Development of a High Efficiency Induction Motor and the Estimation of Energy Conservation Effect

Minoru KONDO
Drive Systems Laboratory,
Formerly Drive Systems Laboratory,
Vehicle Control Technology Division

Minoru MIYABE
Formerly Drive Systems Laboratory,
Vehicle Control Technology Division

Shinichi MANABE
Drive Systems Laboratory,

Induction motors are widely used as traction motors on trains. Because energy loss from traction motors accounts for a large portion of energy consumption in commuter trains, highly efficient traction motors are very effective in saving energy. A high efficiency induction motor was therefore developed. Its efficiency was verified through analysis and tests with a prototype machine. This paper presents the calculation results of running simulations for estimating the energy conservation effect of the high efficiency induction motor. The results indicate that the energy consumption is reduced by 6% to 11%.

Keywords: induction motor, energy consumption, running simulation

1. Introduction

Improving the efficiency of traction motors is very effective in saving energy on commuter trains, because the energy loss of the motors accounts for a large proportion of their energy consumption. A high efficiency induction motor was developed and its efficiency was verified through magnetic field analysis and performance tests with a prototype machine [1], [2], [3]. This paper briefly introduces the loss reduction technologies used in the developed motor and shows the calculation results of running simulations for estimating the energy conservation effect of the high efficiency induction motor.

The developed motor is not only highly efficient but also has a high regenerative braking capability. Running simulations were conducted on a train with high regenerative braking performance as well as one with conventional regenerative braking performance.

2. Development of the high efficiency induction motor

2.1 Specification of the high efficiency induction motor

The specifications of the prototype motor were based on that of a conventional induction motor. The outer dimensions, torque performance, and rated output of the developed motor are equal to those of the conventional motor. On the other hand, the efficiency of the prototype motor is higher owing to the improvements of the design. The improvements include use of low loss materials, optimization of the stator winding design, the improvement of rotor slot design and the reduction of the cooling air flow rate, which are described in the following section.

2.2 Introduction of low loss materials

Table 1 shows the materials used in the conventional motor and the prototype motor.

Table 1 Comparison of materials used in the motors

<table>
<thead>
<tr>
<th></th>
<th>Prototype motor</th>
<th>Conventional motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor conductor</td>
<td>Silver bearing copper</td>
<td>Red brass</td>
</tr>
<tr>
<td>Resistivity(@115 °C)</td>
<td>2.37 μΩcm</td>
<td>4.72 μΩcm</td>
</tr>
<tr>
<td>Iron core</td>
<td>35A300</td>
<td>50A800</td>
</tr>
<tr>
<td>Electrical wire for stator winding</td>
<td>Kapton insulated wire</td>
<td>Glass insulated wire</td>
</tr>
</tbody>
</table>

The rotor conductor bar of the prototype motor is made of silver bearing copper which has a resistivity equal to copper and much lower than that of red brass used in the conventional motor. The silver bearing copper is a copper alloy with a small addition of silver to improve the strength. It is a common material used for the commutator of direct current traction motors. The change of the material halves the rotor copper loss.

The iron core material was upgraded from 50A800 to 35A300. The symbols are defined in the Japanese industrial standard JIS C 2550 and the three digit number in the symbols represents the density of iron loss of the material. That means the change of the iron core material reduces the iron loss by roughly 3/8.

The electric wire of the stator winding is changed from glass insulated wire to Kapton insulated wire. Kapton insulated wire has thinner insulation which improves the filling ratio of the conductor in stator windings and reduces the stator copper loss.

These changes of materials improve the efficiency by 1.8% compared with the conventional motor.

2.3 Optimization of stator winding design

The number of turns in series in the stator winding was reduced from the 72 used in the conventional motor to 54 in the prototype motor. The number of turns in the conventional motor is designed to minimize the required capacity of the traction inverter. In contrast, it is designed to improve efficiency in the prototype motor.

The voltage of a motor increases in proportion to the product of the number of turns and the magnetic flux density in the motor. In general, the voltage is fixed at...
the maximum in the high speed region and at the rating point. Therefore, reducing the number of turns increases the magnetic flux density. The output of a motor increases roughly in proportion to the product of the magnetic flux density and the current density in the winding. Thus the increase of the magnetic flux density reduces the current density. As a result, the stator and rotor copper losses decrease. The change of the number of turns improves the efficiency further by 0.5%.

Furthermore, the decrease of the number of turns improves the regenerative braking performance in the high speed region, because of the increase in the magnetic flux density. As a result, the regenerative braking is capable of producing all the required braking force, contrary to the conventional motor which needs to be supplemented by mechanical braking force in the high speed region (Fig. 1).

### 2.4 Improvement of the rotor slot shape

The rotor of the prototype motor has improved slot shape design to reduce secondary harmonic copper loss. The magnet flux from the stator teeth induces joule loss in the rotor conductors in the rotor slots. In particular, the areas near the rotor surface in the conductors are vulnerable to the flux. Therefore, the rotor design of the prototype motor eliminates conductors from the surface area and makes the area work as vent ducts for cooling to improve the cooling performance (Table 2, Fig. 2). This design reduces the secondary harmonic copper loss and improves the efficiency by a further 0.4%.

### 2.5 Reduction of the flow rate of cooling air

The total loss of the prototype motor is much lower than that of a conventional motor owing to its higher efficiency. As a result, the prototype motor needs less cooling than a conventional one and the flow rate of cooling air can be moderated. The diameter of the cooling fan of the prototype motor can thus be reduced by about 10% and all of the vent holes (Fig. 3) in the rotor were blocked to reduce the cooling air. Figure 4 shows the test results before and after the reduction. The mechanical loss decreases by half in the improved prototype motor. On the other hand, the temperature rise is well below its limit and almost the same as that of the conventional motor. Meanwhile, the mechanical loss of the prototype motor is less than that of the conventional motor even before reducing the cooling air. The reason for this is assumed to be that the improved rotor slot shape reduces the air friction between the stator and the rotor.

![Fig. 1 Comparison of regenerative braking performance](image1)

![Fig. 2 Rotor slots of the prototype motor](image2)

![Fig. 3 Rotor of the prototype motor](image3)
This reduction of mechanical loss improves the efficiency by a further 0.5%.

2.6 Summary of the loss reduction effects of the improvements

Figure 5 shows the loss reduction effects of the improvements described above. These effects are calculated using finite element analysis except for the mechanical loss which is calculated from the test results described above. Figure 5 shows the value of the loss divided by the input. The subtraction of the value from 100% becomes the efficiency. The values of the efficiency improvement described in the previous sections are based on these calculations. Calculations were made not only for the prototype motor and the conventional motor but also for the partially improved motor to show the effect of each improvement. Table 3 shows the specifications of the motors for which calculations were made.

The calculation results show that the various improvements increased the efficiency of the prototype motor by 3% in relation to the conventional motor, raising overall efficiency to about 96%. The calculation results are consistent with the test results and the efficiency of the prototype motor calculated from the test results is also about 96% [3].

3. Running simulations for energy consumption evaluation

3.1 Running simulation model

The energy conservation effect of the prototype motor was evaluated through running simulations based on an actual railway route and train. An energy calculation simulator [4], developed on the basis of a train performance calculation system called "Speedy," was used.

The assumed route and train were a suburban route and a DC electric train. Their specifications are summarized in Table 4 and Table 5. The efficiencies of the traction gear and the traction converter are both 98% as shown in Table 5. In the simulation, the losses of these machines as well as the traction motor loss and running resistance loss were all taken into account.

### Table 4 Summary of the hypothetical route

| Total distance traveled | 130.8 km |
| Number of stops          | 34       |
| Maximum speed            | 130 km/h |

### Table 5 Summary of hypothetical train

<table>
<thead>
<tr>
<th>Train set</th>
<th>3 motor-cars and 5 trailer-cars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross weight (with 100% load) [t]</td>
<td>320</td>
</tr>
<tr>
<td>Tare weight [t]</td>
<td>252</td>
</tr>
<tr>
<td>Passenger capacity [person]</td>
<td>1128</td>
</tr>
<tr>
<td>Maximum speed [km/h]</td>
<td>130</td>
</tr>
<tr>
<td>Starting acceleration [km/h/s]</td>
<td>2.5</td>
</tr>
<tr>
<td>Deceleration [km/h/s]</td>
<td>2.6</td>
</tr>
<tr>
<td>Gear ratio</td>
<td>6.53</td>
</tr>
<tr>
<td>Wheel diameter [mm]</td>
<td></td>
</tr>
<tr>
<td>Inverter efficiency [%]</td>
<td>98</td>
</tr>
<tr>
<td>Gear efficiency [%]</td>
<td>98</td>
</tr>
</tbody>
</table>

3.2 Calculation of traction motor loss

The traction motor loss should be calculated exactly in the simulations, because the objective of the simulations is to estimate the energy conservation effect of the prototype motor in comparison with the conventional motor. There-
fore, the traction motor loss is calculated based on finite element analyses of magnetic fields for an exact evaluation.

The finite element analyses were conducted at several operating points on the traction performance curve as well as on the braking performance curve. The loss on an operating point other than the calculated points was interpolated linearly from the nearest two points. The details of the finite element analyses are as described in a previous report [2]. Figure 6 and Fig. 7 show the traction electric power and regenerative braking electric power respectively.

The traction electric power is calculated as the summation of mechanical output and the loss of the traction motor. The regenerative braking power is calculated as the subtraction of the loss from the mechanical input of the traction motor. However, the mechanical loss of the traction motor is not included in the loss of the traction motor here, because it accounts for a part of the running resistance which should be calculated separately in the simulation [5]. As seen in these figures, there is less electric traction power and more regenerative electric power with the prototype motor owing to its lower loss compared with the conventional motor.

In addition, as described in the section 2.3, the prototype motor has a higher regenerative braking performance in the high speed region. The regenerative braking electric power with improved braking performance is also shown in Fig. 7. As seen in Fig. 7, the regenerative braking electric power improves significantly in the higher speed region than 90 km/h and a significant energy saving is achievable when the train operation includes braking in the high speed region.

3.3 Running resistance calculation

As mentioned above, the mechanical loss of the traction motor is taken into account in running resistance calculation in this simulation. The mechanical loss of the prototype motor is significantly reduced from that of the conventional motor due to the reduction of the flow rate of cooling air. The mechanical loss of a traction motor arises even when the train is coasting because the loss is irrelevant to the electromagnetic status of the motor. That means the loss accounts for a part of the running resistance. Therefore, the loss is considered as a component of the running resistance in this simulation.

The running resistance of a train with the conventional motor is calculated using an empirical formula which is commonly used in Japan for conventional electric trains. On the assumption that the mechanical loss of the traction motor accounts for the running resistance, the proportion of the force caused by the loss can be illustrated in the manner shown in Fig. 8. On the same assumption, the running resistance for a train with the prototype motor was calculated as shown in Fig. 9 adding the force caused by the mechanical loss of the prototype motor.

The running resistance in Fig. 9 is less than in Fig. 8 because of the difference in the mechanical losses of the traction motors.
As seen in the figures, the proportion of the force caused by mechanical loss from the running resistance is not negligible, and the decrease in the mechanical loss reduces the running resistance by about 7% at the maximum speed.

3.4 Results and discussion

Figure 10 shows the calculation results for specific energy consumptions and Figure 11 shows the decrease ratios of the specific energy consumptions normalized with the results from the train with the conventional motor. The specific energy consumption is a quantity which represents the energy consumption per car-km. The 'Energy Saving Act' requires major railway operators to make an effort to reduce the specific energy consumption.

In these figures, the horizontal axes are distances between stations and each plotted point corresponds to a running section between stops. The assumed operation includes local operations; i.e., such that the train stops every station, and rapid operations; i.e., such that the train skips several stations. Therefore, the distances between stations range from 1 km to 10 km. In general, shorter distances raise specific energy consumptions because of the increase of machine loss due to a higher proportion of powering and braking time in relation to the total running time, as seen in Fig. 10.

The reduction ratios of the prototype motor range from 6% to 11% as seen in Fig. 11 and the average reduction ratio on the total route is 9%. Although the difference of the efficiencies of the prototype motor and the conventional motor is about 3%, its impact on the energy consumption is significant. In general, the impact of the efficiency improvement tends to be greater on routes with a shorter distance between stations because of the higher portion of machine losses. Figure 11 shows the same general trend except for distances of less than 2 km whereby the reduction ratios are lower than those for distances of 3 to 4 km. Among the efficiency improvements to the prototype motor, several were effective only in the high speed region. The improvements include the optimization of the stator winding design, the improvement of the rotor slot design and the reduction of the flow rate of cooling air. In the case of distances of less than 2 km, the maximum speed of the train does not reach the high speed region and the margin in efficiency improvement becomes less significant.

In addition, the prototype motor reduces the energy consumption even in the case of longer distances because of the reduction of running resistance owing to the decreased mechanical loss of the traction motor.

In the case of improved regenerative braking performance, the reduction ratios of specific energy consumption are higher for distances of around 5 km, and the maximum decrease ratio is 23%. On the other hand, improved regenerative braking performance has no impact on performance for distances less than 2 km. This is because the maximum speed of the train does not reach the high speed region for distances less than 2 km, and the improvement of the regenerative braking performance in the high speed region becomes less significant.

Figure 12 show the regenerative ratios for each section.
between stations. Energy consumption of auxiliary machines was excluded from the calculations for the regenerative ratio.

The values of the regenerative ratios vary widely because of various conditions such as gradients, and so, they range from 20% to 50% for the train with the conventional motors. The regenerative ratios of the train with the prototype motors slightly improve in all sections because of the higher efficiency. On the other hand, the regenerative ratios of the train with improved regenerative braking increase further except for sections with a distance under 2 km. This is because the regenerative braking performance increases only in the high speed region which the train cannot reach in the case of short sections of less than 2 km.

Meanwhile, it requires large-capacity inverters to improve the regenerative braking performance, though the consequent increase of the mass was not taken into account for this simulation. The realization of energy saving with the improved regenerative braking performance requires not only improved traction motor performance but also lightweight and small-sized large capacity inverters which should be feasible by virtue of technologies such as SiC power devices.

4. Conclusion

A high efficiency induction motor was developed for conventional electric railway vehicles and running simulations were conducted to evaluate the energy saving effect of a prototype motor with a higher efficiency performance than conventional motors. As a result, the calculated energy saving effects obtained through the higher efficiency range from 6% to 11%. In addition, it was possible to reduce energy consumption by up to 23% with the utilization of higher performance regenerative braking on the prototype motor, which has higher torque performance than conventional motors in the high speed region. Efforts are being pursued in order to further improve the efficiency of equipment with a view to achieving an even greater reduction in energy consumption.

Acknowledgment

This work is financially supported in part by the Japanese Ministry of Land, Infrastructure and Transport.

References


Authors

Minoru KONDO, Dr. Eng.
Senior Researcher, Drive Systems Laboratory, Vehicle Control Technology Division
Research Areas: Traction motor, Energy Consumption Evaluation, Condition Monitoring

Minoru MIYABE
Formerly Researcher, Drive Systems Laboratory, Vehicle Control Technology Division
Research Areas: Traction motor, Energy Consumption Evaluation

Shinichi MANABE
Researcher, Drive Systems Laboratory, Vehicle Control Technology Division
Research Areas: Energy Consumption Evaluation, Condition Monitoring

QR of RTRI, Vol. 55, No. 3, Aug. 2014