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Research on Induction Motor for Mini Electric Vehicles

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Abstract

The motor of a mini electric vehicle uses dozens of storage batteries as power supply, which has low voltage and large current. Therefore, the loss and temperature raise of the motor is high. In this paper, the loss of different induction motors for mini electric vehicles is calculated and the effects of rotor materials and air gap length on the performance of these motors are studied. The analyses show that the efficiency of the motor with a copper mouse cage rotor is considerably higher than that of the motor with a aluminum rotor. The temperature raise of both an air-cooling and a water-cooling induction motor is analyzed, which demonstrates that the temperature raise of the motor windings is higher than that of the other parts, and the temperature raise of the water-cooling motor is lower than that of the air-cooling motor. To verify the results of the theoretical analyses, four prototype induction motors (aluminum rotor, copper mouse cage rotor, air-cooling and spiral groove machine) have been designed and processed. The experiments to measure the efficiency and temperature raise were carried out on these motors. The experimental results prove that the theoretical analyses are correct.

1. Introduction

Energy deficiency and environmental contamination are two major challenges which were met in the development of automobile industry in contemporary society[1]. Electric vehicle which was used as a kind of energy-efficient, non-pollution, ideal “zero discharge” vehicle has been paid more attention to in recent years. With the rapid development of high-technology of power electric and control, the mini electrical vehicle has a rapid development in recent years. However owing to the high price of mini electrical vehicle, popularizing the mini electrical vehicle is still a certain difficulty. Mini electrical vehicle which has advantages of small volume, energy conversation, convenience and low prices and so on has been a hot research spot in today’s electric vehicle fields.
The motor drive and control system is the core of electric vehicle. Induction motor which has advantages of simple structures, low prices, easy maintenances, broader constant power operation scope and so on has a broadest application in electric vehicle fields. It is demanding that the motor drive system applied in Electric Vehicle not only has a high starting torque and wide constant-power range of variable speed, but also has a high efficiency in all velocity range. The mini electrical vehicle uses the storage battery with induction motor as power supply. The low supply voltage leads to a large motor current, and a large current leads to the high Temperature raise and loss of motor. The loss increases and the efficiency decreases. The temperature raise has an effect on the performances, insulations and service life of motor, so how to reduce loss and temperature raise of motors, and to increase the efficiency of motors and reliability of operation has become the key of the motor design for of mini electrical vehicle.

This paper discusses how to reduce loss and temperature raise and to increase the efficiency of motors, aiming at the features of low supply voltage and large current of motors for mini electrical vehicle.

2. THE Analysis of Magnetic Performance of Induction Motor for the Mini Electric Vehicle

Loss Analysis

The loss of motor mainly includes the copper loss of stator winding, copper (or aluminum) loss of rotor winding, iron-core loss, mechanical loss and additional loss. Equation (1) is shown as follows:

\[ P_L = P_{Cu1} + P_{R2} + P_{Fe} + P_{me} + P_{\alpha} \]  

Where, \( P_L \) is total loss; \( P_{Cu1} \) is copper loss of stator winding; \( P_{R2} \) is rotor loss (aluminum loss or copper loss); \( P_{Fe} \) is iron-core loss; \( P_{me} \) is mechanical loss; \( P_{\alpha} \) is stray loss. Copper loss of stator winding \( P_{Cu1} \), rotor loss \( P_{R2} \) and the square of current are proportional to the value of resistance. Equation (2) and equation (3) are shown as follows:

\[ P_{Cu1} = I^2 R_{Cu1} \]  
\[ P_{R2} = I^2 R_{R2} \]

When the power and the voltage are given, the copper loss of stator winding can be decreased by increasing wire diameter. However, increase of wire diameter restricted by the slot filling factor. So it is hard to calculate mechanical loss \( P_{me} \) correctly. Generally we refer to existing motor parameters and calculate on the basis of empirical formula. Because of mechanical loss which has little influence on efficiency generally is relatively small, we do not take it into consideration for the time being. Iron loss includes eddy current loss and hysteresis loss. Stator and rotor core which adopts lamination structure can decrease eddy current loss vastly. Rotor loss and the square of current are proportional with resistance. Rotor current is generated by stator rotating magnetic field. And rotor current is not easy to change restricted by the voltage of motor. If the rotor resistance droops, the rotor loss will decrease. Decreasing rotor resistance is an effective measure to reduce motor loss.

Effects on the Performance of Motor by Rotor Materials

Rotor materials determine rotor resistances. Choosing lower resistivity can reduce rotor resistances effectively. Because the resistance rate of copper is half of aluminum’s. Adopting induction motor of copper rotor can vastly reduce rotor loss, thus efficiency of motor is increased.

To research how much copper rotor and aluminum rotor affect the performance of motor, this paper is emulated and calculated to aluminum and copper rotor using rated voltage 34 voltages (the voltage inverted by direct current 48 voltages), frequency 50Hz, rated power 4kw, stator 30 slots, rotor 26 slots and rotor skewed slot motor by magnetic circuit calculation and Flux simulation. The induction motor (prototype obtained by transforming Y2 motor) of aluminum rotor and copper rotor are manufactured. Table 1 shows the performance of motor obtained from aluminum rotor and copper rotor by magnetic circuit calculation.
From Table 1, when other conditions are given and the material of rotor bar is just changed for copper, the stator and rotor losses of motor will all decrease. This is because when output power and voltage are certain, the drop of stator current leads to decreasing loss. Table 1 is shown that stator phase current decreases from 52.4 A to 49.9 A as follows. Motor efficiency increases from 81.7% to 86.3%. It is clear that changing rotor material can vastly increase the efficiency of electrical motor.

To probe the veracity of calculation further, we build finite element of motor by Flux software. Figure 1 is shown the motor. Figure 2 shows one period waveform of the stator current which is from the motor of aluminum and copper rotor with rated load.

![Figure 1. Finite element mesh drawing of induction motor](image-url)
Figure 2. Stator currents of the motor of copper, aluminum rotor

From Figure 2, the stator current at rated load of aluminum rotor motor is higher than that of the induction motor of copper squirrel cage rotor, and the results match the calculation results.

**Influences on the Performance of Motor by the air gap length**

The air gap length of induction motor is an important parameter in motor design. The air gap length not only influences the loss of motor, but also the power factor of motor. The air gap length is too big which will make the exciting current increase and the power factor decrease. The air gap length is too small which will make mechanical production difficult. In order to analysis the influence by air gap length on the performances of motor, this paper will contrast the current and power parameters of induction motor of copper rotor at different air gap length by magnetic circuit calculation and Flux simulation. Table 2 shows the results from different air gap length by magnetic circuit calculation.

**TABLE II. PERFORMANCES COMPARISON OF MOTOR WITH DIFFERENT AIR GAP LENGTH**

| Property                  | 0.3 mm     | 0.45 mm    | 0.55 mm    | 0.65 mm    |
|---------------------------|------------|------------|------------|------------|
| efficiency                | 85.46%     | 85.29%     | 85.118%    | 84.965%    |
| stator phase current      | 49.213A    | 49.885A    | 50.502 A   | 51.096 A   |
| no-load stator phase current | 14.539A  | 17.247A    | 19.664 A   | 21.474 A   |
| exciting current          | 10.436A    | 13.069A    | 14.982     | 16.658     |
| Stator Thermal Load       | 1798 A/cm·mm² | 1848 A/cm·mm² | 1894 A/cm·mm² | 1939 A/cm·mm² |
| Mechanical Shaft torque   | 12.963Nm   | 12.936Nm   | 12.909 Nm  | 12.885Nm   |
| copper loss of stator winding | 401.533 W | 412.578 W  | 422.855 W  | 432.861 W  |
| copper loss of rotor winding | 108.198 W | 107.667 W  | 107.452 W  | 107.299 W  |
| iron-core loss            | 105.085 W  | 104.058 W  | 104.013 W  | 102.894 W  |
| mechanical loss           | 45.739 W   | 45.317 W   | 45.038 W   | 44.759 W   |
| Rated Slip                | 0.02559    | 0.025473   | 0.025424   | 0.025394   |
| Power factor              | 0.935      | 0.923      | 0.912      | 0.901      |

From table 2, as the air gap length is increasing, the exciting current is clearly increasing, and the power factor is decreasing. Because the increasing air gap length leads to the high air gap reluctance. The efficiency of motor drops a little. The current and copper loss of stator increases, but the amplification is not big.

Because the increasing air gap length flux leads to the increasing air gap length. The efficiency of motor drops a little. The current and copper loss of rotor increases, but the amplification is not big.
To probe the veracity of calculation further, Flux motor model with skewed rotor is built and five-layer model is used to simulate a skewed slot rotor. Figure 3 shows the model as follows. As shown in Figure 4 is current waveform from next cycle at different air gap length. As shown in figure 5 is waveform of no-load exciting current.

Figure 3. Model of induction motor with skewed rotor

Figure 4. Waveform of stator phase current with different air-gap length

Figure 5. Waveform of no-load phase current with different air gap length

From Figure 4 and 5, it can be seen that the Stator phase current don't changed with the increasing of air gap length. No-load current increases with the air gap length. Because no-load phase current is nearly equal to exciting current, which indicates that air gap length has a little more influence on the exciting current, and the results match the calculation results. In addition, from Table 2, as the air gap length is increasing, the thermal load is also increasing. In motor design, the power factor needs to be considered, and thermal load and mechanical production is to choose reasonable length of air gap length. 0.45mm as prototype air gap length is chosen in this paper.

In addition, silicon steel sheet of good permeability and small loss are chosen which will help decrease iron loss in the motor design. Rotor slot skewing structure will decrease harmonic and torque pulsate effectively.

3. Cooling Structure Design of the Motor
Induction motor applied to the mini vehicle has the characteristics of low voltage and large current. On one hand the loss of motor increases, on the other hand large current causes the temperature raise in the motor. While the temperature raise affects the performance of the motor, insulation properties, and service life, so how to decrease the temperature raise to guarantee the reasonable temperature scope and how to develop the reliability of the motor operation become another key point in the motor design.

The heat exchange in motor mainly includes the heat conduction and convective heat. According to the theory of heat conduction, steady heat-conduction differential equation is equation (4) [4,5].

\[
\lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + q_v = 0
\] (4)

In equation (4) \( \lambda \) is the thermal conductivity of objects, and \( T \) is the temperature of the objects (°C), and \( q_v \) is the unit volume of heat-producing rate. From (4), we know that the heat transferred by conduction is proportional to thermal conductivity. To ensure the safety of the motor running, the large motor often uses the iron core of the stator and of the rotor to the air-cooling or hydrogen-cooling structure of the air ventilation [6-8]. Small motor has less calorific value and setting the air ventilation of the stator and rotor increases the complexity and difficulty of machining process. Thus, cooling structure by surface of the motor is generally used. The thermal conductivity of water is larger than that of the air, so the water-cooling structure is far more advantageous to reducing temperature of the motor.

Via establishing the heat circuit model of air-cooling motor with fins and of the water-cooling motor with spiral groove, we analyze the temperature raise in all parts of the motor. The model is shown in figure 6. In Figure 6, \( P_1 \), \( P_2 \) and \( P_{Fe} \) are stator copper loss, rotor copper loss and iron loss respectively. \( R_{11}, R_{12}, R_4 \) are thermal resistances between stator iron and stator winding, stator iron and rotor, stator iron and housing. \( R_2, R_3, R_5 \) are thermal resistances at the end of the rotor, at the end of the stator, at the end of stator winding. \( R_6 \) is thermal resistance of the surface of the foot. Due to the heat productivity of the motor winding being the most serious, we mainly analyze the slot windings.

![Figure 6. Model of heat circuit analysis of the motor](image)

(a) The model of air-cooling motor [9]  (b) The model of water-cooling motor

Figure 6. Model of heat circuit analysis of the motor

![Figure 7. Temperature curves of different cooling ways in each part of the motor](image)

Figure 7. Temperature curves of different cooling ways in each part of the motor
Figure 7 shows the curves of temperature raise from the simulation of slot windings, end windings and the iron core of the stator of the air-cooling motor and the water-cooling motor. In Figure 7, WaterEW, WaterSW, Wateryoke respectively represent the temperature of end windings, slot windings and the yoke of iron core of the stator of water-cooling motor, and WindEW, WindSW, Windyoke respectively represent the temperature of end windings, slot windings and the yoke of iron core of the stator of air-cooling motor. Figure 7 shows that the temperature raises in the slot windings, end windings and the iron core of the air-cooling motor are significantly higher than that of the water-cooling motor. The slot and end windings of the air-cooling motor are equal in temperature raise, while in the water-cooling motor, the temperature raise in the end windings is higher than that of the slot windings. The iron core of the stator is connected to the housing of the motor. Because the thermal conductivity of water is larger than that of the air, the temperature raise of the water-cooling motor is lower than that of the air-cooling motor. The heat from the windings can be transmitted to iron core and housing via the insulation of the slot, the slot and the teeth of the stator, and then the heat is taken away by wind (floating air) or water. The water-cooling structure can effectively reduce the temperature rise of the motor, improve the reliability of the operation of the motor and prolong operation life of the electric motor.

4. Experimental analysis

Experiment of the Motor Efficiency

To verify the accuracy of the calculation further, we test the motor of the rotor of processed aluminum and copper. The test consist of the induction motor of aluminum rotor, the induction motor of copper rotor, YASKAWA Inverter Varispeed G7, Dynamometer MagtrolHD-825, Power Analyzer WT3000 and so on. The test platform is shown in Figure 8. Figure 9 shows the distribution of motor efficiency when different rotational speed and torque happens to the motor of aluminum rotor and the motor of copper rotor.

Figure 8. Test platform of the motor efficiency

Figure 9 (a) and (b), the efficient area of the motor of copper rotor is significantly greater than that of the aluminum rotor. The motor efficiency of the copper rotor is quite high about 87% when the rotational speed is faster, and can reach 90% at some individual points. While the high efficient area of the aluminum
rotor is concentrated on high speed and large torque area (the rated torque of the motor is 13Nm), and the efficiency is about 82%. Thus changing the material of the cage of the rotor from aluminum to copper can make great improve in the efficiency of the motor.

Temperature Experiment of the Motor

The temperature experiment of the motor consists of air-cooling and water-cooling induction motor of copper rotor, drag motor, Torque Sensor JN338-50Nm, YASKAWA Inverter Varispeed G7, Telemecanique Inverter Altivar 58 and Power Analyzer WT3000. The experiment platform is shown in Figure 10. The temperature is measured by heat resistance WT100 buried in the slot of the motor, the end windings and the yoke of iron core of the stator. When we measure that motor speed is 2880rpm and the torque of motor is 10Nm, the temperature curves of slot windings, end windings and the yoke of iron core of the stator are shown in Figure 11, in which WaterEW, WaterSW, Wateryoke respectively represent the temperature of end windings, slot windings and the yoke of iron core of the stator of water-cooling motor, and WinEW, WinSW, Wynoke respectively represent the temperature of end windings, slot windings and the yoke of iron core of the stator of air-cooling motor. Figure 11 illustrates that the temperature is higher in all parts of the water-cooling motor than that of the air-cooling motor. In the air-cooling motor, the temperature of windings is higher than that of the iron core, and the temperature of slot windings is the same as that of the end windings, while in the water-cooling motor the highest temperature happens at the end windings, and the temperature of the iron core is far lower than that of the windings. Above all, the results accord with theoretical analysis.

From the analysis above, due to the advantages of low voltage and large current of the induction motor applied to the vehicle, copper rotor can effectively increases the efficiency of motor, and using the water-cooling motor is more useful to reduce temperature of the motor and increase the reliability of operation of the motor.

5. Conclusions

By magnetic circuit calculation and numerical simulation, the effects of rotor materials and air gap length on the performance of different induction motors are studied. It shows that the efficiency of the motor with a copper cage rotor is 5% higher than that of the motor with a aluminum cage rotor. The air-gap length has a great effect on the exciting current, which means as the air-gap length increases, the heat load and exciter current will increase. Hence, decreasing the air-gap length can help decrease the exciter current and improve the power factor, but it should be noted that to reduce gap length may bring difficulties to mechanical processing. For the motor with a processed air-cooling aluminum rotor and the motor with a copper rotor, the experimental results show that both the efficiency and the effective area of the latter motor are higher than those of the former motor. The numerical simulation and experiments also show that the temperature raise of the water-cooling motor is lower than that of the air-cooling motor.
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