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Design of Low Cost Single Phase 8S-8P Field Excitation Flux Switching Motor for Hybrid Electric Vehicles

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ABSTRACT

Hybrid electric vehicles (HEVs) by means the combinations of battery- operated electric machine with ICE are widely considered as promising green vehicle. Interior permanent magnet synchronous motor (IPMSM) is the only machine that has been successfully installed in HEVs to enhance the power density of the motor but the main problems are existing IPMSM have complicated structure that give difficulty to undertake optimization process and use high permanent magnet (PM) volume resulting in increases the cost of the motor because of the rare earth magnet prices. In order to overcome these problems, a new structure of field excitation flux switching motor (FEFSM) in which the uses of PM is totally excluded and has simple structure is presented in this paper. Initially, the coil arrangement tests are examined to validate the operating principle of the motor and to identify the zero rotor position. Furthermore, the profile of flux linkage, induced voltage, cogging torque, torque and power characteristics are observed based on 2D finite element analysis (FEA). The results obtained show that the initial torque and power obtained are 236.63Nm and 45.56kW, respectively which had achieved the target performances for HEV application. The machine weight designed is less than 35kg resulting in that the proposed FEFSM promises to attain the maximum power density more than existing IPMSM.

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INTRODUCTION

The ICE technology being matured over the past 100 years, nevertheless it will continue to improve with the aid of automotive electronic technology and it will mainly rely on alternative evolution towards improvement in the fuel economy and emission reductions significantly (Ehsani *et al.*, 2007) . Therefore, in order to obtain a wide-range full performance high fuel efficiency vehicle with less-emissions, the most feasible solution at present is hybrid electrical vehicle (HEV) a combination of battery-operated electric machine with ICE (Gao *et al*., 2007). Selection of traction motors for hybrid propulsion systems is a very important step that requires special attention. In fact, the automotive industry is still seeking for the most appropriate electric-propulsion system for HEVs and even for EVs. In this case, key features are efficiency, reliability and cost. The process of selecting the appropriate electric-propulsion systems should be carried out at the system level. Mainly, the choice of electric-propulsion systems for HEV depends on three factors: driver's expectation, vehicle design constraints, and energy source. With these considerations, it is understood that the specific motor operating points are difficult to define (Rahman *et al*., 2000).

Example of successfully developed electric machines for HEVs is Interior permanent magnet synchronous motor (IPMSM) which has been employed primarily to increase the power density of the machines (Rahman, 2007). In spite of their good performances and well operated, IPMSM installed in HEV, have some demerits such as the present IPMSM has a multifaceted shape and structure which are quite complicated to perform the design optimization. Secondly, the constant flux from PM is hard to control especially at light load high speed operating points. In the meantime, the volume of PM used in IPMSM is very high which increases the expenditure of the machine and it has high copper loss due to distributed armature windings. The cross section of IPMSM is depicted as in Figure 1.

Therefore, as one of the candidates that can overcome the problems, a new structure of field excitation flux switching motor (FEFSM), not consist of rare-earth PM and DC field excitation coil (FEC) is located on the stator has been proposed (Sulaiman *et al*., 2013). In this paper, performance analysis of 8S-8P FEFSM is

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presented to determine the optimal performances. Initially, the coil arrangement tests are examined to validate the operating principle of the motor and to identify the zero rotor position. Furthermore, the effect on the electromagnetic performance such as DC FEC flux linkage, cogging torque, induced voltage (back-emf), output torque and power are analyzed based on 2-D finite element analysis (FEA).

1. *Operating Principle of FEFSM:*

The first concept of flux switching motor (FSM) has been founded and published in the mid1950s. 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). The operation of the motor is based on the principle of switching flux (Rauch and Johnson, 1955). 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 (Hoang *et al*., 2007). 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 (1).

$$f_e = N_r f_m \tag{1}$$

The principle operation of FEFSM is demonstrated in Figure 2. Figure 2 (a) and (b) show the movement of the FEC flux into the rotor while (c) and (d) visualize the movement of FEC flux into the stator which creates one complete cycle movement of fluxes. The stator fluxes switches between the alternate stator teeth because of the each reversal of armature current shown by the transition involving Figure 2 (a) and (b) (Sulaiman *et al*., 2012).

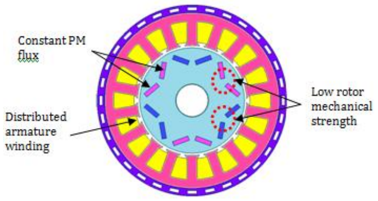

Fig. 1: Cross section of IPMSM.

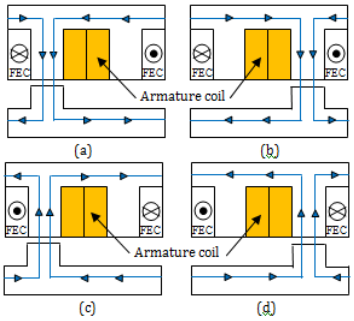

Fig. 2: Operating principle of FEFSM (a) θ*e*=0° and (b) θ*e*=180° fluxes move from stator to rotor (c) θ*e*=0° and (d) θ*e*=180° fluxes move from rotor to stator.

2. *Design Restrictions, Parameters and Specification of FEFSM:*

The motor restrictions and target specifications of the projected FEFSM for HEV applications are scheduled in Table 1 while the design parameters of proposed FEFSM are illustrated and listed from Figure 3 and Table 2, respectively. The inverter is set at the maximum of 375V DC bus voltage as well as inverter current at 360V. Assuming water jacket system is in use as the cooling system for the machine the limit of the current density is set to the maximum $30A_{rms}/mm^2$ for armature winding and $30A/mm^2$ for FEC, respectively. The motor stack length, the outer diameter, the air gap and the shaft radius of the major parts of the machine design being 70mm, 264mm, 0.8mm and 30mm, respectively, similar with existing IPMSM. The electrical steel 35H210 is used for stator and rotor body.

Primarily, the selection of the proposed FEFSM is designed with the following assumptions; (i) The inner radius is set to 30 mm for the motor's shaft while rotor radius is 97.2 mm which is 73% of 132 mm motor radius and within the range of general machine split ratio, (ii) The stator outer core thickness is set to be half of the stator inner length with the assumptions that the fluxes are divided into two parts, (iii) The depth of the rotor pole is set to be 1/3 of rotor radius to give much depth for the flux to flow, (iv) The FEC and armature coil slot opening angle are set to 5.625°, which is half of the stator slot opening angle of 11.25°, (v) The total coil slot area of both FEC and armature coil is less than the stator teeth area. Therefore, it is expected that all fluxes from both coils to have sufficient space to flow in the stator yoke, without magnetic saturation.

Table 1: Restrictions and Target Specifications of 8S-8P FEFSM.

Items	Unit	8S-8P FEFSSM
Max. DC-bus voltage inverter	V	375
Max. inverter current	A_{rms}	360
Max. current density in armature winding, J_a	A_{rms}/mm^2	30
Max. current density in excitation winding, J_e	A/mm^2	30
Stator outer diameter	mm	264
Motor stack length	mm	70
Shaft radius	mm	30
Air gap length	mm	0.8
PM weight	kg	0
Maximum torque	Nm	>70
Maximum power	kW	>41
Power density	kW/kg	>1.17

Table 2: Parameters of 8S-8P FEFSM.

Parameter	Description	Initial
D_1	Rotor outer radius (mm)	97.2
D_2	Rotor pole width (mm)	10.3
D_3	Rotor pole depth (mm)	33.2
D_4	FEC width (mm)	8.9
D_5	FEC depth (mm)	22.02
D_6	Armature coil depth (mm)	22.02
D_7	Armature coil width (mm)	8.9
Area of FEC (mm^2)		196
Area of armature coil (mm^2)		196
FEC coil number (turns)		60
Armature coil number (turns)		8

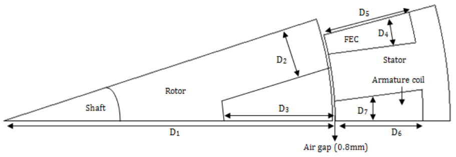

Fig. 3: Design parameters of 8S-8P FEFSM.

The numbers of turns of FEC and armature coil are defined from (2) and (3), respectively. The motor's filling factor is put at 0.5, whilst the slot area of armature slot and FEC slot is calculated, correspondingly. To ensure flux moves from stator to rotor equally without any flux leakage, the design of the proposed machine is defined as in (4). The rotor is consisted of only stacked soft iron sheets and can be expected to rotate at high-speed because the rotor structure is mechanically robust. Furthermore, the maximum expected torque of 70Nm and power is set to be higher than 41kW, respectively. The commercial finite elemet analysis (FEA) package, JMAG-Designer ver.13.1, released by Japan Research Institute (JRI) is used as 2D FEA solver in this design.

$$N_a = \frac{J_a \alpha S_a}{I_a} \tag{2}$$

$$N_e = \frac{J_e \alpha S_e}{I_e} \tag{3}$$

$$S_W = R_W \tag{4}$$

Where *N, J, α, 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. The FEC directions for 8S-8P FEFSM is in alternate direction, counter-clockwise polarity and clockwise polarity. Figure 4 shows the windings configuration of 8S-8P FEFSM.

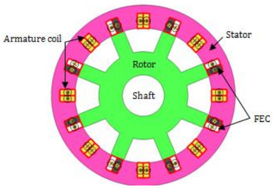

Fig. 4: Configuration 8S-8P FEFSM.

Open Circuit and Short Circuit Analysis Based on 2D FEA:

Performance investigation at open circuit condition such as coil test, DC FEC flux linkage, cogging torque, induced voltage and at short circuit condition for instance torque and power characteristics have been analyzed in order to obtain the optimal performance. Coil arrangements test are examined in each armature coil slots singly in order to verify the principle operation of the FEFSM and to set the arrangement of each armature coil phase, where all armature coils are wounded in counter-clockwise direction while FEC are wounded in clockwise and counter-clockwise direction. The flux linkages at each coil are observed and the armature coil phases are defined according to the conservative single-phase as demonstrated in Figure 5. The armature coil flux can start the rotor at the maximum as the U flux satisfies the zero rotor position indicated by red dotted line.

Figure 6 demonstrates DC FEC flux linkage for the proposed motor at various DC FEC current densities, J_E. It is visibly shows that the flux linkage increases as higher JE is injected but at J_E equal to 25A/mm2 the flux start to constant and slightly decrease at the end. This is because the material used for FEC, copper, has reached its limit to produce 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.

The fundamental of induced voltage generated is presented in Figure 7 as it is use for regenerative breaking and the value produce must not exceed the supply voltage because it will disturb the performance of the motor. The torque ripple feature for 8S-8P FEFSM is shown in Figure 8. From the graph, is evidence that the peak to peak torque ripple is 530.0Nm. This is due to the effect of high FEC flux linkage flow to the rotor. High torque ripple will give high noise and high vibration that is unnecessary for the performance of the motor. Therefore in the future, by further design refinement and optimization, it is expected can be reduced into an acceptable condition.

At last, by situate the armature coil current density, J_A at maximum conditions, the torque profile and power at a various FEC current densities, J_E is validated in Figure 9 and Figure 10, correspondingly. From the figure, it is revealed that the torque and power obtained are 236.63Nm and 45.56kW, respectively.

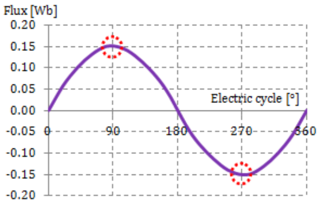

Fig. 5: Conventional Single Phase flux.

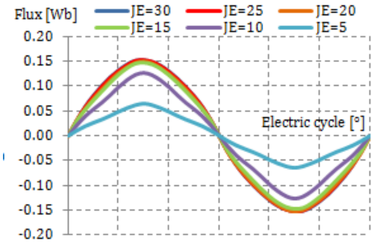

Fig. 6: DC FEC flux linkage.

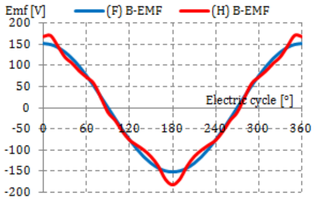

Fig. 7: Induced voltage.

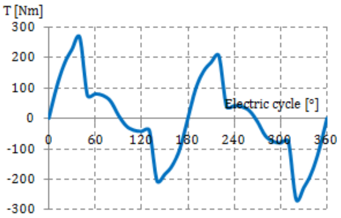

Fig. 8: Cogging torque.

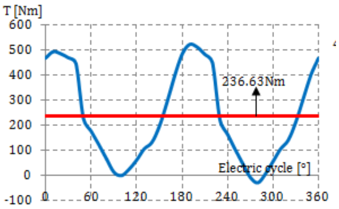

Fig. 9: Instantaneous torque characteristic.

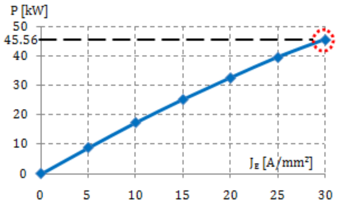

Fig. 10: Power vs J_E at maximum J_A.

3. *Conclusion:*

As a conclusion, performance predictions of 8S-8P FEFSM for traction drive in HEV applications have been presented. The profile of flux linkage, induced voltage, cogging torque, torque characteristics and power are observed based on 2D finite element analysis (FEA). There is no usage of permanent magnet and thus, it can be expected as very low cost machine. The shape of the proposed motor is very simple which expose better way of design optimization. It can be expected that the rotor structure is mechanically robust to rotate at high speed because it consists of only stacked soft iron sheets. The target maximum torque of 70Nm and power is set to be more than 41kW and the motor weight to be designed is less than 35kg, resulting in that the proposed FEFSM promises to attain the maximum power density better when compared to that estimated IPMSM were achieved as listed in Table 3. Finally, the proposed FEFSM is suitable for various applications with various performances.

Table 3: Overall Performance of 8S-8P FEFSM.

Items	Target	Initial	% from target
Torque (Nm)	>70	236.63	70.41%
Power (Kw)	>41	45.56	10.01%
Machine weight (kg)	<35	25	18.83%
Power density (Kw/kg)	>1.17	1.82	35.71%
Torque density (Nm/Kg)	>3.17	9.46	66.49%

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