Abstract—This paper presents a new structure of 6Slot-14Pole E-core hybrid excitation flux switching machine (HEFSM) with single piece rugged rotor structure for Hybrid Electric vehicles (HEVs) drives. The new design of E-core HEFSM is easy to manufacture due to simple design of structure. It has the potential to be extremely low cost due to less Permanent magnet (PM) usage. In addition, all flux sources including PM, DC field excitation coil (FEC) and armature coil are located on the E-shape stator body with the advantages of concentrated armature and FEC windings, less coil end length, variable flux capabilities of FEC, less PM volume, and simpler structure which paves better way for design optimization. The design of the motor and its simulation using Commercial 2D-FEA package, J MAG-Designer ver. 13.0 released by JSOL Corporation is presented. Initially, coil arrangement test is analyzed to all armature coil slots to confirm the polarity of the phase and to validate the operating principle of the motor. Then, flux interaction analysis is performed to investigate the flux capabilities at various current densities. Torque and power performances are investigated at various armature and FEC current densities for HEV applications.

Index Terms—Field Excitation Flux Switching Motor, Hybrid Electric Vehicle and Field Excitation Coil (DC FEC)

I. INTRODUCTION

A demand for vehicles using electrical propulsion systems has recently become more and more in terms of preventing global warming and saving fossil fuel. As one of them with better compatibility with existing ICE vehicles, many automotive companies have been commercializing HEVs in which interior permanent magnet synchronous motors (IPMSMs) using rare-earth permanent magnets (PMs) have been employed as their main traction motor. This has been due to its smaller size and lighter weight providing with design freedom of the vehicles and its higher efficiency contributing to less fuel consumption [1]–[3]. As an example, the historical progress in power density of IPMSM installed on Toyota HEVs has showed that the power density of each motor employed in Lexus RX400h '05 and GS450h '06 has been improved approximately five times and more, respectively, compared to that installed on Prius '97 [4]. One of the driving forces behind this successful improvement has been an adoption of a combination of reduction gear and IPMSM operated with high-speed more than 12 000 r/min. As one of the effective strategies for increasing the motor power density, the technological tendency to employ the combination of a high-speed machine and a reduction gear would be promoted.

For this trend, however, IPMSM design tends to be difficult. All permanent magnets of IPMSM are embedded in the rotor core and hence, to ensure the mechanical strength of rotor core relies on increases in ribs thickness and/or number of bridges around PMs. Although the increase in number of bridges would improve the mechanical strength, it would also reduce the maximum torque of the machine due to an increase in flux leakage [5]. Therefore, a new alternative machine, which has rugged rotor structure suitable for high-speed operation while keeping high torque and power density, would play an important role for future researches and developments.

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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 categorized into four categories such as (i) both PM and FEC at rotor side (ii) PM in the rotor while FEC in the stator (iii) PM in the rotor while the FEC is in the machine end (iv) PM and FEC in the stator. All HEMs mentioned in the first three is categorized as “hybrid rotor – PM with FEC machines” because they consist of PM on the rotor, while the fourth HEM is known as “Hybrid Excitation Flux Switching Machine (HEFSM)” based on its operating
principles. With all active parts situated on the stator, HEFSM has advantages of robust rotor structure and more proper for high speed drive application [12-13]. Varieties of combinations of stator and rotor pole for HEFSM have been developed and can be seen as illustrated in Figure 1.

The foregoing HEFSM having magnets on the stator also suffers from one of three disadvantages (i) The dc excitation fields are in series with the field excited by magnets, which limits the flux-adjusting capability due to low permeability of magnets (ii) The flux path of dc excitation significantly reduces the main flux excited by magnets and even short circuits the magnet flux (iii) Torque density may be significantly less. Therefore, as one of the candidates that can overcome the problems, a new structure of field excitation flux switching motor (HEFSM), with rare-earth PM, field excitation coil (FEC) and armature coil are located on the stator has been proposed. In this paper, performances analysis of E-core 6S-14P based on flux linkage, cogging torque and torque ripple, back electromagnetic force (back-emf), output torque and power are analyzed based on 2-D finite element analysis (FEA).

II. Operating Principle of HEFSM

The first concept of flux switching motor (FSM) has been founded and published in the middle of 1950s. Generally, the FSM can be categorized into three groups that are permanent magnet flux switching motor (PMFSM), field excitation flux switching motor (FEFSM) and hybrid excitation flux switching motor (HEFSM). Both PMFSM and FEFSM has only PM and field excitation coil (FEC), respectively as their main flux sources, while HEFSM combines both PM and FEC as their main flux sources. The operation of the motor is based on the principle of switching flux. The term “flux switching” is coined to describe machines in which the stator tooth flux switches polarity following the motion of a salient pole rotor [14-16]. The advantage of this machine is robust rotor structure that suitable for high speed applications. In addition, the FEC can be used to control the generated flux with variable capabilities. In this proposed motor, the motor rotation through $1/N_r$ of a revolution, the flux linkage of armature has one periodic cycle and thus, the frequency of back-emf induced in the armature coil is $N_r$ times of the mechanical rotational frequency. In general, the mechanical rotation frequency, $f_m$ and the electrical frequency, $f_e$ for the proposed machine can be expressed as in Eq. 1,

$$f_e = N_r f_m$$  \hspace{3cm} (1)

where $f_e$, $N_r$ and $f_m$ is the the electrical frequency, number of rotor poles and mechanical rotation frequency, respectively.

The operating principle of the HEFSM is illustrated in Fig. 2. Fig. 2 (a) and (b) show the direction of the PM and FEC fluxes flow from stator to the rotor while (c) and (d) illustrate the direction of PM and FEC fluxes flow from stator to the rotor which produces a complete one cycle flux. Each reversal of armature current shown by the transition between (a) and (b) causes the stator flux to switch between the alternate stator teeth [16].

Fig. 1: Combination stator and pole of HEFSM
III. PRELIMINARY DESIGN OF THE PROPOSED E-CORE HEFSM: GEOMETRY & SPECIFICATION

Design study and flux interaction between FE coil and armature coil of the 6Slot-14Pole E-Core HEFSM are investigated. The design requirements, parameters and specifications for the proposed E-core HEFSM are depicted in Table I while the initial machine configuration is illustrated in Fig. 3, respectively. According to the structure in Fig. 3(a), the E-Core HEFSM consists of 14 rotor poles number, 6 E-core stator teeth. The FE coil and slot of armature coil is placed around the stator. The DC FE coil1 is wound in counter-clockwise direction however the DC FE coil2 is wound in clockwise as demonstrated in Fig 3(b). The 6 slot of armature coils are placed in between them and it is looped in one direction. There are non-overlapping between FE coil and armature windings. Neomax 35AH are used as PM material for this machine which is having the coercive force at 20°C and residual flux density is 932kA/m and 1.2T, respectively while for the stator and rotor structure, electrical steel 35H210 is used. The weight of the PM is limit to 1.0kg in this design. The electrical restrictions related with the inverter such as maximum 650VDC bus voltage and maximum 360V inverter current are set. The relationship between the number of rotor pole and stator slot for the three phase structure that used to find the attainable numbers of slot and pole can be express as

\[ n_r = n_s \left( 1 \pm \frac{k}{2q} \right) \]  \hspace{1cm} (2)

where \( f_e \) is the electrical frequency, \( f_m \) is the mechanical rotation frequency and \( n_r \) is the number of rotor poles correspondingly.

Assuming water jacket system is employed as the cooling system for the machine, the limit of the current density is set to the maximum 30Arms/mm² for armature winding and 30A/mm² for FEC, respectively. The outer diameter, the motor stack length, the shaft radius and the air gap of the main part of the machine design being 264mm, 70mm, 30mm and 0.8mm respectively, are identical with those of IPMSM. The number of turns of armature coil and FEC are defining from Eq. 2 and Eq. 3, respectively while the filling factor of the motor, \( \alpha \) is set at 0.5.

\[ N_a = \frac{J_a \alpha S_a}{I_a} \]  \hspace{1cm} (3)

\[ N_e = \frac{J_e \alpha S_e}{I_e} \]  \hspace{1cm} (4)

where \( N, J, \alpha, S \) and \( I \) are number of turns, current density, filling factor, slot area and input current, respectively. For the subscript \( a \) and \( e \) represent armature coil and FEC, respectively.

Commercial FEA package, JMAG-Designer ver. 13.0, released by Japan Research Institute (JRI) is used as 2D-FEA solver for this design. Firstly, the rotor, stator, armature coil, FEC and PM of the proposed 6Slot-14Pole E-Core HEFSM is drawn by using Geometry Editor. The area of armature coil, \( S_a \) and the area of field excitation coil, \( S_e \) are used to calculate the optimum natural number of turns of armature coil \( N_a \) and FEC \( N_e \). The armature current density, \( J_a \) and maximum...
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current density of FEC, \( J_e \) are set to 30\( \text{A/mm}^2 \) and 30\( \text{A/mm}^2 \) respectively. In this study the number of turns of armature coil and FEC is set to 21 and 147 turns correspondingly. Then, the materials, conditions, circuits and properties of the machine are set in JMAG Designer. Furthermore, coil arrangement tests are examined to validate the operating principle of the machine and to set the position of each armature coil phase. The flux linkage is conducted to validate the magnetic flux generated by PM and FEC. Finally, the flux interaction between DC FEC, armature coil and PM, FEC flux capabilities at various current condition, and initial torque are also investigated.

Basically, the design parameters are divided into two categories such as those related to stator core and rotor core. On the stator core, it is subdivide into three groups which are the FEC slot shape, armature slot shape, and PM. The rotor parameters involved are the outer rotor radius (D1), rotor pole depth (D2), angle of rotor pole width (D3). The PM slot shape parameters are the PM width (D4), and the permanent magnet height (D5), while for the armature coil slot parameters are armature coil height and width, (D6) and (D7) respectively. Finally, the FE coil parameters are FE coil height (D8) and FE coil width (D9). The design free parameters, from D1 to D9 are illustrated in Fig. 4 while the initial design parameters of the proposed E-core HEFSM are depicted in Table II.

Fig. 4: Initial Design Parameter for E-Core HEFSM

IV. OPEN CIRCUIT TEST ANALYSIS
A. Armature Coil Arrangement Test of PM Flux

To determine the operating principle of E-Core HEFSM, the generated flux and the positions of each armature coil phase, no-load coil arrangement test are examined in all 6 armature coils separately. Initially, six pairs of armature coil and FEC are wound in counter-clockwise direction while PM polarities are set in alternate direction to create 6 north and 6 south poles. In this test, the FEC current density is set to 0 \( \text{A/mm}^2 \), while the PM is set to 1.0 kg. In other word, the PM is used as the main flux source of the machine. The flux linkage of each coil is observed and it is defined according to the conventional 3-phase system. The magnetic flux profile with the same phase is combined on the same graph by assuming U, V and W phase of coil test. It is noticeable that the maximum amplitude of generated magnetic flux from PM only is approximately 0.0341Wb with acceptable sinusoidal waveform. Fig. 5 illustrates the flux linkage defined as U, V, and W respectively of the PM only with zero rotor position. The U flux of PM is shifted 3 degree mechanical clockwise to get U flux intercept with 90\( ^\circ \) and 270\( ^\circ \) electrical. The investigation on zero rotor position is realized to confirm the initial position of the rotor for a maximum generated magnetic flux. Otherwise, the rotor position needs to be adjusted until zero magnetic flux is exactly on that position. Fig. 6 demonstrates the flux linkage at various conditions of PM, FEC and PM with FEC of the design 6Slot-14Pole E-Core HEFSM and it successfully proof the principles to get 3-phase flux linkage of this machine.
The cross-sectional view of flux paths caused by both PM and mmf of FEC at open circuit condition of the initial E-core HEFSM design are investigated based on 2D-FEA as depicted in Fig. 7. The presence of excitation coil makes these types of machines more attractive in terms of modulating the PM flux. Fig. 7(a) represent the generated flux path due to mmf of PM alone, while, Fig. 7(b) shows the flux path due to mmf of both PM and FEC at the maximum $J_e$ of 30A/mm². It is clear that the combination of mmf from both PM and maximum FEC current produce a large amount of fluxes flow to the rotor side by field strengthening excitation, resulting in the maximum torque production with the aid of hybrid excitation.

Furthermore the back electromagnetic force (back-emf) and cogging torque of the initial 6Slot-14Pole E-core HEFSM are also investigated in no load condition as shown in Fig. 8 and Fig. 9, respectively at 1200r/min. From Fig. 8, the induced voltage with $J_e$ of 0A/mm² is the induced voltage generated due to the mmf of PM only. It is obvious that the peak-peak of the harmonic component is 76.81 V and the induced voltage waveform is slightly distorted. Hence, when the secondary flux source is applied with the current density

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Initial Design</th>
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<tr>
<td>$D_1$</td>
<td>Radius of outer rotor (mm)</td>
<td>85</td>
</tr>
<tr>
<td>$D_2$</td>
<td>Depth of rotor pole (mm)</td>
<td>25</td>
</tr>
<tr>
<td>$D_3$</td>
<td>Width of rotor pole (mm)</td>
<td>14.4</td>
</tr>
<tr>
<td>$D_4$</td>
<td>Width of PM (mm)</td>
<td>6.826</td>
</tr>
<tr>
<td>$D_5$</td>
<td>Height of PM (mm)</td>
<td>46.2</td>
</tr>
<tr>
<td>$D_6$</td>
<td>Width of armature coil slot (mm)</td>
<td>10.21</td>
</tr>
<tr>
<td>$D_7$</td>
<td>Depth of armature coil slot (mm)</td>
<td>33.46</td>
</tr>
<tr>
<td>$D_8$</td>
<td>Width of FE coil slot (mm)</td>
<td>11.24</td>
</tr>
<tr>
<td>$D_9$</td>
<td>Depth of FE coil slot (mm)</td>
<td>33.07</td>
</tr>
</tbody>
</table>
of 15 A/mm², the amplitude of the back-emf is increased drastically to 139.19 V. The main reason of this condition is due to the strengthening effect of the flux from secondary flux source. When \( J_e \) set to maximum of 30 A/mm², the amplitude of back-emf has reduced back to 85.59 V. Moreover, the peak-peak cogging torque obtained from the initial design 6Slot-14Pole E-core HEFSM is approximately 12.242 Nm.

C. FEC Flux Linkage at Various FEC Current Densities

The FEC flux linkage at various FEC current densities is also investigated to verify the flux characteristics. The FEC flux linkages for E-Core HEFSM at combination of PM with FEC are plotted in Fig. 10, while the maximum flux comparison is illustrated in Fig. 11, respectively. From the \( J_e \) characteristic, 6Slot-14Pole E-Core HEFSM have flux that increases to some values then decrease and constant in the end. This is because the material used for FEC, copper, has reached its limit to generate flux. Furthermore, inside the machines, there are some fluxes that flow in opposite direction and result in cancelling each other. Apart from that when the FEC current density is higher more heat will be generated in the copper hence create more loss.

D. Armature Flux Linkage at Various Armature Current Densities

To verify the flux characteristics, the armature coil flux linkage at various armature current densities is investigated.

The armature flux linkage at U phase is depicted in Fig. 12, while Fig. 13 illustrated the maximum U phase flux at various armature current densities for 6Slot-14Pole E-Core HEFSM. It is clear that armature coil flux linkage is increased with the increase of armature current density and maximum armature coil increase linearly with increasing armature current densities. In addition, increment of the armature flux linkage with increasing armature current makes the machine possible to be applied for high current density condition, without reducing the performances. This is a great advantage of the E-Core HEFSM with variable flux capabilities suitable for HEV applications.
V. SHORT CIRCUIT TEST ANALYSIS

The performance of 6Slot-14Pole E-Core HEFSM at the maximum armature coil current density (Ja) and field excitation coil current density (Je) of 30Arms/mm² and 30A/mm², respectively, are analyzed. From the analysis, the torque obtained is 155.2Nm with the machine running at the speed of 1200r/min. The instantaneous torque profile for this condition is depicted in Fig. 14.

A. Torque Vs Je at Various Ja

As the initial design torque performance is far from the target requirements, performance characteristics of the initial 6Slot-14Pole E-Core HEFSM are investigated. The drive performance of initial design in term of torque versus FES current density, Je at various condition of Ja is analyzed as shown in Fig. 15. From the plot, at Ja of 5A_rms/mm², 10 A_rms/mm² and 15A_rms/mm² it is obvious that, initially the torque is increased with increasing Je up to certain Je value and starts to reduce when higher Je is injected to the system. Based on observation of magnetic flux density distribution, it is found that, flux at higher Je cancels the armature flux thus reducing the torque generation. On the other hand, at Ja of 20A_rms/mm², 25A_rms/mm² and 30A_rms/mm² it is obvious that, similar torque characteristics are obtained in all conditions. Thus Ja higher than 20A_rms/mm² will not increase the torque performance, hence design improvement should be conducted to overcome the problem.

B. Torque and Power versus Speed Characteristics

The torque and power versus speed characteristics of the initial design E-Core HEFSM is illustrated in Fig. 16. At base speed of 2263r/min, the maximum torque obtained is 177Nm with corresponding power of 41.95kW. It can be seen that the torque ripple is slightly high with approximately 50.0Nm, or 28.3% with respect to the maximum torque. Since the target torque and power are far from the target performances of HEV, design optimization based on deterministic optimization method will be conducted in future.

VI. CONCLUSION

In this paper, design study and performances of 6Slot-14Pole E-Core HEFSM with PM, FEC and armature windings located on the stator have been analyzed for HEV applications. The coil arrangement test and zero rotor position of the proposed design have been examined to validate each armature coil phase, to locate the initial rotor position and to proof the operating principle of the machine. The performances of the E-Core HEFSM such as flux capability, torque and power versus speed curves have been investigated. From the initial design results, the proposed machine has viability to be further improved that can be applied for HEV applications. The design also has very simple configuration compared with other design of HEFSM which expose better way of design optimization and less permanent magnet used thus can be expected as low cost machine.

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