Slot Optimization Design of Induction Motor for Electric Vehicle

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Abstract. Slot design of induction motor has a great influence on its performance. The RMxprt module based on magnetic circuit method can be used to analyze the influence of rotor slot type on motor characteristics and optimize slot parameters. In this paper, the authors take an induction motor of electric vehicle for a typical example. The first step of the design is to optimize the rotor slot by RMxprt, and then compare the main performance of the motor before and after the optimization through Ansoft Maxwell 2D. After that, the combination of optimum slot type and the optimum parameters are obtained. The results show that the power factor and the starting torque of the optimized motor have been improved significantly. Furthermore, the electric vehicle works at a better running status after the optimization.

Keywords: Induction motor; Type of rotor slot; Finite element method; Optimization design

1. Introduction

With the increasing popularity of low-carbon living in China, energy conservation becomes an important part of automobile research, which has greatly promoted the development of electric vehicle (EV) [1]. As the core component of EV, electric motor is of vital importance for operational characteristics of vehicle. Compared with other types of motor, induction motor (IM) has the advantages of high adaptability to working environment, low cost and long service life [2]. In recent years, it has won the favor of many electric vehicle manufacturers such as Tesla, BMW and BYD.

As the main carrier of energy conversion between mechanic and electricity, rotor slot plays a key role in transmission of electromagnetic energy. The types and the parameters of rotor slot have vital factors to affect motor performance, especially on efficiency, power factor and torque. Due to their special structures, traditional analysis methods cannot get the specific impact of slot parameters on motor performance accurately. Therefore, using finite element method to analyze the influence of micro-deformation of slot is necessary [3]. In this paper, a 3kW electric vehicle induction machine is used to analyze the influence of rotor slot parameters on power factor and efficiency by RMxprt module. On the basis of it, the optimums parameters constitute are obtained. The last step is building simulation models in Ansoft Maxwell 2D and then calculating their performance [4]. According to the results, the characteristics of the optimized motor have been improved significantly.

2. Selection of Rotor Slot

The differences between induction motor of EV and conventional type about rotor slot design are enormous [5]. Conventional motor usually adopts deep slot for better start-up characteristics, which will bring about large skin effect and increase leakage resistance of rotor. In addition, it can also deteriorate
the high-speed performance and reduce both efficiency and maximum torque. However, the motor of EV will be able to realize soft start by variable-frequency controller, so the great majority of them adopt shallow slot design. Secondly, there are so many harmonics in control system of EV. Reasonably large slot area will be capable of increasing the rotor impedance to suppress high-frequency harmonics. Furthermore, the structures of shallow slot and wide slot are used to reduce the rotor leakage resistance, which will result in the promotion of power factor and peak torque. The width of slot opening determines the interaction between fundamental magnetomotive force and harmonics of magnetic conductivity. Therefore, using semi-enclosed slot not only reduces the harmonics caused by slot, but also diminishes copper loss and harmonic current of motor. Finally, in order to obtain a parallel tooth structure for better characteristics, it requires the structure that wide at the top and narrows at the bottom. This design can effectively reduce the detrimental effect of high-frequency harmonics. In a word, the influence of slot parameters on motor performance should be integrally considered when designing a specific motor.

A 3kW induction motor, operating at a rated speed of 3000 r/min is analyzed and optimized in this paper. The basic design parameters of the machine are shown in Table 1. The structure of initial rotor slot is parallel slot, which is shown on Fig.1, whose parameters are given in Table 2.

| Table 1. Design parameters of the motor |
|-----------------------------------------|
| Rated power [kW] | 3 |
| Rated frequency [Hz] | 102 |
| Rated voltage [V] | 36 |
| Stator outer diameter [mm] | 155 |
| Stator inner diameter [mm] | 98 |
| Rotor outer diameter [mm] | 97.7 |
| Number of stator slots | 36 |
| Number of rotor slots | 28 |

| Table 2. Initial slot parameters |
|----------------------------------|
| h₀ [mm] | 0.8 |
| h₁ [mm] | 1.23 |
| h₂ [mm] | 9.0 |
| b₀ [mm] | 0.8 |
| b₁ [mm] | 4.2 |
| b₂ [mm] | 4.2 |

Figure 1. Initial slot
According to the design principle, parallel slot is not suitable for EV motor because of noticeable skin effect. Considering that the rated power of the motor is comparatively low, so it is appropriate to choose round bottom slot and inverted trapezoid slot as optimizing slot (shown on Fig.2 and Fig.3). We can see from the figures that the parameters of rotor slot are $b_{s0}$, $b_{s1}$, $b_{s2}$, $h_{s0}$, $h_{s1}$ and $h_{s2}$, respectively. The variation of each part of the slot has different effect on characteristics.

3. The Influence of Slot Parameters on Motor Performance

The performance of EV is closely related to the characteristics of electric motor. Induction motor of EV can get excellent starting characteristics by controller. Under these circumstances, it is preferable to promote power factor and efficiency at first. According to the motor simulation of RMxprt, motor efficiency is fairly satisfactory, but the power factor of it is relatively low. Low power factor will bring a series of problems, such as reducing input power factor of the inverter, which requires a larger capacity of controller, and controller is more expensive than motor itself. Therefore, lower power factor not only increases the cost of electric vehicle and the current of armature winding but also reduces the assurance coefficient of EV. To sum up, it's essential to improve the power factor emphatically with the efficiency of the motor not decreasing obviously. We establish simulation model of round bottom slot motor (RBSM) and inverted trapezoid slot motor (ITSM) in Maxwell Ansoft and use parametric analysis optimizing slot parameters at a small range around initial value one by one. In this paper, the initial parameters of optimizing slot come from the former rotor slot, which can avoid calculating from zero for each prioritization scheme.
3.1. Width of slot opening: $b_{s0}$

The width of slot opening can affect air-gap permeance and leakage inductance of the motor through the impact on motor air gap. Take 0.8 mm as the initial value of $b_{s0}$, establish the range of parametric analysis from 0.3mm to 1.5mm. The efficiency and the power factor of RBSM and ITSM varying with $b_{s0}$ are shown on Fig. 4.

![Figure 4. Power factor and efficiency of RBSM and ITSM vary with $b_{s0}$](image)

3.2. Height of slot head: $h_{s0}$

The initial parameter of slot head height is 0.8mm. Take 0.3 mm to 1.3 mm as the range of parametric analysis. The results show that the efficiency, power factor, starting torque and rated torque of the two motors are all drop with the rising of $h_{s0}$. So the smaller of $h_{s0}$, the better. But considering the rotor slot requires sufficient mechanical strength, set $h_{s0}$ to an empirical value of 0.3 mm.

3.3. Height of slot shoulder: $h_{s1}$

The initial height of the slot shoulder is 1.23mm, set 0.5mm to 1.8mm as the analysis range. The curves of efficiency and power factor varying with $h_{s1}$ are given on Fig. 5.

![Figure 5. Power factor and efficiency of RBSM and ITSM vary with $h_{s1}$](image)

3.4. Width of slot shoulder: $b_{s1}$

The rotor slot should be a structure of wide upper part and narrow under part according to the design principle. In order to avoid the large range in optimizing parameters and the heavy workload in calculation of $b_{s1}$ and $b_{s2}$, the two variables are optimized separately. The first is to select the initial
optimizing value of each parameter. And then put them together to find optimal combination. Because the initial parameter of $b_{s1}$ is 4.23mm, so the range from 4.23mm to 8mm is analyzed. With the increase of $b_{s1}$, efficiency and power factor of the two kinds of motors are both decrease, so 4.23mm is selected as the optimizing parameter of $b_{s1}$ temporarily.

3.5. Height of slot: $h_{s2}$
According to the original parameters, 9mm is taken as initial value of $h_{s2}$. Because the design requires a shallow structure, selecting the range from 3mm to 12mm for analysis is appropriate. The efficiency and the power factor varying with $h_{s2}$ are shown on Fig. 6.

![Figure 6. Power factor and efficiency of RBSM and ITSM vary with $h_{s2}$](image)

As the figure shows, the power factor of the RBSM decreases with the growth of $h_{s2}$, and the efficiency increases initially and decreases afterwards with $h_{s2}$, so the value of $h_{s2}$ is considered to be 5.4mm, where the value of efficiency and power factor can achieve a relatively balance. The power factor of the ITSM decreases with the raising of $h_{s2}$, but the tendency of efficiency is on the contrary. It reaches its maximal value between 8mm and 10mm and then gradually declines. Considering the motor is given priority to improve its power factor and that the value of efficiency fluctuates slightly with $h_{s2}$, 4.25mm is the optimal value of $h_{s2}$.

3.6. Width of slot: $b_{s2}$
The initial parameter of $b_{s2}$ is 4.2mm, and the length of $b_{s2}$ should be less than $b_{s1}$. Therefore, the range of $b_{s2}$ is selected from 1.5mm to 4.2mm. The variation of two properties with $b_{s2}$ are shown on Fig.7.

![Figure 7. Power factor and efficiency of RBSM and ITSM vary with $b_{s2}$](image)

It can be seen from the tendency that the efficiency of RBSM increases slowly with the enlargement of $b_{s2}$, and the trend of power factor demonstrates a sawtooth pattern. Since the power factor of the motor is preferred, the value of $b_{s2}$ is chosen at 1.95mm. The power factor of ITSM shows a tendency from rise to decline with $b_{s2}$ until 3.3mm. In contrast with efficiency, the change of power factor is more significant. Take all this into consideration, power factor should be taken precedence over efficiency, so the optimizing parameter of $b_{s2}$ is 3.3mm.
4. Parameters of Optimizing Slot and the Motor Performance

As mentioned above, we are able to get the optimized parameters of the round bottom slot motor and the inverse trapezoid motor. However, these parameters might not be the final solution, because the optimal value of each parameter may vary with the diversification of the others. To solve the problem, optimized parameters of the rotor slot are required to be optimized again in a small scope synchronously using parametric analysis, and then select the best combination of parameters. The power factor, efficiency, rated torque and starting torque of the motor are all target values. The optimum parameter combinations are shown in Table 3.

Table 3. The latest optimal slot parameters

|                      | $h_{s0}$[mm] | $h_{s1}$[mm] | $h_{s2}$[mm] | $b_{s0}$[mm] | $b_{s1}$[mm] | $b_{s2}$[mm] |
|----------------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Round bottom slot    | 0.3          | 0.44         | 5.4          | 0.8          | 4.1          | 1.85         |
| Inverted trapezoid   | 0.3          | 0.87         | 4.7          | 0.65         | 5.5          | 1.6          |

We establish three simulation models in Ansoft Maxwell 2D according to the parameters shown in the Table 3, the simulation model of the initial motor is shown on Fig. 8, and the simulation of the round bottom slot motor and the inverse trapezoid slot motor are shown on Fig.9 and Fig.10.

Figure 8. Initial motor

Figure 9. Model of RBSM

Figure 10. Model of ITSM
Through the finite element method analysis, the main performance of the optimized motors is given in Table 4.

Table 4. Comparison of motor performance

| Performance | Power factor | Efficiency | Rated torque [N·m] | Starting torque [N·m] |
|-------------|--------------|------------|--------------------|-----------------------|
| Initial motor | 0.687        | 86.8%      | 9.5N·m             | 31.53N·m              |
| RBSM        | 0.766        | 86.2%      | 9.63N·m            | 67.75N·m              |
| ITSM        | 0.774        | 86.6%      | 9.65N·m            | 68.37N·m              |

As shown in Table 4, the power factor and the starting torque of RBSM and ITSM have increased significantly although the rated torque and the efficiency change a little bit. The higher power factor can effectively reduce the stator current and the cost of controller and improve the safety margin of EV. The larger starting torque can shorten the startup time and bring a better dynamic response performance for electric vehicle. The only defect is that the efficiency of RBSM and ITSM is reduced slightly, but it's so tiny that it has almost no effect on motor performance. Overall, the motor performance has been improved obviously after the optimization especially that of inverted trapezoid slot.

5. Conclusions

The paper studies the slot optimization design of a 3kW induction motor for electric vehicle. We analyze the type of two optimizing slots, and then determine the value of optimal parameters using RMxpert module. After that, three simulation models are established in Maxwell 2D to compare the main performance of the motor before and after the optimization. The results show that both power factor and starting torque of the motor have increased observably after optimization, which effectively reduce the cost of electric vehicle and improve its dynamic performance. And the type of inverted trapezoid slot is better to meet the requirements of EV.

6. References

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