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Effect of Load Characteristics on Demagnetization in 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 arise from complex air-gap magnetic field harmonics; the demagnetization characteristics of permanent magnets in this structure differ substantially from those in conventional motors. Based on the principle that magnetic field vectors are essentially identical throughout the permanent magnet, this paper employs the magnetic flux density at a single internal point to characterize the variation of magnetic flux density in the entire permanent magnet during operation, and conducts theoretical investigation and finite element simulation on the operating points of permanent magnets in asynchronous-start permanent magnet synchronous motors with non-uniform air gap structures. The factors influencing motor demagnetization are analyzed, the magnetic flux density variation in permanent magnets under different loads and moments of inertia is investigated, the evolution 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.

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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 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 this structural permanent magnet differ significantly from those of ordinary motors. Based on the principle that the magnetic field vectors are essentially identical throughout the permanent magnet, this paper uses the magnetic flux density at a single internal point to represent the magnetic density variation of the entire permanent magnet during operation. Theoretical investigation and finite element simulation are conducted on the working points of permanent magnets in LSPMSMs with non-uniform air gap structures. The factors influencing motor demagnetization are analyzed, and the magnetic density variation of permanent magnets under different loads and moments of inertia is examined. The variation patterns of permanent magnet working points during both steady-state operation and starting processes are obtained, and a research methodology for determining the minimum working 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 nationwide is expected to increase to approximately 5 billion kW within the next 15–20 years. If this enormous electricity consumption 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 [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, compared with adjustable-speed permanent magnet synchronous motors, they possess self-starting capability, making their use and promotion in industrial production increasingly attractive [4].

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 working 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 methods for permanent magnet working points are critically important [5]. Accurate prediction of the maximum demagnetization working point is essential for the electromagnetic design of permanent magnet motors. In traditional designs, the maximum demagnetization working point is typically calculated using conventional magnetic circuit design methods [6]. However, the maximum demagnetization working point obtained through equivalent magnetic circuit methods represents only an average working point and cannot account for local demagnetization of the permanent magnet, making it difficult to accurately reflect the actual operating state of the magnet.

Existing literature has employed finite element numerical methods to calculate local element working points of permanent magnets in variable-frequency permanent magnet motors without cage structures [7]. For line-start permanent magnet synchronous motors, however, the magnetic field is more complex due to their unique structure, making accurate calculation of local working points under maximum demagnetization field distribution particularly challenging. Therefore, research on accurately calculating demagnetization fields within the motor is necessary to determine the maximum demagnetization working point precisely. Previous studies have improved permanent magnet demagnetization resistance by optimizing magnetic circuit structures [8], analyzing demagnetization conditions of permanent magnets in three different rotor magnetic circuit structures as functions of power angle and rotor position. The proposed average flux density analysis method can accurately evaluate permanent magnet demagnetization performance. Other research [9] has enhanced demagnetization resistance by changing rotor cage materials to conductive and magnetic composite materials, though this increases manufacturing costs. Regarding improvement of LSPMSM starting performance, literature [10] proposed a 6/8 pole-changing starting permanent magnet synchronous motor that improves starting performance by optimizing stator winding structure. The aforementioned research on permanent magnet demagnetization methods and work primarily focuses on ordinary uniform air gap structure permanent magnet motors. This paper specifically investigates the demagnetization of permanent magnets in non-uniform air gap structure LSPMSMs designed to reduce air gap magnetic field harmonic content and suppress torque ripple.

2 Motor Model

This study investigates the demagnetization characteristics using a 90kW, 4-pole line-start permanent magnet synchronous motor as an example. The basic electromagnetic parameters of the motor are shown in Table 1 .

The fundamental cause of high iron losses and electromagnetic noise in ordinary line-start permanent magnet synchronous motors 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. The rotor structure is illustrated in Figure 1a [Figure 1: see original paper]. The rotor outer surface consists of four circular arcs with centers that are not concentric with 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, and t is the eccentric distance. The rotor is equipped with damping bars made of brass, which prevents the bars from fusing due to overheating during the starting process when currents are large.

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, 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 working point of the permanent magnet. This calculation method better reflects local demagnetization conditions.

Bg = B cos!

For motors with 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 when the motor has uniform air gap, O is the center of the rotor outer circle, O is the center of the rotor inner circle, R is the rotor outer diameter with uniform air gap, and R is the rotor inner radius. The air gap length   is given by:

!! =!0 + R ! (R ! “R)cos” ! “R 2 ! (R !” R)2 sin 2 ”

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

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

Based on the above analysis, the magnetic flux density magnitude within the permanent magnet essentially reflects the strength of the demagnetization field. The finite element mesh of the permanent magnet is shown in Figure 5a [Figure 5: see original paper]. Investigating the magnetic density at points along the magnet centerline yields the curve shown in Figure 5b. During rated load steady-state operation at this instant, the magnetic 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 density reference point, with its magnetic density calculated to represent the entire permanent magnet.

A comparative finite element analysis of the starting process demagnetization characteristics was conducted for motors with ordinary uniform air gap and non-uniform air gap structures. The two motors differ only in their rotor designs, both carrying a rated load torque of 573 $\mathrm{N \cdot m}$ and considering a combined moment of inertia of the rotor and load system of 0.85 $\mathrm{kg \cdot m^2}$. The speed variation and permanent magnet magnetic density during starting were compared.

Figure 6a [Figure 6: see original paper] shows the starting speed of motors with uniform and non-uniform air gap structures. Both motors start successfully and reach synchronous operation with similar speed trends, but the non-uniform air gap motor requires longer starting time and exhibits greater speed fluctuations. Figure 6b compares the permanent magnet magnetic density during starting. The non-uniform air gap structure exhibits larger fluctuations in permanent magnet magnetic density, and the permanent magnet working point is lower when reaching synchronous steady state. Consequently, the demagnetization characteristics of permanent magnets in non-uniform air gap structure motors differ significantly from those in ordinary motors, necessitating dedicated research.

3 Load Characteristics and Permanent Magnet Demagnetization

During the starting process of non-uniform air gap structure 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 working point magnetic 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 effects of different load torques during starting on speed and permanent magnet magnetic density were analyzed. Figures 7 [Figure 7: see original paper] and 8 [Figure 8: see original paper] show the speed curves and permanent magnet magnetic density variation curves for non-uniform air gap structure 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, resulting in large cage currents, while the permanent magnet magnetic density does not reach 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 on the rotor permanent magnets diminishes, and the most severe demagnetization occurs. For example, under rated load starting conditions, the minimum permanent magnet magnetic density occurs at 75 ms with a value of 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 operation, the fundamental relationship between stator and rotor MMFs 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, the stator current increases, resulting in a larger stator MMF amplitude F1 and a correspondingly larger angle Δ , which reduces the steady-state permanent magnet magnetic density. For the non-uniform air gap structure motor, the no-load permanent magnet magnetic density is 0.94 T, decreasing to 0.79 T under rated load torque and further to 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 structure 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 moment of inertia of the motor system to the rotor' s inherent moment of inertia is defined as the inertia multiplier. Starting conditions with inertia multipliers of 1, 3, and 6 were selected, yielding the speed and permanent magnet magnetic density curves shown in Figures 10 [Figure 10: see original paper] and 11 [Figure 11: see original paper].

As shown in Figure 10, with constant load torque, larger moment of inertia results in longer starting time. Figure 11 reveals that the permanent magnet magnetic density working point exhibits three minima for an inertia multiplier of 1, eight minima for a multiplier of 3, and sixteen minima for a multiplier of 6. Larger moment of inertia creates a more severe demagnetization environment for the permanent magnet. 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 magnetic density working point of 0.79 T during steady-state operation.

4 Relationship Between Permanent Magnet Demagnetization and Load Characteristics

Further investigation of the relationship between the minimum permanent magnet magnetic density and both load torque and 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 magnetic density and load torque for constant-torque starting with different torque multiples when the motor load system' s moment of inertia equals the rotor' s inherent value. Figure 13 shows the relationship between minimum magnetic density and motor moment of inertia for constant-torque starting at rated torque with different inertia multipliers. The trends in both figures demonstrate that the variation of minimum magnetic density follows no discernible pattern. Therefore, changing the torque value or moment of inertia value of the load system during motor starting cannot establish a predictable relationship for the occurrence of minimum permanent magnet magnetic density.

During starting of non-uniform air gap structure 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 the load torque and moment of inertia of the motor system are small (e.g., no-load condition), the starting time is short, and the probability that the combined MMF of rotor cage bars and permanent magnets becomes opposite to the stator armature MMF (Δ = 180°) is low, resulting in a low probability of minimum permanent magnet magnetic 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 long, substantially increasing the probability that the combined MMF of rotor cage bars and permanent magnets becomes opposite to the maximum stator armature MMF, thus increasing the probability of minimum permanent magnet magnetic density occurrence.

Permanent magnets are most susceptible to severe demagnetization during the synchronization process because the rotor is near synchronous speed, cage currents are small (weakening the shielding effect), while the motor has not yet achieved synchronous operation and stator armature current remains large. For motors with short starting times, the maximum demagnetization condition where the maximum stator armature MMF opposes the rotor permanent magnet MMF ($\Delta = 180°$) may not necessarily occur during the synchronization process from 80% to 100% synchronous speed, necessitating further investigation to determine the maximum demagnetization working point.

In finite element simulation, setting the motor system' s moment of inertia too large prevents the motor from pulling into synchronous operation. This characteristic can be utilized to accurately obtain the minimum working point of permanent magnet magnetic density for a given constant-torque load during starting. Figure 15 [Figure 15: see original paper] shows the speed and permanent magnet magnetic density curves when the motor fails to pull into synchronization under constant-torque starting (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 can only fluctuate below synchronous speed. The permanent magnet magnetic density also fluctuates violently, with the minimum value 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 MMF of rotor cage bars and permanent magnets varies periodically between 0° and 360°. Applying this simulation method during the motor starting process can identify the minimum working point of permanent magnet magnetic density.

5 Conclusion

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

1. Compared with ordinary motors, non-uniform air gap structures exhibit longer starting times, larger fluctuations in permanent magnet magnetic density during starting, and lower magnetic density values after achieving synchronous steady-state operation.
2. For non-uniform air gap structure motors, larger load torque results in greater fluctuations in permanent magnet magnetic density during starting and lower steady-state magnetic density values. As the motor system' s moment of inertia increases, starting time extends and the number of magnetic density fluctuations increases, but the permanent magnet working point remains identical after reaching steady state. During the starting process, no definitive relationship exists between load torque, moment of

inertia, and the minimum permanent magnet working point due to the continuously changing relative position between stator armature MMF and the combined MMF of rotor cage bars and permanent magnets.

3. In finite element simulation, setting the moment of inertia sufficiently large to prevent the motor from pulling into synchronous speed—causing the motor speed to fluctuate around a value slightly below synchronous speed—enables accurate determination of the minimum permanent magnet magnetic density working point during constant-torque load starting.

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

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