Irreversible Demagnetization of a Large Capacity Line-Start Permanent Magnet Synchronous Motors considering Influence of Permanent Magnet Temperature

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1. Introduction

Line-start permanent magnet synchronous motor (LSPMSM) has been widely investigated for its high efficiency and power factor advantage in recent years. A large number of literatures pay more attention to the electromagnetic performance and novel topological structure of LSPMSM [1–8], and intelligent algorithms have been applied to deal with problems such as limited installation space and criteria for successful synchronization [9]. However, large capacity LSPMSM does not need to use expensive high-voltage inverters, which further reduces the cost of enterprises, and thus has been promoted and paid attention by researchers [2–4].

The phenomenon of irreversible demagnetization (ID) is not conducive to the development and application of permanent magnet synchronous motors. In order to solve the adverse effects of demagnetization, the authors in [10–14] analyzed the strength of antidegradation ability under different rotor structures.

Compared with the small capacity motor, the load connected by the large capacity motor has characteristic of large moment of inertia, which leads to prolong startup time of the motor [15–17]. Furthermore, the accumulation of rotor loss because of startup time extension will aggravate the temperature rise of PMs.

However, less attention has been paid to the ID problem of LSPMSM considering the temperature of PMs [18]. Considering the effects of both electromagnetic and temperature on LSPMSM, an electromagnetic-temperature coupling model was created and analysis software was developed. Furthermore, the coupling model further proves the difference of the area of the ID region with different temperatures of PM. However, the effect of ID on the performance of motor is not discussed, so it is necessary to study the ID phenomenon considering the effect of PMs’ temperature to protect the LSPMSM.

In this paper, the prototype 630 kW LSPMSM is fabricated, and the characteristics of different demagnetization magnetomotive forces (MMFs) in the starting process are studied. The magnetic flux density curves of PMs at different positions are compared. When the demagnetization ratio of PMs reaches a certain level, the motor fails to pull-in and cannot operate at synchronous speed. According to the
analysis in this paper, LSPMSM can reduce the temperature of PMs by improving the cooling ability of rotor to avoid demagnetization in the stage of pull-in.

2. Structure of the LSPMSM

The structure of the LSPMSM is shown in Figure 1, and the PM is divided into four segments for easy fabrication at each pole. The electromagnetic parameters of motor are shown in Table 1. The PMs’ material demagnetization curves at different temperature are shown in Figure 2, and the knee points on the demagnetization curve are 0, 0.2, and 0.4 tesla when the temperature of PMs is 100°C, 120°C, and 150°C, respectively. The increase of temperature not only enhances knee point but also decreases the demagnetization curve to a certain extent. At the same coercivity, the magnetic flux density amplitude of PMs with high temperature is lower.

3. Demagnetization Mechanism of PMs

3.1. Magnetomotive Force Analysis. The PMs of a LSPMSM are mainly subjected to three kinds of MMFs during the starting process including the stator current \( F_s \), the rotor current \( F_r \), and \( F_g \) generated by the current in the stator windings induced by the PMs. These abovementioned three MMFs and \( F_{pm} \) by PMs excited combined action result in the ID phenomenon that the working point of PM is located below the knee point. On the contrary, the PMs are operating normally when the working point is on the top of the knee point. Taking the magnetization direction X of PM as the positive direction, projection of different MMFs on the X direction is shown in Figure 3. The worst case of demagnetization is that all of MMFs are on the negative direction to produce demagnetization except \( F_{pm} \) which is on the positive direction as shown in Figure 3.

\[
F = F_{pm} + F_s + F_r + F_g,
\]

where \( F_s \) and \( F_r \) have the same angular velocity and can be combined into \( F_{gb} \), whose angular velocity is synchro speed \( \omega_1 \). The angular velocity of \( F_g \) is the rotor speed \( \omega_r \), and the difference of angular velocity between synchronous and rotor is \( \omega_0 \).

3.2. Electromagnetic Shielding. During the starting process of LSPMSM, the squirrel cage has electromagnetic shielding effect which protects the PMs from demagnetized influence of the \( F_g \) crossing the cage bar. On the other hand, the shielding of the squirrel cage has no effect on \( F_g \) because \( \omega_0 \) is zero [19].

As shown in Figure 4, the impact of electromagnetic shielding can be measured by the depth of penetration. Its calculation formula is as follows:

\[
B_x = B_{gb} e^{-\frac{x}{\Delta}},
\]

\[
\Delta = \frac{2}{2\pi f_{s1} \mu_r \sigma_r},
\]

Table 1: Electromagnetic parameters.

<table>
<thead>
<tr>
<th>Items</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power (kW)</td>
<td>630</td>
</tr>
<tr>
<td>Rated voltage (V)</td>
<td>6000</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>50</td>
</tr>
<tr>
<td>Number of poles</td>
<td>4</td>
</tr>
<tr>
<td>Number of stator slots</td>
<td>54</td>
</tr>
<tr>
<td>Stator external diameter (mm)</td>
<td>740</td>
</tr>
<tr>
<td>Stator inner diameter (mm)</td>
<td>521</td>
</tr>
<tr>
<td>Core length (mm)</td>
<td>670</td>
</tr>
<tr>
<td>Air-gap length (mm)</td>
<td>2</td>
</tr>
<tr>
<td>Number of rotor slots</td>
<td>44</td>
</tr>
<tr>
<td>Moment of inertia of rotor (kg·m²)</td>
<td>40</td>
</tr>
<tr>
<td>Moment of inertia of impeller (kg·m²)</td>
<td>60</td>
</tr>
<tr>
<td>Iron core</td>
<td>DW470</td>
</tr>
<tr>
<td>PM type</td>
<td>N38SH</td>
</tr>
<tr>
<td>PM width (mm)</td>
<td>69.5</td>
</tr>
<tr>
<td>PM thickness (mm)</td>
<td>20</td>
</tr>
<tr>
<td>PM remanence at 20°C (T)</td>
<td>1.23</td>
</tr>
</tbody>
</table>
where $B_0$ is the magnetic flux density at the surface of the cage bar; $x$ is the distance between a point in the cage bar and the surface; $\Delta$ is the penetration depth; and $\mu_1$, $\sigma_1$, $s$, and $f_1$ are the permeability, conductivity, the slip, and frequency, respectively.

$B_x/B_0$ represents the percentage of the magnetic field penetrating into the cage winding bar. The rotor squirrel cage bar height is 34 mm, $f_1$ is 50 Hz, $\sigma_1$ is $1.24 \times 10^7$ S/m, and $\mu_1$ is $4\pi \times 10^{-7}$ H/m, respectively.

As shown in Figure 5, percentage penetration of $F_\delta$ is at the bottom of the cage bar during the starting process. The penetration depth is 20.2 mm and has 19% at the initial time ($s = 1$). With the continuous rise of speed, the electromagnetic shielding effect of the squirrel cage gradually weakens and the percentage increases. After the motor enters the synchronous speed, the electromagnetic shielding influence disappears at this moment ($s = 0$) and 100% of $F_\delta$ directly acts on the PMs across the cage bar. Therefore, the risk of ID is higher with closing synchronous speed, which is also the essential reason for ID in the pull-in stage.

### 3.3. Inducted Magnetomotive Force ($F_g$)

The rotation difference between $F_g$ and rotor was zero; hence, the amplitude was not affected by the shielding effect. $F_g$ is expressed as follows:

$$F_g = 0.45m \frac{N k_{w1}}{p} I_{\psi},$$

where $N$ is the number of turns per phase, $k_{w1}$ is the fundamental winding coefficient, $p$ is the pole pairs, $I_{\psi}$ is the rms value of phase current according from induced voltage, and $m$ is the winding phase numbers.

$\psi_m \cos (\omega_r t - \theta)$ represents the magnetic flux under a pair of poles. According to Ohm’s law, the induced current is as follows:

$$I = \frac{\varepsilon_{pm} \cos (\omega_r t - \theta)}{R_1 + X_1},$$

$$X_1 = \omega_r L,$$

$$\varepsilon_{pm} = \frac{d\psi_m \cos (\omega_r t - \theta)}{dt},$$

Therefore, according to (6), $R_1/\omega_r$ is much larger than $L$ at the beginning of motor starting because $\omega_r$ starts from zero, resulting in an approximate linear increase of $F_g$ with $\omega_r$. After $R_1/\omega_r$ gradually decreases, $L$ plays an important role while $F_g$ tends to be stable and does not change greatly.

This section introduces the demagnetization principle of LSPMSM in detail. After the motor starts, the amplitude of $F_\delta$ is greatly weakened due to electromagnetic shielding, but there is a few $F_\delta$ through the cage bar, resulting in the PM demagnetization. The amplitude of $F_g$ is not affected by electromagnetic shielding, and the amplitude gradually increases and tends to be stable. In the next section, the demagnetization simulation and demagnetization rate calculation of the motor starting process are carried out by using the finite element analysis.
Compared with the analytical method, the finite element method can accurately calculate the demagnetization rate and demagnetization region distribution. The finite element software adopts Ansys Electronics 2021 version for analysis and calculation.

4. Results and Discussion

PMs have risk of local demagnetization at the starting process and are affected by a variety of MMFs, and the magnetic flux density of each position is different. The cusp area of PMs is most prone to ID; however, multisharp corners exist in one pole when PM is installed in segments [20]. As shown in Figure 6, one pole is divided into four sections (I–IV), and each cusp position (1–16) of the PM is numbered. Analysis of N38SH at 120°C is carried out. The motor load is the fan type. The total moment of inertia is 100 kg\(\cdot\)mm\(^2\), as shown in Table 1.

As shown in Figure 7, the average magnetic flux density changes of four PMs are the same, and the situation at different stages is observed combined with the speed curve. The magnetic flux density of the PM begins to decline between 0 s and 0.3 s, and the oscillation amplitude of magnetic flux density increases continuously from 0.3 s. In the pull-up process, the minimum magnetic flux density appears and the demagnetization risk of the PM is higher after 3 s. With the end of the starting process, the average magnetic flux density of PMs does not change at the rated speed; meanwhile, III and IV are lower than I and II. Through the abovementioned analysis, the ID phenomenon is more likely to occur in the PM that is near the direct axis.

According to the simulation results, although the variation rule of the average magnetic flux density of PMs is consistent with the theoretical study mentioned above, different cusp positions are significantly distinct. Figures 8 and 9 show the distinction of 16 locations, and some spots show hardly any fluctuation such as number 12 and 13, while the amplitude of some points dramatically enhances at the pull-in stage such as number 2 and 6. Because of the magnetic flux density amplitude below the knee point, additional attention should be paid to spots 4 and 5, which are the lowest of all positions. Each point does not change after end of the starting process, and point 5 is the smallest among all positions on the steady state.

More attention should be paid to cusp corners numbered 4 and 5 because they are close to the direct axis and close to \(F_0\).

The magnetic flux density amplitudes of number 4 and 5 are analyzed. Since the amplitudes of these two points are lower than 0.2T, the magnetic flux density values at the initial starting stage are already close to the lowest value, which is different from the variation rules of other points. Therefore, the magnetic flux density in the direction of magnetization is further analyzed, as shown in Figure 10. Similar to the change of the average magnetic flux density of PMs, resulting ID phenomenon occurred at the moment of 3.5 s, and it is the lowest at the pull-in stage.

The most likely location of ID is investigated in the abovementioned analysis, but the demagnetization area could not be accurately obtained. It is an effective method to obtain the demagnetization ratio indirectly by using the change rate of back electromotive force (EMF). The ID ratio of PMs can be determined by the difference of before \((E_0)\) and after \((E_0')\) starting process of EMF.

The demagnetization ratio \(K_{EMF}\) can be expressed as follows:

\[
K_{EMF} = \frac{E_0 - E_0'}{E_0} \times 100\%.
\]  

It is assumed that the temperature distribution of PM is uniform and the temperature values at different positions of the PMs are the same. The analysis of N38SH at 100°C, 120°C, and 150°C is conducted at the starting process, respectively. Due to the difference in the remanence of the PM
at different temperatures, $E_0$ at the initial time was different. The comparison of EMF before and after at the three temperatures is shown in Table 2.

As shown in Figure 11, the motor starts with load when the PM at four temperatures, of which the ambient temperature is 20°C. The difference between 150°C and other temperatures is that the motor fails to pull-in synchronous speed and speed fluctuates greatly at the steady state. An interesting phenomenon is that the increase of temperature accelerates the growth of motor speed in the asynchronous state because the PM torque amplitude is weakened. At lower temperature, the PM takes shorter time to pull in to synchronous speed because their PM torque amplitude is larger.

The average magnetic flux density of PM at 120°C finally stabilizes at 0.82T, while fluctuates periodically after 3 s when PM is at 150°C, as shown in Figure 12.

A prototype is fabricated to verify the electromagnetic performance and temperature rise of the motor. Figure 13 shows the stator core and rotor core. Figure 14 shows the test platform, and asynchronous motor is used to perform as the load. Figure 15 is the control cabinet to measure the value of line EMF. Table 3 measures the no-load EMF before start at ambient
Figure 10: Magnetic flux density on the direction of magnetization curves.

Table 2: Rate of change of EMF.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>$E_0$ (V)</th>
<th>$E'_0$ (V)</th>
<th>$K_{EMF}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100°C</td>
<td>3467</td>
<td>3467</td>
<td>0</td>
</tr>
<tr>
<td>120°C</td>
<td>3394</td>
<td>3390</td>
<td>0.12</td>
</tr>
<tr>
<td>150°C</td>
<td>3307</td>
<td>2726</td>
<td>17.6</td>
</tr>
</tbody>
</table>

Figure 11: Speed curve with PM at different temperatures.
Figure 12: Average magnetic flux density curve of PM at different temperatures.

Figure 13: Motor configuration: (a) stator and (b) rotor.

Figure 14: Experiment platform of LSPMSM.
temperature (20°C) and after running with a load of a period of time (post start), respectively, and the difference between the two values was 3%. The experimental result shows the influence of PMs’ temperature on motor electromagnetic performance.

5. Conclusion
In this paper, the ID of a 630 kW LSPMSM considering the temperature of PMs is analyzed. The MMFs on PMs are studied theoretically. The electromagnetic shielding effect has different influences on each type of MMF during the starting process. The highest risk of ID occurs at the position close to the PMs’ corner of direct axis at the pull-in stage. The temperature of PMs has a great effect on the demagnetization of the motor, further leading to pull-in failure. Finally, a prototype was fabricated, and the effect of PMs’ temperature on no-load EMF of the motor was tested. At the same time, this paper also provides another idea; the air velocity inside the rotor can be increased to avoid ID at the starting stage for large capacity LSPMSM.

Data Availability
The data used to support the findings of this study are included within the article.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

Authors’ Contributions
D.L. and Q.W. wrote the original draft and developed methodology. B.Z. and Y.X. were in charge of data curation and investigation. G.F. and W.L. supervised the study and wrote and reviewed the article. Y.C. and J.Z. were in charge of software and visualization. All authors read and agreed to the published version of the manuscript.

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