Improved Method for Calculating Magnetic Field of Surface-Mounted Permanent Magnet Machines Accounting for Slots and Eccentric Magnet Pole

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Abstract – This paper presented an improved analytical method for calculating the open-circuit magnetic field in the surface-mounted permanent magnet machines accounting for slots and eccentric magnet pole. Magnetic field produced by radial and parallel permanent magnet is equivalent to that produced by surface current according to equivalent surface-current method of permanent magnet. The model is divided into two types of subdomains. The field solution of each subdomain is obtained by applying the interface and boundary conditions. The magnet field produced by equivalent surface current is superposed according to superposition principle of vector potential. The investigation shows harmonic contents of radial field can be reduced a lot by changing eccentric distance of eccentric magnet poles compared with conventional surface-mounted permanent-magnet machines with concentric magnet poles. The FE(finite element) results confirm the validity of the analytical results with the proposed model.

Keywords: Permanent magnet machines, Magnetic field, Eccentric magnet pole, Surface current

1. Introduction

Permanent-magnet machines have become more and more popular in the commercial, industrial and military products benefiting from higher power ratio to mass, torque ratio to volume, efficiency and lower vibration and noise over conventional electrically produced synchronous machines and asynchronous machines [1-3]. The magnetic field distribution in the air-gap is one of the most important issues in the permanent-magnet machines. It is foundation to other issues. At the present time, the numerical methods for magnetic field calculation, such as finite-elements method, provide accurate results concerning all kinds of magnetic sizes of permanent magnet machines, taking into account the saturation and without making any simplification of the geometry. But the numerical methods are very time-consuming, not suit to the initial design and optimization of the machines. Usually, the numerical methods are very good for the adjustment and validation of the design. Furthermore, the results which are obtained by numerical methods may be not accurate to calculate cogging torque and unbalanced magnetic force [4, 5] since it is sensitive to the FE meshes. Indeed, the motor performance can be obtained by the analytical methods of

...]
series. Its high accuracy for the flux density distributions in both air-gap and magnets of the machines with different slot opening widths was confirmed by FE. Zhu [14] extended [7] to account for any pole and slot combinations, and an accurate analytical subdomain model with stator slotting effects was presented for computation of the open-circuit magnetic field in surface-mounted permanent magnet machines. Some mistakes were clarified at the same time. Wu [15] developed an improved analytical subdomain model for calculating the open-circuit magnetic field in surface-mounted permanent magnet machines accounting for the tooth-tips in the slots based on 2-D polar coordinate.

In [7], and [11-14], the field domain was divided into some types of subdomains, and calculated according to interface and boundary condition. The radial and circumferential components of magnet magnetization were expressed in the form of Fourier series to solve Poisson equation in the concentric permanent magnet. But the interface between eccentric permanent magnet and air-gap is very difficult to be obtained. K. Boughrara [16] used two-dimensional field theory in polar coordinates to determine the flux density distribution, cogging torque, back EMF and electromagnetic torque in the slotted air-gap of permanent-magnet motors with surface mounted magnet bars which are magnetized in shifting direction, but not like Halbach array magnetization. The sinusoidal waveform of the flux density distribution was obtained, but installation process of the permanent magnet bars is not easy to achieve.

Eccentric magnet pole is a typical example of eccentric magnet pole, and performance of motors can be optimized by changing eccentric distance of the eccentric magnet poles. Zhang[17] deduced expressions of Fourier transform coefficient for magnetomotive force of eccentric magnet pole. The main exciting force wave can be reduced through suitable selection of the eccentric distance. Xu [18] analyzed the influence of the eccentric magnet poles on the waveform of air-gap flux density and the motor performances, proposed a novel optimal designing method for the eccentric magnet poles with analytical expression. In [19], based on the magnetic field which was produced by a pair of windings on the air-gap, the expressions of the flux density produced by parallel-magnetized permanent magnet with different shapes were deduced with surface-current method. But slots were not accounted. At the present time, the analytical model of permanent-magnet machines accounting for eccentric magnet poles and slots has not been analyzed comprehensively.

In this paper, an improved analytical method accounting for slots and eccentric magnet pole is derived for calculating the magnetic field distribution of machine. In the derivation, magnetic field produced by radial and parallel eccentric permanent magnet is equivalent to that produced by surface current according to surface-current method of permanent magnet. The field domain is divided into two types of subdomains. The analytical field expressions of two subdomains produced by a pair of windings are obtained by the variable separation method. The coefficients in the field expressions are determined by applying the interface and boundary conditions. The magnet field produced by equivalent surface current is superposed according to superposition principle of vector potential. Compared with conventional surface-mounted permanent-magnet machines with concentric magnet poles, harmonic content of radial flux density can be reduced a lot by changing eccentric distance of eccentric magnet poles. The investigation shows the developed model has high accuracy to calculate the flux density of surface-mounted permanent magnet machines with eccentric magnet poles. The finite element (FE) results verify the validity of the analytical model.

2. Analytical Field Modeling

2.1 Equivalent surface current of magnet pole

In this paper, the analytical modeling is based on the following assumptions:

(1) Linear properties of permanent magnet;
(2) Infinite permeable iron materials;
(3) The relative permeability in the PM is equal to 1;
(4) Negligible end effect;
(5) Simplified slot as shown in Fig. 1.

The two-dimensional conventional subdomain model is shown in Fig. 1. The magnet field is divided into two types of subdomains for the convenience of analysis: (1) subdomain of permanent magnet and air-gap (The first subdomain is limited by a circle characterised by a $R$, radius); (2) subdomain of slots.

The permanent magnet with eccentric structure is shown

![Fig. 1. Symbols and types of subdomains.](http://www.jeet.or.kr)
Improved Method for Calculating Magnetic Field of Surface-Mounted Permanent Magnet Machines Accounting for Slots and Eccentric ~

in Fig. 2. The distance between point E and point O can be given by

\[ OE = H \cdot \cos \zeta + \sqrt{(R_r + h_{\text{max}} - H)^2 - (H \cdot \sin \zeta)^2} \]  (1)

where \( H \) is the eccentric distance, \( R_r \) is the radius of rotor, \( h_{\text{max}} \) is the maximum thickness of permanent magnet and \( \zeta \) is the radian between OE and the center line of permanent magnet.

The radian between point \( O_1 \)E and the center line of permanent magnet can be given by

\[ \zeta' = \arcsin \left( OE \cdot \sin \zeta / R_2 \right) \]  (2)

where \( R_2 \) is the radius of arc BC.

The radius of arc BC can be given by

\[ R_2 = R_r + h_{\text{max}} - H \]  (3)

The eccentric distance of the permanent magnet can be given by

\[ H = \frac{(h_{\text{max}} - h_{\text{min}})(2R_r + h_{\text{max}} + h_{\text{min}})}{2(R_r + h_{\text{max}}) - 2(R_r + h_{\text{min}}) \cos \left( \alpha_p \pi / (2P) \right)} \]  (4)

where \( h_{\text{min}} \) is the minimum thickness of PM, \( \alpha_p \) is pole-arc to pole-pitch ratio and \( P \) is pole pairs.

The equivalent surface current is equal to the circumferential component of coercivity on the surface of magnet pole[19]. And the equivalent surface current of eccentric magnet pole is shown in Fig. 3(a) for parallel magnetization.

The current density of AB and CD can be given by

\[ J_1 = H_{ij} \cos \left( \alpha_p \pi / (2P) \right) \]  (5)

where \( H_{ij} \) is coercivity of permanent magnet.

The surface current density of side BC can be given by

\[ J_2 = H_{ij} \sin \left( \zeta' \right) \]  (6)

The surface current density of side AD can be given by

\[ J_3 = H_{ij} \sin \zeta \]  (7)

The equivalent surface current of eccentric magnet pole is shown in Fig. 3(b) for radial magnetization.

The surface current density of side AB and CD can be given by

\[ J_1 = H_{ij} \]  (8)

The surface current density of side BC can be given by

\[ J_2 = H_{ij} \sin \left( \zeta' - \zeta \right) \]  (9)

The surface current density of side AD is zero.

2.2 Magnet field produced by a pair of windings

Equivalent surface-current method is based on magnet field produced by a pair of windings. The current of windings can be given by

\[ i_x = J_x \Delta l \quad (x = 1, 2, 3) \]

where \( \Delta l \) is the length infinitesimal in the side AB, CD, AD and BC of magnet pole.

In this section, magnet field produced by a pair of windings is analyzed. Subdomain model with a pair of windings is shown in Fig. 4.

2.2.1 Magnet field in the first type of subdomains

Since in the 2-D field, the vector potential has only \( z \)-axis component which satisfies:
\[
\frac{\partial A_{r1}}{\partial r^2} + \frac{1}{r} \frac{\partial A_{r1}}{\partial r} + \frac{1}{r^2} \frac{\partial A_{r1}}{\partial \theta} = 0
\]  
(10)

\(\alpha\) and \(\beta\) are the labels of winding. \(a\) and \(\zeta\) present the position of the windings in the polar coordinate system. \(i_k\) is current. The vector potential of point \(Q(r, \theta)\) produced by \(\alpha\) and \(\beta\) is given by

\[
A_{r1}^\alpha = -\frac{\mu_0 i_\alpha}{2\pi} \ln \rho_\alpha + \sum_m \left[ (A_m^\alpha r^m + B_m^\alpha r^{-m}) \cos(m(\theta - \zeta)) \right] + 
\sum_m \left[ (C_m^{\alpha r^m} + D_m^{\alpha r^{-m}}) \sin(m(\theta - \zeta)) \right]
\]  
(11)

\[
A_{r1}^\beta = \frac{\mu_0 i_\beta}{2\pi} \ln \rho_\beta + \sum_m \left[ (A_m^\beta r^m + B_m^\beta r^{-m}) \cos(m(\theta + \zeta)) \right] + 
\sum_m \left[ (C_m^{\beta r^m} + D_m^{\beta r^{-m}}) \sin(m(\theta + \zeta)) \right]
\]  
(12)

respectively.

According to (11) and (12), the sum of vector potential can be given by

\[
A_{r1} = -\frac{\mu_0 i_A}{2\pi} \ln \rho_A + \sum_m \left[ (A_m r^m + B_m r^{-m}) \cos(m\theta) \right] + 
\sum_m \left[ (C_m^{r^m} + D_m^{r^{-m}}) \sin(m\theta) \right]
\]  
(13)

where \(A_m, B_m, C_m, D_m\) are coefficients to be determined, \(\mu_0\) is the permeability of the air, \(r\) is the radial of point \(Q\), \(\theta\) is the degree between point \(Q\) and center line of the windings, \(\rho_A\) and \(\rho_\beta\) are the coordinates when the origins are \(\alpha\) and \(\beta\) respectively.

If the origin is point \(O\), \(\ln \rho_\alpha\) and \(\ln \rho_\beta\) can be expanded into infinite series about \(\theta\) and \(r\).

\[
\ln \rho = \ln \rho_A - \ln \rho_\beta
\]

\[
= \begin{cases} 
-2 \sum_m \left( \frac{a}{r} \right)^m \sin(m\zeta) \sin(m\theta), & r > a \\
-2 \sum_m \frac{1}{m} \sin(m\zeta) \sin(m\theta), & r = a \\
-2 \sum_m \left( \frac{r}{a} \right)^m \sin(m\zeta) \sin(m\theta), & r < a
\end{cases}
\]  
(14)

The radial and circumferential components of flux density can be obtained from the vector potential distribution by

\[
B_r = -\frac{\partial A}{\partial r} \quad \text{and} \quad B_\theta = \frac{1}{r} \frac{\partial A}{\partial \theta}
\]  
(15)

While \(r < a\), the flux density in the first subdomain can be given by

\[
B_{r1} = -\sum_m \left[ (A_m r^{m-1} - mB_m r^{-m-1}) \cos(m\theta) \right]
\]

\[
\sum_m \left[ mC_m r^{m-1} - mD_m r^{-m-1} + \frac{\mu_0 i_\beta}{2\pi} \left( \frac{r}{a} \right)^m \sin(m\zeta) \right] \sin(m\theta)
\]  
(16)

for the circumferential component.

In the outer surface of rotor, the circumferential component of the flux density is zero

\[
B_{\theta1} \big|_{r=R} = 0
\]  
(17)

Substituting (16) into (17), \(B_{r1}\) and \(D_{n1}\) can be given by

\[
B_{r1} = A_{r1} R^{2n} 
\]

\[
D_{n1} = \frac{\mu_0 i_\beta}{m\pi} \frac{R^{2n}}{a^n} \sin(m\zeta) + C_{n1} R^{2n} 
\]  
(18)

While \(r > a\), substituting (18) and (19) into (13), the general solution of vector field in the first subdomain can be given by

\[
A_{r1} = \sum_m A_m G_{1m} \cos(m\theta) + \sum_m (C_m G_{1m} + G_{0m} r^{-m}) \sin(m\theta)
\]  
(20)

where

\[
G_{1m} = r^m + R^{2n} r^{-m} 
\]

\[
G_{0m} = \frac{\mu_0 i_\beta}{m\pi} \frac{R^{2n}}{a^n} \sin(m\zeta) 
\]  
(21)

While \(r > a\), the flux density in the first subdomain can be given by

\[
B_{r1} = \frac{m}{r} \left[ -\sum_m A_m G_{1m} \sin(m\theta) + \sum_m (C_m G_{1m} - G_{0m} r^{-m}) \cos(m\theta) \right]
\]  
(23)

for the radial component, and

\[
B_{\theta1} = -\frac{1}{r} \left[ \sum_m A_m G_{2m} \cos(m\theta) + \sum_m (C_m G_{2m} - G_{3m}) \sin(m\theta) \right]
\]  
(24)

for the circumferential component, where
Improved Method for Calculating Magnetic Field of Surface-Mounted Permanent Magnet Machines Accounting for Slots and Eccentric ~

\[ G_{2n} = m(r^n - R_e^{2n}r^{-m}) \]
\[ G_{3n} = \frac{\mu_0}{\pi} \frac{R_e^{2n} + a^{2n}}{a^n} r^{-m} \sin(m\zeta) \]

The vector potential produced by the equivalent surface current of \( j \)th magnet pole can be given by:

\[ A_{21j} = \sum_m A_{mj} \cos\{m[\theta + (j - 1)\pi / P]\} + \sum_m \{C_{mj} + G_{0mj}\} r^{-m} \sin\{m[\theta + (j - 1)\pi / P]\}\]
\[ G_{0mj} = (-1)^{j-1} \frac{\mu_0}{\pi} \frac{R_e^{2m} + a^{2m}}{a^n} \sin(m\zeta) \]

where \( A_{mj} \) and \( C_{mj} \) are coefficients to be determined, and \((j - 1)\pi / P\) is the angle between center line of first pole and that of \( j \)th pole.

2.2.2 Magnet field in the second type of subdomains

The governing function in the slots is:

\[ \frac{\partial A_{21i}^2}{\partial r^2} + \frac{1}{r} \frac{\partial A_{21i}^2}{\partial r} + \frac{1}{r^2} \frac{\partial A_{21i}^2}{\partial \theta^2} = 0 \]

The vector potential in the subdomain \( 2i \) is:

\[ A_{21i} = \sum_n D_{2i1} \left[ G_{4n} \left( \frac{r}{R_{sh}} \right)^{E_{n-1}} + \left( \frac{r}{R_s} \right)^{-E_{n-1}} \right] \]
\[ \cos\left[ E_n \left( \theta + b_{sa} / 2 - \theta_i \right) \right] \]

where \( R_s \) is the inner radial of the stator, \( R_{sh} \) is the radial of the slot bottom, \( \theta_i \) is the angle between center line of the \( i \)th slot and center line of the windings as shown in Fig. 4, \( b_{sa} \) is the slot opening width angle, \( D_{2i1} \) is coefficient to be determined, and

\[ E_n = n\pi / b_{sa} \]
\[ G_{4n} = \left( R_s / R_{sh} \right)^{E_{n-1}} \]

So the flux density in the second subdomain can be given by

\[ B_{r2i} = -\sum_n E_n D_{2i1} \left[ G_{4n} \left( \frac{r}{R_{sh}} \right)^{E_{n-1}} + \left( \frac{r}{R_s} \right)^{-E_{n-1}} \right] \]
\[ \sin\left[ E_n \left( \theta + b_{sa} / 2 - \theta_i \right) \right] \]

for the radial component, and

\[ B_{\theta2i} = -\sum_n E_n D_{2i1} \left[ G_{4n} \left( \frac{r}{R_{sh}} \right)^{E_{n-1}} - \left( \frac{r}{R_s} \right)^{-E_{n-1}} \right] \]
\[ \cos\left[ E_n \left( \theta + b_{sa} / 2 - \theta_i \right) \right] \]

for the circumferential component.

2.2.3 Interface condition between two types of subdomain

(a) The First Interface Condition

The first interface condition is that the circumferential component of the flux density in the inner surface of stator \( r = R_s \) is equal.

By evaluating (34) at the \( r = R_s \) interface, (34) simplifies down to

\[ B_{\theta2i} |_{r=R_s} = \sum_n B_{\theta i0} \cos\left[ E_n \left( \theta + b_{sa} / 2 - \theta_i \right) \right] \]

where

\[ B_{\theta i0} = -E_n D_{2i1} \left( G_{4n}^{2 - 1} / R_s \right) \]

The circumferential component of the flux density along the stator bore outside the slot is zero since the stator core material is infinitely permeable. So Fourier series of the circumferential component of the flux density in the inner surface of stator can be given by

\[ B_{\theta i0} = \sum_n \left[ C_{ms} \cos(m\theta) + D_{ms} \sin(m\theta) \right] \]

Where

\[ C_{ms} = \frac{1}{\pi} \int_0^{2\pi} B_{\theta i0} \cos(m\theta) d\theta \]
\[ = \frac{1}{\pi} \sum_n \sum_{\theta_i - b_{sa} / 2}^{\theta_i + b_{sa} / 2} B_{\theta i0} \cos\left[ E_n \left( \theta + b_{sa} / 2 - \theta_i \right) \right] \]
\[ \cos(m\theta) d\theta \]
\[ = \sum_n \sum_{\theta_i} B_{\theta i0} \eta_j(n, m) \]

Fig. 4. Subdomain model with a pair of windings
According to the vector potential distribution in the first subdomain, the circumferential component of the flux density in the inner surface of stator can be given as

\[
B_{s02} = B_{\theta1} \big|_{-R_s}
\]

(42)

According to (24), (37) and (42):

\[
\begin{bmatrix}
G_{sR}^{-1}A_m + G_{sI}^{-1}C_{ns} \\
G_{sR}^{-1}C_{ns} - G_{sI}^{-1}R_{sm} = -R_{C_{ms}}
\end{bmatrix}
\]

(43)

Combining (36), (38), (39) and (43), the following equations can be obtained:

\[
\begin{bmatrix}
K_{11}A_{i1} + K_{13}D_{2i} = 0 \\
K_{22}C_{i1} + K_{23}D_{2i} = Y_2
\end{bmatrix}
\]

(44)

(b) The Second Interface Condition

The second interface condition is that the vector potential of the \(i\)th slot opening is equal in the two types of the subdomains.

According to (20), the vector potential in the inner surface of stator can be given as

\[
A_i = A_{z21} \big|_{-R_s} = \sum_n \left[ A_{m} \cos(m\theta) + A_{ms} \sin(m\theta) \right]
\]

(45)

where

\[
A_{m} = G_{1m}^{-1}A_m \\
A_{ms} = G_{1m}^{-1}C_{sm} + G_{0m}R_{sm}
\]

(46)

(47)

The equation (45) can be expanded into Fourier series along the stator inner surface of the \(i\)th slot:

\[
A_i = \sum_n A_n \cos\left[ E_n (\theta + b_{sa} / 2 - \theta_i) \right]
\]

(48)

\[
A_{ms} = \frac{2}{b_{sa}} \sum_n \left[ A_{nc} \cos(m\theta) + A_{nc} \sin(m\theta) \right]
\]

(49)

According to (30), the vector potential in the inner surface of stator can be obtained:

\[
A_{z21} \big|_{-R_s} = \sum_n D_{n21}(G_{4n}^2 + 1) \cos\left[ E_n (\theta + b_{sa} - \theta_i) \right]
\]

(52)

The vector potential in the inner surface of stator is equal in two subdomains.

\[
A_{z21} \big|_{-R_s} = A_i
\]

(53)

Substituting (48) and (52) into (53), the following equation can be obtained:

\[
\sum_n D_{n21}(G_{4n}^2 + 1) \cos\left[ E_n (\theta + b_{sa} / 2 - \theta_i) \right] = \sum_n A_{ms} \cos\left[ E_n (\theta + b_{sa} / 2 - \theta_i) \right]
\]

(54)

Then

\[
D_{n21}(G_{4n}^2 + 1) = A_{ms}
\]

(55)

Substituting (49) into (55), the following equation can be obtained:

\[
D_{n21}(G_{4n}^2 + 1) = \sum_n \left( A_{nc} \sigma_i (n, m) + A_{ms} \tau_i (n, m) \right)
\]

(56)

while \(n = 1, 2, 3, \ldots\).

Combining (46), (47) and (53), the following equation can be obtained:

\[
K_{31}A_{i1} + K_{32}C_{i1} + K_{33}D_{2i} = Y_3
\]

(57)

According to (44) and (57), the matrix format can be
given as
\[
\begin{bmatrix}
K_{11} & 0 & K_{13} \\
0 & K_{22} & K_{23} \\
K_{31} & K_{32} & K_{33}
\end{bmatrix}
\begin{bmatrix}
A_1 \\
C_1 \\
D_{21}
\end{bmatrix}
= 
\begin{bmatrix}
0 \\
Y_2 \\
Y_3
\end{bmatrix}
\] (58)

Then the coefficients A1, C1 and D2i can be obtained according to (58).

2.2.4 The superposition principle of vector potential

The superposition principle can be applied to the vector potential by equivalent surface current in the surface-mounted permanent magnet machines.

In the Fig. 3, the vector potential produced by equivalent surface current of side AB and CD can be superposed:
\[
A_{211} = \sum_{k_1} A_{11} \int_{-R_{k1}}^{R_{k1}} \rho_{k1,AR}\,
\] (59)

where \( \Delta r \) is the length infinitesimal in the side AB and CD of PM and
\[
k_1 = \{1, 2, \cdots, h_{\max} / \Delta r\}
\] (60)

The vector potential produced by equivalent surface current of side BC can be superposed:
\[
A_{212} = \sum_{k_2} A_{12} \int_{-R_{k2}}^{R_{k2}} \rho_{k2,AR}\,
\] (61)

where \( \Delta \gamma_1 \) is the angle infinitesimal in the side BC of PM, and the origin is point O1,
\[
k_2 = \{1, 2, \cdots, \zeta_{\max} / \Delta \gamma_1\}
\] (62)
\[
\zeta_{\max} = \arcsin \{OB \times \sin (a_p \pi / (2P)) / R_1\}
\] (63)

The vector potential produced by equivalent surface current of side AD can be superposed:
\[
A_{213} = \sum_{k_3} A_{13} \int_{-R_{k3}}^{R_{k3}} \rho_{k3,AR}\,
\] (64)

where \( \Delta \gamma_2 \) is the angle infinitesimal in the side AD of PM, and the origin is point O,
\[
k_3 = \{1, 2, \cdots, [a_p \pi / (2P)] / \Delta \gamma_2\}
\] (65)

According to (15), (59), (61) and (64), the radial and circumferential components can be obtained.

3. Finite-Element Validation

The major parameters of two 30-pole/36-slot prototype machines which are used for validation are shown in Table 1. The minimum thickness of permanent magnet is 7mm in the prototype machine with eccentric magnet poles. And it is 12mm in the prototype machine with concentric magnet poles. The analytical prediction is compared with the linear FE prediction.

Fig. 5 show the results between analytical and FE predictions of flux density in the air-gap at \( r=198.5 \) mm of motor with eccentric magnet poles: (a) Radial component; (b) circumferential component.
almost completely matches FE results.

Harmonic analysis of radial component of flux density with five pair of magnet poles in air-gap is shown in Fig. 7. Because five pair of magnet poles are one cycle to radial component of flux density in the air-gap. Then the 5th order spatial harmonic is fundamental harmonic. The same harmonic orders are 7th, 17th, 19th, 29th 31th et al. because of the influence of slots. The main different harmonic orders between Eccentric magnet poles and concentric magnet poles are the 15th and 25th order spatial harmonic. The harmonic content of radial component of flux density is 10.59% in the motor with eccentric magnet poles. The harmonic content of radial component of flux density is 23.17% in the motor with concentric magnet poles.

4. Conclusion

This paper presented an improved method for calculating the magnetic field in the surface-mounted permanent magnet machines accounting for slots and eccentric magnet pole. Magnetic field produced by radial and parallel eccentric permanent magnet is equivalent to that produced by surface current according to surface-

Fig. 6. FE and analytically predicted flux density waveforms in the air-gap at \( r=198.5 \text{mm} \) of motor with concentric magnet poles: (a) Radial component; (b) circumferential component.

Fig. 7. Harmonic analysis of radial component of flux density at \( r=198.5 \text{mm} \) of motor. (a) Eccentric magnet poles; (b) Concentric magnet poles.

References

Improved Method for Calculating Magnetic Field of Surface-Mounted Permanent Magnet Machines Accounting for Slots and Eccentric ~


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Yu Zhou, Huaishu Li, Wei Wang, Qing Cao and Shi Zhou

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