Performance Comparison between Two Different Designs of 12S-10P HEFSM for High-speed HEV's

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Abstract-**This paper present an investigation into two designs of 12Slot-10Pole Hybrid Excitation Flux Switching Machine (HEFSM) which consists of permanent magnet (PM) and field excitation coil (FEC) as their main flux sources. The advantages of this machine are easy cooling of all active parts is housed in the stator and robust rotor structure that makes it better and suitable for high speed applications. The design construction and the basic operation principle of HEFSM are overviewed. Initially, coil arrangement test is analyzed to all armature coil slots to confirm the polarity of the phase. Furthermore, flux interaction, back-emf, cogging torque and average torque are observed based on 2D finite element analysis (2D-FEA).**

***Index Terms*—permanent magnet, filed excitation coil, Hybrid Excitation Flux Switching Machine (HEFSM), high speed applications.**

I. 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[1-3]. The second group consists of PM in the rotor while DC FEC in the stator [4], while 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 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], 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 [11-14].

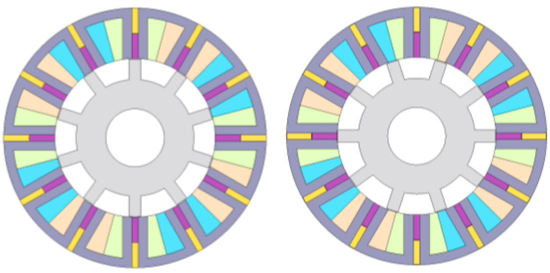
This paper compares analysis of two different designs which are 12S-10P with bridge and 12S-10P with radial direction HEFSM having toothed-rotor structure and non-overlap armature and field windings. Design feasibility, working principle and performance analysis of different slot and rotor pole number are compared on the basis of coil arrangement test, peak armature flux linkage, back emf, cogging torque and average torque. FEA simulations, conducted via JMAG-Designer ver. 13.0 released by Japan Research Institute (JRI) are used to study various characteristics of design.

II. DESIGN METHODOLOGY OF THE PPROPOSED HEFSM

In this paper, design study and performance of 12S-10P with bridge and 12S-10P with radial direction are studied. The configurations and dimensions for both designs are described in Fig.1, Fig.2 and Table I, respectively. For high speed applications, different arrangements of rotor pole and stator slot for HEFSM motor have been developed. For Fig.1 (a), 12S-10P motor has been proposed such as in [15-16] whereas the machine in [16] has insufficient power and torque production at high current density condition. This is because of inadequate width of stator yoke between armature coil slots and FEC that creates problem of negative torque production and magnetic saturation. However, the machine in [17] having separated C-type stator core and PM makes it complex to manufacture, and the optimization techniques is not so far applied to the design for HEV applications. To overcome, the topologies of hybrid-excited flux-switching machines incorporating iron flux bridges to enhance the effectiveness of the field coil excitation [18].

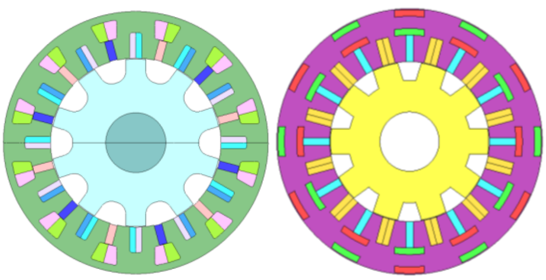
The cross-sectional view of the main machine part of the initial 12S-10P with bridge HEFSM motor is illustrated in Fig.1 (b). In Fig.1 (b), initial design of three phase 12S-10P HEFSM with two iron bridges is proposed which consist of 10 salient rotor pole numbers while the stator core consists of 12 modular C-Type laminated segments placed next to each other with circumferentially magnetized PMs and FE coils placed in between them. Moreover, the proposed machine was added with the 1 mm outer iron flux bridges. In addition, this design has build up of 12 DC FEC coil slots and 12 armature coil (AC) slots. Both of FEC and AC are wound in counter-clockwise (CCW).

Hybrid excitation machine (HEMs) consists of permanent magnet (PM) and field excitation coil (FEC) as their main flux sources. It has several attractive features compared to interior permanent magnet synchronous machines (IPMSM) which conventionally employed in hybrid electric vehicles (HEVs). The comparison between the previous design of 12S-10P HEFSM and a new design of proposed HEFSM are illustrated in Fig. 2(a) and Fig.2 (b), respectively. Among various types of HEM, the machine with theta direction have problem of flux cancellation. To eliminate flux cancellation effect in HEM, a new HEFSM having 12S-10P arrangement has been proposed. Other than that, a design is added 1mm layer on the upper FEC which is to reduce the flux saturation and generate more flux in stator. It has also characteristics of improving the torque as compare to the machine having theta direction. Both permanent magnet and excitation coil located in stator has the advantage of robust rotor structure similar with switch reluctance machine (SRM) which is suitable to be applied for high speed motor drive systems. In this research, a new structure of 12S-10P HEFSM in which arrangement of FEC in radial direction with 1mm layer in stator is proposed for HEV applications.



(a) (b)

Fig.1. Initial design of 12S-10P HEFSM
(a) without bridge (b) with bridge



(a) (b)

Fig.2 Initial design of 12S-10P HEFSM
(a) theta direction (b) radial direction

Furthermore, the component part that involved for both designs likes PMs, FEC and AC are rectangle in shape thus can make the proposed motor has a very simple structure. It is clearly shown that both FEC and AC are wounded separately at their own slots. The PM used in this design is NEOMAX-35AH with residual flux density and coercive force at 20° are 1.2T and 932kA/m, respectively, whilst electromagnetic steel 35H210 is used for the rotor and stator body. 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.

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 J_a is armature coil current density, set to maximum of $30A_{rms}/mm^2$, N_a is number of turn of armature coil, α_a is armature coil filling factor (set to 0.5) and S_a is the armature coil slot area. Similarly for the number of turn of FEC coil, N_e is determined by using (2) where the maximum current density of FEC, J_e is set to 30 A/mm^2.

$$N_A = \frac{J_A \alpha_A S_A}{A_{rms}} \tag{1}$$

$$N_E = \frac{J_E \alpha_E S_E}{A_F} \tag{2}$$

III. PERFORMANCE ANALYSIS OF INITIAL DESIGNS BASED ON 2D FEA

A. Coil arrangement test

Coil arrangement tests are conducted in order to examine the generated flux of each armature coil. It is important to ensure that the proposed machine is valid for the position of each armature coils phase during no load analysis and has the good magnetic flux characteristic. Besides, the rotor must properly align on zero rotor position. To make sure that condition, the U flux must be 0 at the intercept of 90° and 270° or U flux will be at the maximum at 180°. In addition, the sequence of each phase or armature coil supply must be set correctly in order to give a sinusoidal profile of generated magnetic flux.

Since the generated flux from PM is always constant, PM flux linkage is firstly investigated under zero FEC current to be in the same phase or called as PM only. The result for flux linkages at each coil are compared according to the conventional 120° phased shifted between all phases or called as U, V, and W flux as shown in Fig.3. From Fig.3, it is clearly show that 12S-10P with bridge produced more flux

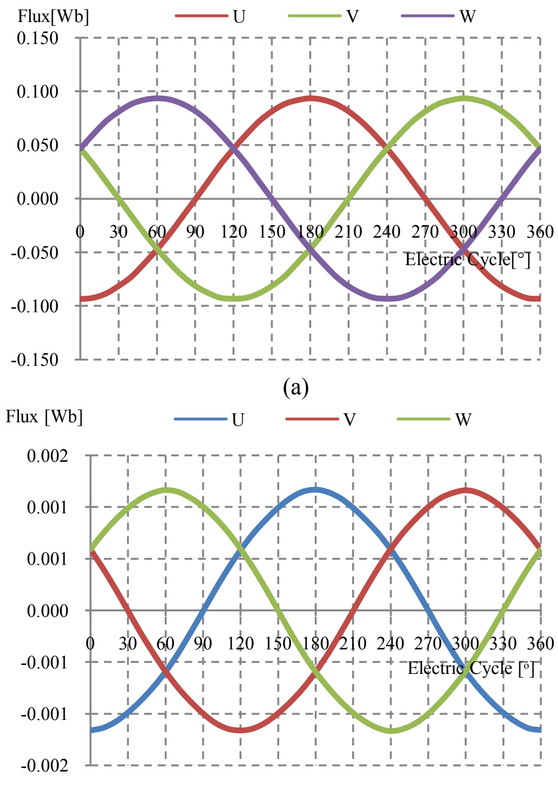


Fig.3 UVW for 12S-10P HEFSM
(a) with bridge (b) with layer

linkage compared with the 12S-10P with radial direction. Because of that, 12S-10P with bridge has possibility to produce higher torque and power.

B. Back Emf

The induced voltage or also called as back-emf is generated at the speed of 1200r/min. The predicted result obtained for the different current density is illustrated in Fig.4. This condition is investigated under PM with maximum FEC that means J_e of 30A/mm^2. Based on the Fig.4, the amplitude of 12S-10P with bridge and 12S-10P with radial direction are approximately 279.82V and 66.20V, respectively. From the result, it is obvious show that the amplitude of 12S-10P with radial direction is lower and slightly sinusoidal.

C. Cogging Torque

The cogging torque profile for both machines HEFSM under the condition of PM with maximum FEC is demonstrated in Fig.5. Obviously, 6 cycles of cogging torque are generated in electric cycle. 12S-10P with bridge has highest peak-peak cogging torque compared with 12S-10P with radial direction that approximately 28.03Nm and 9.31Nm, respectively. Since the cogging torque values produced must not exceed 10% of the average torque, the generated cogging torque of the proposed HEFSM is unnecessary for the performance of the machine due to production of high vibration and noise. Thus, further design refinement and optimization should be conducted to get the target torque and reduce cogging torque.

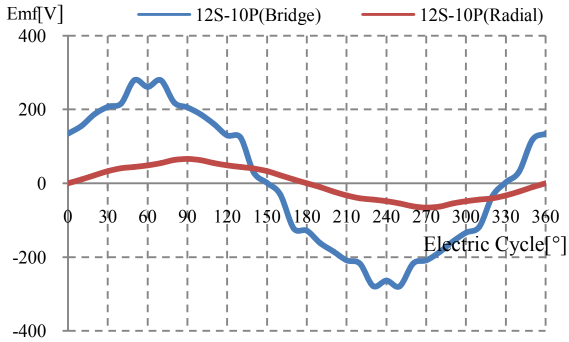


Fig.4. Back-emf at rated speed 1200r/min

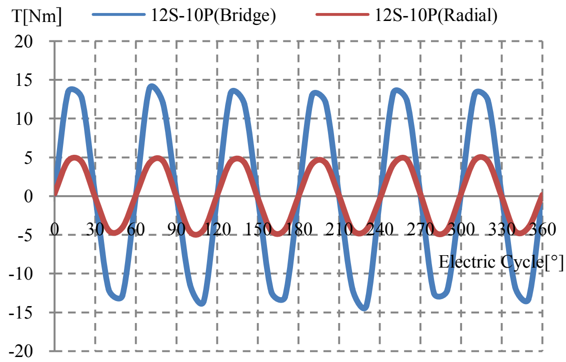


Fig.5 Cogging torque

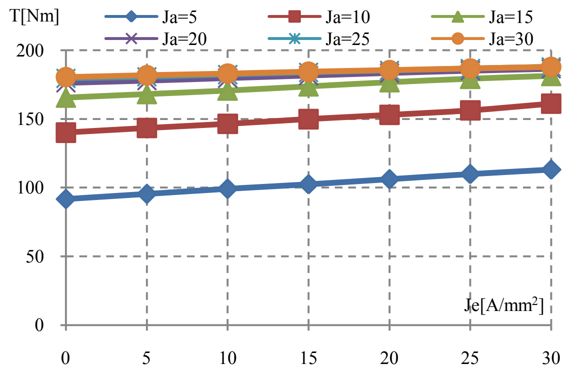


Fig.6 Torque vs J_a at various J_e for 12S-10P with bridge

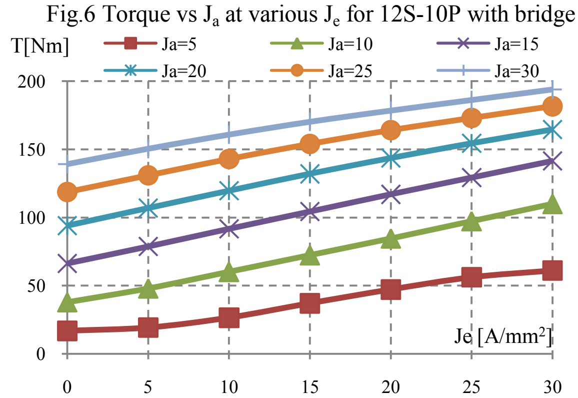


Fig.7 Torque vs J_a at various J_e for 12S-10P with radial direction

D. Torque vs. armature current density, J_a at various field excitation current density, J_e

Torque versus J_a at various J_e characteristic is obtained in short circuit analysis. Fig.6 and Fig.7 explains the drive performances of the initial design machine in terms of torque versus FEC current density characteristics for both designs, correspondingly. Fig.6 shows that with increasing in J_e, the torque also increased linearly with the same pattern at 0 A_{rms}/mm^2 until 20 A_{rms}/mm^2. Meanwhile, the similar torque pattern is attained at 25 A_{rms}/mm^2 and 30 A_{rms}/mm^2. The maximum torque is approximately to 187.96Nm when J_a of 30A_{rms}/mm^2 and J_e of 30 A/mm^2. This is due to low armature coil flux that limits the force to move the rotor.

Furthermore, Fig.7 plots the torque versus J_a at various J_e for 12S-10P with radial direction. From the graph, it can see that the torque is increased with the increasing of J_e. The torque increased linearly with the same pattern at 0 A_{rms}/mm^2 until 30 A_{rms}/mm^2. The maximum torque is gained at 30 A_{rms}/mm^2 and 30 A/mm^2 that approximately 193.89Nm.

IV. CONCLUSION

In this paper, 12S-10P HEFSM for traction drive in the target HEV with PM, FEC and armature windings located in the stator are proposed based on the flux switching topology. The novelty of the proposed design is the arrangements of FEC in radial direction in contrast with traditional HEFSM with the FEC arrangements in theta direction. The other design is the cross-sectional view of the main machine part of the initial 12S-10P with bridge HEFSM motor. Initially, the coil arrangement and zero rotor position tests have been carried out to recognize shape and phase of armature coil and identify initial position of the rotor. Then, the comparison peak armature flux linkage, back emf, cogging torque and torque characteristics of both machines are analyzed.

ACKNOWLEDGMENT

This work was supported by Centre of Graduate Studies Universiti Tun Hussein Malaysia (UTHM), Batu Pahat, Johor.

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