Effect of Load Characteristics on Demagnetization of Line-Start Permanent Magnet Synchronous Motors with Non-Uniform Air Gap Structure Postprint

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Abstract

The asynchronous-start permanent magnet synchronous motor with a non-uniform air gap structure is proposed to address the issues of large torque ripple and high electromagnetic noise during operation in conventional asynchronous-start permanent magnet synchronous motors, which are caused by complex air-gap magnetic field harmonics; the demagnetization characteristics of permanent magnets in this motor structure differ significantly from those in conventional motors. Based on the principle that magnetic field vectors are essentially identical at various locations within the permanent magnet, this paper employs the magnetic flux density at a single point inside the permanent magnet to characterize the flux density variation of the entire permanent magnet during operation, and conducts theoretical research and finite element simulation on the operating point of permanent magnets in asynchronous-start permanent magnet synchronous motors with non-uniform air gap structures. The factors affecting motor demagnetization are analyzed, the variation of permanent magnet flux density under different loads and moments of inertia is investigated, the variation patterns of the permanent magnet operating point during both steady-state operation and the starting process are obtained, and a research methodology for determining the minimum operating point of permanent magnet flux density is proposed.

Full Text

Preamble

Influence of Load Characteristics on Demagnetization of Line-Start Permanent Magnet Synchronous Motors with Non-Uniform Air Gap Structure

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Abstract

The line-start permanent magnet synchronous motor (LSPMSM) with non-uniform air gap structure is proposed to address issues such as high torque ripple and electromagnetic noise in conventional LSPMSMs caused by complex harmonic distortion in the air gap magnetic field. The demagnetization behavior of permanent magnets in this structure differs significantly from that in conventional motors. Based on the principle that the magnetic field vectors are essentially uniform throughout the permanent magnet, this paper uses the magnetic flux density at a single internal point to characterize the magnetic flux density variation of the entire permanent magnet during operation. Theoretical analysis and finite element simulation are conducted to investigate the operating point of permanent magnets in non-uniform air gap LSPMSMs. The factors influencing motor demagnetization are analyzed, and the magnetic flux density variation of permanent magnets under different loads and moments of inertia is examined. The variation patterns of permanent magnet operating points during steady-state operation and starting processes are obtained, and a research methodology for determining the minimum magnetic flux density operating point of permanent magnets is proposed.

Keywords: Permanent magnet synchronous motor, permanent magnet demagnetization, moment of inertia, line-start

1 Introduction

According to authoritative analysis reports, China' s total installed motor capacity is expected to increase to approximately 5 billion kW within the next 15–20 years. If this massive electricity demand continues to rely primarily on thermal power generation, fossil fuel consumption will increase substantially, and greenhouse gases and inhalable particulate matter will threaten ecological stability, severely testing environmental carrying capacity. Consequently, high-efficiency, high-power-factor permanent magnet motors represent the primary development direction for the motor industry. Compared with conventional induction motors, the "dual-high" characteristics (high power factor and high efficiency) are the most significant advantages of line-start permanent magnet synchronous motors. Moreover, compared with variable-speed permanent magnet synchronous motors, they possess self-starting capability, making them increasingly attractive for industrial production applications.

The demagnetization issue that occasionally occurs during permanent magnet motor operation has long troubled manufacturers and users. To prevent demagnetization, designs must verify the maximum demagnetization operating point and the knee point of the permanent magnet material' s demagnetization curve at operating temperature to enhance reliability and reduce production costs. Therefore, accurate analysis of permanent magnet motor performance and calculation of permanent magnet operating points are critically important. In conventional designs, the maximum demagnetization operating point is typically calculated using traditional magnetic circuit design methods. However, the equivalent magnetic circuit method yields only an average operating point and cannot account for local demagnetization, making it difficult to accurately reflect the actual operating condition of permanent magnets.

Previous literature has employed finite element numerical methods to calculate local element operating points of permanent magnets in variable-frequency permanent magnet motors without cage bars. For LSPMSMs, the magnetic field is more complex due to their unique structure, making accurate calculation of local operating points under maximum demagnetization field distribution challenging. Therefore, research on accurately calculating demagnetization fields within the motor is necessary. Some studies have improved permanent magnet demagnetization resistance by optimizing magnetic circuit structures, while others have enhanced demagnetization resistance by changing rotor cage materials to conductive and permeable composite materials without reducing starting capability, though this increases manufacturing costs. In terms of improving LSPMSM starting performance, some researchers have proposed pole-changing starting methods and optimized stator winding structures. However, all these studies on permanent magnet demagnetization methods have focused on conventional uniform air gap structures. This paper specifically investigates the demagnetization characteristics of the non-uniform air gap structure proposed to reduce air gap magnetic field harmonic content and suppress torque ripple.

2 Motor Model

This study examines the demagnetization characteristics of a 4-pole, 90 kW line-start permanent magnet synchronous motor. The basic electromagnetic parameters are listed in Table 1 .

Conventional LSPMSMs suffer from high core losses and electromagnetic noise primarily due to complex harmonic content in the air gap magnetic field. The non-uniform air gap structure effectively attenuates air gap magnetic field harmonics, thereby reducing losses and noise while improving motor performance. The rotor structure of this motor is shown in Figure 1a [Figure 1: see original paper]. The rotor outer surface consists of four arcs with centers offset from the stator outer circle, causing the air gap length to vary sinusoidally along the circumferential direction. Figure 1b illustrates one rotor pole, where O is the center of the rotor outer circle, t is the eccentric distance, and the cage bars are made of brass to prevent fusing due to high currents during starting.

The magnetic flux density at various points on the permanent magnet can be decomposed as shown in Figure 2 [Figure 2: see original paper]. The component along the magnetization direction represents the effective magnetic flux density, which can be calculated using Equation (1). When the Bg direction is opposite to the magnetization direction (as shown by B2 in Figure 2), the effective magnetic flux density of the permanent magnet becomes negative. The minimum value among all points' effective magnetic flux densities represents the minimum operating point of the permanent magnet, providing better reflection of local demagnetization conditions.

For non-uniform air gap structures, the air gap length varies with angle , as shown in Figure 3 [Figure 3: see original paper]. In the figure, 0 is the constant air gap length for a uniform air gap motor, O is the rotor outer circle center, O is the rotor inner circle center, R is the rotor outer radius for a uniform air gap motor, and R is the rotor inner radius. The air gap length is given by:

$$ = 0 + R - (R - R)\cos - \surd[R^2 - (R - R)^2\sin^2]$$

Equation (2) shows that the air gap length varies periodically with the central angle for non-uniform air gap structures, resulting in significantly different magnetic flux density distributions compared with uniform air gap motors and consequently altering permanent magnet operating points. Therefore, investigating the demagnetization characteristics of this special structure is essential.

Finite element analysis using Ansoft software reveals the magnetic flux density distribution in permanent magnets during rated load steady-state operation, as shown in Figure 4a [Figure 4: see original paper]. The magnetic flux density distribution is essentially uniform across the permanent magnet at any given moment, with slightly higher values at the ends. Figure 4b shows the flux line distribution at the same instant, demonstrating that flux lines are generally parallel to the magnetization direction, with slight deviation only at the permanent magnet ends. This confirms that magnetic flux density magnitude and direction are essentially uniform throughout the permanent magnet, with minor differences only at the edges due to flux concentration effects.

Based on this analysis, the magnetic flux density magnitude within the permanent magnet effectively reflects the strength of the demagnetization field. Finite element meshing of the permanent magnet is shown in Figure 5a [Figure 5: see original paper]. Analyzing the magnetic flux density along the centerline of the permanent magnet yields the curve shown in Figure 5b. During rated load steady-state operation, the magnetic flux density is essentially uniform along the centerline, with only slightly higher values at the ends. Therefore, the triangular element marked in Figure 5a can be selected as a reference point, with its magnetic flux density used to represent the entire permanent magnet's magnetic flux density.

A comparative finite element analysis of the starting process for conventional uniform air gap and non-uniform air gap motors was conducted. Both motors are identical except for their rotor structures, operating with a rated load torque of 573 N · m and considering a total moment of inertia of 0.85 kg · m² for the rotor and load system. The speed variation and permanent magnet magnetic flux density during starting were compared.

Figure 6a [Figure 6: see original paper] shows the starting speed curves for both structures. Both motors start successfully and reach synchronous operation, though the non-uniform air gap motor requires longer starting time with greater speed fluctuations. Figure 6b compares the permanent magnet magnetic flux density during starting. The non-uniform air gap structure exhibits larger fluctuations in permanent magnet magnetic flux density, and the operating point is lower after reaching synchronous steady state. Consequently, the demagnetization characteristics of non-uniform air gap LSPMSMs differ significantly from conventional motors, necessitating dedicated investigation.

3 Load Characteristics and Permanent Magnet Demagnetization

During starting of non-uniform air gap motors, the steady-state back EMF is not established, resulting in large inrush currents. Due to slip, large currents are also induced in the rotor cage bars. Both stator and rotor currents affect the permanent magnet operating point magnetic flux density, potentially causing demagnetization. Therefore, further investigation of permanent magnet demagnetization during starting is necessary to analyze demagnetization factors and summarize demagnetization patterns.

3.1 Influence of Load Torque on Demagnetization

Considering the motor rotor' s inherent moment of inertia of 0.85 kg · m², the influence of different load torques on speed and permanent magnet magnetic flux density during starting was analyzed. Figures 7 [Figure 7: see original paper] and 8 [Figure 8: see original paper] show the speed curves and permanent magnet magnetic flux density variation curves for non-uniform air gap motors starting under no-load, rated load torque, and 1.5 times rated load torque conditions.

The speed curves in Figure 7 indicate that during the first 50 ms of starting, the speed fluctuates upward under all load conditions but remains low (below 420 r/min). During this period, the slip remains large and cage currents are substantial, preventing the permanent magnet magnetic flux density from reaching its minimum value. This represents the demagnetization shielding effect of the starting cage during the initial starting phase. As the motor is gradually pulled into synchronization, the shielding effect diminishes and the most severe demagnetization occurs. For example, under rated load starting, the minimum permanent magnet magnetic flux density occurs at 75 ms with a value of 0.15 T at approximately 960 r/min.

During steady-state operation, the rotor cage bars carry no current, and the rotor magnetomotive force (MMF) is generated solely by the permanent magnets. The fundamental MMF relationship between stator and rotor during steady-state operation is shown in Figure 9 [Figure 9: see original paper]. The stator MMF and permanent magnet MMF remain relatively stationary with a constant angle Δ . As motor load increases, stator current increases, resulting in larger stator MMF amplitude F1 and increased angle Δ , which reduces the steady-state permanent magnet magnetic flux density. For the non-uniform air gap motor, the steady-state permanent magnet magnetic flux density is 0.94 T under no-load, 0.79 T under rated load torque, and 0.68 T under 1.5 times rated load torque.

3.2 Influence of Moment of Inertia on Demagnetization

For the non-uniform air gap motor operating under the same load torque (rated torque of 573 N · m), the entire starting process from 0 to 1500 r/min was analyzed for different moments of inertia. The ratio of the actual system moment of inertia to the rotor' s inherent moment of inertia is defined as the moment of inertia multiplier. Starting processes with multipliers of 1, 3, and 6 were investigated, yielding the speed and permanent magnet magnetic flux density curves shown in Figures 10 [Figure 10: see original paper] and 11 [Figure 11: see original paper].

Figure 10 demonstrates that with larger moment of inertia, the motor starting time increases. Figure 11 shows that the permanent magnet magnetic flux density operating point exhibits 3 minimum values for a multiplier of 1, 8 minimum values for a multiplier of 3, and 16 lower points for a multiplier of 6. Larger moment of inertia creates more severe demagnetization conditions for the permanent magnet. After stabilizing at synchronous speed, all three cases operate with rated torque load, resulting in identical stator steady-state current values and stator MMF amplitude F1. Consequently, the permanent magnet magnetic flux density operating point is the same in steady state (0.79 T) for all cases.

4 Relationship Between Permanent Magnet Demagnetization and Load Characteristics

Further investigation of the relationship between the minimum permanent magnet magnetic flux density and load torque as well as moment of inertia during starting of non-uniform air gap LSPMSMs yields the relationship curves shown in Figures 12 [Figure 12: see original paper] and 13 [Figure 13: see original paper]. Figure 12 shows the relationship between minimum permanent magnet magnetic flux density and load torque for constant-torque starting with different torque multiples when the system moment of inertia equals the rotor' s inherent value. Figure 13 shows the relationship between minimum permanent magnet magnetic flux density and moment of inertia for constant-torque starting at rated torque with different moment of inertia multipliers. These figures reveal no discernible pattern in the variation of minimum magnetic flux density, indicating that changing load torque or moment of inertia values during starting does not produce a predictable pattern for minimum permanent magnet magnetic flux density occurrence.

During starting of non-uniform air gap motors, the combined MMF of rotor cage bars and permanent magnets rotates relative to the stator armature MMF, causing the angle Δ to vary. If both load torque and moment of inertia are small (e.g., no-load starting), the starting time is short, and the probability of the combined rotor MMF being opposite to the stator armature MMF (Δ = 180°) is low, resulting in a low probability of minimum permanent magnet magnetic flux density occurrence. Conversely, when both load torque and moment of inertia are large (e.g., rated load torque with 6 times the rotor' s inherent moment of inertia), the starting time is long, significantly increasing the probability of the combined rotor MMF opposing the maximum stator armature MMF and thus increasing the probability of minimum permanent magnet magnetic flux density occurrence.

The most severe demagnetization occurs during the pull-in synchronization process when the rotor approaches synchronous speed, cage currents are small (reducing shielding effect), and stator armature current remains large. For motors with short starting times, the maximum demagnetization condition (Δ = 180°) may not occur during the pull-in process from 80% to 100% synchronous speed, necessitating further investigation to determine the maximum demagnetization operating point.

In finite element simulation, setting the moment of inertia sufficiently large prevents the motor from pulling into synchronous operation. This characteristic can be exploited to accurately obtain the minimum permanent magnet magnetic flux density operating point for constant-torque starting. Figure 15 [Figure 15: see original paper] shows the speed and permanent magnet magnetic flux density curves when the motor fails to pull into synchronization under constant-torque starting (rated torque 573 N·m) with 10 times the rotor' s inherent moment of inertia.

As shown in Figure 15, when the drive system moment of inertia is sufficiently large, the non-uniform air gap LSPMSM cannot pull into synchronization, and the speed fluctuates below synchronous speed. The permanent magnet magnetic flux density also fluctuates dramatically, with the minimum value continuously decreasing until stabilizing at approximately 0.2 T at about 1427 r/min. Under these large moment of inertia starting conditions, the angle Δ between the stator armature MMF and the combined rotor MMF varies periodically between 0° and 360°. Applying this simulation method during the starting process can identify the minimum operating point of permanent magnet magnetic flux density.

Conclusions

This paper analyzes the demagnetization characteristics of permanent magnets in a 90 kW, 4-pole line-start permanent magnet synchronous motor with non-uniform air gap structure. By analyzing magnetic flux density variation at a specific point within the permanent magnet, the demagnetization behavior during starting and steady-state operation is investigated, yielding the following conclusions:

1. Compared with conventional motors, non-uniform air gap structures exhibit longer starting times with greater fluctuations in permanent magnet magnetic flux density during starting, and lower magnetic flux density after reaching synchronous steady state.
2. For non-uniform air gap motors, larger load torque results in greater fluctuations in permanent magnet magnetic flux density during starting and lower steady-state magnetic flux density. As the system moment of inertia increases, starting time extends and fluctuation frequency increases, but the steady-state operating point remains identical. During starting, no definitive relationship exists between load torque, moment of inertia, and the minimum permanent magnet operating point due to the continuously changing relative position between stator armature MMF and the combined rotor MMF.
3. In finite element simulation, setting the moment of inertia sufficiently large to prevent the motor from pulling into synchronous speed—causing speed to fluctuate around a value slightly below synchronous speed—enables accurate determination of the minimum permanent magnet magnetic flux density operating point for constant-torque starting.

The research presented herein provides valuable reference for motor designers to more accurately and comprehensively consider permanent magnet demagnetization conditions and estimate maximum demagnetization operating points, thereby improving design rationality.

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