Research Article

Electromagnetic performance analysis of multilayer interior PMSM with fractional slot concentrated windings for electric vehicle applications

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Abstract: This paper presents the design and analysis of fractional slot multilayer interior permanent magnet synchronous machines (PMSMs) with concentrated winding for electric vehicles applications. The major advantages of concentrated winding will be analyzed first. The significant design consideration of multilayer interior permanent magnet machines will be illustrated, as well. Finally, the advanced finite element method will be employed to verify the detailed electromagnetic performance of the proposed interior PMSMs.

Key words: Permanent magnet synchronous machines, fractional slot, concentrated winding, electric vehicle

1. Introduction

Electric vehicles (EVs) or hybrid EVs have received attention due to energy crises and environment concerns [1–5]. Various electrical machines are candidates for EV drive applications, including conventional induction machines, switched reluctance machines, and permanent magnet machines. Induction machines are not ideal for EV applications due to relatively low efficiency, low power factor, and torque density. On the other hand, from the control strategies point of view, field-oriented or vector control, including direct and indirect field orientation, was widely used for high-performance induction machine drive systems. Unfortunately, both direct and indirect field orientation algorithms are sensitive to parameter variation caused by temperature change and magnetic saturation. For direct field orientation control strategies, the flux observer implementation is a challenging issue in induction machine drives, as well.

Permanent magnet machines using high-performance rare earth permanent magnets, due to their high torque density and high efficiency, play a key role in EV and/or hybrid vehicle traction applications. In particular, the permanent magnet can be buried inside the rotor core as a so-called interior permanent magnet (IPM) machine. Compared to simple surface-mounted permanent magnet machines, the torque density of IPM machines is enhanced by asymmetrical magnetic circuit or saliency and a more robust rotor structure suitable for high-speed operation [6]. Furthermore, a new rotor optimization method for torque density improvement in IPM machines was proposed in [7]. The optimal rotor shape of IPM machines for efficiency and operating range improvement was designed in [8]. The vibration characteristics of IPM machines were analyzed using structure and magnetic finite element methods in [9]. A flux-intensifying IPM machine was designed and evaluated in [10]. Compared to distributed winding, the attractive advantages of concentrated winding include inherent

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short end windings and significant reduction of copper volume in the end region, higher slot fill factor, and ease of construction [11].

The purpose of this paper is to present the design and analysis of multilayer interior permanent magnet synchronous machines (PMSMs) with fractional slot concentrated winding for EV applications. Optimal multilayer flux barrier topologies have been adopted to enhance reluctance torque contribution and minimize the size of the permanent magnet. The main characteristics will be analyzed, including the recent definition of fractional slot and concentrated winding, advantages and opportunities, disadvantages and challenges, criteria for choosing the slot/pole combination, and determination of the winding layer. For electromagnetic design procedure, the classical analytical model will be used for initial calculation and design, including operating point of magnetic circuits, winding parameters, and loss and efficiency prediction. Finally, the advanced finite element method will be employed to verify the detailed electromagnetic performance of the proposed interior PMSMs.

2. Analysis of concentrated windings

In AC machines, the number of pole/slot combinations and winding topologies can be divided into integral slot, fractional slot, distributed, and concentrated windings. The sinusoidal distributions of electromotive force (EMF) and magnetomotive force (MMF) are desirable in order to produce more smooth electromagnetic torque and reduce additional losses. Conventional distributed winding is used to reduce the harmonic components of EMF and MMF in AC machines. In conventional AC machines, the fraction slot winding is popular only in low-speed large hydroelectric generators. The primary reason for this is that the numbers of poles of a low-speed synchronous generator is large and it is difficult to increase the numbers of stator slots proportionally if integral slot winding is adopted. In addition, the fractional slot combination can reduce tooth-slot-related harmonics and improve the EMF waveform. The theory and the analysis of conventional distributed winding are well established, including winding arrangement, calculation of fundamental and harmonic components of EMF and MMF, and analytical determination of pitch factor and distributed factor.

In recent years, the combination of fractional slot and concentrated winding has received more attention due to attractive advantages, particularly for permanent magnet machine applications. The first issue is the definition of the fractional slot combination and concentrated winding arrangement. The number of slots per pole and per phase (SPP) can be defined as

$$spp = \frac{Q_s}{2mp},\tag{1}$$

where Q_s, m, and p are the numbers of stator slots, phases, and poles, respectively. If spp is not an integral number, this type of winding is called fractional slot winding. The classic definition of concentrated winding is a winding having one number of slot/phase/poles. However, the recent definition of concentrated winding is a winding concentrated around one tooth [11].

The attractive advantages of this type of winding are inherent short end windings, the volume of copper in the end region being significantly reduced, a higher slot fill factor, and increased ease of construction, particularly when the stator core can be segmented. Concentrated winding is also suitable for modular PM machines with a high number of phases for fault tolerant operation. However, the harmonic components produced by concentrated winding will be much higher than those for distributed winding. This will result in more iron loss, particularly in the rotor, and other parasitic effect,, such as higher torque ripple, vibration, and noise. The important considerations for choosing the combination of slot/pole numbers are as follows: higher

winding factor, minimization of cogging torque, and suitability for multiphase fault-tolerant operation [11–13].

3. Electromagnetic design consideration

Figure 1 shows the specified continuous torque and power capability envelope of an interior PMSM for EV drives. Based on the requirement for EV traction applications discussed in Section 1, the main machine specifications are as follows: electromagnetic torque of 160 Nm over constant torque range, continuous power of 50 kW, maximum speed of 12,000 rpm (4:1 constant power speed ratio), and efficiency of 94% over a wide speed range. Other significant design restrictions are volume, weight, and cost. In this paper, the advanced fractional slot and concentrated winding topologies will be employed to meet several challenging design requirements of interior PMSMs for EV traction drives.
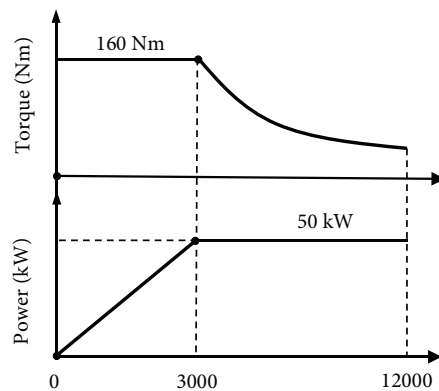
Figure 1. Specified continuous torque and power capability envelope of proposed interior PMSM.

In the electromagnetic design process, the classical analytical method, including magnetic equivalent circuit and analytical parameter calculation, and loss prediction and advanced finite element analysis will be employed to determine the optimal electromagnetic design results. Thermal and structure analyses are required as well because of higher electric and magnetic loading and high rotor mechanical stress under deep flux weakening operation. Minimization of vibration and noise are also desired for EV traction applications.

The most significant design requirement of interior PMSMs is efficiency over wide speed ranges, particularly for the machines equipped with concentrated winding. The harmonic components of MMF are higher than conventional distributed winding. The major losses in this machine are stator iron loss, rotor and magnet loss, and copper loss [14,15]. Stator core losses can be a significant issue in interior PMSM over wide constant power ranges. According to the classical loss mechanism of ferromagnetic materials, iron loss can be divided into hysteresis loss and eddy current loss as

$$P = k_h f B^\alpha + k_e f^2 B^2 \quad , \tag{2}$$

where P is loss in W/kg, f is frequency in Hz, and B is peak flux density in T. k_h, k_e, and α are coefficients determined by loss data of ferromagnetic materials. From this equation, it can be observed that eddy current loss is proportional to the square of frequency; therefore, eddy current loss will be dominant in the high speed range. Furthermore, harmonic eddy current loss is dominant due to its higher frequency than the fundamental component. Rotor geometry optimization is required to minimize stator core loss in interior PMSMs.

Theoretically, rotor loss can be negligible in synchronous machines because the rotor is synchronized with a fundamental rotating air-gap field. However, in practice, due to spatial and time harmonics in the

air-gap field, especially when the machine is driven by a modern pulse width modulated power converter, eddy currents will be induced in the rotor, including permanent magnets [16]. Therefore, it should be pointed out that reduction of rotor loss, including magnet loss, is a challenging issue in electromagnetic design of interior PMSMs, especially when concentrated winding is adopted. The stator MMF harmonics component produced by concentrated winding is relatively higher than in conventional distributed winding, which was discussed in the previous section. As a result, special design considerations are required to reduce rotor loss. For magnet loss reduction, both circumferential and axial segmentations are effective ways to reduce the eddy current loss of the magnet. From the construction point of view, axial segmentation will be more convenient in the machines.

4. Finite element analysis verification

Figures 2 and 3 show the cross-section and key parameters of the proposed interior PMSM. Figure 4 shows the no-load flux distribution of the interior PMSM. It can be seen that the flux line distribution is not symmetric due to the special magnetic field determined by fractional slot topologies, because the numbers of slots per pole and per phase (*spp*) are no longer integral; they are 2/5 in this prototype. Figure 5 shows the predicted cogging torque. Cogging torque results from the interaction between the permanent magnet and the stator slot without stator current excitation. It can be calculated by the Maxwell tensor method in finite element analysis. Cogging torque has no contributions for average electromagnetic torque and will increase vibration, noise, and torque ripple, particularly in the low-speed region. Therefore, some methods, such as a slew slot or magnet, are adopted to reduce cogging torque in permanent magnet machines [17–21]. Fortunately, the cogging torque of fractional slot topology-based interior PMSMs is inherently low and no additional measures are needed to reduce cogging torque in electromagnetic design. It can be seen from Figure 5 that the peak value of cogging torque is very low (400 mNm).
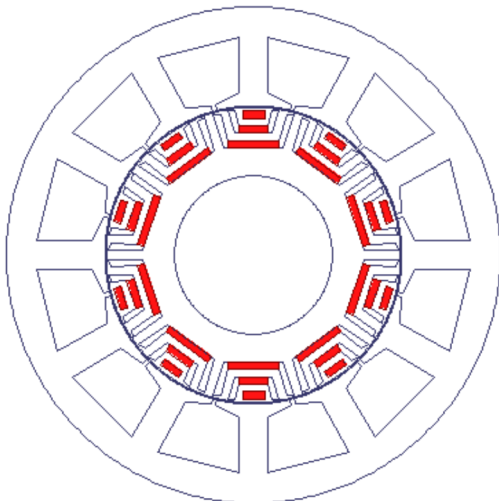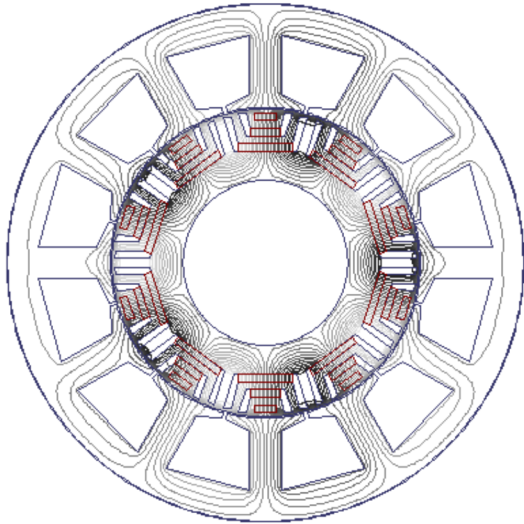

Figure 2. Cross-section of proposed interior PMSM.

MACHINES PARAMETERS AND KEY DIMENSIONS

| Parameter	Value
Rated power	50 kW
DC bus voltage	320 V DC
Rated speed	3000 rpm
Number of phases	3
Number of poles	10
Number of slots	12
Stator outer diameter	270 mm
Stator inner diameter	165 mm
Rotor outer diameter	163.5 mm
Rotor inner diameter	86 mm
Axial length	125 mm
Air-gap length	0.75 mm
Thickness of magnet	20 mm
Width of magnet	129.2 mm

Figure 3. Key dimensions and parameters of proposed interior PMSM.

Figure 6 shows torque as a function of *q*-axis current and Figure 7 shows torque as a function of stator current space vector, including both magnitude and phase angle. An important goal of interior PMSMs is to

increase reluctance torque and reduce the use of permanent magnets. The reluctance torque can be enhanced by increase the inductance difference of d-axis and q-axis magnetic circuits. Another issue is torque ripple, which can be decreased by rotor flux barrier optimization.
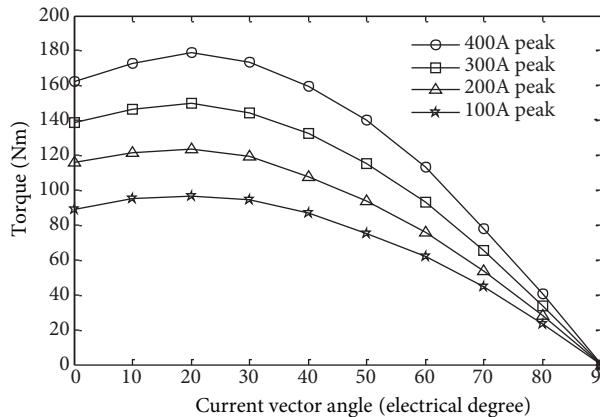

Figure 4. FE-predicted 2D no-load flux distribution of proposed interior PMSM.
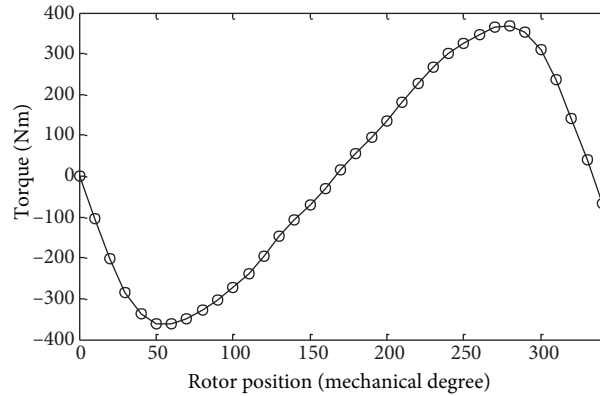
**Figure 5.** FE-predicted cogging torque of proposed interior PMSM.
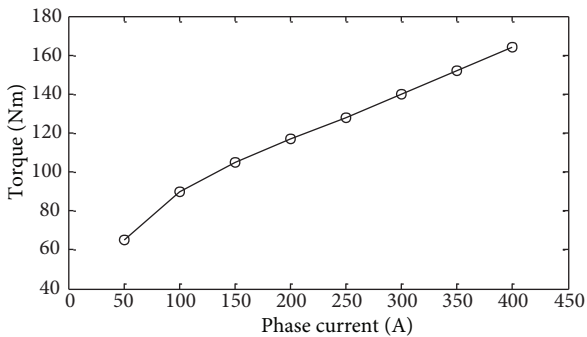
Figure 6. FE-predicted electromagnetic torque as a function of phase current (current vector angle between q-axis equal to 0).

Figure 7. FE-predicted electromagnetic torque as a function of current vector angle between q-axis.

For loss and efficiency prediction, copper loss can be estimated by a simple and well-known equation $(3I^2R)$. The core loss will be dominant in high-speed and deep flux-weakening regions. Figure 8 shows the stator and rotor core loss of the interior PMSM. The relatively higher rotor loss, including magnet loss, is a challenging issue in concentrated winding-based interior PMSMs due to higher MMF space harmonics as compared with conventional distributed winding topologies. It can be seen that the rotor core losses are lower than stator core losses. However, it will still increase the rotor temperature. Higher efficiency over a wide operating range is desirable due to the high price of batteries in EVs.
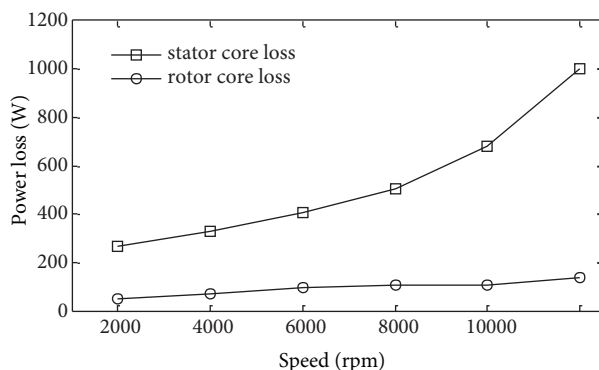
Figure 8. FE-predicted stator and rotor core loss of interior PMSM.

5. Conclusion

Design and analysis of an interior PMSM using fractional slot and concentrated windings for EV drive applications has been presented in this paper. The novelty of this paper is to propose a new IPM machine, which combines the advantage of concentrated windings and multilayer rotor topologies. Definitions, advantages, and disadvantages of fractional slot and concentrated windings topologies have been analyzed. For efficiency enhancement, loss components and related minimization strategies have been analyzed, as well. Both the classical analytical model and the advanced finite element method were employed to calculate and verify the electromagnetic performance of the interior PMSM. The high-performance interior PMSM will be a good candidate for EV drive applications. Experimental verification and evaluation will be published in future papers.

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