Design Investigation of Hybrid Excitation Flux Switching Machine for High-Speed Electric Vehicles

Siti Khalidah Rahimi, Nurul ‘Ain Jafar, Erwan Sulaiman and Siti Nur Umira Zakaria
Power Department of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia, Locked Bag 101
Batu Pahat, Johor, 86400 Malaysia
sitikhalidah17@gmail.com, erwan@uthm.edu.my

Abstract—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 permanent magnet and field excitation coil located on the stator is robust rotor structure alike with switch reluctance machine (SRM). Furthermore, this machine becoming more attractive because of variable flux control capabilities from FEC, which is appropriate to be applied for high-speed motor drive systems. This HEM can be categorized as hybrid excitation flux switching machine (HEFSM). In this paper, a novel 12Slot-10Pole HEFSM in which the FEC is wounded in radial direction on the stator is proposed for traction drives in HEVs. The design target of maximum torque and power are 303Nm and 123kW, respectively. Moreover, maximum power density of more than 3.5kW/kg is to be achieved, resulting that proposed motor have better power density compareed to existing IPMSM. Deterministic design optimization technique based on 2D-FEA is used to treat design parameters defined in rotor, armature coil slot and FEC slot until the target performances are achieved, under maximum current density condition for both armature coil and FEC. The final results prove that the final design HEFSM is able to keep the equivalent torque density in existing IPMSM installed on commercial HEV.

Index Terms—Hybrid electric vehicles, Hybrid excitation flux switching machine, radial direction.

I. INTRODUCTION

With dramatic accomplishments and 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 circumstances. 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 placed in stator body, such as combination rotor hybrid excitation machines (CRHEMs) and PM hybrid synchronous machines [1-3]. The second group consists of PM in the rotor while DC FEC in the stator [4], whilst the third type consists of PM in the rotor and DC FEC in the machine end [5-6]. Finally, the fourth HEMs are the machine with both PM and DC FEC placed in the stator [7-9]. Among several HEMs, it should be highlighted that all HEMs stated in the first three, PM are 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 [10], HEFSMs with PM, DC FEC and armature coil as active parts placed on the stator have a robust rotor structure as their advantage similar with switch reluctance machines (SRMs), simple and rugged rotor; easy 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.

II. HYBRID EXCITATION FLUX SWITCHING MACHINE

Machine that utilized primary excitation by PMs as well as DC FEC as a secondary source is known as Hybrid excitation flux switching machines (HEFSMs). Typically, PMFSMs which employ PM flux only can be functioning beyond base speed in the flux weakening region by means of controlling the armature winding current. 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 also potential irreversible demagnetization of the PMs. Therefore, HEFSM is an alternative option where the benefits of both PM machines and DC FEC synchronous machines are combined. 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 [11-14].

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 [15-16].

Furthermore, based on the topology of a purely PM excited PMFSM, a new 12-slot 10-pole HEFSM is developed [17]. 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.

![Image](38x374 to 291x649)

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 PMFSM

Meanwhile, the HEFSM shown in Fig. 1(c) is a threephase 12-slot 10-pole PMFSM which incorporates the DC FEC at outer boundary of the stator [18-19]. 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 HEFSM, as depicted in Fig. 1(d) [20]. 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 the 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. Nevertheless, the original 12-slot 10-pole outer FEC HEFSM has a limitation of torque and power production in high current density condition due to insufficient stator yoke width between FEC and armature coil slots resulting in magnetic saturation and negative torque production. 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 [21-23]. 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 topology of HEFSM, a new 12-slot 10pole 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 12-slot 10-pole HEFSM with DC FEC in radial polarity are investigated. The design restrictions and specifications of the motor are discussed in Section III. 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 Section IV. In addition, the short circuit analysis such as flux interaction of PM, DC FEC and armature coil at maximum current density condition, instantaneous torque characteristic, and torque characteristics at various current density conditions are also predicted and discussed in Section V. Finally the conclusions are drawn in Section VI.

### III. THE PROPOSED MACHINE DESIGN SPECIFICATION.

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. From Table I, the limits of the current densities are set to the maximum of 30A/mm^2 and 30A/mm^2 for armature winding and DC FEC, respectively. 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. The parameter specifications for the proposed 12Slot-10-Pole is depicted in Table I.

![Table](38x374 to 291x649)

**TABLE I. HEFSM PARAMETER SPECIFICATIONS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>HEFSM</th>
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<tbody>
<tr>
<td>D_1</td>
<td>Rotor radius (mm)</td>
<td>80.25</td>
</tr>
<tr>
<td>D_2</td>
<td>Rotor pole height (mm)</td>
<td>20.2</td>
</tr>
<tr>
<td>D_3</td>
<td>Rotor pole width (mm)</td>
<td>9.5</td>
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Basically, the proposed machine design parameter is divided by two main parts which are stator and rotor. Stator consists of FEC slot, armature slot, and permanent magnet (PM) while the rotor parameters involved are the rotor radius ($D_1$), rotor pole height ($D_3$), and rotor pole width ($D_4$). The PM height is represent by ($D_4$), while the FEC parameters are FEC coil width and FEC coil height, ($D_5$) and ($D_6$) respectively. Finally, armature coil parameters are armature coil width ($D_7$) and armature coil height ($D_8$).

From the analysis, it is found that four armature coil slots produce one phase of flux linkage, while the remaining eight armature coil slots also produce another two flux linkages with different phases. The three-phase flux linkage in which the flux source is produced by PM only is illustrated in Fig.4.

From the graph, the flux characteristics can be considered as sinusoidal with maximum flux of approximately 0.0083 Wb. 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. For Test UVW Coil the connection of the circuit and linked of the coil must be correct.

Zero rotor position has been set to get the highest flux consequently the highest torque can be achieved. In order to check whether U flux of armature coil to be at zero position, cos waveforms of U flux must be 0 at 90° and 270°. While at 180°, the cos waveform must be at maximum value. It can be negative or positive value depends on the shape of the waveform. Fig. 5 shows U flux in zero rotor condition.

B. PM Cogging Torque

Figure 6 illustrates the PM cogging torque for one electric cycle of 36° rotor position of design. The cogging torque of the initial design of HEFSSM for one electric cycle obtained from initial is 8.4Nm investigated in open circuit condition at 1200 r/min. This is due to the effect of high PM flux linkage flow to the rotor.

C. Flux Analysis of PM and DC FEC at Various Current Density Condition

The flux linkage of PM with various DC FEC current density conditions graph is illustrated in Fig.7. This graph use to compare between flux and rotor position. From the graph, similar flux shape is obtained with increasing DC FEC current density. The maximum flux linkage obtained in this condition is 0.0475Wb. At maximum DC FEC current density of 30A/mm² the flux linkage increase more than four times when compared with flux linkage of PM only. This condition proves that the additional DC FEC can improve the total flux, thus giving variable flux control capability.

V. SHORT CIRCUIT TEST ANALYSIS

A. Instantaneous Torque Characteristic at Maximum Current Density Condition

Fig.8 illustrates the instantaneous torque waveform of the proposed HEFSM based on 2D-FEA at maximum current density condition of 30A/mm² and 30A/mm² for DC FEC and armature coil, respectively. The average torque obtained is 199Nm with the peak-to-peak torque of approximately 40Nm, Since peak-to-peak value of 40Nm is greater than 10 % of average torque, it is expected that the condition of high cogging torque will results in high vibration and noise in practical applications. Therefore design improvement should be conducted to reduce the infirmity.
B. Torque Characteristics at Various Current Density Conditions

The torque versus DC FEC current density characteristics of the proposed motor is plotted in Fig. 9, where both armature coil and DC FEC current densities are varied from 0 to 30A/mm. According to the conventional theory on d-q coordinate, the torque can be defined as the following formulas under the assumptions that d-axis current is controlled to be zero and voltage drop due to the armature resistance is negligible compared to the induced voltage.

\[ T = P_n \cdot (\Phi_m + \Phi_e) \]  \hspace{1cm} (3)

Where \( P_n \) is the number of pole-pairs, \( \Phi_m \) is the PM flux linkage and \( \Phi_e \) is the flux linkage produced by mmf of DC FEC. From the equation it is clearly show that the torque generated is proportional to the PM and DC FEC flux. Thus increasing both fluxes will increase the torque.

The plots clearly show that the maximum torque of 199Nm is obtained when armature coil and DC FEC current densities are set to the maximum of 30A/mm\(^2\) and 30A/mm\(^2\), respectively.

CONCLUSIONS

In this paper, design study and performance analysis of 12-slot 10-pole 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. From the results obtained, it is expected that the motor will successfully achieved the target performances by further design refinement and optimization.

REFERENCES


