Abstract

This paper presents design optimization studies on high torque and high power density hybrid excitation flux switching motor (HEFSM) as a candidate for traction drives in hybrid electric vehicles (HEVs). Firstly, the construction and the basic working principle of the selected HEFSM are overviewed. Then, under some design restrictions and specifications for the target HEV drives, the initial performances of the selected HEFSM are evaluated based on 2D-FEA. As the initial motor fails to achieve the target performances, design parameters are set and treated by using deterministic optimization approach. After several cycles of iteration, the target torque and power of 333Nm and 123kW respectively, are achieved with much higher power density when compared with existing interior permanent magnet synchronous motor (IPMSM) used in HEV.

1. Introduction

Hybrid excitation machine (HEM) consists of permanent magnet (PM) and field excitation coil (FEC) has several unique features that can be applied in HEV drive system. In general, HEM can be classified into four categories based on the location of PM and FEC such as (i) both PM and FEC are located at rotor side [1-3] (ii) the PM is in the rotor while the FEC is in the stator [4] (iii) the PM is in the rotor while the FEC is in the machine end [5-6], and (iv) both PM and FEC are located in the stator [7-9]. All HEMs mentioned in the first three consists of a PM in the rotor and can be categorized as “hybrid rotor-PM with FEC machines” while the final machine can be referred as “hybrid stator-PM with FEC machines”. Based on its principles of operation, the fourth machine is also known as “hybrid excitation flux switching machine” (HEFSM) which is getting more popular recently [10-11]. With all active parts located on the stator, HEFSM has the advantages of (i) robust rotor structure suitable for high-speed drive applications (ii) a simple cooling system due to all active parts are located in the stator body, and (iii) variable flux capabilities from FEC.

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Various combinations of stator slot and rotor pole for HEFSM have been developed for high speed applications. For example, 12Slot-10Pole HEFSM has been proposed such as in [12-13]. However, the machine in [12] has a separated PM and C-type stator core that makes it difficult to manufacture, and the design is not yet optimized for HEV applications while the machine in [13] has a limitation of torque and power production in high current density condition. This is due to insufficient stator yoke width between FEC and armature coil slots resulting in magnetic saturation and negative torque production. To reduce the supply frequency of inverter, 6Slot-5Pole HEFSM has been proposed by the authors. Although the proposed machine has met the target performances, the problem of unbalanced pulling force due to odd number of poles is difficult to overcome [14]. In addition, some researchers have proposed 6Slot-8Pole machines but these types of machines have problems of high torque ripple and distorted induced-emf waveforms [15-16].

Fig. 1. Original design of 12Slot-10Pole HEFSM

In this paper, design and optimization studies are conducted to the original 12Slot-10Pole HEFSM in effort to achieve the target performances for HEV applications. Fig. 1 illustrates the cross-sectional view of the main motor part of the initial HEFSM [13]. The motor is composed of 12 PMs and 12 FECs distributed uniformly in the midst of each armature coil while the three-phase armature coils are accommodated in the 12 slots for each 1/4 stator body periodically.

2. Design Requirements, Restrictions and Specifications for HEV Applications

The design requirements, restrictions and specifications of the selected HEFSM for HEV applications are similar with IPMSM in Lexus RX400h listed in Table 1 [17]. The electrical restrictions related with the inverter such as maximum 650V DC bus voltage and maximum 360V inverter current are set. The limit of the armature coil current density, \( J_a \) and the FEC current density, \( J_e \) are set to 30A/mm\(^2\) and 30A/mm\(^2\), respectively. The weight of the PM is 1.1kg similar with PM volume in IPMSM. The target torque of 333Nm with reduction gear ratio of 2.478 is set, hence, realizing the maximum axle torque via reduction gear of 825Nm. The maximum operating speed is set to 12,400r/min and the target power is set to be more than 123kW. As the proposed HEFSM consists of very simple structure with concentrated winding in all coils, the target motor weight to be designed is set to be less than 35kg, resulting in that the proposed motor promises to achieve the maximum power density of more than 3.5kW/kg. Commercial FEA package, JMAG-Designer ver.11.0, is used as 2D-FEA solver in this design.
Table 1. HEFSSM Design Restrictions and Specifications

<table>
<thead>
<tr>
<th>Items</th>
<th>IPMSM</th>
<th>HEFSSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. DC-bus voltage inverter (V)</td>
<td>650</td>
<td>650</td>
</tr>
<tr>
<td>Max. inverter current ($A_{rms}$)</td>
<td>360</td>
<td>360</td>
</tr>
<tr>
<td>Max. current density in armature coil, $J_a$ ($A/mm^2$)</td>
<td>31</td>
<td>30</td>
</tr>
<tr>
<td>Max. current density in FEC, $J_e$ ($A/mm^2$)</td>
<td>NA</td>
<td>30</td>
</tr>
<tr>
<td>Stator outer diameter (mm)</td>
<td>264</td>
<td>264</td>
</tr>
<tr>
<td>Motor stack length (mm)</td>
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<td>70</td>
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<tr>
<td>Shaft radius (mm)</td>
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<td>30</td>
</tr>
<tr>
<td>Air gap length (mm)</td>
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<td>0.8</td>
</tr>
<tr>
<td>PM weight (kg)</td>
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<td>1.1</td>
</tr>
<tr>
<td>Maximum speed ($r/min$)</td>
<td>12,400</td>
<td>12,400</td>
</tr>
<tr>
<td>Maximum torque (Nm)</td>
<td>333</td>
<td>333</td>
</tr>
<tr>
<td>Reduction gear ratio</td>
<td>2.478</td>
<td>2.478</td>
</tr>
<tr>
<td>Maximum axle torque via reduction gear (Nm)</td>
<td>825</td>
<td>825</td>
</tr>
<tr>
<td>Maximum power (kW)</td>
<td>123</td>
<td>&gt;123</td>
</tr>
<tr>
<td>Power density (kW/kg)</td>
<td>3.5</td>
<td>&gt;3.5</td>
</tr>
</tbody>
</table>

3. Initial Performances of The Proposed HEFSM

Initially, performances of the proposed HEFSM in open circuit condition such as induced emf and cogging torque are analyzed as shown in Figs. 2 and 3, respectively. In Fig. 2, the amplitude of the fundamental component in which the induced voltage is generated from the flux of PM only is 123.6V. The induced emf is slightly sinusoidal which results a small amount of cogging torque of approximately 1.06Nm peak-to-peak. However, when $J_e$ is set to 15A/mm$^2$, the induced voltage is slightly distorted and the amplitude is increased to 263.2V which is more than double of that under no FEC current. This is due to the field strengthening effect by the additional FEC. For load analysis, performances of the motor at maximum $J_a$ and $J_e$ are analyzed. The torque and power obtained at base speed 5731.4r/min are 175.9Nm and 105.6kW, respectively, which is less than the target value. To investigate this issue, the torque versus $J_e$ at various $J_a$ is plotted as depicted in Fig. 4. It is obvious that the torque is increased with increasing $J_e$ up to certain $J_e$ and begins to decrease when higher $J_e$ is applied as shown in red circle. For instance, at $J_a$ of 30A$_{rms}$/mm$^2$, the maximum torque of 181.66Nm is obtained when $J_e$ is set to 20A/mm$^2$. However, the torque starts to reduce when $J_e$ is set higher than this value. For $J_a$ of 20A$_{rms}$/mm$^2$ and 25A$_{rms}$/mm$^2$, the maximum torque obtained are 152.72Nm and 170.94Nm respectively, when $J_e$ is set to 15A/mm$^2$. The torque also starts to reduce when $J_e$ is set higher than this value. Similarly, the same phenomenon occurs at the condition of $J_a$ of 5A$_{rms}$/mm$^2$, 10A$_{rms}$/mm$^2$ and 15A$_{rms}$/mm$^2$ where the torque starts to reduce when $J_e$ is set higher than 10A/mm$^2$. 
Fig. 3. Cogging torque of the original design HEFSM

Fig. 4. Torque versus $J_x$ at various $J_s$.

Fig. 5. Flux vector diagram of various $J_s$ at maximum $J_x$. 
To explain this phenomenon, further investigation is examined on the flux density distribution at three conditions such as (i) before maximum torque, (ii) at maximum torque, and (iii) after maximum torque. For example, at maximum $J_a$ of 30A/mm², flux distribution at $J_e$ of 10A/mm², 20A/mm² and 30A/mm² are investigated as shown in Fig. 5. It can be seen that for low $J_e$ of 10A/mm², the flux can easily flow to the direction according to its principle as shown in Fig. 5(a). Nevertheless, the flux flow to the left part starts to saturate between armature coil upper slot and FEC lower slot marked in blue circle when $J_e$ is set to 20A/mm² as shown in Fig 5(b). In this case, some of the flux from FEC which flow to the right side cancelled the flux from PM as shown in red circle which results in reducing the torque production. Hence, for the maximum $J_e$ of 30A/mm² where much FEC flux is generated, the flux flow to the left part is totally saturated between armature coil upper slot and FEC lower slot marked in blue circle. Therefore, much higher flux from the stator outer yoke passes the FEC pitch move towards the PM in the right side. This flux also cancelled the PM flux and some of the flux is forces to flow into the rotor side producing much negative torque as shown in Fig. 5(c), hence reducing the torque production. Thus, one of the methods that can be used to overcome this problem is by investigating the suitable length between armature coil upper slot and FEC lower slot to avoid flux saturation.

4. Design methodology for improvements

To make a simple design, the shape of armature coil slot and air gap between the inner and outer PM are redesign, and design free parameters of $D_1$ to $D_{10}$ are defined as illustrated in Fig. 6. The first step is carried out by updating the rotor parameters, $D_1$, $D_2$ and $D_3$ while keeping $D_4$ to $D_{10}$ as constant. As the torque increases with the increase in rotor radius, $D_1$ which is considered as the dominant parameter that can improve the torque is firstly treated. In this condition, $D_4$, $D_6$, $D_8$, $D_9$ and $D_{10}$ are simply shifted to the new position by following the movement of $D_1$, while $D_5$ and $D_7$ are kept constant.

Figure 6. Design parameter defined as $D_1$ to $D_{10}$
Then, by selecting $D_1$ at its maximum performance, both rotor pole width $D_2$ and rotor pole depth $D_3$ are varied. Once the maximum performance from the combination of $D_2$ and $D_3$ is determined, the second step is carried out by changing the FEC slot parameters $D_4$, $D_5$ and $D_6$ while keeping the other parameters constant. Then, by using the combination of $D_4$ to $D_6$ that bring out the maximum performance at the second step, the third step is carried out by varying the armature coil slot parameters $D_7$ and $D_8$ with keeping other parameters constant. The necessary armature coil slot area, $S_a$ is determined by varying armature coil depth, $D_7$ and armature coil width, $D_8$ to accommodate natural number of turns, $N_a$ for armature coil. Furthermore, to ensure the PM is not demagnetized at temperatures as high as 180°C, $D_9$ and $D_{10}$ are adjusted with keeping the same PM volume. The method of changing $D_1$ to $D_{10}$ is treated repeatedly until the target performances are achieved. All design parameters are adjusted with keeping air gap length of 0.8mm constant under maximum $J_a$ and $J_e$. In addition, at the final design, the corners circled in Fig. 6 are designed as a curve to ensure all flux at the edge of the shape flow more smoothly, hence increases the performance of the motor. For the rotor inner pole, the curve designed not only increased the flux flows but also increase the rotor mechanical strength of the motor, make it more robust to work in high speed condition. Finally, after few cycle of optimization, the motor satisfied the target requirements and performances for HEV applications.

The cross sectional views of the final design HEFSM is depicted in Fig. 7. The differences between the initial and the final design HEFSM are (i) the rotor radius of the final design is longer than the initial rotor radius which gives more torque as had been expected (ii) the armature coil width of the final design is less than the initial design, but has high armature coil depth which results in more number of turns (iii) the FEC slot area is reduced approximately 40% from the initial design to cover some volume of stator yoke used for armature coil (iv) the final design has less PM depth with high PM width to keep the same PM volume of 1.1kg (v) the final design has no gap between armature coil upper slot and FEC lower slot which solved the flux saturation problem (vi) the stator outer core thickness is higher than the initial design to allow more flux to flow smoothly, and (vii) the final design has a stator yoke with a straight “I shape” that makes the flux flow more easily into the rotor. As a proof, Fig. 8 illustrates the flux distribution of the final design HEFSM for $J_e$ of 20A/mm² and 30 A/mm² with maximum $J_a$ of 30A_rms/mm². As the gap between armature coil upper slot and FEC lower slot in the final design HEFSM is expanded and considered negligible, the magnetic saturation caused by higher FEC current is relaxed. Thus, the improved design maintains the same torque for both current density conditions and enables to extract much higher power.
5. Results And Performances Of The Final Design

5.1. Flux Path of PM at Open Circuit Condition

The flux path of PM at open circuit condition of the final design HEFSM is illustrated in Fig. 9. It is obvious that, almost 100% flux of PM flow into the stator iron around the FEC. This yields negligible cogging torque and almost no back-emf at open-circuit condition under the maximum speed operation, which makes it easy to protect the switching devices when the inverter is shut down due to some failures. Furthermore, Figs. 10 and 11 illustrate the comparison between back-emf and cogging torque of the initial and final design at 3000r/min, respectively. It is clear that the back emf of the final design is more sinusoidal and much less by approximately 36% of the initial design. The final cogging torque is also reduced by more than 50% of the initial design.
5.2 Torque and Power Factor Versus $J_e$ Characteristics

The torque and power factor versus $J_e$ characteristics are plotted in Figs. 12 and 13, respectively. From the plot, it is obvious that increasing $J_e$ will increase the torque but will reduce the power factor. To equilibrate this situation, $J_e$ is increased so that the power factor can be improved and kept constant even if $J_a$ is very high. The plots clearly show that maximum torque of 334.4NM is obtained when $J_a$ and $J_e$ are set to 30A/mm$^2$ as their maximum with the power factor of 0.452. However, for low $J_a$ of less than 15A$_{rms}$/mm$^2$, the torque are slightly reduced with the increasing of $J_e$ of more than 20A/mm$^2$. This situation occurs due to excessive FEC flux that generates negative torque thus reducing the performances, similar with the original HEFSM discussed previously. The comparison between the torque and power factor versus $J_e$ under maximum $J_a$ for the initial and final design HEFSM is depicted Fig. 14. The torque and power factor of the final design HEFSM increased approximately 50% and 23%, respectively when compared with the original design.

5.3 Torque and Power Versus Speed Characteristics

The torque versus speed characteristics of the IPMSM and the final design HEFSM are plotted in Fig. 15. The maximum torque obtained for IPMSM and HEFSM are 333Nm and 334.4Nm, respectively. It is obvious that the HEFSM has better torque condition and produced much higher torque capability in high speed region. Meanwhile, Fig. 16 illustrates the power versus speed characteristics of the IPMSM and the final design HEFSM. From the graph, (i) at maximum torque, the power achieved for IPMSM and the final design HEFSM is 72.1kW and 129.6kW, at the speed of approximately 2,100r/min and 3701r/min, respectively (ii) the maximum power obtained is 123kW for IPMSM and 162.8kW for HEFSM (iii) the average power of the IPMSM and the HEFSM at normal driving mode of 3,000-6,000r/min are 113.7kW and 133.7kW, respectively, which proves that the HEFSM has better performance than IPMSM in frequent driving condition. The total weight of the final design HEFSM including stator iron, rotor iron, PM, armature coil, FEC, and estimation of both coil ends is 29.3kg, which is 16.2% less than IPMSM. Thus, the maximum torque density and maximum power density are 11.41Nm/kg and 5.55kW/kg, respectively, which is much higher than the target requirements for HEV applications. The maximum torque and power density of the final design HEFSM are increased approximately by 20.0% and 36.9%, respectively when compared with 9.51Nm/kg and 3.51kW/kg of existing IPMSM.
Fig. 13. Power factor vs $J_e$

Fig. 14. Torque and power factor vs $J_e$

Fig. 15. Torque vs speed
5.4 Motor Losses and Efficiencies

The motor losses and efficiencies are calculated considering iron losses in all laminated cores, and copper losses in armature coil and FEC. The detailed losses and motor efficiencies of the final design HEFSM at maximum torque, maximum power, and frequent operating point under light load driving condition noted as No. 1 to No. 8 in Fig. 15 are illustrated in Fig. 17. At high torque operating points No. 1, the efficiency is slightly degraded due to increase in copper loss while at high-speed operating point No. 2, the motor efficiency is degraded due to increase in iron loss. Furthermore, at frequent driving operation No. 3 to No. 8 under low load condition, the proposed motor achieves relatively high efficiency of more than 93%.

5.5 Rotor Mechanical Strength

The mechanical stress prediction of rotor structure is calculated by centrifugal force analysis based on 2D-FEA. The maximum stress at 12,400r/min reaches 46MPa and 28MPa for the original and final design, respectively, which is much smaller than allowable maximum stress of 300MPa in conventional electromagnetic steel. This is a great advantage of the HEFSM that makes it more applicable and suitable to operate in high-speed condition when compared with the conventional IPMSM.

6. Conclusion

In this paper, design studies, optimization and performance analysis of 12Slot-10Pole HEFSM for traction drive in the target HEV is presented. The design refinement is clearly demonstrated and finally achieved the target performances. In addition, the rotor mechanical stress predicted is good enough for the motor to run in high-speed region. Finally, the power density of the final design HEFSM is increased more than one third when compared to the existing IPMSM used in Lexus RX400h. As conclusion, the goal of this research to get maximum performances for HEV applications is successfully achieved.
References


