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

Authors: Chen Lei, Wu Changjiang, Bao Xiaohua

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Abstract

Asynchronous-start permanent magnet synchronous motors with non-uniform air gap structures are proposed to address the problems of large torque ripple and high electromagnetic noise during operation in conventional asynchronous-start permanent magnet synchronous motors caused by complex air gap magnetic field harmonics. The demagnetization behavior of permanent magnets in this structural motor differs significantly from that in conventional motors. Based on the principle that the magnetic field vectors at various locations within the permanent magnet are essentially identical, this paper employs the magnetic flux density at a single point inside the permanent magnet to characterize the variation of magnetic flux density throughout 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 magnetic flux density in permanent magnets under different loads and moments of inertia is investigated, the changing patterns of permanent magnet operating points during steady-state operation and starting process are obtained, and a research methodology for determining the minimum magnetic flux density operating point of permanent magnets is proposed.

Full Text

Preamble

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

Chen Lei, Wu Changjiang, Bao Xiaohua
(School of Electrical Engineering and Automation, Hefei University of Technology, Hefei 230009, China)

Abstract

The line-start permanent magnet synchronous motor (LSPMSM) with non-uniform air gap structure is proposed to address the problems of high torque ripple and electromagnetic noise in conventional LSPMSMs caused by complex harmonic distortion in the air gap magnetic field. The demagnetization characteristics of the permanent magnets in this structural configuration differ significantly from those in ordinary motors. Based on the principle that the magnetic field vectors are essentially uniform throughout the permanent magnet material, this paper uses the magnetic flux density at a single internal point to represent the magnetic state of the entire permanent magnet during operation. Theoretical analysis and finite element simulation are conducted to investigate the operating points of permanent magnets in non-uniform air gap LSPMSMs. The factors influencing motor demagnetization are analyzed, and the variation of permanent magnet flux density under different load conditions and moment of inertia values is examined. The variation patterns of permanent magnet operating points during both steady-state operation and starting processes are obtained, and a research methodology for determining the minimum 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 [1], the total installed capacity of electric motors in China is expected to increase to approximately 5 billion kW within the next 15 to 20 years. If such enormous power consumption continues to rely primarily on thermal power generation, fossil fuel consumption will increase dramatically, while greenhouse gases and inhalable particulate matter will threaten ecological stability and severely test environmental carrying capacity. Consequently, high-efficiency, high-power-factor permanent magnet motors represent the primary development direction for the motor industry [2-3]. 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, unlike adjustable-speed permanent magnet synchronous motors, LSPMSMs possess self-starting capability, making them increasingly attractive for industrial applications [4].

The persistent demagnetization issues that occur during permanent magnet motor operation have 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 [5].

Accurate prediction of the maximum demagnetization operating point is essential for the electromagnetic design of permanent magnet motors. Traditional designs typically calculate the maximum demagnetization operating point using conventional magnetic circuit methods [6]. 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 state 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 [7]. For LSPMSMs, due to their unique structural characteristics, the internal magnetic field is more complex, making accurate calculation of local operating points under maximum demagnetization field distribution more challenging.

Consequently, research on accurately calculating demagnetization fields within the motor to determine the maximum demagnetization operating point is necessary. Existing literature has improved permanent magnet demagnetization resistance by optimizing magnetic circuit structures. For instance, reference [8] analyzed demagnetization conditions for three different rotor magnetic circuit structures as functions of power angle and rotor position, demonstrating that the proposed average flux density analysis method can accurately evaluate permanent magnet demagnetization performance. Reference [9] improved demagnetization resistance by changing rotor cage bar materials to conductive and magnetic composite materials, achieving this without reducing motor starting capability, though at increased manufacturing cost. Regarding starting performance improvement in LSPMSMs, reference [10] proposed a 6/8 pole-changing starting permanent magnet synchronous motor that enhanced starting performance through optimized stator winding structures. The aforementioned research methods and works focused on ordinary uniform air gap permanent magnet motors. 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 investigates the demagnetization characteristics of a 4-pole, 90 kW LSPMSM. The basic electromagnetic parameters of the motor are listed in Table 1 .

The fundamental reason for high core losses and electromagnetic noise in ordinary uniform air gap LSPMSMs is the complex harmonic content in the air gap magnetic field. The rotor structure of a non-uniform air gap LSPMSM can effectively weaken air gap magnetic field harmonics, thereby reducing losses and noise while improving motor performance. This rotor structure is illustrated in Figure 1a [Figure 1: see original paper]. The rotor outer surface consists of four circular arcs with centers offset from the stator outer circle, causing the air gap length to vary sinusoidally along the circumferential direction from large to small and back to large. Figure 1b shows a schematic diagram of one rotor pole, where O is the center of the rotor outer circle, O is the center of the rotor inner circle, and t represents the eccentric distance. The rotor is equipped with damping cage bars made of brass, which prevents the bars from fusing due to overheating during the starting process when currents are large.

When the motor has a non-uniform air gap structure, the air gap length varies with angle , as shown in Figure 3 [Figure 3: see original paper]. In the diagram, 0 represents the constant air gap length when the air gap is uniform, O is the center of the rotor outer circle, O is the center of the rotor inner circle, R is the rotor outer diameter when the air gap is uniform, and R is the rotor inner radius. The air gap length is given by:

$$\delta_\theta = \delta_0 + R - \sqrt{R'^2 - (R - R')^2 \sin^2\theta} - (R - R')\cos\theta$$

Equation (2) demonstrates that the air gap length varies periodically with the central angle in a non-uniform air gap configuration, resulting in significantly different magnetic flux density distributions compared to uniform air gap motors and consequently altering the permanent magnet operating points. Therefore, investigation of the demagnetization characteristics specific to this non-uniform air gap structure is necessary.

As shown in Figure 2 [Figure 2: see original paper], the magnetic flux density at various points on the permanent magnet can be decomposed, with the component along the magnetization direction representing the effective flux density. The effective flux density 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 flux density of the permanent magnet becomes negative. The minimum value obtained after calculating the effective flux density at each point represents the minimum operating point of the permanent magnet. This calculation method better reflects local demagnetization conditions.

$$B_g = B\cos\phi$$

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

The above analysis indicates that the magnetic flux density magnitude within the permanent magnet essentially reflects the strength of the demagnetization field. Finite element meshing of the permanent magnet is shown in Figure 5a [Figure 5: see original paper]. Investigating the magnetic flux density at points along the permanent magnet centerline yields the curve shown in Figure 5b. During rated load steady-state operation at this moment, the magnetic flux density at various points along the centerline is essentially identical, with only slightly higher values at the ends. Therefore, the triangular element marked in Figure 5a can be selected as a magnetic flux density reference point, with its calculated flux density representing the magnetic state throughout the permanent magnet.

A comparative finite element analysis of the starting process was conducted for both ordinary uniform air gap and non-uniform air gap motors. The two motors differ only in rotor structure, both carrying rated load torque of 573 N • m and considering a combined moment of inertia of 0.85 kg • m² for the rotor and load system. The speed variation and permanent magnet flux density changes during motor starting were compared.

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

3 Load Characteristics and Permanent Magnet Demagnetization

During the starting process of non-uniform air gap motors, the steady-state back EMF is not yet 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 flux density, potentially causing demagnetization. Therefore, further investigation of permanent magnet demagnetization phenomena during the starting process of non-uniform air gap LSPMSMs 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 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 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 motor slip remains large and cage bar currents are substantial, preventing the permanent magnet flux density from reaching its minimum value. This represents the demagnetization shielding effect of the starting cage on the permanent magnets during the initial starting stage. As the motor is gradually pulled into synchronization, the shielding effect of the starting cage diminishes, and the most severe demagnetization occurs. For example, under rated load starting, the minimum permanent magnet flux density occurs at 75 ms as 0.15 T, corresponding to a speed of approximately 960 r/min.

When the motor enters steady-state operation, the rotor cage bars carry no current, and the rotor magnetomotive force (MMF) is generated entirely by the permanent magnets. During steady state, the fundamental MMF relationship between stator and rotor is shown in Figure 9 [Figure 9: see original paper]. The stator MMF remains stationary relative to the permanent magnet MMF with a constant angle Δ . As motor load increases, stator current increases, the stator MMF amplitude F1 grows larger, and the angle Δ increases accordingly, reducing the steady-state permanent magnet flux density. For the non-uniform air gap motor, the steady-state permanent magnet 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 under constant load torque (rated torque of 573 N · m), the entire starting process from 0 to 1500 r/min was analyzed for different moment of inertia values. The influence of moment of inertia on permanent magnet flux density during starting was investigated by defining the ratio of the actual motor system moment of inertia to the rotor’ s inherent moment of inertia as the inertia multiplier. Starting conditions with inertia multipliers of 1, 3, and 6 were selected, yielding the speed and permanent magnet flux density curves shown in Figures 10 [Figure 10: see original paper] and 11 [Figure 11: see original paper].

Figure 10 demonstrates that under constant load torque, larger moment of inertia results in longer starting time. The permanent magnet flux density operating point exhibits three minimum values for an inertia multiplier of 1, eight minimum values for a multiplier of 3, and sixteen lower points for a multiplier of

6. Larger moment of inertia creates more severe demagnetization conditions for the permanent magnets. After stabilizing at synchronous speed, all three cases operate under rated torque load with identical stator steady-state current values and stator MMF amplitude F1, resulting in the same permanent magnet flux density operating point of 0.79 T.

4 Relationship Between Permanent Magnet Demagnetization and Load Characteristics

Further investigation of the relationship between the minimum permanent magnet flux density and both load torque and moment of inertia during starting of non-uniform air gap LSPMSMs yielded 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 flux density and load torque when the motor load system' s moment of inertia equals the rotor' s inherent value under constant torque starting at different torque multiples. Figure 13 shows the relationship between minimum permanent magnet flux density and motor moment of inertia under constant torque starting at rated torque with different inertia multipliers. The variation trends in these figures reveal no discernible pattern in the minimum flux density values. Therefore, changing either the load torque or moment of inertia during motor starting does not yield predictable patterns for the occurrence of minimum permanent magnet flux density.

During starting of non-uniform air gap motors, the combined MMF of rotor cage bars and permanent magnets moves relative to the stator armature MMF, with the angle Δ continuously varying. If both load torque and moment of inertia are small (e.g., no-load condition), 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 flux density occurrence. Conversely, when both load torque and moment of inertia are large (e.g., rated load torque with six times the rotor' s inherent moment of inertia), the starting time is prolonged, significantly increasing the probability of the combined rotor MMF opposing the maximum stator armature MMF and resulting in a higher probability of minimum permanent magnet flux density occurrence.

Permanent magnets are most vulnerable to severe demagnetization during the synchronization pull-in process because the rotor approaches synchronous speed with reduced cage bar current, diminishing the shielding effect, while stator armature current remains large. For motors with short starting times, the maximum demagnetization condition where the stator armature MMF opposes the rotor permanent magnet MMF (Δ = 180°) may not necessarily occur during the pull-in process from 80% to 100% synchronous speed, necessitating further investigation of the maximum demagnetization operating point.

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

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

Conclusions

This paper analyzes the demagnetization characteristics of permanent magnets in a 90 kW-4 pole non-uniform air gap LSPMSM. By analyzing flux density variations at a specific point within the permanent magnet to reflect demagnetization conditions during starting and steady-state operation, the following conclusions are drawn:

1. Compared with ordinary motors, non-uniform air gap structures exhibit longer starting times with greater permanent magnet flux density fluctuations during starting, and lower permanent magnet flux density after reaching synchronous steady state.
2. For non-uniform air gap motors, larger load torque results in greater permanent magnet flux density fluctuations during starting and lower steady-state flux density. As the motor system' s moment of inertia increases, starting time extends and flux density fluctuation frequency increases, though the steady-state operating point remains identical. During starting, no definite 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 flux density operating point under constant torque starting conditions.

The research content of this paper provides valuable reference for motor designers to more accurately and comprehensively consider permanent magnet demagnetization conditions and predict maximum demagnetization operating points, thereby improving the rationality of motor designs.

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