Design and Analysis of Permanent Magnets in a Negative-Salient Permanent Magnet Synchronous Motor

XIAOKUN ZHAO, BAOQUAN KOU, (Member, IEEE), LU ZHANG, (Member, IEEE), AND HAOQUAN ZHANG
Harbin Institute of Technology, Harbin 150001, China
Corresponding author: Baoquan Kou (koubq@hit.edu.cn)

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ABSTRACT The $L_d$ of a negative-salient permanent magnet synchronous motor (NSPMSM) is greater than $L_q$. When a NSPMSM is operating at or below the rated speed, the $i_d$ is flux-intensifying current, which can improve the flux density of permanent magnets (PM). First, a NSPMSM is proposed and compared with a positive-salient permanent magnet synchronous motor (PSPMSM). The d-axis and q-axis equivalent magnet circuits of the NSPMSM are then established. According to the limitation of the equivalent magnet circuit, the PM dimensions formula and optimization of the finite element method (FEM), PM dimensions are determined, and the constant power speed ranges of the two motors are calculated. Second, the influence of the saliency ratio on the internal power factor angle and the average flux density of PM at different internal power factor angles are calculated. Third, the flux density of PM in two motors are calculated when the windings are short-circuited. Finally, the bypass function of the NSPMSM magnetic bridges during the flux-weakening state is analyzed. The results show that the flux-weakening magneto motive force (MMF) of the NSPMSM is smaller at high speed, the short-circuit current (SCC) is smaller when the windings are short-circuited, and the magnetic bridges protect the PM in the flux-weakening state, so the flux density of PM is larger.

INDEX TERMS Demagnetization, inner power factor angle, permanent magnets, short-circuit current.

I. INTRODUCTION

The flux density of permanent magnets (PM) is related to motor design, PM materials and operating environment [1]–[3]. When a permanent magnet synchronous motor (PMSM) operates in the flux-weakening state, a large d-axis flux-weakening current is required at high speed, which decreases the flux density of PM and even causes PM irreversible demagnetization [4]–[6]. PM demagnetization will decrease the no-load back electromotive force (EMF) amplitude, increase the torque ripple and decrease the efficiency. Additionally, it may even cause the PMSM to be out of control and suffer damage in severe cases [7]–[10]. Thus, it is very important to improve the flux density of PM in PMSM design.

The literature [11], [12] shows that the flux density of PM is affected by the angle between the PM field and armature field. Literature [13] calculated the flux density of PM by equivalent magnet circuit to obtain the minimum PM volume. Literature [14] calculated the flux density of PM via a bidirectional magnetic network. Literature [15], [16] investigated demagnetization of PM under short-circuit faults.

Scholars have conducted substantial work on the design and analysis of PM in positive-salient permanent magnet synchronous motors (PSPMSMs). However, the design and analysis of PM in negative-salient permanent magnet synchronous motors (NSPMSMs) have not been studied. In recent years, the NSPMSM has attracted the attention due to the following advantages. In order to utilize reluctance torque, $i_d$ is the flux-intensifying current when a NSPMSM operates at or below the rated speed. When $i_d$ is a flux-intensifying current, the d-axis armature magneto motive force (MMF) is in the same direction as the PM MMF. When $i_d$ is a flux-weakening current, the value of the internal power factor angle is smaller than that of the PSPMSM, which...
makes the d-axis flux-weakening MMF smaller. The no-load back EMF of a NSPMSM is lower, so the short-circuit current (SCC) is smaller, and the flux-weakening MMF generated by the SCC is smaller. The above two points are beneficial to improve the flux density of PM. The magnetic bridge width of a NSPMSM are larger than those of a PSPMSM, which not only increases the mechanical strength of the rotor but also provides a path for flux-weakening magnetic flux to protect PM from irreversible demagnetization. In addition, the wider current angle adjustment range and larger \( L_d \) are conducive to widening the constant power speed range [17]–[19]. In the same flux-weakening state, a greater \( L_d \), smaller \( i_d \), and greater \( i_q \), help to maintain the PM torque. For a NSPMSM with magnetic barriers on the q-axis, the magnetic circuit is not easily saturated, so the NSPMSM has stronger overload capacity [20]–[22]. The NSPMSM proposed in this article is a fractional slot concentrated winding with 10 poles and 12 slots. By adopting an alternate tooth winding method, thermal isolation, magnetic isolation and physical isolation can be achieved. When each phase winding is powered by a separate H bridge, electrical isolation can be realized. According to the above analysis, the NSPMSM has strong SCC suppression capability and high PM flux density. Thus, the NSPMSM proposed in this article has fault tolerance. When short-circuit faults or PM demagnetization faults occur, incipient fault diagnosis and fault tolerant control methods should be applied [25]–[27].

This article proposes a new NSPMSM and compares it with PSPMSM. In Section II, the topology of the two motors is compared. The d-axis and q-axis equivalent magnetic circuit of the NSPMSM is established to obtain the relationship between the dimensions of the magnetic bridges, magnetic barriers and PM when \( L_d \) is greater than \( L_q \). According to the magnetic circuit constraints, PM dimension formula and optimization of finite element method (FEM), the PM dimensions are determined and the constant power speed ranges of two motors are calculated. In Section III, the influence of the saliency ratio on internal power factor angle and flux density of PM at different internal power factor angles are calculated by FEM. In Section IV, the SCC and flux density of PM are calculated when the windings terminal are short-circuited. In Section V, the function of magnetic bridges is analyzed. Finally, the conclusions are given in Section VI.

II. MOTOR TOPOLOGY AND PM DESIGN

A. MOTOR TOPOLOGY

To compare and analyze the characteristics of the NSPMSM, we design a PSPMSM as the reference motor, with the same rated voltage, rated speed, stator inner diameter and axial length as the NSPMSM. The topologies of two motors are shown in Fig. 1 and Fig. 2, respectively.

Arc magnetic barriers are set at the q-axis of the NSPMSM, and the maximum distance between the rotor outer edge and the stator inner diameter is 5 mm. The shapes of the magnetic barriers are flexible, and can be arc, strip, triangle, trapezoid, rectangle or other irregular shapes. To choose of the shapes of magnetic barriers and optimization of the dimensions can change the saliency ratio, improve the sinusoidal property of the no-load back EMF and reduce the torque ripple simultaneously. The PSPMSM improves its no-load back EMF sinusoidal property by optimizing the rotor shape. The maximum distance between the rotor outer edge and the stator inner diameter is 2.4 mm. The PM of the two motors are segmented by magnetic bridges, and they are arranged in a “V” shape. On the one hand, the magnetic bridges effectively reduce the eddy current loss of the PM, which makes the PM less prone to high-temperature demagnetization. On the other hand, the existence of the magnetic bridges increases the flux leakage. For the PSPMSM, to reduce flux leakage, the length of the magnetic bridges should be as small as possible under the condition of meeting the required mechanical strength. The final length of the magnetic bridges is 0.5mm. For the NSPMSM, the length of the magnetic bridges should be selected to increase \( L_d \) and reduce flux leakage simultaneously. The final length of the magnetic bridges is 0.75mm. Therefore, the NSPMSM has higher mechanical strength and is more suitable for operating at high speed.

B. DETERMINATION OF PM DIMENSIONS

To ensure that \( L_d \) is larger than \( L_q \), the d-axis reluctance should be less than the q-axis reluctance. When analyzing the d-axis and q-axis reluctance, only reluctance is considered. Thus, PM are artificially removed and are equivalent to air. The d-axis and q-axis magnetic circuits of the NSPMSM are shown in Fig. 3. Due to the small air gap in the d-axis magnetic circuit, the magnetic flux does not pass through the magnetic barriers, but enters the rotor through the uneven air

![FIGURE 1. 10-pole 12-slot NSPMSM.](image1)

![FIGURE 2. 10-pole 12-slot PSPMSM.](image2)
The d-axis uneven air gap permeance is denoted as $p_{d-air1}$, and the d-axis magnetic circuit is shown in Fig. 4(a). However, the q-axis arc-shaped magnetic barriers have larger magnetic resistance. Part of the q-axis magnetic flux enters the rotor through the arc-shaped magnetic barriers, and some enters the rotor through the uneven air gap. The permeance of the q-axis arc-shaped magnetic barrier is denoted as $p_{q-air2}$. The q-axis nonuniform air gap is symmetrical, and its permeance is denoted as $p_{q-air1}$. $p_{q-air1}$ and $p_{q-air2}$ are connected in parallel, and the q-axis magnetic circuit is shown in Fig. 4(b).

Because the permeability of magnetic bridges is much larger than that of the PM, some magnetic flux passes through the magnetic bridges directly instead of passing through the PM, which simultaneously reduces the magnetic resistance of the d-axis magnetic circuit. The existence of the q-axis magnetic barriers effectively increases the q-axis resistance.

During the normal operation of a motor, the stator and rotor cores are not saturated, and their relative permeability is much larger than that of the magnetic barriers, PM and magnetic bridges. To simplify the calculation, assume that the permeability of the stator and rotor cores is infinite. However, the magnetic bridges are in a saturated state, and their permeability cannot be assumed to be infinite. The magnetic bridge and PM are connected in parallel, and their permeability is denoted as $p_M$, which is shown in Fig. 7.

The d-axis and q-axis equivalent magnetic circuits of the NSPMSM are shown in Fig. 5.

The d-axis air-gap can be divided into a uniform air-gap and a nonuniform air-gap in series, as shown in Fig. 6. The uniform air-gap permeability $p_{d-air1}$ is given by (1)

$$p_{d-air1} = \frac{\mu_0 l_{ef} r_3}{\delta} \theta = \frac{2\mu_0 l_{ef} r_3}{\delta} \theta$$

where $\mu_0$ is the vacuum permeability, $l_{ef}$ is the axial length of the motor, and $r_3$, $\delta$, and $\theta$ are shown in Fig. 6.

The nonuniform air-gap permeability $p_{d-air2}$ is given by (2)

$$p_{d-air2} = \int_{\theta}^{\delta} \frac{\mu_0 l_{ef} r_3}{\sqrt{r_1^2 + r_3^2 - 2r_1 r_3 \cos \theta - r_2^2}} \theta$$

where $r_1$ and $r_2$ are shown in Fig. 6.

The d-axis air-gap permeability $p_{d-air}$ is given by (3)

$$p_{d-air} = \frac{p_{d-air1} p_{d-air2}}{p_{d-air1} + p_{d-air2}}$$

The equivalent magnetic circuit of each pole-segmented PM is shown in Fig. 7. The total magnetic permeability $p_M$ is formed by 6 segment PM, 4 segment magnetic bridges between the PM and 2 segment magnetic bridges of the rotor outer edge in parallel. $p_M$ is given by (4)

$$p_M = \frac{2k_1 \mu_{fe} l_{ef} b_{air1}}{h_M} + \frac{6\mu_0 l_{ef} b_M}{h_M} + \frac{4k_2 \mu_{fe} l_{ef} b_{air2}}{h_M}$$

where $\mu_{fe}$ is the permeability of the core, $h_M$ is the PM magnetization direction length, $b_M$ is the PM width, $b_{air1}$ is
where \( l \) is the magnetic bridge width of the rotor outer edge, \( b_{\text{int}2} \) is the magnetic bridges width between PM, and \( k_1 \) and \( k_2 \) are coefficients related to saturation.

The d-axis inductance is given by (5)

\[
L_d = N^2 \frac{\text{PM}d-\text{air}1}{2(p\text{M} + p\text{d-\text{air}1})}
\]

The q-axis magnetic circuit can be seen as a parallel connection of three arc magnetic barriers, as shown in Fig. 8. The q-axis magnetic circuit can be seen as a parallel connection of three arc magnetic barriers, as shown in Fig. 8. The q-axis magnetic barriers can be divided into those of the uniform air-gap and nonuniform air-gap in series. The permeability \( p_{\text{q-air1}} \) and \( p_{\text{q-air2}} \) can be divided into those of the uniform air-gap \( p_{\text{q-air11}} \) and nonuniform air-gap \( p_{\text{q-air12}} \) in series.

\[
p_{\text{q-air11}} = \beta_1 \frac{\mu_0 l_1 \beta \beta}{n} = \mu_0 l_1 \beta_1 (\beta - \beta_1) \quad (6)
\]

\[
p_{\text{q-air12}} = \beta_1 \frac{\mu_0 l_1 \beta \beta}{\sqrt{l_1^2 + l_2^2 - 2l_1 l_2 \cos \theta - l_2}} \quad (7)
\]

\[
p_{\text{q-air1}} = \frac{p_{\text{q-air11}} p_{\text{q-air12}}}{p_{\text{q-air11}} + p_{\text{q-air12}}} \quad (8)
\]

where \( l_1, l_2, l_3, n \) and \( \beta \) are shown in Fig. 8.

Similarly, the permeability \( p_{\text{q-air2}} \) can be divided into that of the uniform air-gap \( p_{\text{q-air21}} \) and nonuniform air-gap \( p_{\text{q-air22}} \) in series.

\[
p_{\text{q-air21}} = \int_{-\alpha}^{\alpha} \mu_0 l_2 m d\alpha = 2 \mu_0 l_2 m \alpha \quad (9)
\]

\[
p_{\text{d-air22}} = 2 \int_{0}^{\alpha} \mu_0 l_2 m d\alpha = \mu_0 l_2 m \alpha \quad (10)
\]

\[
p_{\text{q-air2}} = \frac{p_{\text{q-air21}} p_{\text{q-air22}}}{p_{\text{q-air21}} + p_{\text{q-air22}}} \quad (11)
\]

\[
L_q = N^2 \left( \frac{\text{PM}q-\text{air1}}{p\text{M} + p\text{q-\text{air1}}} + \frac{p_{\text{q-air2}}}{2} \right) \quad (12)
\]

where \( \alpha, m \) and \( n_1 \) are shown in Fig. 8.

According to Equation (5) and (12), if \( L_d \) is larger than \( L_q \), the following relationship is obtained.

\[
N^2 \frac{\text{PM}d-\text{air1}}{2(p\text{M} + p\text{d-\text{air}1})} > N^2 \left( \frac{\text{PM}q-\text{air1}}{p\text{M} + p\text{q-\text{air1}}} + \frac{p_{\text{q-air2}}}{2} \right) \quad (13)
\]

\[
N^2 \frac{\text{PM}d-\text{air1}}{2(p\text{M} + p\text{d-\text{air}1})} > \frac{\text{PM}q-\text{air1}}{p\text{M} + p\text{q-\text{air1}}} + \frac{p_{\text{q-air2}}}{2} \quad (14)
\]

\( L_d \) and \( L_q \) depend on the PM magnetization direction length, PM width, magnetic bridge width, the dimensions of the d-axis nonuniform air gap and the dimensions of the q-axis magnetic barriers. The above parameters of the NSPMSM should satisfy formula (14).

It is very important to determine the PM dimensions. If the PM dimensions are excessive, the cost of the motor will increase and \( L_d \) will decrease, which is not conducive to widening the constant power speed range. If the PM dimensions are deficient, the flux density of the PM will decrease and the PM may be irreversibly demagnetized. The PM dimensions includes the PM axial length \( h_M \), magnetization direction length \( h_M \) and width \( b_M \). Generally, \( L_d \) can be determined according to the axial length of the motor, so only \( h_M \) and \( b_M \) need to be determined in the motor design. The initial values of \( h_M \) and \( b_M \) are given in (15)

\[
\begin{aligned}
h_M &= \frac{K_s K_f b_{\text{nd}0} H_r}{\sigma_0 (1 - b_{\text{mf}}) \delta} \\
b_M &= \frac{\pi b_{\text{nd}0} B_1 K_\phi L_M}{\sigma_0 B_1 L_r e_f}
\end{aligned}
\]

where \( K_s \) is the saturation coefficient of the magnetic circuit, \( K_f \) is the air gap coefficient, \( b_{\text{nd}0} \) is the estimated no-load operating point of the PM, \( \mu_r \) is the relative permeability of the PM, \( \delta \) is the length of the air gap, \( \sigma_0 \) is the no-load magnetic leakage coefficient, \( B_1 \) is the fundamental amplitude of the air gap flux density, \( r \) is the polar distance, \( B_1 \) is the calculated remanence, and \( K_\phi \) is the waveform coefficient of the air gap flux.

According to (14) and (15), the initial \( h_M \) and \( b_M \) can be determined, and the final \( h_M \) and \( b_M \) can be determined by FEM. The inductance varies with \( h_M \), as shown in Fig. 9. The inductance of the two motors decreases with an increase in \( h_M \). Compared with that of the PSPMSM, the \( L_d \) of the NSPMSM is larger for the same \( h_M \). Because two motors have a fractional slot concentrated winding, the difference between \( L_d \) and \( L_q \) is not obvious [28]. The \( L_d \) of the PSPMSM is smaller than the \( L_q \). The inductance relationship of the NSPMSM is opposite to that of the PSPMSM, so it is named NSPMSM.

The two motors proposed in this article are interior PMSMs. In the rated state, the risk of PM partial demagnetization is small, so the average flux density of the PM is compared with the knee point flux density to judge whether the PM is demagnetized. When the motors operate at the
high-speed flux-weakening state or short-circuit state, partial demagnetization is likely to occur. At this time, the partial flux density of the PM is compared with the knee point flux density to judge whether the PM is demagnetized. The average flux density of the PM varies with $h_M$ as shown in Fig. 10. The longer the $h_M$, the higher the average flux density of the PM. The average flux density of the PM and $L_d$ should be considered comprehensively when determining $h_M$. To increase $L_d$ and reduce the amount of the PM, it should be designed to be as thin as possible. The final $h_M$ values of the NSPMSM and PSPMSM are 3.6 mm and 4 mm, respectively.

The PM flux linkage $\psi_f$ is the interlink between the PM flux and stator winding. The PM flux linkage $\psi_f$ varies with $b_M$, as shown in Fig. 11. The $\psi_f$ of the two motors increases with an increase in $b_M$. Limited by rotor space, when the $b_M$ of the NSPMSM is greater than 6 mm, an increase in $b_M$ causes the width of the magnetic bridges to decrease, and the leakage flux decreases accordingly. Therefore, the PM flux increase is more obvious as $b_M$ increases. Similarly, compared with that of the PSPMSM, the magnetic bridge width of NSPMSM is larger, and its PM flux linkage is smaller. On the one hand, its PM torque is smaller. On the other hand, the characteristic current (the ratio of PM flux to $L_d$) is smaller, which makes its constant power speed range wider.

The average flux density of the PM varies with $b_M$, as shown in Fig. 12. The average flux density of the PM decreases as $b_M$ increases. In the design of the PMSM, the average flux density of the PM, PM torque and rotor space should be considered. The $b_M$ values of the NSPMSM and PSPMSM are 6 mm and 7.6 mm, respectively. The main dimensions and parameters of the two motors are shown in TABLE 1.

### TABLE 1. The main dimensions and parameters.

| Dimensions and parameters | NSPMSM | PSPMSM |
|---------------------------|--------|--------|
| Stator outer diameter     | 169mm  | 169mm  |
| Stator inner diameter     | 100mm  | 100mm  |
| Minimum air gap length    | 0.8mm  | 0.8mm  |
| Maximum air gap length    | 5mm    | 2.4mm  |
| Axial length              | 100mm  | 100mm  |
| Width of magnetic bridges | 0.75mm | 0.6mm  |
| $b_M$                     | 6mm    | 7.6mm  |
| $h_M$                     | 3.6mm  | 4mm    |
| Rated power               | 4kW    | 4.6kW  |
| Rated voltage             | 380V   | 380V   |
| Rated speed               | 1200rpm| 1200rpm|

### C. CONSTANT POWER SPEED RANGE

Compared with those of that PSPMSM, the flux leakage is larger and the main flux is smaller because of the wider magnetic bridges of the NSPMSM. In addition, the $L_d$ of the NSPMSM is larger, so its characteristic current is smaller, and its constant power speed range is wider. The torque-speed curve and power-speed curve of the NSPMSM and PSPMSM are shown in Fig. 13 and Fig. 14, respectively. Due to the existence of flux leakage, the PM torque is smaller, so the electromagnetic torque of the NSPMSM is smaller than that of the PSPMSM when they run at or below the rated speed and the electromagnetic torques of two motors are 31.7 N·m
and 36.4 N\cdot m respectively. As the speed increases, $i_q$ of the NSPMSM is greater than that of the PSPMSM, which makes its PM torque larger, so its constant power speed range is wider.

### III. INFLUENCE OF THE INTERNAL POWER FACTOR ANGLE ON THE FLUX DENSITY OF THE PM

#### A. INFLUENCE OF THE SALIENCY RATIO ON THE INTERNAL POWER FACTOR ANGLE

The $L_d$ of the NSPMSM is greater than the $L_q$. To describe the relationship between $L_d$ and $L_q$, the saliency ratio $\rho$ is given by (16)

$$\rho = \frac{L_q}{L_d}$$  \hspace{1cm} (16)

The current control laws of the NSPMSM and PSPMSM are different due to the different saliency ratios. When two motors operate under maximum torque per ampere (MTPA) control, $i_d$ is flux-intensifying and flux-weakening current, respectively, and the internal power factor angle $\psi$ is different. The internal force factor angle $\psi$ is the angle between the no-load back EMF and the armature current. When the armature current phase lags behind the no-load back EMF, $\psi$ is defined as positive. Fig. 15 and Fig. 16 show the phasor diagram of the PMSM when $i_d$ is flux-intensifying and flux-weakening current, respectively. The angle between the PM MMF and armature MMF is denoted as $\alpha$, which is given by (17). Then the projection of the armature MMF on the PM MMF $F_{ad}$ is given by (18)

$$\alpha = 90^\circ - \psi$$  \hspace{1cm} (17)

$$F_{ad} = F_a \cos \alpha = F_a \sin \psi$$  \hspace{1cm} (18)

where $F_a$ is the armature MMF.

It can be seen from (18) that $\psi$ can explain the angle between the armature MMF and PM MMF. When $i_d$ is flux-intensifying current, $\psi$ is positive, $\alpha$ is an acute angle, and $F_{ad}$ is positive, which increases the flux density of the PM. When $i_d$ is flux-weakening current, $\psi$ is negative, $\alpha$ is an obtuse angle, and $F_{ad}$ is negative, which decreases the flux density of the PM. The positive or negative state of $\psi$ can explain the positive or negative state of $F_{ad}$, that is, the flux-intensifying or flux-weakening effect of the armature MMF on PM MMF. When the motor is operating in the flux-weakening state, the larger the $\psi$ value is, the greater the armature flux-weakening MMF is, which increases the likelihood of irreversible demagnetization of the PM.

When the PMSM is operating in the MTPA state, the change in $\psi$ with $\rho$ is shown in Fig. 17. For a NSPMSM with a saliency ratio less than 1, $\psi$ is positive and $i_d$ is flux-intensifying current, which can improve the flux density of the PM. The smaller the $\rho$ is, the greater the $\psi$, and the greater the d-axis flux-intensifying MMF. By contrast, for a PSPMSM with a saliency ratio greater than 1, $\psi$ is negative, and $i_d$ is always flux-weakening current. The greater the $\rho$ is, the greater the value of $\psi$, and the greater the d-axis flux-weakening MMF. The direction of the armature MMF is always opposite to that of the PM MMF for a PSPMSM, which decreases the flux density of the PM.

#### B. INFLUENCE OF THE INTERNAL POWER FACTOR ANGLE ON THE FLUX DENSITY OF THE PM

The PM material used in two motors is N35UH. At room temperature, the demagnetization curve of N35UH is a straight line, and it coincides with a recoil line. As the temperature increases, the remanence and coercive force of the PM decrease. When the temperature is greater than 150 °C,

![Phasor diagram of the PMSM when $i_d$ is flux-intensifying Current.](image1)

![Phasor diagram of the PMSM when $i_d$ is flux-weakening Current.](image2)

![The change in $\psi$ with $\rho$ when the PMSM operates in the MTPA state.](image3)
the demagnetization curve of the PM has a knee point, as shown in Fig. 18. $P_k$ is the knee point, and its flux density is 0.17 T. When the flux density of the PM is lower than the knee point, the recoil line and demagnetization curve do not coincide, and the PM will be irreversibly demagnetized. When $\psi$ is equal to 0, $i_d$ is in neither a flux-intensifying nor flux-weakening state. The intersection of the load line and PM demagnetization curve moves from $P_0$ to $P_1$. When $\psi$ is greater than 0, $i_d$ is a flux-intensifying state. The intersection of the load line and PM demagnetization curve moves from $P_0$ to $P_2$. When $\psi$ is less than 0, $i_d$ is a flux-weakening state. The intersection of the load line and PM demagnetization curve moves from $P_0$ to $P_2$. The flux density of PM decreases. Therefore, when the PMSM is operating in the MTPA state, we want $\psi$ to be positive. When the PMSM is operating in a flux-weakening state, we want a negative $\psi$ that is as small as possible.

Fig. 19 shows how $\psi$ varies with the speed of two motors. When a PSPMSM operates at full speed, $\psi$ is always negative. According to (17), $F_{ad}$ is always negative, which decreases the average flux density of the PM. When the NSPMSM operates at or below the rated speed, $\psi$ is positive and $F_{ad}$ is positive, which increases the average flux density of the PM. As the speed increases, $\psi$ gradually becomes negative. Compared with that of the PSPMSM, the value of $\psi$ for the NSPMSM is always smaller. Therefore, the average flux density of the PM for a NSPMSM is higher. Notably, the two motors designed in this article adopt fractional slot concentrated winding. The saliency ratio of the two motors is close to 1, so the difference in $\psi$ between them is not significant. If the saliency ratios of two motors were considerably different, the difference in $\psi$ would be more obvious. At this time, the advantage of a larger PM average flux density of the NSPMSM will be more obvious.

The variation in the average flux density of the PM with $\psi$ for the two motors is shown in Fig. 20. Due to the design of the NSPMSM magnetic bridges, the average flux density of the PM is higher when $\psi$ is the same. From the above analysis, it can be seen that when the PMSM is operating in a flux-weakening state, the value of $\psi$ for the NSPMSM is smaller at the same speed, so its average PM flux density is higher.

The variation of the $i_d$ of the two motors with speed is shown in Fig. 21. When the motor design is completed, the number of winding turns remains unchanged, so the value of $i_d$ represents the value of the d-axis MMF. The change law of the d-axis MMF is the same as the conclusion drawn in Fig. 19.

To verify that the average flux density of the PM for the NSPMSM is larger in the flux-weakening state, taking the speed of 4800rpm as an example, we calculated the average flux density and partial easy demagnetization area flux density of the PM. The $\psi$ values of the NSPMSM and PSPMSM operating at 4800 rpm are $-67^\circ$ and $-75^\circ$, respectively. The flux density distribution is shown in Fig. 22.

The average flux density of the PM for two motors are shown in Fig. 23. The average PM flux density of NSPMSM is larger. Notably, the PM thicknesses of the NSPMSM and PSPMSM are 3.6 mm and 4 mm respectively, which does not decrease the PM average flux density of the NSPMSM. This characteristic of the NSPMSM can make its PM design thinner. On the one hand, it is beneficial to increase $L_d$ and improve the constant power speed range. On the other hand, the PM dimensions are reduced, which decreases the cost of motor.

Fig. 22 shows that point A of the NSPMSM is prone to irreversible demagnetization, while both point A and point B of the PSPMSM are prone to irreversible demagnetization.
The flux densities of points A and B are calculated by FEM, as shown in Fig. 24. Compared with those of the PSPMSM, the flux densities of point A and point B of the NSPMSM are always higher. Because the magnetic bridge width of the NSPMSM is larger, the flux density of point B for the NSPMSM is much larger than that of the PSPMSM, and the average flux density is 1.1 T.

IV. INFLUENCE OF WINDING SHORT-CIRCUITS ON THE FLUX DENSITY OF THE PM

When windings are short circuited, the SCC is usually larger than the rated current. The direction of the SCC is opposite to the rated current, that is, the MMF direction generated by the SCC is opposite to the PM MMF. Therefore, the larger the SCC is, the stronger the demagnetization effects. The no-load back EMF of the two motors at the rated speed is shown in Fig. 25. Compared with that of the PSPMSM, the no-load back EMF of the NSPMSM is lower. When the two motors have the same impedance, the NSPMSM has stronger SCC suppression capability. This article considers only the steady-state situation when one phase winding terminal is short circuited and compares the impact of SCC on the flux density of the PM. Both the winding terminal SCC and the interturn SCC are proportional to the no-load back EMF. Thus, similar conclusions will be obtained in other states.

The SCC of the two motors when one phase winding terminal is short circuited are shown in Fig. 26. The steady-state SCC values are 1.11 and 1.38 times the rated current.

The flux density distributions of the two motors when winding terminals are short circuited are shown in Fig. 27. Similarly, the PM average flux density of the NSPMSM is higher. The PM average flux densities of two motors are

![Figure 22. Flux density distribution at 4800 rpm. (a) NSPMSM. (b) PSPMSM.](image)

![Figure 23. Average flux density of PM at 4800 rpm.](image)

![Figure 24. The flux density of points A and B for the two motors.](image)

![Figure 25. The no-load back EMF of the two motors.](image)

![Figure 26. Terminal SCC of the two motors.](image)

![Figure 27. Flux density distribution during winding terminal SC. (a) NSPMSM. (b) PSPMSM.](image)
V. INFLUENCE OF MAGNETIC BRIDGES ON THE FLUX DENSITY OF THE PM

The magnetic bridges and PM are connected in parallel as a part of the d-axis magnetic circuit, and the width affects the value of \( L_d \). To increase \( L_d \), it is not necessary to minimize the magnetic bridge width of the NSPMSM. When designing its width, both increasing \( L_d \) and reducing flux leakage should be considered. \( \psi \) is different at different speeds, and the distribution relationship between flux leakage and PM flux is also different due to the influence of saturation. The change in PM flux linkage with \( \psi \) is calculated via the frozen permeability method, as shown in Fig. 30. At the rated speed, \( \psi = 2^\circ \) and the PM flux linkage is the smallest. As the speed increases, the value of \( \psi \) becomes negative. In the extreme case, \( \psi = -90^\circ \) and the PM flux linkage is the largest. In other words, when the motor is running at the rated speed, the flux leakage is the largest, and the flux leakage decreases as the speed increases.

According to the above analysis, if the influence of the armature current on the magnetic bridges is not considered, the magnetic bridge flux density is the largest when \( \psi = 2^\circ \), and the magnetic bridge flux density is the smallest when \( \psi = -90^\circ \). Fig. 31 shows the flux density distribution of the magnetic bridges when \( \psi = 2^\circ \) and \(-90^\circ \). When \( \psi = 2^\circ \), the magnetic bridge flux density is 2.35 T. When \( \psi = -90^\circ \), the magnetic bridge flux density is 2.64 T. This result is contrary to the above conclusions because during the flux-weakening state, a part of the magnetic flux does not pass through the PM but passes through the magnetic bridges directly, which makes the flux density of the magnetic bridges increase. Therefore, the magnetic bridges provide a path for flux-weakening magnetic field lines and have a bypass.
function, which further reduces the risk of PM irreversible demagnetization.

In addition to a bypass function, the magnetic bridges divide the PM into segments, which can effectively reduce the eddy current loss of the PM. When the motor is operating at high speed, the high-order harmonics of the rotating armature MMF induce eddy current in the PM. The eddy current transforms electric energy into heat energy, which increases the PM temperature. Thus, the risk of PM irreversible demagnetization increases. Fig. 32 compares the eddy current loss of the “V”-shape PM without a magnetic bridge, two-segment magnetic bridges and four-segment magnetic bridges. Dividing the PM into segments is an effective way to reduce the eddy current loss of the PM.

VI. CONCLUSION

This article proposed a new NSPMSM. The PM were designed according to d-axis and q-axis equivalent magnetic circuits, the permanent magnet dimensions formula and FEM optimization. The influence of the internal power factor angle ψ, SCC and magnetic bridges on the flux density of the PM were analyzed and calculated. The \( L_d \) of the NSPMSM is greater than \( L_q \), which makes its current control law and internal power factor angle variation law different from those of that PSPSM. When the NSPMSM is operating at or below the rated speed, \( i_d \) is flux-intensifying current and \( F_{al} \) is in the same direction as the PM MMF, which increases the flux density of the PM. When the NSPMSM is operating at high-speed, the value of negative \( \psi \) is smaller, so the d-axis demagnetization armature MMF is smaller. The no-load back-EMF of the NSPMSM is lower, so the demagnetization MMF generated by SCC is smaller. In addition, magnetic bridges not only reduce the eddy current loss of the PM but also provide a path for flux-weakening magnetic field lines. Therefore, the NSPMSM has higher PM flux density and is more suitable for high-speed operation.

The NSPMSM proposed in this article adopted a single-layer fractional slot concentrated winding and had stronger SC current suppression capability. Therefore, the NSPMSM had fault tolerance. In future research, the current change law, torque characteristics, fault diagnosis and fault tolerant control when motor faults occur will be studied.

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**XIAOKUN ZHAO** was born in 1993. She received the B.S. degree from the School of Electrical Engineering and Automation, Northeast Forestry University, Harbin, China, in 2015. She is currently pursuing the Ph.D. degree with the Harbin Institute of Technology, Harbin. Her research interest includes permanent magnet synchronous motor and its control.

**BAOQUAN KOU** (Member, IEEE) was born in 1968. He received the Ph.D. degree in electrical engineering from the Harbin Institute of Technology (HIT), Harbin, China, in 2004. He has been a Professor with the Department of Electrical Engineering, HIT. His research interests include linear motor and plane motor systems, new special motor and its control, electric drive system of electric vehicles, electromagnetic catapult, and electromagnetic braking.

**LU ZHANG** (Member, IEEE) was born in Shandong, China. He received the B.S., M.S., and Ph.D. degrees in electrical engineering from the Harbin Institute of Technology (HIT), Harbin, China, in 2008, 2010, and 2014, respectively. Since 2017, he has been an Associate Professor with the School of Electrical Engineering and Automation, HIT. His research interests include magnetic levitation planar actuators and linear motors.

**HAOQUAN ZHANG** was born in 1994. He received the B.S. and M.S. degrees in electrical engineering from the Harbin Institute of Technology, Harbin, China, in 2017 and 2019, respectively, where he is currently pursuing the Ph.D. degree. His research interest includes permanent magnet synchronous motor and its control.