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DETERMINISTIC OPTIMIZATION OF SINGLE PHASE 8S-4P FIELD EXCITATION FLUX SWITCHING MOTOR FOR HYBRID ELECTRIC VEHICLE

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ABSTRACT

Recently, the reduction or avoidance of permanent magnet (PM) usage in an electric motor has become significant research area due to high price of rare-earth materials. Under definite specifications and limitations of conventional interior permanent magnet synchronous (IPMS) motor in existing hybrid electric vehicle (HEV), the early performances of the recommended field excitation flux switching (FEFS) motor with no PM are evaluated based on 2-D Finite Element Analysis (FEA). Since the initial performances fail to acquire the target torque and power, design optimization based on deterministic approach of FEFS motor parameters is presented in this paper to attain the target performances. After a few cycles of design optimization, the enhanced FEFS motor has achieved the target power and torque of 41kW and 70Nm, respectively. In conclusion, the final design FEFS motor has the maximum power density of 1.75kW/kg which is approximately 49% more than power density in existing IPMS motor.

Keywords: optimization, flux switching motor, hybrid electric vehicle.

INTRODUCTION

Many alternative energy resources have been used for hybrid vehicles to substitute the exhausted supply of petroleum worldwide. Fossil fuel in the vehicles is not used due to its destructive environmental effects. Battery, fuel cell (FC), super capacitors (SC) and photovoltaic cell i.e. solar are studied for vehicle use. These sources of renewable energies can be well-designed for hybrid electric vehicle (HEV) for next invention of transportation. Literature reviews have been explained many issues, disputes and problems sustainable next generation hybrid vehicle [Hannan, Azidin and Mohamed, 2014]. Additionally, some researchers have discussed modeling of backup energy systems (Diesel Generator, Ultra-capacitor, Battery, and Fuel Cell), hybrid energy resources (Photovoltaic systems), power conditioning components (Battery chargers, Buck/Boost converters) and other methods to manage the energy flow in detail [Bajpai and Dash, 2012].

In electrical machines, electric motors are used to transform one form of energy into another (electrical energy to mechanical energy). Electrical motor is categorized into two main classes that are alternating current (AC) motor and direct current (DC) motor and then advance classified as shown in Figure-1. In general, flux switching (FS) motor consists of permanent magnet (PM) FS motor, field excitation (FE) FS motor and hybrid excitation (HE) FS motor where both PMFS and HEFS motor uses PM as their flux source similar with IPMS motor, resulting in constant flux source and high cost because of the rare earth magnet [Husin, Sulaiman and Kosaka, 2014].

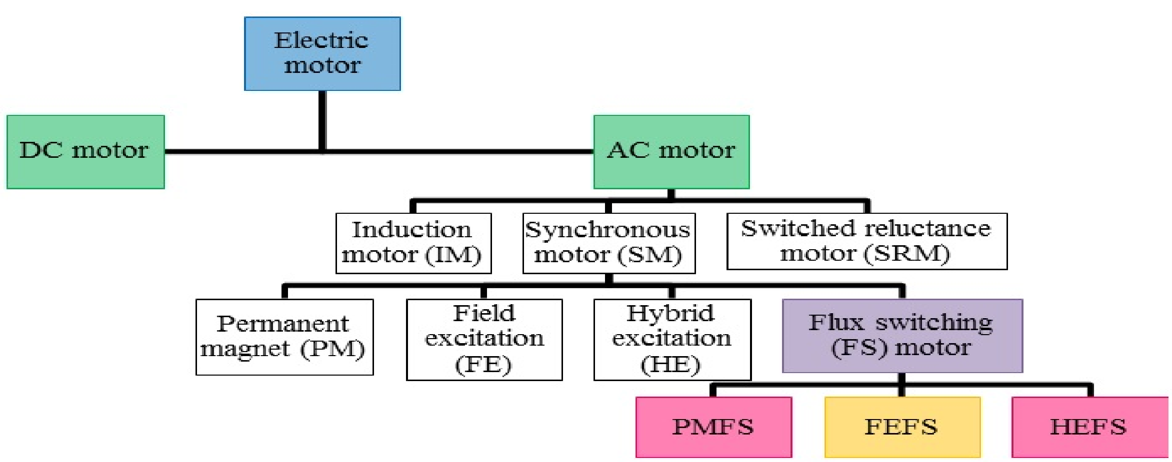

Figure-1. Main classification of electrical motors.

In FEFS motor, all active parts are placed on stator. Thereby, it has the advantages of (i) robust rotor structure which make it more appropriate to be used in high-speed drive applications, (ii) simple cooling mechanism can be used because all major heats are accumulated in stator part, compared with a complex water jacket system used in IPMS motor and (iii) the FE coil to control flux with variable flux capabilities. The proposed motor has a simple and easy structure and it is expected to provide much higher power density and torque [Sulaiman, Kosaka, and Matsui, 2014], [F. Khan *et al.*, 2014]. The term, "flux switching", is created based on the changes in polarity of each flux in each stator tooth, depending on the rotor position. Figure-2(a) is an example of single-phase four-stator-slot and two-rotor-pole (4S-2P) FEFS motor composed of a FE coil, a toothed rotor structure, and fully-pitched windings on the stator [Pollock and Wallace. 1999]. Two single phase FEFS motor topologies with DC field and armature windings having the same coil-pitch of 2 slot-pitches and having different coil-pitches of 1 and 3 slot-pitches respectively have been discussed [Zho and Zhu, 2013]. It shows that the iron loss of FEFS motor has been reduced and thus increasing the efficiency. Nonetheless, these topologies have problems of overlap windings, as illustrated in Figure-2(b). Single-phase 12S-6P FEFS motor for high density air-conditioner with segmental rotor has been designed and discussed [Omar, Sulaiman, and Soomro, 2015]. The proposed motor has less copper losses due to non-overlap armature and field windings as shown in Figure-2(c). Although 12S-6P has high average power but the rotor is not robust due to segments, hence cannot be used for high speed applications. To overcome the above mentioned obstacles and accomplish the target performances for HEV applications, design optimization studies are presented for novel 8S-4P FEFS motor in this paper.

OPTIMIZATION PROCEDURE

The structure of 8S-4P is redesigned to make a simple machine, in order that design free parameters of D_1 to D_7 can be identified as illustrated in Figure-3. The initial step is taken by changing the rotor parameters, D_1, D_2 and D_3 whilst keeping D_4 to D_7 as constant. As the torque increases by increasing rotor radius, D_1 is treated initially because it is the only leading parameter which can improve the torque. In this circumstance, D_3, D_5 and D_6 are simply transferred to the new position by following the movement of D_1, while D_2, D_4 and D_7 are kept constant. The value of D_1 for maximum performance is selected and then to determine the maximum performance from the combine effect of D_2 and D_3, both rotor pole depth D_3 and rotor pole width D_2 are varied.

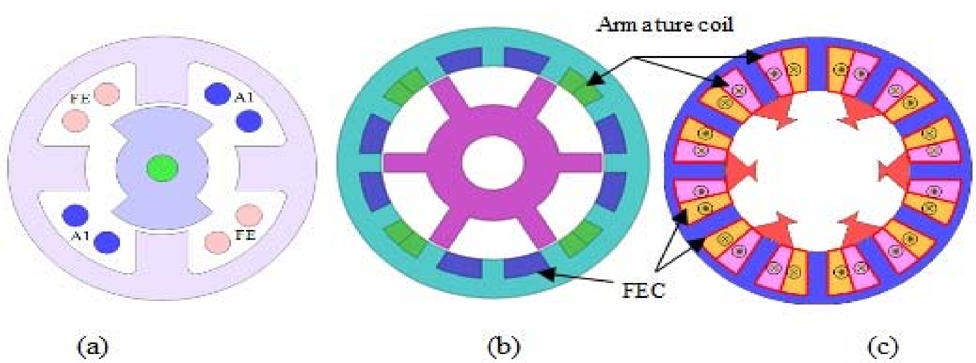

Figure-2. (a) 1-phase 4S-2P FEFS motor, (b)1-phase FEFS motor with salient rotor, (c)1-phase 12S-6P FEFS with segmental motor.

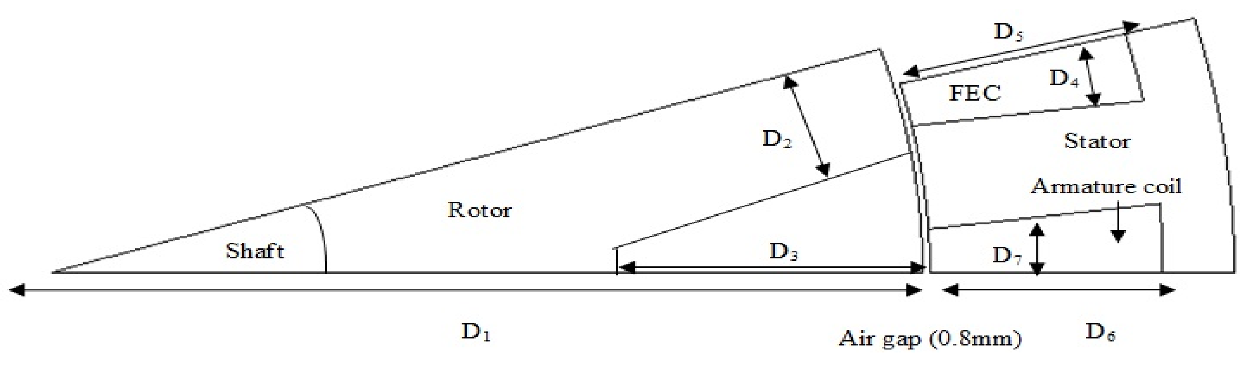

Figure-3. Design parameters defined as D_1 to D_7.

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By keeping the other parameters constant, the second step is taken by varying the FE Coil slot parameters D_4 and D_5. Then, by using the arrangement of D_4 to D_5 that reveal the maximum performance at the second step, the third step is taken by changing the armature coil slot parameters D6 and D7 while keeping other parameters constant. The required armature coil slot area, Sa is determined by changing armature coil depth, D6 and armature coil width, D7 to house natural number of turns, Na for armature coil. To attain the target performances, the method of changing D1 to D7 are treated repeatedly [Sulaiman, Kosaka and Matsui, 2012]. Under maximum JA and JE, all design parameters are modified having constant air gap length of 0.8mm. Finally, after three cycle of optimization, the machine fulfilled the target requirements and performances for HEV.

DESIGN LIMITATIONS, REQUIREMENTS AND CONDITIONS

The design limitations, requirements and conditions of the suggested FEFS motor for HEV applications are related with existing IPMS motor for HEV listed in Table-1 [Kamiya, 2006] whereas specifications of final design parameters are listed in Table-2. FE Coil current density, JE and Armature coil current density, JA are set to 30A/mm2 and 30Arms/mm2, respectively. The target torque of 70Nm and power is set to be more than 41kW and the maximum operating speed is set to 20,000r/min. The proposed FEFS motor has simple configuration with concentrated windings in all coils; therefore weight less than 35 Kg is set for the design of target motor to achieve maximum power density more than 1.17 kW/kg for single phase FEFS motor. The electrical limitations related with the inverter are set as maximum 375V DC bus voltage and maximum 360A inverter current. Commercial FEA package, JMAG-Studio ver.13.1, released by Japanese Research Institute (JRI) is used as 2D-FEA solver in this design. The initial and final design FEFS motors are depicted in Figure-4.

PERFORMANCES INVESTIGATION OF FINAL FEFS MOTOR

The FE coil flux linkage at various FE coil current densities, J_E are investigated as illustrated in Figure-5. From the figures, it is clear that the flux pattern is increased with the increase in FE coil current density, J_E. The improved design produced much higher flux and expected to produce much higher power and torque.

Table-1. FEFS motor specifications.

Items	1ϕ IPMS motor	1ϕ FEFS motor
Maximum DC voltage (V)	375	375
Maximum current (A_{rms})	360	360
Maximum J_A (A_{rms}/mm^2)	31	30
Maximum J_E (A/mm^2)	NA	30
Stator diameter (mm)	264	264
Machine length (mm)	70	70
Diameter of shaft (mm)	60	60
Air-gap (mm)	0.8	0.8
PM volume (kg)	1.1	0
Max. speed (r/min)	12,400	20,000
Max. torque (Nm)	111	>70
Max. power (kW)	41	>41
Power density (kW/kg)	1.17	>1.17

J_A is current density in armature coil
J_E is current density in FE Coil

Table-2. Initial and final design parameters.

	Details	Initial	Final
D_1	Rotor radius (mm)	97.2	98.2
D_2	Rotor pole width (mm)	10.3	11.3
D_3	Rotor pole depth (mm)	33.2	12.2
D_4	FE coil width(mm)	8.9	12.9
D_5	FE coil depth (mm)	22.02	21.07
D_6	Armature coil depth (mm)	22.02	11.023
D_7	Armature coil width(mm)	8.9	11.095
ag	Air gap length	0.8	0.8
S_A	Armature coil slot area	196	122.31
S_E	FE coil slot area	196	271.8
N_A	Armature coil turns	8	5
T	Torque (Nm)	51.43	72.9
N	Speed (r/min)	2280	5763
P	Power (kW)	12.28	44.05
V_T	Total volume of motor (kg)	21.38	25.22
P_d	Power density (kW/kg)	0.574	1.75

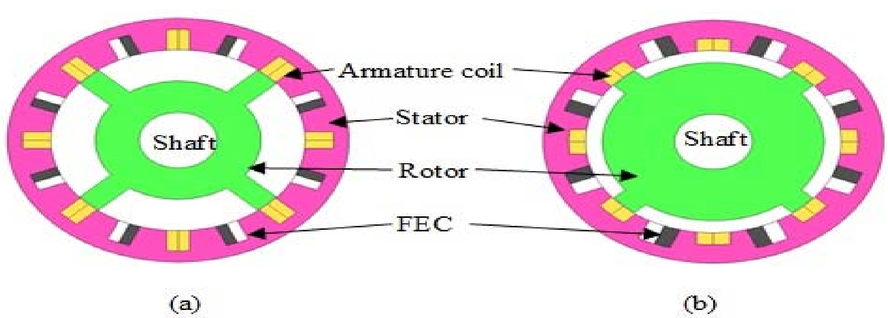

Figure-4. FEFS motors (a) initial design (b) final design.

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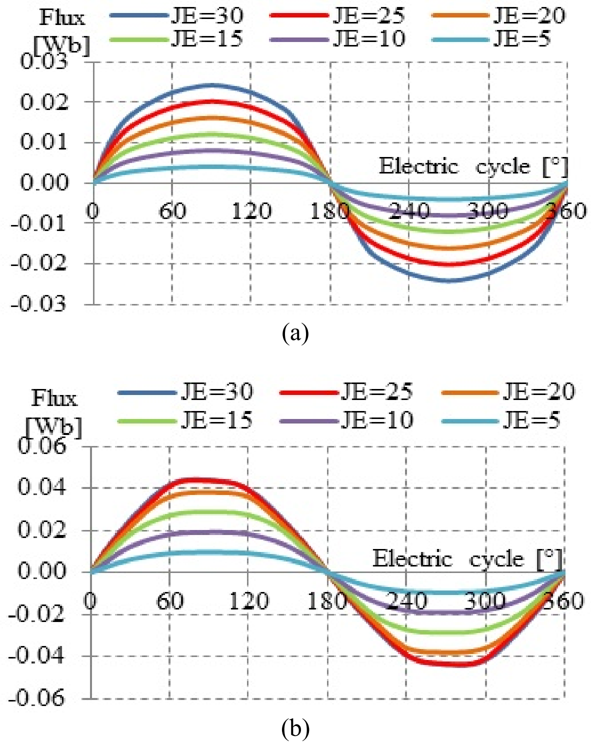

Figure-5. Flux linkage at various FE coil current densities, JE (a) initial FEFS motor (b) final FEFS motor.

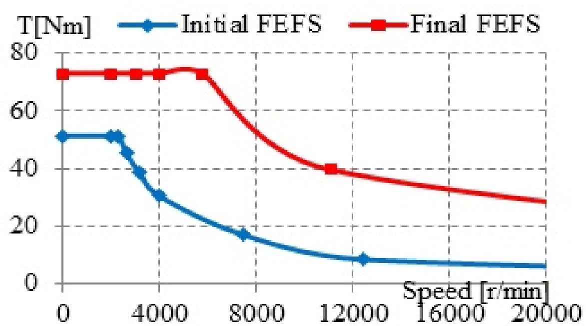

Figure-6. Torque vs speed characteristics.

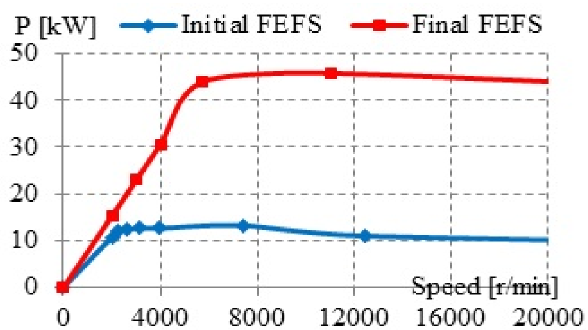

Figure-7. Power vs speed characteristics.

depicted in Figure-6. The maximum torque attained by final design FEFS motor is 72.9Nm, approximately 4% more than expected target. In high speed region, FEFS motor produced much higher torque and has better torque condition. Meanwhile, Figure-7 shows the power versus speed characteristics of the FEFS motor. From the graph, at maximum torque, the power accomplished by final design FEFS motor is 44.05kW at the speed of about 5,763r/min. The total weight of the final design FEFS motor including armature coil, FE Coil, stator iron, rotor iron and estimation of both coil ends is 25.22kg and 35kg for IPMS motor, which has 27% difference such that the weight of final design FEFS motor reduced. Thus, for HEV applications the maximum power density achieved is 1.75kW/kg, much higher than the target requirements. At last, 2D-FEA is used to predict the mechanical stress of rotor design, determined by centrifugal force analysis as illustrated in Figure-8. At speed of 20,000r/min, the final design has achieved the maximum stress of 185MPa, which is much lesser than permissible maximum stress of 300MPa in conservative electromagnetic steel. This is one of the great advantages of the final design FEFS motor that make its appropriate use in high-speed appliances.

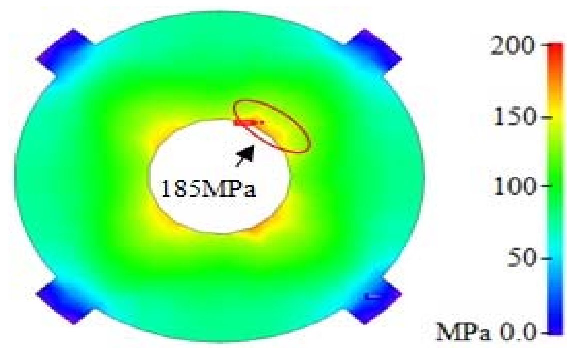

Figure-8. Principal stress distribution of rotor at 20,000r/min.

CONCLUSIONS

Design optimization of 8S-4P FEFS motor for traction drive in the target HEV is presented in this paper. The final design FEFS motor has achieved the expected target of power and torque. Furthermore, in high-speed region, the rotor mechanical stress investigated is satisfactory for the operation of machine. In general, FEFS motor is a low cost machine due to no usage of PM. Finally the power density of the final design FEFS motor is improved 49.6% more than existing motor installed. As conclusion, the aim of this research to obtain maximum performances for HEV applications is effectively accomplished.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Bajpai, P. and Dash, V. (2012). Hybrid Renewable Energy Systems for Power Generation in Stand-Alone Applications: A Review. Renewable and Sustainable Energy Reviews, 16(5), pp. 2926–2939.

[2] Hannan, M. A., Azidin, F. A. and Mohamed, A. (2014). Hybrid Electric Vehicles and Their Challenges: A Review. Renewable and Sustainable Energy Reviews, 29, pp. 135–150.

[3] Husin, Z. A., Sulaiman, E. and Kosaka, T. (2014). Design studies and effect of various rotor pole number of field excitation flux switching motor for hybrid electric vehicle applications. IEEE 8th International Power Engineering and Optimization Conference, pp.144-149.

[4] Kamiya, M. (2006). Development of Traction Drive Motors for the Toyota Hybrid Systems. IEEJ Transactions on Industry Applications, 126 (4), pp. 473-479.

[5] Khan, F., Sulaiman, E., Ahmad, M. Z. and Husin, Z. A. (2014). Parameter Sensitivity Study for Optimization of 12S-8P Three Phase Wound Field Switched-Flux Machine. Journal of Applied Mechanics and Materials, 695, pp. 765-769.

[6] Omar M. F., Sulaiman E. and Soomro, H. A. (2015). New topology of Single-Phase Field Excitation Flux Switching Machine for High Density Air-Condition with segmental rotor. Applied Mechanics and Materials, 695, pp. 783-786.

[7] Pollock, C. and Wallace, M. (1999) The flux switching motor, a DC motor without magnets or brushes. in Proc. Conf. rec. IEEE IAS Annual Meeting, 3, pp.1980-1987.

[8] Sulaiman, E., Kosaka, T. and Matsui, N. (2012). Design optimization and performance of a novel 6-Slot 5-Pole PMFSM with hybrid excitation for Hybrid Electric Vehicle. IEEJ Trans. on Industry Appl., 132 (2), pp. 211-218.

[9] Sulaiman, E., Kosaka, T. and Matsui, N. (2014). Design and analysis of high-power/high-torque density dual excitation switched-flux machine for traction drive in HEVs. Renewable and Sustainable Energy reviews, 34, pp. 517-524.

[10] Zho, Y. J. and Zhu, Z. Q. (2013). Comparison of low-cost single-phase wound-field switched-flux machines. IEEE International Electric Machines & Drives Conference (IEMDC), pp. 1275-1282.