Design and Analysis of New Five-Phases Fault-tolerant in-Wheel Permanent-Magnet Motors

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Abstract — In this paper, a new 20/22-pole in-wheel permanent magnet (PM) motor is proposed, designed and analyzed. It offers inherently negligible coupling between phases, namely, fault-tolerant characteristic. The developed slot and pole number combinations aim to ensure that a fault in one phase does not undesirably affect the remaining healthy phases. In addition, it should be noted that the cogging torque in the interior PM motor causes torque and speed ripples, as well as acoustic noise and vibration. Compared with the 20/24-pole IPM motor topology, the proposed 20/22-pole one offers improved cogging torque. The displacement angle of magnets in one pole also is investigated in order to reduce cogging torque. Finally, finite-element analysis results are given for verification.

I. INTRODUCTION

Permanent-magnet (PM) machines are increasingly required to have a high power density and high fault-tolerance for use in critical applications where any failure of the machine or power electronics would jeopardize safety and convenience (such as in aircraft and other transport systems). For surface-mounted PM motors, slot and pole number combination has been proposed to reduce mutual inductance [1]. However, the preferred slot and pole number combination of fault-tolerant interior PM (IPM) machine for in-wheel electric vehicles (EVs) was not set out.

Cogging torque caused by the interaction between PMs and stator teeth is usually an inherent problem in IPM motors. Cogging torque, showing itself as tending to make the rotor remain at certain positions or preventing the motor to rotate smoothly, is a major factor of torque ripple which results in undesirable vibration and noise. For surface-mounted permanent-magnet motors, many methods have been proposed to reduce cogging torque, such as a fractional number of slots per pole [2], slot skewing [3], magnet skewing [4], [5], "goodness" of slot number and pole number combination [5], slot or tooth pairing [6], etc. However, there is no study for outer rotor permanent-magnet motors with the IPM by now. For the IPM motors, the magnetic saturation makes it difficult to analytically predict the cogging torque accurately. Many methods used in cogging torque reduction for surface-mounted permanent magnet appear to be effective for outer rotor IPM motors.

The purpose of this paper is to present the design details of new in-wheel fault-tolerant IPM motors. A 20 slots and 22 poles (the called 20/22-pole) IPM motor with outer-rotor will be proposed. The combination of slot number and pole number will be investigated. Its cogging torque will be discussed. Meanwhile, finite element analysis (FEA) will be given for verification.

II. MOTOR STRUCTURE AND FEATURES

The structure and configuration of the proposed in-wheel IPM machine is shown in Fig. 1, in which it has an outer rotor. The rare earth magnets are inset in the rotor, and the single-layer concentrated windings are located in the inner stator.

Fig. 2 compares the single-phase armature flux pattern (ignoring the flux associated with slot leakage) for 5-phase 20/22-pole and 20/24-pole. For clarity, in each case, the magnets are unmagnified and only phase-A is excited. It is clear that the 20/24-pole machine in Fig. 2(a) has an eight-pole armature flux pattern, whereas the 20/22-pole one in Fig. 2(b) has a two-pole armature flux pattern. It is also can be seen that the eight-pole flux pattern of Fig. 2(a) has appreciable magnetic coupling between phases, whereas the two-pole flux pattern of Fig. 2(b) has no coupling between phases (only between the coils of one phase).

The significant interphase coupling of the 20/24-pole design means that a fault such as a terminal short circuit of one phase would have an undesirable effect on the remaining (unfaulted) phases. Fig. 3 compares that the 20/22-pole combination appears to have zero coupling between phases and therefore it seems that a better design is achieved for fault-tolerant operation.

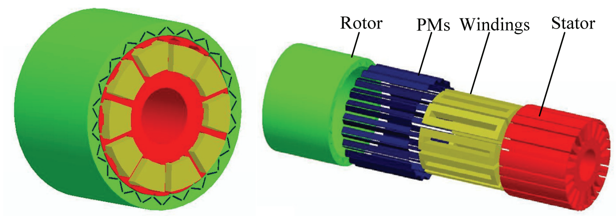
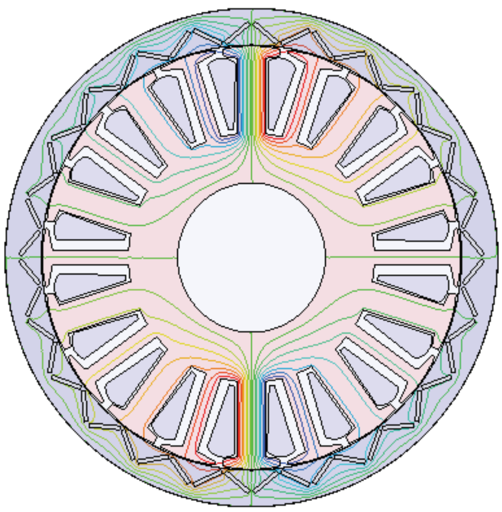
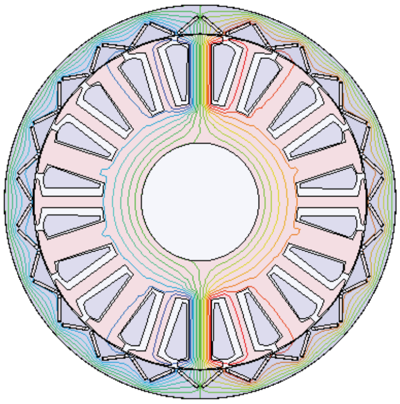


Fig. 1. 20/22-pole IPM motor



(a) 20/24-pole



(b) 20/22-pole

Fig. 2. Comparison of armature flux for 20/24-pole and 20/22-pole motor

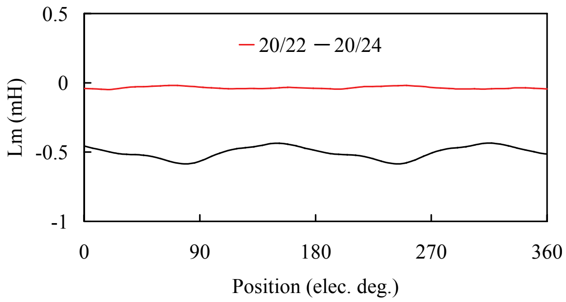


Fig. 3. Comparison of mutual inductance

III. OPTIMIZATION OF COGGING TORQUE

Cogging torque is caused by the variation of reluctance across the air gap and contributes to the vibrations and noise leading to the severe restrictions in the machine especially during low speed operations. Reduction of cogging torque can be done by choosing an appropriate number of slots and poles; chosen such that a high lowest common multiple (LCM) of slots and poles can be achieved.

By observation of Fig. 4, cogging torque waveforms produced by 20/22-pole motor have a peak to peak magnitude which is lower than that of the 20/24-pole motor due to the former having a higher LCM.

The displacement angle of magnets in one pole also is important to reduce cogging torque. Two rectangular magnets in the shape of V-shape form one pole in the proposed machine. This section will present the comparative characteristics on the several angles of the V-shape of the 20/22-pole machine. As shown in Fig 5, the proposed machine has an angle of 140° between the V-shape magnets, which yields the lowest cogging torque, according to the finite element analysis.

IV. CONCLUSION

In this paper, the design and analysis of a new 20/22-pole IPM motor has been presented. The optimal design has 20/22-pole force the coupling between phases to be essentially zero that has been proved. The effect of slot number and pole number has been investigated. Therefore, the higher the LCM of slot number and pole number is, the smaller the cogging torque. FEA results have shown that the angle of 140° of permanent magnet in one pole is the best choice to IPM motor. Also, it has been verified that tooth pairing can translate trapezoidal air-gap magnetic field to sinusoidal air-gap magnetic field, and therefore produce sinusoidal back-EMF.

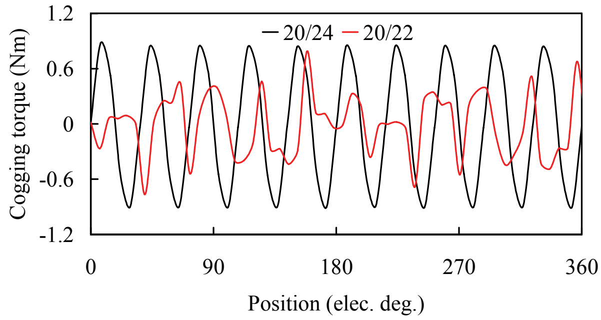


Fig. 4. Comparison of cogging torques of both motors

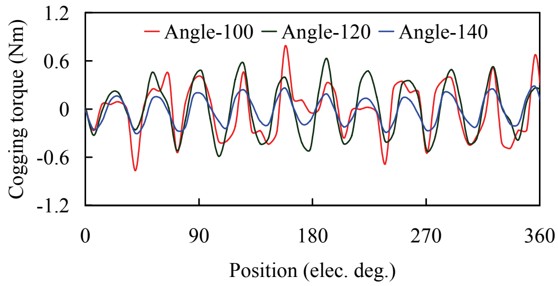


Fig. 5. Influence of magnet shape

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V. REFERENCES

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