Electromagnetic Performance Analysis of a New Permanent-magnet Machine for Four-wheel Independently Driven EVs Using Finite Element Method

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Abstract — This paper proposes a new fault-tolerant permanent-magnet (PM) brushless machine for four-wheel independently driven electric vehicles (EVs). The key of the proposed machine is to make tooth widths unequal of inner stator, hence, offering more trapezoidal back-EMF waveform. The radial PMs are embedded in outer rotor, which incorporate the merits of high torque-to-weight ratio, mechanical robustness and air gap flux density. In addition, multi-phase and single-layer fractional slot concentrated windings are employed to improve the reliability. The static characteristics of the proposed machine are analyzed by using the time-stepping finite element method (FEM), such as magnetic field distribution, flux destiny and flux linkage, verifying the effectiveness of the theoretical analysis.

I. INTRODUCTION

In recent years, due to problems like the energy crisis and environmental pollution, the electric vehicles (EVs) have been researched and developed more and more extensively [1]. Currently, most EVs are driven by two front wheels or two rear wheels. To improve the efficiency and the available space on the vehicle, people have paid more and more attention to four-wheel independently driven EVs employing the in-wheel motors. Their outer-rotor topology is particularly attractive, because it facilitates direct coupling with wheel. Also, it has been identified that the outer rotor machine has the advantages of high torque-to-weight ratio and high efficiency as compared with inner rotor machine [2]-[3]. However, the mechanical robustness of the conventional out rotor machine is low, because the magnets are surface-mounted [4]-[5]. In order to solve this problem, interior PM fault-tolerant machines have been proposed, offering mechanical robustness and extended flux weakening region [6]. However, the width of flat top of back-EMF is only 120 electrical degrees. It is necessary to inject third harmonic current to achieve smooth torque, which increases the complexity of control strategy.

In this paper, a new in-wheel fault-tolerant IPM (IWFT-IPM) machine for four-wheel independently driven EVs will be proposed, which incorporates the attractive features of outer-rotor IPM machine and fault-tolerant machine. In Section II, the configurations and advantages of IWFT-IPM machine will be introduced. The finite element analysis (FEA) results and discussion of IWFT-IPM machine will be performed in Section III. Finally, conclusions will be drawn in Section IV.

II. MACHINE CONFIGURATIONS

Fig. 1 shows the configurations of IWFT-IPM machine. Clearly, for any modular winding with negligible electromagnetic coupling between phases, the basic winding module (with the smallest allowable number of slots and poles) has just two anti-phase coils per phase. For any such winding with m phases and S slots, the required number of poles is given by:

$$2p = S(1 \pm \frac{n}{2m}) \tag{1}$$

where n=1, or n=any non-zero odd integer less than m, such that n and m do not share any common factors. It should be noted that good design practice necessitates a high coupling between the magnets and coils, which implies that n/m should be no greater than about 0.6. Since a five-phase topology is adopted, the numbers of plot and slot can be 18 and 20 respectively. Meanwhile, the radial magnets are embedded in outer rotor, in which NdFeB35 with Br=1.03 T is adopted.

The IWFT-IPM machine combines the advantages of outer rotor machine and interior PM machine, providing high torque-to-weight ratio and mechanical robustness. Meanwhile, the most appropriate pole and slot numbers are investigated for the purpose of electrical, magnetic, thermal, and physical separation of the various phases. Hence, the IWFT-IPM machine can offer high reliability.

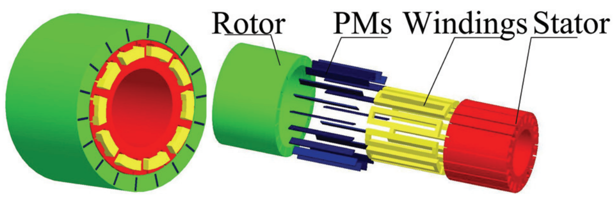

Fig. 1. Configurations of IWFT-IPM machine

III. FINITE ELEMENT ANALYSIS

In this section, finite element method (FEM) is employed to calculate the magnetic field distribution, flux destiny and flux-linkage of IWFT-IPM machine. Fig. 2 shows the magnetic field distribution of the machine at no load. It can be observed that the flux linkages of each stator tooth are generated by two permanent-magnets. Therefore, the flux density of stator tooth is enhanced. Fig. 3 shows the flux destiny of proposed machine. From the numerical point of view, the flux density of stator tooth (B_t) is obviously higher than that of air gap (B_g). The relationship of them can be approximated as:

$$B_t = 2B_g \tag{2}$$

Eq. (2) reveals that the IWFT-IPM machine has strong flux-concentration. Fig. 4 shows the flux linkage of phase-A by PMs only. Fig. 5 shows the corresponding phase back-EMF. It should be noted that the width of flat top is almost 144 electrical degrees, which inherently suitable for brushless DC (BLDC) operation. The FEM-based cogging toque waveform of the machine is shown in Fig. 6. It can be seen that the amplitude of cogging torque is insignificant and on the contrary the frequency is large, which is benefit for the start of the machine.

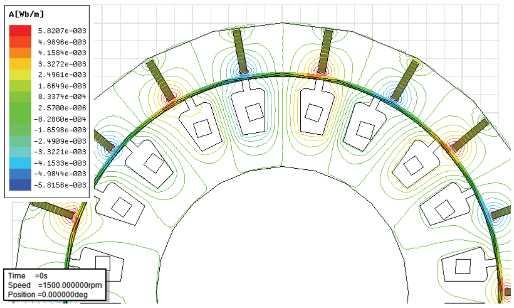

Fig. 2. Magnetic field distribution

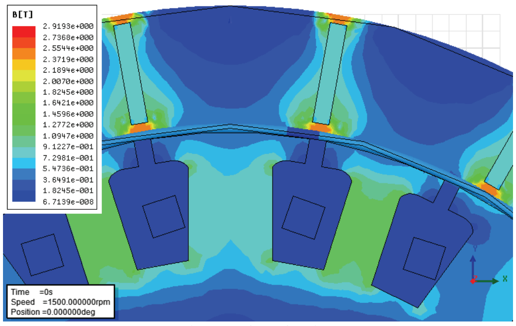

Fig. 3. Flux destiny

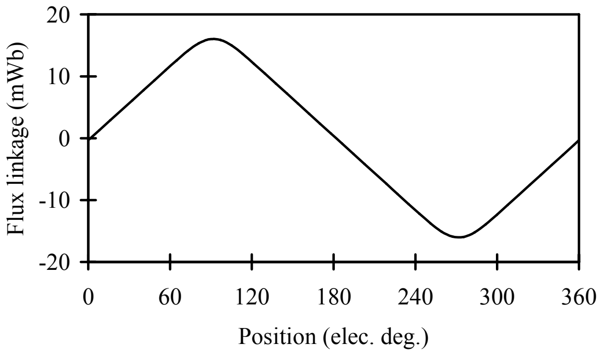

Fig. 4. Flux-linkage waveform

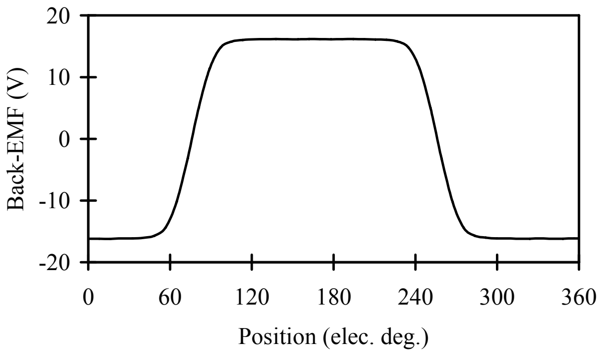

Fig. 5. Phase back-EMF waveform

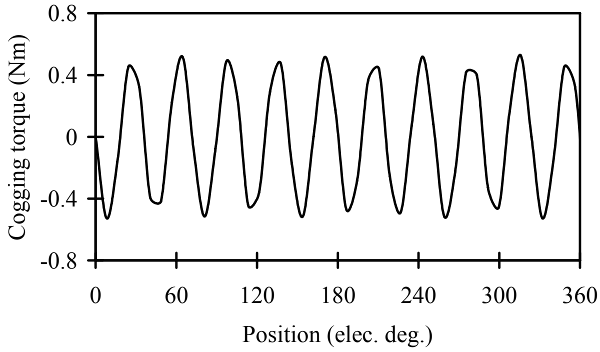

Fig. 6. Cogging torque waveform

IV. CONCLUSION

A New fault-tolerant permanent-magnet machine has been presented, and its main advantages are as follows:

- High torque-to-weight ratio and mechanical robustness because PMs are embedded in outer rotor.
- High reliability and low amplitude of cogging torque because the motor is five-phase.
- More trapezoidal back-EMF due to unequal tooth widths of inner stator.
- Low cost of permanent-magnets due to flux-concentration.

Hence, the proposed machine is a good candidate for high reliability operation of four-wheel independently driven Evs.

More detailed results, discussion and mathematical expressions of proposed machine will be given in the full paper.

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