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A Concentrated Winding Permanent-Magnet Motor Improved with Magnetic Saturation

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Abstract—This paper proposes a core structure to achieve variable-flux characteristics enhanced by magnetic saturation in fractional-slot concentrated winding (FSCW) configurations. The magnetic saturation in the stator core achieves the variable-flux characteristics that are effective for decreasing electromotive force (EMF) with an identical torque or increasing torque with an identical EMF. The efficacy of the proposed design is determined by estimating motor performance through a finite element method analysis.

1. Introduction

Varible-flux characteristics have attracted much attention to achieve motor operation over a wide range of torque and speed in permanent-magnet (PM) motors [1]. High-torque operation requires high PM flux linkage under an input current limit. Low-torque operation requires low PM flux linkage under an input voltage limit. The PM flux linkage suited for each operating point minimizes copper and iron losses. The variability of PM flux linkage in operation is realized by many design methods [1] such as field winding excitation [2, 3], adjustable magnetization [4, 5], and mechanical flux regulation [6, 7, 8]. However, these design methods require additional excitation systems, complicated structures, or active controls.

Variable leakage-flux motors have been proposed to achieve variable-flux characteristics without additional excitation systems, complicated structures, or active controls [9, 10, 11]. Such motors positively induce magnetic saturation in iron cores to vary the PM flux linkage of armature windings. The magnetic saturation is indirectly controlled with the q-axis current. At high-torque operation, the magnetic saturation appears to enhance the PM flux linkage with large q-axis current. At low-torque operation, the magnetic saturation does not appear to suppress the PM flux linkage with small q-axis current. To realize these phenomena, magnetic paths are established between adjacent PM poles for the leakage flux of PMs in the rotors. At high-torque operation, the large input current induces magnetic saturation around the magnetic paths. This leads to suppress the PM flux through the paths to enhance the PM flux linkage of armature windings. At low-torque operation, the magnetic paths do not induce magnetic saturation, because of the small input current. This allows that the PM flux passes through the magnetic paths to suppress the PM flux linkage of armature windings. The PM flux through the magnetic paths is regarded as the leakage of the PM flux. Therefore, such motors simply achieve high-efficiency operations over a wide range of torque and speed without additional excitation systems, complicated structures, or active controls.

Fractional-slot concentrated winding (FSCW) configurations achieve lower cogging torque, lower copper loss, and shorter axial length design than integral-slot distributed winding configurations in PM motors [12, 13]. The FSCW configurations include several dominant space harmonics in the magnetic field due to the armature windings. One of them produces drive torque. The others increase loss without contributing to torque production [14, 15]. These dominant space harmonics induce magnetic saturation asymmetrically for each pole because of the different periodicities in the spatial distribution of the air-gap flux density.

The variable leakage-flux motors have been proposed in distributed winding configurations that generate the fundamental as a dominant space harmonic [9, 10, 11]. The space harmonic induces magnetic saturation symmetrically for each pole in the rotor cores. The magnetic saturation in the rotor cores contributes to the variable leakage-flux characteristics. Whereas, FSCW configurations with several dominant space harmonics do not effectively achieve the variable leakage-flux characteristics because magnetic saturation is induced asymmetrically for each pole in rotor cores. In this paper, variable-flux characteristics are achieved with magnetic saturation in stator cores for a 12-slot 10-pole concentrated winding (CW) configuration as one of FSCW configurations. Therefore, the proposed design decreases electromotive force (EMF) with an identical torque or increases torque with an identical EMF. The efficacy of the design concept is determined by estimating PM flux linkage of armature windings, torque, and motor performance through a finite-element method (FEM) analysis.

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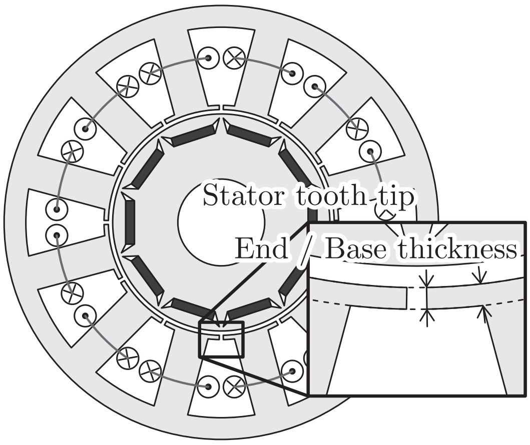
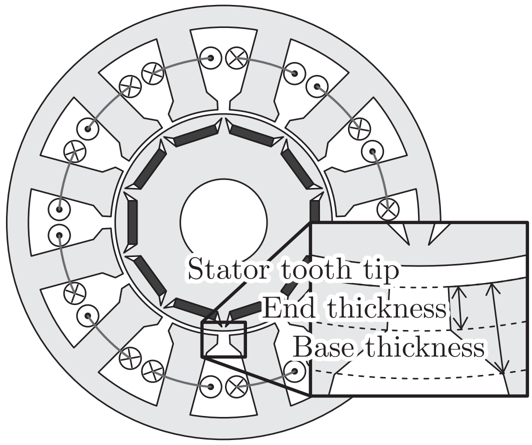


(a)



(b)

Figure 1: Cross sections of 12-slot 10-pole PM motors that have (a) a proposed stator (PROP) and (b) a conventional stator (CONV).

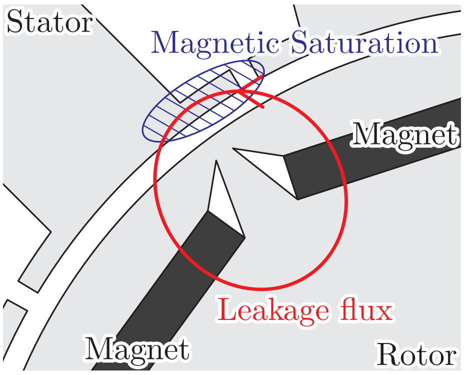


Figure 2: Conceptual diagram for the leakage of PM flux through a stator tooth tip in PROP.

Table 1: Dimesions of Analyzed Motors

	PROP	CONV
Stack length	50 mm	50.45 mm
Stator outer diameter	160 mm	160 mm
Rotor outer diameter	88 mm	88 mm
Air gap length	1 mm	1 mm
Stator yoke width	14 mm	14 mm
Stator tooth width	14 mm	14 mm
Stator tooth tip base thickness	2 mm	7 mm
Stator tooth tip end thickness	2 mm	3 mm
Stator slot opening width	4°	5°
Magnet thickness	3.5 mm	3.5 mm
Magnet width	16 mm	16 mm
Number of turns per coil	30	30

2. Analyzed Motors

The variable leakage-flux characteristics achieve variable-flux characteristics by passively controlling flux through magnetic circuits that consist of rotor magnets, stator windings, and cores with magnetic saturation. The variable leakage-flux characteristics in distributed winding configurations are achieved by magnetic saturation in rotor cores [9, 10, 11]. However, the variable leakage-flux characteristics are not effective in CW configurations. For CW motors, variable-flux characteristics similar to the variable leakage-flux characteristics in distributed winding configurations can be achieved by magnetic saturation in stator cores. Based on the concept, a 12-slot 10-pole CW motor is proposed to achieve variable-flux characteristics induced by magnetic saturation. Figs. 1(a) and (b) show the cross sections of analyzed motors, namely, the proposed motor, which is designated as PROP and a conventional 12-slot 10-pole CW motor, which is designated as CONV, for comparison. In PROP, the stator core has tooth tips that are thin from the base to the end for inducing magnetic saturation. The stator slot opening is narrower than that of CONV. Hence, the width of stator tooth tips is wider than that of CONV to establish magnetic paths for the leakage of PM flux in the stator, as shown in Fig. 2. The stator tooth tips saturated magnetically suppresses the leakage of PM flux. The dimensions of the analyzed motor are presented in Table 1. The dimensions of stator tooth tips are determined through an optimization with an FEM analysis.

3. FEM Analysis

This section performs an FEM analysis to determine the efficacy of PROP in comparison with CONV with ANSYS Maxwell. The efficacy of the proposed method is determined with variable-flux characteristics and motor performance.

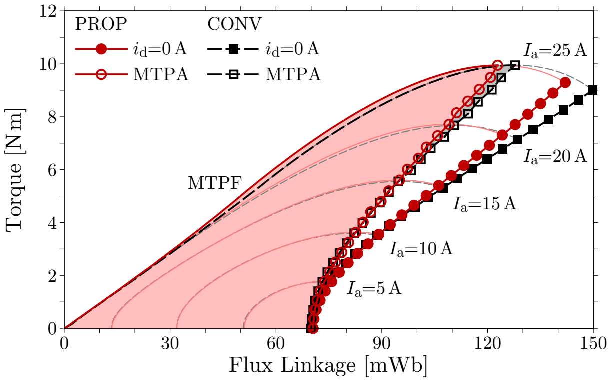


Figure 3: Operating regions for maximizing efficiency in the flux linkage and torque of PROP and CONV.

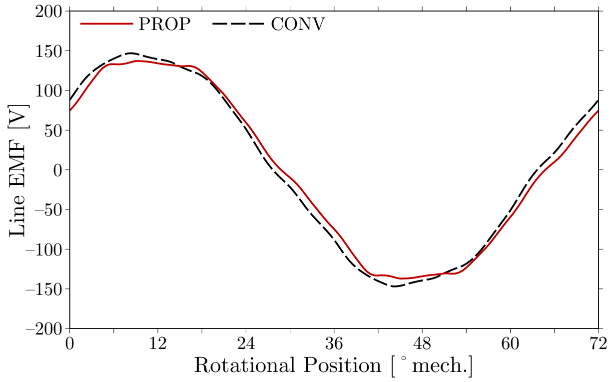
3.1. Variable-Flux Characteristics

Figure 3 shows the actual operating regions for maximizing efficiency, which are enclosed by the curves corresponding to maximum torque per ampere (MTPA) control, the curves corresponding to the maximum torque per flux-linkage (MTPF) control, and the lines for zero torque. The actual operating region of PROP appears in the area with lower flux linkage than that of CONV. The motor PROP produces an identical torque with lower flux linkage or lower EMF than CONV. At the maximum armature current $I_a = 25$ A on the MTPA control, the flux linkage decreases with the proposed stator by approximately 4.7 %. The proposed stator expands the operating region toward high speed range. This implies that the proposed stator improves the efficiency at each operating point. Therefore, the motor PROP exhibits more effective variable-flux characteristics than CONV.

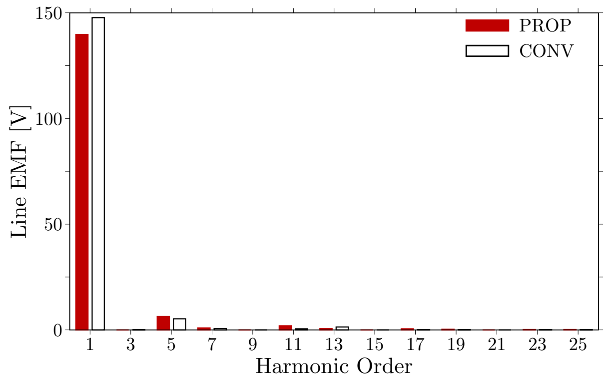
3.2. Motor Performances

Figure 4 shows the waveforms and the harmonic components of line EMF on the MTPA control for PROP and CONV at an armature current of 25 A and a rotational speed of 1 500 min^{-1}. On the MTPA control, the current phases β are set at 18° for PROP and at 21° for CONV. The current input causes differences between the waveforms of the EMF. The fundamental amplitudes of the EMFs are 141.00 V for PROP and 146.40 V for CONV. The proposed stator decreases the fundamental line EMF on the MTPA control by approximately 3.7 %. This corresponds to the decrease of the flux linkage, as shown in Fig. 3. The harmonic components are not significantly influenced by the proposed stator.

Figure 5 shows the waveforms of torque on the MTPA control for PROP and CONV at an armature current of 25 A. The average torque is 9.94 Nm. The torque ripple is slightly increased by the proposed stator. This is caused by the increased width of the stator tooth tips in the proposed design. Therefore, the proposed stator produces almost the identical torque in spite of the active induction of magnetic saturation.



(a)



(b)

Figure 4: Line EMF on the MTPA control at an armature current of 25 A and a rotational speed of 1 500 min^{-1} for PROP and CONV. (a) Waveform. (b) Harmonic components.

4. Concluding Remarks

A core structure is proposed to achieve variable-flux characteristics enhanced by magnetic saturation in FSCW configurations based on the variable leakage-flux motors. The proposed stator, which has thin tooth tips for inducing magnetic saturation, achieves effective variable-flux characteristics with magnetic saturation in the stator core. The proposed stator decreases the flux linkage or EMF with an identical torque or increases torque with an identical EMF. The efficacy of the proposed method is determined numerically. An FEM analysis shows that an expected performance is achieved by the proposed stator. The operational efficiency is shown in the presentation.

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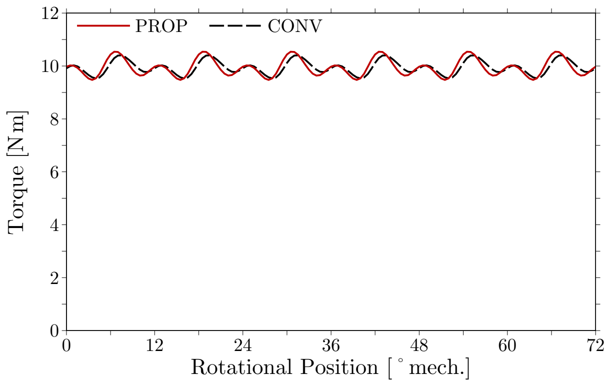

Figure 5: Torque on the MTPA control at an armature current of 25 A for PROP and CONV.

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