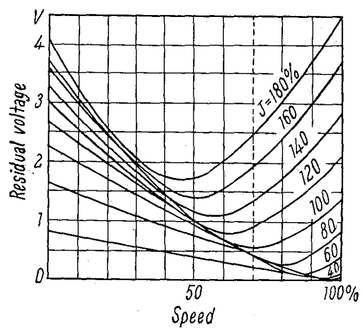

Fig. 7. Effect of higher harmonics to the residual voltage-speed character

This is aggravated when the interpole is saturated and especially when the current is large. This generates injurious sparks during the starting process and causes overload, resulting in damage to the commutator. The residual voltage curve shown in Fig. 3 change as shown in Fig. 7 with relatively high degree of saturation. In view of this, the ampere-turn of the exciting coil was increased with a greater gap, together with maximum reduction of saturation phenomena in the main and interpole magnetic circuits so that the saturation curve would be straightened.

Increase of the exciting ampere-turn had a great effect simultaneously on the reduction of the demagnetizing action by short-circuit currents at start. As the results, the input from the line at starting was greatly lessened.

As in the case of other stator coils, bar winding crossing conductors were used for the exciting coil, and the number of parallel circuits is limited to two.

IV. STRUCTURAL FEATURES

These motors are based on the long experience gained by the Company for many years in the manufacturing of a.c. commutator motors and d.c. railway motors, together with reference to European a.c. railway motors ; their structure was given meticulous care and designing and manufacture were proceeded that they worked satisfactorily under any operating conditions. The structure has been made sufficiently strong to resist the severe torque required in the starting and during operation, with all of its parts protected from external forces and vibrations resulting from the one step speed reduction drive and nose suspension system. Consideration has been also given to reduce the motor weight as much as possible. In order that the required output would be fully obtained within the limits of the various factors, an unique 3 devided-flow ventilation has been adopted to permit the output required and suppress temperature rises of various part reasonably, particularly the temperature rise of the commutator that was considered to the most difficult, in which the Company takes a great pride. A brief description of the structure of each part is made as follows.

1. Stators

The stator frame and bearing shield are constructed of welded iron sheets, sufficiently annealed to remove residual heat stress.

For the stator core sector sheet steel are not used, and punched-out silicon sheet steels of ring shape are laminated and pressed into the stator frame. The rigidity of the stator frame is thus assured greatly.

For the main field-interpole and compensating-coils H class insulation has been employed to enlarge heat resistance, and all joints are silver soldered. The varnish used is all silicon varnish.

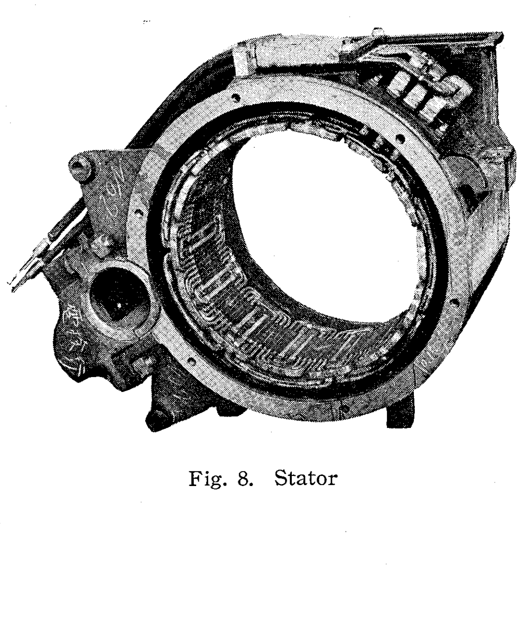

Fig. 8. Stator

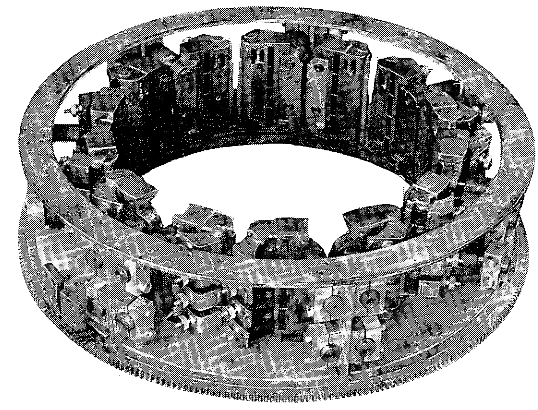

Fig. 9. Brush holder

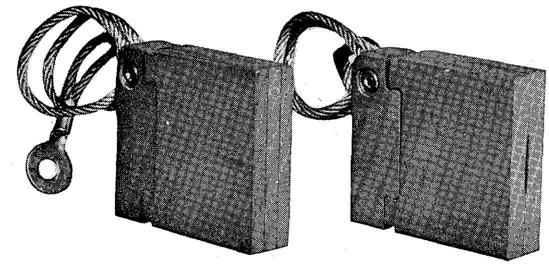

Fig. 10. Combined brush

The structure of the brush holder is such that the brush pressure may be adjusted within the range of $0.2\sim0.45\ kg/cm^2$ and although the brush may be used until it becomes half the length of a new one, it will still maintain adequate brush pressure without adjusting springs.

Furthermore, in order that replacement, inspection and maintenance of brushes be conducted conveniently, the brush locker may be freely turned from outside of the motor by means of a rachet handle. It may be returned again to a neutral position after inspection. The lead is completely made waterproof with rubber packing.

2. Rotors

High silicon steel sheets have been used for the rotor core. The steel sheets after groove cutting are throughly annealed to reduce iron loss.

The bearings are designed to have sufficiently high safety against the vibration loads expected during the operation by using the highest grade roller bearings. As so called DN value is relatively high,, the popular BRP No. 1 grease is used. The structure of facilitating grease changing makes possible the elongation of the bearing life greatly.

As the commutator pheripheral speed at the maximum running speed is very large and the segment pitch is small, special consideration is paid for increasing the mechanical strength by providing a shrink

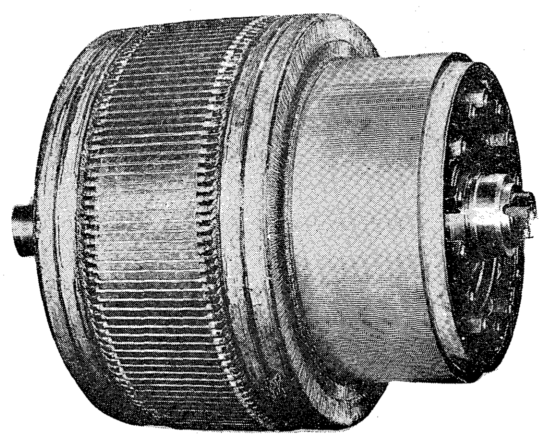

Fig. 11. Rotor

ring on the inner side of the riser. Overspeed test at 1,900 r.p.m. was conducted very satisfactorily.

Copper silver alloy, which has a high softening temperature, is used for the material of the commutator segment to prevent damages on the commutator surface by short-circuit currents at the starting.

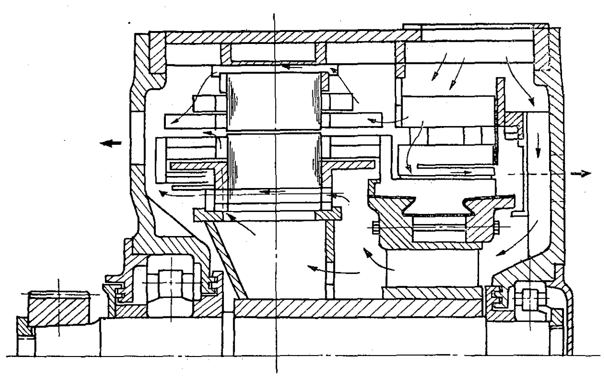

Fig. 12. Cooling method of 335 kW main motors

3. Cooling Method

Special consideration must be given to the cooling method of railway motors, of which outside dimensions are restricted, to obtain a large output. The cooling method as shown in Fig. 12 has been adopted for this motor. A separately installed blower sends cooling air through a wind channel into the motor where the flow is divided into three at the entrance and then follows the path described below, cooling each part of the stator, rotor and commutator with a wind volume in response to the losses thereabout.

a. Stator Cooling Air

The air is passed through the coil end on the commutator side, back of the stator, and the coil end on the gear side, then being discharged outside. Part of the air passes through the gap between the stator and rotor.

b. Rotor Cooling Air

The air passed through the wind channel in the shield on the commutator side and then the center of the commutator, after which it passes through the interior of the air ducts in the rotor core and is discharged outside. Part of the air passes through the groove in the press ring from the inner periphery of the rotor and then passes out to the coil end on the gear side.

c. Commutator Cooling Air

After entering, the air passes along the whole length of the commutator surface by a special guide provided by the brush holder and is discharged outside on the brush side of the motor.

Fresh cooling air is constantly supplied to each part by this method, and the loss of air pressure for each part is reduced compared with the ordinary series cooling method, making possible narrower cooling channels with higher wind velocity so as to obtain a higher heat exchange efficiency.

There are many other features, such as prevention of brush dust from being drawn inside the motor.

It was learned from the result of actual measurements that the total air pressure required of the blower to send the necessary volume of air to each part was about 110 mm W.C., proving the excellence of this cooling method.

V. TEST RESULTS

1. Factory Test

Tests were conducted with one hour rating temperature rise based on the IEC standards, as there is no definite agreements concerning the rating in Japan. As a result, the rated output was 200 V 50∿ at 70 % of the maximum speed (=45.5 km/h) the particulars being as follows:

One hour rating output 335 kW 2,350 A
Continuous rating output 300 kW 2,100 A
One hour rating tractive force per wheel 2,640 kg
Continuous rating tractive force per wheel 2,360 kg

The output per pole reached 32 H.P., which equals that of the latest European 50∿ commutator motors. By parallel shunt resistance, perfect commutation is carried out for only some specific revolutions of the entire rotation range of the a.c. single-phase series motor. However, for practical purposes, as the motor must be driven at all speed, the revolutions at which perfect commutation is possible must be suitably selected. It is desirable that even at other speeds, the residual voltage shall be selected as low as possible. From this standpoint, the rated speed (70 % of maximum speed) was selected as a target for perfect commutation, aud almost perfect sparkless commutation was obtained at this speed.

Furthermore, special consideration has been given to saturation characteristics of the magnetic circuit to minimize residual voltage, so that the characteristics similar to that at rated speed were obtained at speeds above 30 % of the maximum speed. Therefore, it is possible to drive at low speeds without changing-over the parallel shunt resistances.

Concerning characteristics, the power factor is about 90 % at rated speed and about 93 % at the maximum speed, and efficiency of 80 % was obtained at the rated speed. The values are expected to be further improved by a few per cent in future.

High voltage tests were satisfactory conducted on both stator and rotor at 2,000 V for one minute. The overspeed test was also made with very little vibration and ample margine.

2. Field Test

The characteristic obtained by factory tests converted into locomotive output characteristics are shown in Figure 13.

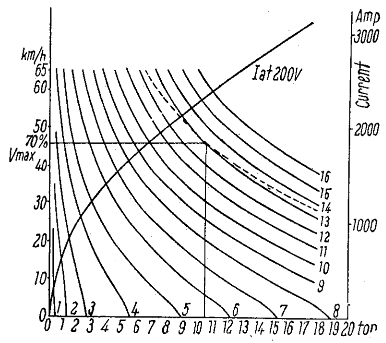

Fig. 13. Characteristics of speed and tractive effort

Two main motors were manufactured, and at the field tests, two motor driving was carried out with one truck. The tractive force at each notch agreed closely to that obtained in the factory tests, and tractive effort at high speeds was very great, testifying the advantage of commutator motor over the d.c. traction motor.

Furthermore in the tests for starting tractive force, which could not be measured in the factory tests, was made in the field. On a 25‰ slope with 180 t load the starting on the grade was made at 8 notches to testify that the torque reduction ratio from demagnetizing effect by short-circuit currents at the starting was very small. The input current was also very small and the maximum available starting tractive force within the limit of adhesion was obtained.

VI. CONCLUSION

The Company has for many years been manufacturing various types of three-phase commutator machines, and with this valuable experience, it was able to design and manufacture 335 kW single-phase series commutator motors for a 50∿ a.c. electric locomotive with fine results. These motors are the first home products, and of course, the first product of the Company. Though they are not perfect in every respect, the defects can be improved hereafter.

It has become obvious from the experience gained in manufacturing the motors that the cooling system adopted by the Company is extremely satisfactory and that in the future both dimensions and weight may be considerably reduced. Furthermore, confidence has been obtained that there will be no great difficulty in manufacturing a main commutator electric motor for 60∿ use.

As a result of trial running on the Sendai-Yamagata line it has been found that not only the main motor, but also the equipping wiring and control method have considerable effect on the locomotives performance. These points will be improved in the future to perfect an ideal a.c. commutator motor type locomotive.