Comparison of 12S-10P and 12S-14P of Hybrid Excitation Flux Switching Machine for High-speed HEVs

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ABSTRACT

Hybrid excitation flux switching machine (HEFSM) can be categorized as Hybrid Excitation Machine (HEMs). Permanent magnet (PM) and field excitation coil (FEC) in Hybrid Excitation machine (HEMs) act as a main flux sources which has numerous attractive features compared to interior permanent magnet synchronous machines (IPMSM) usually employed in hybrid electric vehicles (HEVs). The advantage of both PM and FEC located on the stator is robust rotor structure alike with switch reluctance machine (SRM). Among various types of HEM, the machine with theta direction has a problem in flux cancellation. In this paper, a novel 12Slot-10Pole and 12Slot-14Pole HEFSM in which the FEC is wounded in radial direction on the stator are investigated to eliminate flux cancellation effect in HEM. Initially, coil arrangement test is analyzed to all armature coil slots to confirm the polarity of the phase. Futhermore, flux interaction analysis is performed to investigate the flux capabilities at various current densities are observed based on 2D finite element analysis (FEA). Finally, torque and power performances are investigated at various armature and FEC current densities. The results show that the 12S-14P has the highest torque and small value back-emf waveform which are needed for motor. The instantaneous torque of 12S-14P is 18.556Nm-p operated in low vibration and noise. The highest torque and power achieved are 226.78Nm and 110.615kW respectively. Since the initial design performances not achieved target torque and power, design modification and optimization should be conducted in future.

Keywords: Hybrid electric vehicles Switch reluctance machine Robust rotor structure Radial direction

INTRODUCTION

Developments of power electronics devices and permanent magnet (PM) materials, brushless machines generated by PM and DC FEC flux are increasing drastically for a variety of application. As the PM flux is always constant, the DC FEC provides variable flux control capabilities in term of field strengthening or field weakening conditions. These machines are called hybrid excitation machines (HEMs) which generally categorized into four groups. For the first groups, both PM and DC FEC embedded in rotor part while the armature coil is located in stator body, such as combination rotor hybrid excitation machines (CRHEMs) and PM hybrid synchronous machines (L. Xiaogang et al. 2000). The second group consists of PM in the rotor while DC FEC in the stator , while the third type consists of PM in the rotor and DC FEC in the machine end (J. A. Tapia et al. 2003). Finally, the fourth HEMs are the machine with both PM and DC FEC placed in the stator (E. Sulaiman et al. 2011). Among several HEMs, it should be located at rotor body and can be named as “hybrid rotor-PM with DC FEC machines” while the fourth machines can be referred as “hybrid stator-PM with DC FEC machines”. The fourth HEMs are also known as “hybrid excitation flux switching machines (HEFSMs)” become more practical recently. When compared with “hybrid rotor-PM with DC FEC machines” and conventional IPMSM (M. Kamiya et al. 2006), hybrid stator-PM with DC FEC machines have many advantages such that all the active parts (PM, FEC, armature coil) are located in the stator and make the rotor robust. This will help to provide cooling system for heat dissipation which makes it suitable to be applied in high current density condition, as well as variable flux capabilities from DC FEC similar as switch reluctance machines (SRMs).

Hybrid excitation flux switching machines (HEFSMs) is that type of machine in which PMs is used as primary source of excitation and DC FEC as a secondary source located in the stator. Typically, in PMFSMs if
the armature winding current is controlled, then the machine can be operated beyond base speed in the flux weakening region. PM flux can be counteracted by applying negative d-axis current. However it also suffers with several disadvantages of high copper loss, less power capability, less efficiency and potential permanent demagnetization of the PMs. Therefore, HEFSM is an alternative option which combines the benefits of both PM machines and DC FEC synchronous machines. As such HEFSMs have the potential to improve torque and power density, flux weakening performance, efficiency and variable flux capability which have been researched broadly over many years (E. Sulaiman et al. 2013).

Stator slots and rotor poles configurations at several combinations for HEFSMs have been developed as depicted in Fig. 1. As seen from the figure, the active parts of 6-slot 4-pole HEFSM are arranged in three layers in the stator. The PM and armature windings is located in outermost and inner stator, respectively, while DC FEC is placed at the midst between them (K. T. Chau et al. 2002). Furthermore, based on the topology of a purely PM excited PMFSM, a new 12-slot 10-pole HEFSM is developed (W. Hua et al. 2009). FEC windings is introduced in order to reduce the PMs dimensions and reduced the space, at the same time both the rotor and stator are unaffected as depicted in Fig. 1(b). The flux regulation capabilities of the machine are depended on the PM length by adjusting the length of PM radial direction. Meanwhile, the HEFS shown in Fig. 1(c) is a three-phase 12-slot 10-pole PMFSM which incorporates the DC FEC at outer boundary of the stator (E. Hoang et al. 2009).

However, the outer diameter of the machine is significantly enlarged for the DC FEC winding, which in turn reduces torque density. Besides, inserting DC FECs on the middle teeth of the E-core stator PMFSM is proposed in new design of HEFS, as depicted in Fig. 1(d) (J. T. Chen et al. 2011). It maintains the same outer diameter and exhibits a simpler 2-D structure than the HEFSM discussed in Fig. 1(c). In addition, it also yields non-overlap between DC FEC and armature windings. Half of the slot area is employed for the armature windings, and another half is employed for the DC FECs where the number of turns per phase of the E-core HEFSM is maintained.

However, Figs. 1(a), (b) and (d) shows the HEFSMs have a PM along the radial of the stator, thus the flux of PM in the outer stator acts as a leakage flux and has no contribution towards the torque production which reduces performances of machine. In addition, due to segmented stator core, the final machine design is also difficult to manufacture. Whereas, the 12-slot 10-pole outer FEC HEFSM in Fig. 1(c) has no flux leakage outside the stator and it also has the single piece stator which is much easier to manufacture when compared with the other design of HEFSMs After some design modifications and improvements especially on the stator yoke mentioned above including both armature coil and DC FEC slots area, the improved machine is able to operate at the target performances (E. Sulaiman et al. 2012). It should be noted that all HEFSM mentioned above are having an arrangement of armature coil and DC FEC in theta direction.

Based on several topologies of HEFSM, a new 12-slot 10-pole and 12-slot 14-pole HEFSM in which the arrangement of DC FEC in radial direction is proposed as depicted in Fig. 2. It is obvious that the main difference of the proposed HEFSM with other HEFSMs discussed above is the DC FEC configuration that are wounded in radial polarity, when compared with theta polarity, respectively.

In this paper, design study and performance investigation of 12S-10P and 12S-14P HEFSM with DC FEC in radial polarity are investigated. The design restrictions and specifications of the motor are discussed. The open circuit analysis such as armature coil test, PM flux distribution, cogging torque and flux linkage of PM with various DC FEC current density conditions analysis is examined. In addition, the short circuit analysis such as flux interaction of PM, DC FEC and armature coil at maximum current density condition, instantaneous

**Fig. 1:** Several HEFSMs topology (a) 6-slot 4-pole (b) 12-slot 10-pole with separated C-core stator (c) 12-slot 10-pole with DC FEC at outer stator (d) 6-slot 10-pole E-core HEFSM.
torque characteristic, and torque characteristics at various current density conditions are also predicted and discussed.

**Fig. 2:** Preliminary design of the HEFSM configurations.

*The Proposed Machine Design Specification:*

The parameter specification of the proposed 12Slot-10Pole HEFSM is listed in Table I. The target performances of the proposed machine are maximum torque of 303Nm and maximum power is 123kW. The PM weight is set to 1.3kg. The rotor structure is mechanically robust to rotate at high-speed because it consists of only stacked soft iron sheets, so that the target maximum operating speed is elevated up to 20,000r/min. Basically, the proposed machine design parameter is divided by two main parts which are stator part and rotor part. In stator part, there have FEC slot shape, armature slot shape, and permanent magnet (PM). The rotor parameters involved are the rotor radius (D1), rotor pole height (D3), and rotor pole width (D3). The PM height is represent by (D4), while the FEC parameters are FEC coil width and FEC coil height, (D5) and (D6) respectively. Finally, armature coil parameters are armature coil width (D7) and armature coil height (D8). Fig. 3 shows design parameter defined as D1 – D8.

**Table 1:** HEFSM Parameter Specification.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>12S-10P</th>
<th>12S-14P</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>Rotor radius (mm)</td>
<td>80.25</td>
<td>80.2</td>
</tr>
<tr>
<td>D2</td>
<td>Rotor pole height (mm)</td>
<td>20.2</td>
<td>20.2</td>
</tr>
<tr>
<td>D3</td>
<td>Rotor pole width (mm)</td>
<td>13.33</td>
<td>9.337</td>
</tr>
<tr>
<td>D4</td>
<td>PM height (mm)</td>
<td>26.775</td>
<td>26.775</td>
</tr>
<tr>
<td>D5</td>
<td>DC FEC width (mm)</td>
<td>29.98</td>
<td>29.98</td>
</tr>
<tr>
<td>D6</td>
<td>DC FEC height (mm)</td>
<td>6.67</td>
<td>6.67</td>
</tr>
<tr>
<td>D7</td>
<td>Armature coil width (mm)</td>
<td>6.46</td>
<td>6.46</td>
</tr>
<tr>
<td>D8</td>
<td>Armature coil height (mm)</td>
<td>26.775</td>
<td>26.775</td>
</tr>
<tr>
<td>Na</td>
<td>No of turns of armature coil</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Ne</td>
<td>No of turns of FEC</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

**Fig. 3:** Design parameters defined as D1 - D8.

Furthermore, Commercial FEA package, J MAG-Designer ver.13.0, released by Japanese Research Institute (JRI) is used as 2D-FEA solver for this design. The PM material used in for this motor is Neomax 35AH whose residual flux density and coercive force at 20°C, 1.2T and 932kA/m, respectively while the electrical steel 35H210 is used for rotor and stator body. Initially, the rotor, stator, armature coil, PM and FEC of the proposed HEFSM is drawn by using Geometry Editor. Then, J MAG Designer is used to set up of materials, conditions, circuits and properties of the machine.

The number of turn of armature coil is investigated to set in the circuit. The number of turn of armature coil is defined as in (1), where JA is armature coil current density, set to maximum of 30Arms/mm², NA is number of turn of armature coil, αA is armature coil filling factor (set to 0.5) and SA is the armature coil slot area. Similarly for the number of turn of FEC coil, NE is determined by using (2) where the maximum current density of FEC, JE is set to 30 A/mm². From both equations, the number of turns of armature coil and FEC are set to 7 turns and 60 turns, respectively.

\[ N_A = \frac{J_A \alpha_A S_A}{A_{pm}} \]  

\[ N_E = \frac{J_E S_E}{A_{pm}} \]  

(1)
The arrangement of 12 armature coil is tested using coil test analysis to the design HEFSM as shown in Fig. 4. Initially, all armature coils are set in counter clockwise direction, while the PM and DC FEC polarities are set in alternate direction to create 12 north and 12 south poles respectively. Then, the flux linkage in each armature coil slot is analyzed for the motor running at speed of 1200r/min. At this condition, the flux source is mainly comes from the PM where the DC FEC current is set to 0.

\[ N_z = \frac{J_e \alpha_r S_e}{A_e} \]  \hspace{1cm} (2)

Coil arrangement test:
Coil arrangement tests are examined in each armature coil separately to validate the principle of proposed HEFSM and to set the position of each armature coil phase. The resulting flux linkages are compared and the armature coil phases are defined according to the conventional three phase system. The three-phase flux linkage in which the flux source is produced by PM only Fig. 5 shows the 3-phase flux linkage defined as U, V, and W respectively of 12S-10P HEFSM and it successfully proof the principles to get 3-phase flux linkage of this machine have been achieved. From the graph, the flux characteristics can be considered as sinusoidal with maximum flux of approximately 0.1233Wb. Thus, it is expected that only small amount of induced voltage will be generated if the motor is to be applied in open circuit condition due to some failure which will not harm the motor. Zero rotor position has been set to get the highest flux consequently the highest torque can be achieved.

PM Cogging Torque:
Fig. 6 illustrates the PM cogging torque for one electric cycle of 36° rotor position of 12S-10P and 12S-14P design. From the graph, the cogging torque of 12S-10P and 12S-14P design have a small value in peak-to-peak cogging torque which approximately 4.3613Nm and 5.5152Nm respectively. This is due to the effect of high PM flux linkage flow to the rotor. When the value of cogging torque is small, it will give only small effect on motor performance in term of noise and vibration.

Flux Linkage at Various Condition of \( J_e \):
The FEC flux linkage at various FEC current densities, \( J_e \) is analysed as well in order to verify the flux characteristics. The FEC flux linkage at U phase for various \( J_e \) are depicted in Fig. 7 and Fig. 8 for 12S-10P and 12S-14P HEFSM. From the graph, similar flux shape is obtained with increasing DC FEC current density.
maximum flux linkage obtained in this condition is 4.75mWb and 4.21mW. It is clear that both fluxes are increased as $J_e$ is increased and slightly decrease in the end. This phenomenon due to the material used for FEC, copper, has reached its limit to produce flux. Furthermore, inside the machines, there are some fluxes that flow opposite direction and result in cancelling each other.

**Fig. 6: Cogging Torque.**

**Fig. 7: Magnetic Flux Linkage of 12S-10P.**

**Fig. 8: Magnetic Flux Linkage of 12S-10P.**

**Induced Voltage:**

The induced voltage of the proposed machine in open circuit condition is examined at the speed of 1200 r/min. The comparison of back-emf for the both design of HEFSM is demonstrated in Fig. 9. According to conventional relationship between voltage and flux as in (3),

$$V = k \phi \omega$$

Where, $k$ is the constant, $\phi$ is the flux magnitude, and $\omega$ is the speed of the machine respectively, the maximum induced voltage generated for 12S-10P and 12S-14P HEFSMs approximately 101.34V to 138.26V respectively. It is clear that the flux linkage and emf induced for 12S-14P higher than 12S-10P design. However, the generated back-emf for both designs are still lower than supply voltage which is safe for the motor to operate at that condition.

**Torque and Power versus Speed Characteristics:**

The graph of torque and power with respect to the speed of 12S-10P and 12S-14P HEFSM is plotted in Fig. 10. The maximum torque for 12S-10P obtained is 193.886Nm with corresponding power of 88.01kW at speed 4223.45 r/min while maximum torque for 12S-14P give 226.786Nm with corresponding power of 110.615 kW achieved at the speed 4657.683 r/min. Then, the instantaneous torque profile of 12S-10P and 12S-14P are plotted and compared as shown in Fig. 11. It is clear that the average torque obtained is 199Nm with peak-to-peak of 12S-10P approximately 40Nm, which is greater than 10% of average torque. For 12S-14P, peak-to-peak value only 18.556 Nm, means only 8.23% from the average torque 226.7812Nm. High cogging torque will...
result in high vibration and noise in practical applications. Therefore, 12S-14P will give better performance compared to 12S-10P design.

**Fig. 9:** Back-emf at 1200 r/min.

**Fig. 10:** Torque and power vs. speed characteristics.

**Fig. 11:** Instantaneous torque characteristics at maximum DC FEC.

**Conclusion:**

In this paper, design studies and performance analysis of 12S-10P and 12S-14P HEFSM for EV traction drive have been presented. To identify each phase of armature coil and to locate the initial position of the rotor, the coil arrangement and zero rotor position tests have been carried out. The performances of the proposed motor such as flux capability and cogging torque have also been investigated and demonstrated. The 12S-14P has higher average torque as well as sinusoidal back-emf waveform when compared with 12S-10P design. From the result, wide range of torque and power characteristics is suitable for high torque, high speed EV applications. Since the initial design performances are less than the target value, it is expected that the motors will successfully achieve the target performances by further design refinement and optimization.

**REFERENCES**


