Design Optimization of Single-Phase Outer-Rotor 8S-8P Hybrid Excitation Flux Switching Motor for Electric Vehicle

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Abstract. Nowadays, in-wheel motors applied in pure electric vehicles (EVs) propulsion systems have attracted great attention in advance research and development. In-wheel direct drive provides quick torque response, higher efficiency, weight reduction, and increased vehicle space. As one of alternative, a new design of outer-rotor hybrid excitation flux switching motor (ORHEFSM) for in-wheel drive EV is proposed. In this paper, the optimization design of single-phase 8S-8P outer rotor HEFSM is analysed. Open and close circuit of initial and final design is compared based on 2-D finite element analysis (FEA). The design optimization has been made on the initial design machine shows that there is great enhancement on torque and power.

Introduction

By increasing number of population in the world, the demand toward vehicles for personal transportation has also been increased dramatically in the past of decade which leads to serious problems called 'global warming'. One of the main causes of global warming is Internal Combustion Engine (ICE) [1]. Electric vehicles (EVs) seem like an ideal solution to deal with the energy crisis and global warming, since they have zero oil consumption and zero emissions [2]. However, most of commercial EV used single motor and transmission gears coupled to the wheels. This system leads to the transmission losses and reduce the efficiency and reliability of the motor [3]. Therefore, in-wheel direct drive mechanism is introduced. In-wheel direct drive eliminates the mechanical transmission, differential gears and drive belts. Thus, in-wheel direct drive provides quick torque response, higher efficiency, weight reduction, and increased vehicle space.

Since the in-wheel direct drive with outer-rotor configuration is more practical for direct drive application, several invention of in-wheel mechanism for EV application has been proposed. For example 12S-22P outer-rotor permanent-magnet flux-switching machine (PMFSM) for electric propulsion in a light weight electric vehicle has been proposed [4]. The proposed machine is a highly possible candidate for in-wheel direct-drives. This PMFSM has physical compactness, robust rotor structure and high efficiency. However PMFSM has several disadvantages of uncontrolled flux and demagnetization [5]. Besides, 36S-24P outer-rotor permanent magnet (PM) hybrid machine also have been proposed [6]. This machine consists of permanent magnet (PM) and field excitation coil (FEC) as a main flux source has more advantage compared to PMFSM. However this design has some disadvantage such as complicated design due to double-layer stator and high cost.

Thus, as one of the candidate that can overcome the problems, a new structure of outer-rotor hybrid excitation flux switching machine (OR-HEFSM) single-phase winding have been proposed [7]. In this paper, the optimization design of single-phase 8S-8P OR-HEFSM is analysed. Flux linkage of PM with DC FEC, cogging torque, and torque and power versus FEC current density, J_E at various armature coil current densities, J_A for initial and final design is been compared.

Design Specifications and Restrictions of 8S-8P OR-HEFSM

Table 1 shows the parameters of the initial and final design of OR-HEFSM. From Table 1, the rotor parameters involved are the outer rotor radius (D_1) which is within the range of general machine split ratio, rotor pole depth (D_2) which is more than the half size of the rotor and to ensure flux moves from stator to rotor equally without any flux leakage, the design of rotor pole arc width (D_3) is reduced to allow optimal flux flows into the rotor pitch.

The PM slot shape parameters are the PM depth (D_5), and the PM width (D_6) calculated by using volume of 1kg PM. The size of D_5 is reduced and expecting will give more flux to flow and increase the motor performances while for the FEC slot depth and FEC slot width, (D_7) and (D_8) calculated from maximum current density, Je of 30 A/mm^2 with 44 turns of FEC winding. The area of optimized FEC slot is higher compared to initial design and give the flux have enough space to flow easily.

Finally, the armature coil parameters are armature coil slot depth (D_9) and the armature coil slot width (D_{10}) calculated by using 168mm area of armature coil and 7 turns of AC winding. The armature slot area is set similar for initial and final design in order to maintain the limitation of the maximum current densities which is set to $30A_{rms}/mm^2$. Therefore, the depth of D_9 is shorter and will prevent flux saturation while the shape of AC changes to make the flux easily through it.

The motor design parameters, from D_1 to D_{10} are demonstrated in Fig. 1. Based on the motor parameters identified, the deterministic design optimization method is used and implemented using 2-D FEA solver to obtain the optimal performances of the proposed motor. In summary, the motor parameters D_1 to D_{10} are changed repeatedly until the target performances of torque and power are achieved. The initial and final design structure of ORHEFSM is illustrated in Fig. 2.

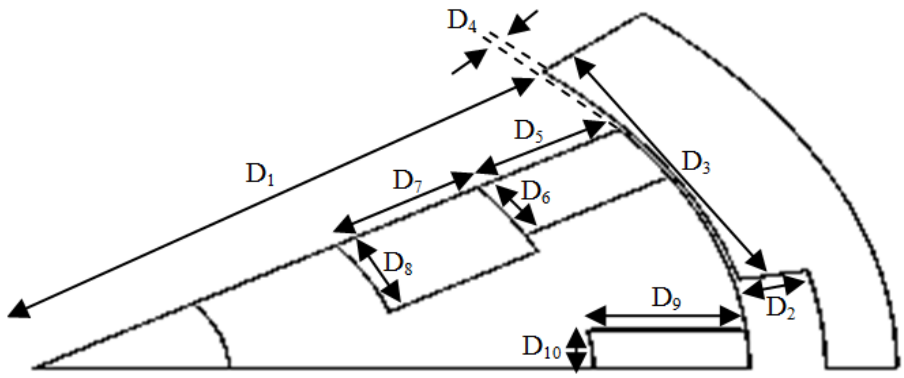

Fig. 1. The motor design parameter

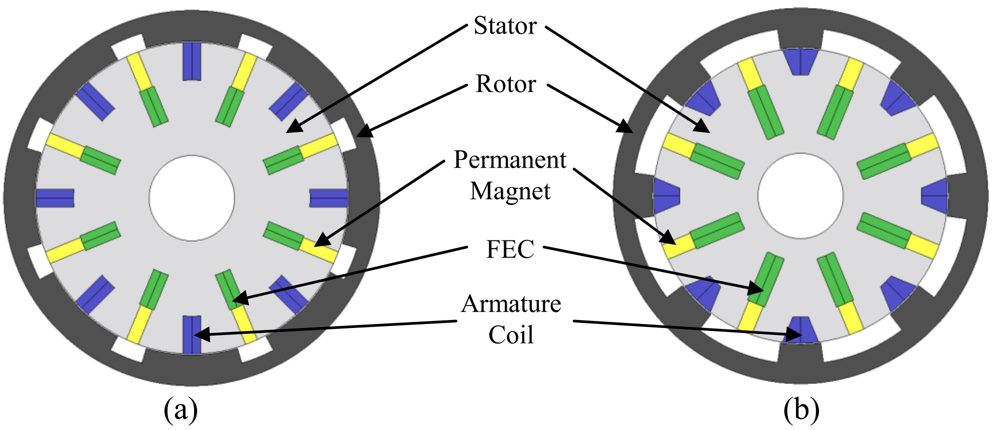

Fig. 2. 8S-8P OR-HEFSM (a) Initial Design (b) Final Design

Table 1. Outer Rotor Design Parameter of 8S-8P HEFSM

Parameter	Description	Initial	Final
D_1	Rotor outer radius (mm)	110.36	104.36
D_2	Rotor pole depth (mm)	10.82	13.82
D_3	Rotor pole width (mm)	16.85	7.85
D_5	PM depth (mm)	26.52	21.52
D_6	PM width (mm)	4.46	5.50
D_7	FEC slot depth (mm)	26.52	37.52
D_8	FEC slot width (mm)	5.53	6.53
D_9	AC slot depth (mm)	26.52	18.52
D_{10}	AC slot width (mm)	6.33	9.07

Performances and Result Based on 2D Finite Element Analysis

Flux linkage of PM with DC FEC, induced voltage of PM with DC FEC, cogging torque, torque and power versus FEC current density, J_E at various armature coil current densities, J_A for initial and final design is compared using commercial 2D-FEA package, JMAG-Studio ver.13.0, released by Japanese Research Institute.

The flux linkage of the initial and final design at various condition of Je is plotted in Fig. 3. From these figure, it is showed that the magnitude of flux linkage of the final design at maximum Je has increased from 0.09Wb to 0.15Wb. Hence, it has the ability to increase the performances of the motor. Then, the cogging torque of the final design ORHEFSM compared with the initial design is exemplified in Fig. 5. The cogging torque generated is low which is good for the motor to produce low torque ripples. From the graph, the final design motor shows increment in peak-to-peak cogging torque ripple where it has increased from 0.46Nm to 3.16Nm. Even the peak-to-peak cogging torque has increase, but the magnitude of peak-to-peak cogging torque is consider small if compared with the target of maximum torque.

The torque versus FEC current density at maximum J_A of the initial and final design is also compared and plotted as depicted in Fig. 5. The maximum torque obtained for the initial design is 89.08Nm, while the final design ORHEFSM is 263.82Nm and has achieved the target value which 111Nm. From the diagram, when J_A is set at maximum of 30 Arms/mm^2, the torque keep increasing as Je is increased from 0 A/mm^2 to 30 A/mm^2 for both initial and final design. Thus, the maximum power also has been increased and it has achieved the target value which 41kW as shown in Fig. 6. The initial design motor the maximum power achieved was 9.83kW, while for the final design motor, it has increased to 66.07kW and obtained when armature coil and DC FEC current densities are set to the maximum of 30Arms/mm^2 and 30A/mm^2. The torque and power is directly proportional to each other. From both graph, when J_A increase, the torque and the power increase smoothly.

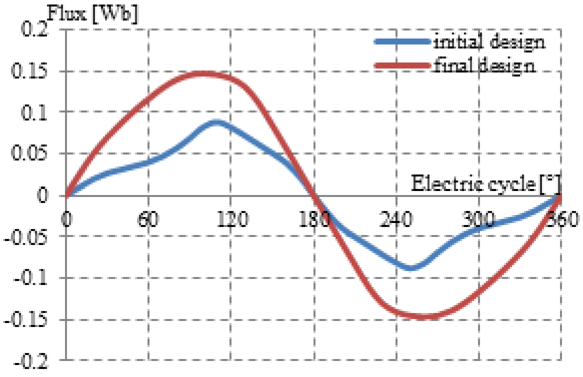

Fig. 3. Flux Linkage of PM with DC FEC

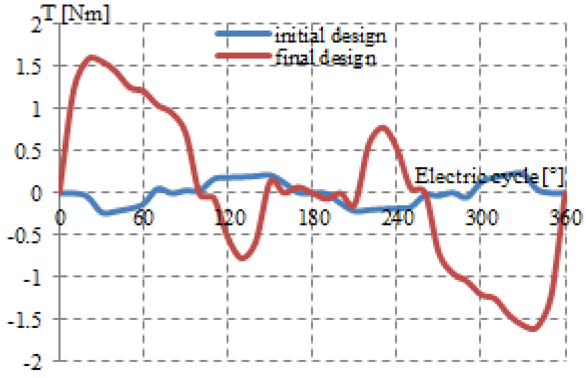

Fig. 4. Cogging Torque of PM Only

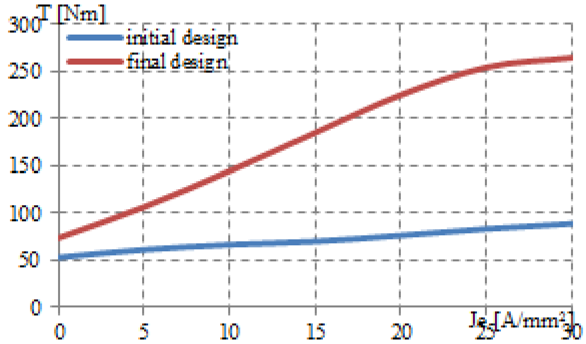

Fig. 5. Torque versus J_E at Maximum J_A

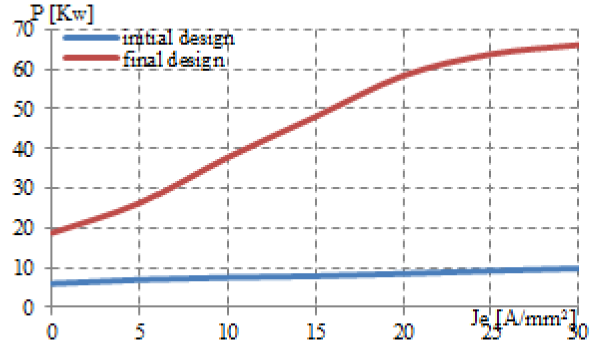

Fig. 6. Power versus J_E at Maximum J_A

Conclusion

Design optimization studies of single-phase 8S-8P Outer-rotor HEFSM for in-wheel drive EV applications have been presented. The final design motor has produced higher torque which is 263.82Nm with 137.67% improvement compared to initial design motor which is 89.08Nm and has achieved the target value which 111Nm. The initial design motor the maximum power achieved was 9.83kW, while for the final design motor, it has increased to 66.07kW, since the target maximum power is 41kW.

Acknowledgement

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References

[1] M. Z. Ahmad, E. Sulaiman, Z. A. Haron, and T. Kosaka, "Impact of rotor pole number on the characteristics of outer-rotor hybrid excitation flux switching motor for in-wheel drive EV", Proc of Int. Conf on Electrical Eng. &Infor., UKM, pp. 593-601, June 2013.

[2] IEA-HEV Outlook, International Energy Agency Implementing Agreement on Hybrid and Electric Vehicles, "Outlook for hybrid and electric vehicles," 2008 [Online] Available: http://www.ieahev.org/pdfs/iahev_ outlook_2008.pdf.

[3] M. Z. Ahmad, E. Sulaiman, Z. A. Haron, and T. Kosaka, "Design improvement of a new outer-rotor hybrid excitation flux switching motor for in-wheel drive EV", IEEE Int. Power Engineering and Optimization Conference, Langkawi, pp. 298-303, June 2013.

[4] W. Fei, P. Chi, K. Luk and J. S. Y. Wang, "A Novel Outer-Rotor Permanent-Magnet Flux Switching Machine for Urban Electric Vehicle Propulsion," in *3rd International Conference on Power Electronics Systems and Applications (PESA)*, pp. 1–6, 2009.

[5] E. Sulaiman, T. Kosaka, and N. Matsui, "Design Optimization and Performance of a Novel 6-Slot 5-Pole PMFSM with Hybrid Excitation for Hybrid Electric Vehicle", *IEEJ Transaction on Industry Application*, Vol. 132 / No. 2 / Sec. D pp. 211-218, Jan 2012. (Scopus).

[6] Chunhua Liu, K. T. Chau, J. Z. Jiang, and LinniJian, "Design of a New Outer-Rotor Permanent Magnet Hybrid Machine for Wind Power Generation", *IEEE Transactions on Magnetics*, Vol. 44, No. 6, June 2008.

[7] M. M. A. Mazlan, E. Sulaiman and T. Kosaka, "Design Studies of Single-Phase Outer-Rotor Hybrid Excitation Flux Switching Machine for Hybrid Electric Vehicle", IEEE Int. Power Engineering and Optimization Conference, Langkawi, pp. 138-143, March 2014.