Development of compact, reliable and high-performance PMSM for a clutch coupling motor module used for Hybrid Vehicles

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Abstract

Traction Motor is the key component of hybrid vehicles and have big influence on function and performance of the vehicle. In this paper, a compact, reliable and high-performance permanent magnetic synchronous motor (PMSM) is developed, which is the key part of a clutch coupling motor (CCM) module used for hybrid vehicles. During the concept design phase, considering about the special boundaries and requirements of motor for CCM, a 20-pole/30-slot (20p/30s) motor and a 20-pole/24-slot (20p/24s) motor are designed and compared. Based on comparison, the 20p/30s design is selected as the final concept. However, the chosen design still has some issues, so detailed analysis and optimizations are made. Since most parameters of motor are interactive, some evaluations and trade-offs are made to accomplish the final design. In the evaluation, the anti-demagnetization, structure strength and temperature distribution are concerned for reliability, the back EMF is concerned for safety of system, cogging torque and torque ripple are concerned for comfort of passenger and impact on transmission, output character and efficiency map are concerned for fuel consumption, and manufacturing, cost and mass are also concerned. And depending on the temperature rise analysis, the continuous power in different revolution speed are calculated. Finally, a prototype is built and tested. The test results show that the design is successful and credible. All performance can meet the requirements.

Keywords: High performance, reliable, PMSM, Clutch coupling motor, hybrid vehicle

1 Introduction

The powertrain of FAW Hongqi C-class PHEV is shown in Figure 1. Since the e-drive module is assembled between engine and DCT, it must be short and compact to fulfill the spatial boundary. In this case, a clutch coupling motor (CCM) module is developed. With the CCM module, the powertrain can meet all requirements of the full-hybrid functions.

Figure 1: Powertrain of FAW's Hongqi C-class PHEV
CCM module's structure is shown in Figure 2, a clutch is integrated in the rotor of a permanent magnetic synchronous motor (PMSM), the motor is water-cooled, the coolant and oil circuit is integrated in the multi-function housing.

Figure 2: Structure of CCM module

Traction Motor is the key component of CCM module and have big influence on acceleration, comfort, safety, reliability, fuel consumption and cost of the vehicle. In this paper, a compact, reliable and high-performance PMSM is developed and validated, some technology and engineering ideas are applied in the process.

2 Specification of CCM

2.1 Special Requirement of Traction motor for hybrid vehicles

According to the requirements of P2 hybrid vehicle, the motor should have characteristics of high power density, wide speed range, high torque, big overload capability and high-efficiency area. Besides the electromagnetic performance, motor should take into account the reliability, environmental adaptability, simple structure, cost and mass production. In a sense, safety, reliability and cost are more important than the electromagnetic performance. Due to the complex work environment and conditions, it is more difficult to design a clutch coupling motor than an industrial motor. Industrial motor focus on one or some operating points, but the clutch coupling motor should consider the whole range of torque and speed. The operating conditions of an industrial motor and a Traction motor for HEV are quite different as shown in Figure 3.

2.2 Specification of motor

In this paper, the clutch coupling motor is IPMSM which is applied in hybrid vehicle. The specification of the IPMSM is shown in Table 1. The motor was supposed to 45kW/280Nm.

Figure 3: Operating points of motor

TABLE 1 Specifications of the clutch coupling motor

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Values</th>
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<tbody>
<tr>
<td>Maximum Size</td>
<td>290*55</td>
</tr>
<tr>
<td>Peak Power</td>
<td>kW 45</td>
</tr>
<tr>
<td>Peak Torque</td>
<td>Nm 280</td>
</tr>
<tr>
<td>Rated Power</td>
<td>kW 21</td>
</tr>
<tr>
<td>Maximum Speed (under load)</td>
<td>rpm 5500</td>
</tr>
<tr>
<td>Rated Voltage</td>
<td>V 245-396</td>
</tr>
<tr>
<td>Maximum Current</td>
<td>Arms 360</td>
</tr>
<tr>
<td>Peak Line to line Voltage (no-load)</td>
<td>V 450</td>
</tr>
<tr>
<td>Cooling type</td>
<td>Water</td>
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3 Concept Design of the Motor

3.1 Two concepts of motor

In the motor, there are different parameters and characteristics such as winding factor, d- and q-axis inductance, saliency ratio and force etc, which depend on the combination of the number of poles.
and slots. Therefore, the combination of the number of poles and slots number is determined carefully in the initial design process to achieve high performance. Comparison analysis is performed according to various combination of the number of poles and slots using finite element method (FEM). Based on the comparison result, the suitable combination for the clutch coupling motor is selected. Considering the limitation of PWM frequency and radial space, the number of poles is identified as twenty. 20p/30s and 20p/24s motor combinations are calculated, and the advantages and disadvantages of two design is compared. In order to compare the combinations of number of poles and slots, we choose the same rotor and magnet design. The structure of analysis model is shown in Figure 4, and it shows half mechanical period of the full model. It is hard to do the detailed design in the beginning period, the design of two combinations is not optimized and just for comparison.

3.2 Compare and select of Concepts

3.2.1 Performance under no-load condition
The back-EMF is the very important parameter that affects the output power and performance in the motor. Because the winding factor of two combinations is different, the number of turns per-phase is also designed in two values in order to keep the back-EMF of two combinations. The number of turns per-phase of 20p/30s is fifty, and the number of 20p/24s motor is forty-eight. The winding type of two combinations is star-connection. Figure 5 shows the curves of back EMF and basic harmonic.

![Figure 4: Structures of two combinations](image1)

![Figure 5: Back EMF & basic harmonic of two combinations](image2)

Table 2 shows the cogging torque and value of back EMF under no-load condition. From Figure 3 and Table 2, it is obviously that the Rms-value of two combinations is almost the same, but the shapes of two combinations is different. And the back-EMF of 20p/30s has more harmonics. The cogging torque of 20p/24s motor is less than a half of 20p/24s motor. In summary, the 20p/24s motor has a better performance under no-load.

<table>
<thead>
<tr>
<th>TABLE 2 Performance under no-load</th>
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<tbody>
<tr>
<td>cogging torque(ppk)</td>
</tr>
<tr>
<td>back EMF@1500rpm</td>
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</table>
3.2.2 Performance under load condition

As we known, the external characteristics of motor is restricted by the inverter maximum voltage and current. The design of motor should use the capability of inverter as much as possible. Figure 6 shows the current map under full-load range of two combinations.

From Figure 6 can be seen that the case of output the maximum torque(280Nm), 20p/24s motor needs more current. And the rest of current maps of two combinations are similar. The capability of using current is also beneficial for the output power of motor. The external characteristics of two combinations is shown in Figure 7.

Figure 6: Current map of two combinations

Figure 7: External characteristics of two combinations

From Figure 7 can be seen that the maximum power of 20p/30s is 5kW bigger than 20p/24s motor. Except the output of motor, we also concern about efficiency of the motor. The efficiency map of two combinations is shown in Figure 8.
The maximum efficiency of two combinations is also 0.94, but the distribution of two combinations is different. Due to the copper loss smaller, the high-efficiency area of 20-pole/24slot is more close to the low speed and small torque range. And the area of high-efficiency (>0.92) which is belong to 20p/30s is more bigger. Considering the operating points of motor, 20p/30s is more suitable for the hybrid vehicle. In summary, the 20p/30s has a better performance under load.

4 Optimization of 20p/30s design

Hybrid vehicle is defined as a high-level car, so it is important for driving comfort and starting performance. And, the motor is supposed to reduce the torque ripple and cogging torque. According to the analysis of the Chapter 2, the 20p/30s has a disadvantage on torque ripple and cogging torque. So, we will do the optimization for the 20p/30s on the torque ripple and cogging torque. The cogging torque results from the interaction of the rotor permanent magnets with the stator slots. It may cause speed ripple, vibrations and torque ripple, particularly under light load and low speed conditions. And the torque ripple results from the cogging torque, the ripple of electromagnetic factors, and the armature reaction. It also influence the performance on vehicle driving and vibrations. Numerous methods have been proposed for analyzing and reducing the cogging torque and torque ripple by optimizing the permanent magnet MMF distribution and minimizing the airgap reluctance variation. All the methods is in order to optimize the back-EMF harmonics. By the design and analysis above, we confirm with 20p/30s combination. While keep the output performance, this paper use the non-uniform airgap by optimizing the structure of rotor out-surface and stator inner-surface to reduce torque ripple and cogging torque. The optimized structure of motor is shown in Figure 7.

From Figure 9 can be seen that the surface of inner-stator and out-rotor is not a uniform, and the open-slot width is limited. They are both good for reducing the slot effect of motor, reduce the mutation rate in the radial direction by the changes of magnetic conductance. Meanwhile, they also reduce the harmonics of the back-EMF, the torque ripple is reduced.
Figure 12: Cogging torque curve of 20p/30s
The peak-to-peak value of cogging torque of 20p/30s combination is 1.35Nm, which can be seen in Figure 12. The cogging torque is almost no influence on the motor starting and low speed performance. And the torque ripple is also well optimized.

Figure 13: Torque ripple MAP of 20p/30s
From Figure 13 can be seen that when the motor output peak torque(280Nm) under low-speed, the peak-to-peak value of torque ripple is 19.5Nm. And when the motor output low torque(50Nm) under low-speed, the peak-to-peak value of torque ripple is 5.6Nm. Under the field-weaken range of speed, the motor has a good performance of torque ripple. It is greatly improved for cogging torque and torque ripple which is compared with the prior motor design.

5 Heat and structure

5.1 Maximum Temperature
The continuous power requirement from vehicle is 21kW, but we know that even the output power is the same, the losses of motor are different in different revolution speed. Therefore, heat analysis simulation of some parts are made in different revolution speed. Max. temperature analysis results are shown in Figure 14.

Figure 14: Max. Temperature in different parts
(Coolant temperature: 70℃, flow rate: 10L/min)
As we can see, the temperature of winding is higher than others in every revolution speed, if the temperature limit is 165℃, the motor can output 21kW when the speed is higher than about 1850rpm.

5.2 Max. Continuous Power
Continuous power is related to losses and cooling condition, if the cooling ability is strong enough and losses are low enough, the continuous power can be quite high, even close to the max. power. As shown in Figure 15, when the temperature limit is 165℃ and bus voltage is rated value, the maximum continuous power of CCM can reach 41kW around 5000rpm.

Figure 15: Max. Continuous Power of CCM
(Coolant temperature: 70℃, flow rate: 10L/min)

5.3 Rotor Structure Strength
Narrow magnetic bridges are quite popular in inner mounted magnet PMSM, but the structure strength of rotor in high speed is a big issue. From the simulation result in Figure 16, max. stress of CCM in 7440rpm(1.2 times of max. mechanical speed) is lower than yield strength, that makes the safety factor higher than 1.2 and the CCM more reliable on mechanical strength. In the subsequent over-speed test of prototype, this result is also testified.
6 Conclusion

In this paper, a compact, reliable and high-performance PMSM is developed and validated. Through pole-slot selection and optimization, the performance of motor fulfill the requirements and reached high specific power and specific torque. Furthermore, the heat and structure analysis shows that the motor has high safety factor on reliability. Finally, a prototype is built and tested. The test results show that the design is successful and credible.

Authors

Jian Gong obtained his master degree from Harbin Institute of Technology. In FAW R&D Center, He has been working on performance design of e-motor in several projects including CCM module for Hongqi PHEV and TMH system for Besturn PHEV.