A New Optimization of Segmented Interior Permanent Magnet Synchronous Motor Based on Increasing Flux Weakening Range and Output Torque

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1. INTRODUCTION

Operation of electric machines which are employed as electric vehicles in over wide speed range is necessary [1–3]. Nominal power preservation of electric machines at speeds higher than nominal value requires flux weakening capability. Flux weakening capability is defined as maximum accessible speed value divided by nominal speed which is called Constant Power Speed Range (CPSR). For example the CPSR of a conventional efficient line-start induction machine (IM) is typically 2.5. Usually electric vehicles require CPSR values higher

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than 3 for over wide speed range. Therefore engineers try to increase the CPSR value by optimizing the design of electric machines which are specially based on induction machine and Permanent Magnet (PM) machine topologies. The CPSR of a permanent magnet motor could be improved by optimizing the rotor structure. One method of doing so is placing flux barriers in the rotor [4, 5]. Interior permanent magnet (IPM) synchronous motors are often more widely considered for high CPSR and high efficiency applications such as electric vehicles and home appliances, because of their higher torque density in relation to other radial PM motors [6–8]. Many techniques for IPM flux-weakening improvement have been proposed in recent years [9–13]. Flux barriers design, PM segmented and various control strategies of IPM are the main focus of these literatures. In other words, these articles only improve the CPSR value while unwantedly decreasing the output torque in the final design. In this paper a new IPM optimization function for keeping the output torque at a nominal value and increasing the CPSR is proposed based on the combination of two variables i.e. normalized characteristic current and saliency ratio. The characteristic current is defined as d-axis flux divided by d-axis inductance. In this paper increasing the CPSR is carried out by decreasing the characteristic current, and output torque is adjusted by increasing the saliency ratio which leads to an increase in the reluctance torque component of IPM. In our new optimization function the CPSR value is controlled by characteristic current and output torque is adjusted by saliency ratio. Therefore these variables are optimized together using optimization of flux barrier shapes with PM segmented in rotor structure. For reducing calculations in the optimization process, a simplified magnetic equivalent circuit of SIPMSM is introduced. Using this equivalent circuit the d-q inductances and air gap flux values are obtained faster than 2D powerful numerical techniques such as Finite Element Method (FEM).

2. MAGNETIC EQUIVALENT CIRCUIT

Figure 1 shows the typical cross section view of SIPMSM. The magnetic flux line distribution of typical SIPMSM per pole is illustrated in Figure 1. A magnetic equivalent circuit of IPMSM has been presented in [12]. But in [12] the rotor PMs is not segmented. In this paper the PM segmentation effects is adopted to the [12] and the simplified SIPMSM is investigated. In SIPMSM there are two additional reluctances in comparison to the magnetic equivalent circuit of [12]. Therefore there are seven reluctances per pole in the proposed equivalent magnetic circuit of SIPMSM which is listed below:

Air gap, Iron bridge above the flux barrier, Leakage flux, Iron bridge between PMs, PM reluctance, Stator core and Rotor core. Consequently, the modified equivalent magnetic circuit per pole considering PM segmentation is illustrated in Figure 2. Where $2\mathcal{R}_g$, $\mathcal{R}_{mm}$, $\mathcal{R}_{mi}$, $\mathcal{R}_{ib}$, $2\mathcal{R}_{most}$, $\mathcal{R}_r$, $\mathcal{R}_d$ are reluctances of half of the air gap, iron bridges above the flux barrier, leakage flux, iron bridges between PMs, PM segmented, rotor and stator back iron respectively. $\varphi_{reb}$ and $\varphi_g$ are ith PM segmented flux (i is the PM segmented number) and air gap flux respectively. There are three assumptions for rearrangement of Figure 2 which are each listed below:

The height and width of all PMs segmented and width of iron bridges between PMs is the same. This magnetic equivalent circuit of Figure 2 using above assumptions can be simplified to the proposed SIPMSM magnetic circuit which is illustrated in Figure 3.

In Figure 3, $\gamma$ and $\mathcal{R}_{ma}$ are the number of the PM segmented and PM segmented reluctances respectively. The relationship between flux pass through the iron bridges and between PMs $\lambda_\text{ib}$ and $\lambda$ can be expressed in Equation (1):

$$\frac{\lambda}{\lambda_\text{ib}} = \frac{(1 + 2\eta + 1/\beta)}{2\left(\frac{A_m}{A_{mn}}\right)} \left(\frac{m_b}{m_{ib}}\right) - 4 - (\gamma - 1) = \frac{\varphi_g}{\varphi_{reb}}$$

where $\beta = \mathcal{R}_g / \mathcal{R}_{ma}$, $\eta = \mathcal{R}_{ma} / \mathcal{R}_{mi}$ and, $A_m, A_{mm}, A_{ib}$ are cross section area of segmented PM, flux barrier and...
iron bridge respectively. \( B_r, B_{sib}, B_{sbdg} \) are residual magnetic flux density of PM, saturation level of the magnetic flux density for iron bridges and flux barrier respectively. Saturation level of upper flux barrier and iron bridges is considered as 1.8T and 1.9T respectively. The d-q inductances of IPMSM are calculated by [13]. But for d-axis air gap the effect of PM segmentation i.e \((y-1)\lambda_{ib}\) is added to [13] which is expressed in Equation (2):

\[
g_d = \frac{k_{d1} g_d}{k_{1ad} - k_{1ad}/(1+\rho(1+2\pi+4\lambda+(y-1)\lambda_{ib}))} \tag{2}
\]

where \( l_1, D, L, K_{ad}, N_{pb}, p, k_c \) are leakage inductance, stator bore, machine axial length, winding coefficient, number of phase turns, pole pairs and carter coefficient. The coefficients \( k_{1ad}, k_{ad}, k_1 \) are expressed in the appendix. The specification of the motor and magnetic characteristic of the core (rotor and stator) which is called M-19 steel are illustrated in Table 1 and Figure 4. The design optimization in this paper for calculation of fluxes is carried out based on the simplified magnetic circuit of SIPMSM. Therefore verification of simplified magnetic circuit must be done. As a result the d-q inductances and air gap flux of mentioned SIPMSM are evaluated by Finite Element Method (FEM) and simplified magnetic circuit.

The results of this comparison are listed in Table 2. Where \( w_{ms}, w_{ib}, h_m, d, d_0, d_1, t_1, t_2 \) are shown in Figure 1. It is seen that maximum error between simplified magnetic circuit and FEM is 3.5%, which is a very good result. Therefore to calculate inductance in the optimization process we used simplified magnetic circuit instead of FEM.

### 3. OPTIMIZATION OF SIPMSM FOR INCREASING CPSR AND OUTPUT TORQUE

Optimization of rotor structure is an interesting technique for increasing the CPSR value. In general the normalized characteristic current must be close to unity during the optimization process. The saliency ratio which depends on reluctance torque component of SIPMSM is added to the usual optimization function of SIPMSM for keeping the output torque at nominal value during CPSR improvement. The proposed optimization function for SIPMSM is expresses in Equation (3):

\[
OF = \min \left( k_1 \left( \frac{\Psi_{PM}}{L_{dn}} - 1 \right) + k_2 \left( \frac{1}{\rho} \right) \right) \tag{3}
\]

where \( L_{dn}, \Psi_{PM}, \rho \) are normalized values of the d inductance, PM flux and saliency ratio respectively. \( k_1, k_2 \) are pre-defined constant coefficients. Minimization of characteristic current and saliency ratio is highly dependent on d and q inductances values. These inductance values are dependent on PM and air bridges configuration in rotor structure too. Therefore a detailed design of rotor must be implemented. Figure 5 shows a detailed cross section view of SIPMSM rotor per pole.

In this paper six variables for optimization of (3) have been considered which are contained upper flux barrier bridge thickness “\( t_1 \)”, distance between two neighbor flux barriers “\( d_0 = DE \)”, flux barrier width “\( d_1 = CD \)”, iron

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**TABLE 1. Machine and PM parameters**

| Symbol | Value | Symbol | Value |
|--------|-------|--------|-------|
| \( l_g \) | 0.5 mm | D | mm 82 |
| \( N_{pb} \) | 46 | L | mm 55 |
| \( y \) | 3 | \( t_1 \) | 2 mm |
| \( d \) | mm 5.9 | \( h_2 \) | 4.2 mm |
| \( w_{ms} \) | mm 13 | \( d_q \) | 2.86 mm |
| \( w_{ib} \) | 1.8 mm | \( h_m \) | mm 4 |
| \( \mu_{rec} \) | 1.21 | \( Br \) | (T) 1.1 |
| Pole pairs | 2 | Hc | 890kA/m |
| Nominal current | A 12 | Nominal power | 550 W |
| Nominal voltage | 20.2 V | Nominal speed | 1750 rpm |

**TABLE 2. Simplified magnetic circuit and FEM results**

| Quantity | FEM | Modified magnetic circuit | Error (%) |
|----------|-----|---------------------------|----------|
| d inductance(mH) | 1.15 | 1.19 | 3.5 |
| q inductance(mH) | 3.12 | 3.09 | 0.96 |
| PM linkage flux(mWb) | 24.19 | 24.8 | 2.5 |

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**Figure 3.** The simplified magnetic circuit of SIPMSM

**Figure 4.** Magnetic characteristic of M-19 steel
bridge width between PM segmented “\(w_{ib}\)”, distance between PM position and rotor centre “\(h_0\)” and number of PM segmented per poles “\(\gamma\)”. Each segmented permanent magnet volume is considered constant which is equal to \(3 \times 4 \times 13 = 156\text{mm}^3\). Then relation between thickness and length of segmented PM is calculated Equation (4):

\[
w_s = \frac{156}{h_m}\text{mm}, \quad \text{HA} = \frac{\gamma}{2}w_s + \frac{\gamma-1}{2}w_b = FB = w
\]

where \(w_s, h_m\) are width and height of PM segmented respectively. According to Figure (5) the relationship between six design variables are expressed in Equations (5) - (12):

\[
OE = r_{oe} - t = r_p
\]

\[
\sin(\angle DOE) = \frac{OE}{OE} = \frac{d_b}{r_s} \approx \theta_o, \sin(\angle COD) = \frac{CD}{AD} = \frac{d_s}{r_s} \approx \theta_1
\]

\[
\alpha = \frac{n/p - 2(\theta_0 + \theta_1)}{\pi/p} = 1 - \frac{2p(\theta_0 + \theta_1)}{\pi}
\]

where \(p, \alpha, r_p\) are poles pairs, pole pitch to pole arc ratio, and outer rotor radius respectively.

\[
\angle HOA = \tan^{-1}\left(\frac{HA}{OH}\right) = \tan^{-1}\left(\frac{w}{h_b}\right) = \beta_1
\]

\[
\angle FOB = \tan^{-1}\left(\frac{FB}{OF}\right) = \tan^{-1}\left(\frac{w}{h_b + h_s}\right) = \beta_2
\]

\[
OA = \sqrt{h_s^2 + w^2}, \quad OB = \sqrt{(h_b + h_s)^2 + w^2}
\]

\[
h_i = BC = \sqrt{OB^2 + r_x^2 - 2r_xOB \cos \left(\frac{\pi}{2p} - \beta_1 - \theta_1 - \theta_2\right)}
\]

\[
h_2 = AD = \sqrt{OA^2 + r_y^2 - 2r_yOA \cos \left(\frac{\pi}{2p} - \beta_1 - \theta_0\right)}
\]

As seen in Figure 5 increasing the “\(t\)” leads to an increase in the flux crossing through neighboring segmented PMs. As a result, the total air gap flux will be decreased, which will consequently reduce the output torque. If “\(t\)” has been selected to be very small the mechanical robustness of the rotor will decrease. An increase in the saliency ratio could possibly reduce the rotor’s mechanical robustness due to the increasing “\(h_0\)”, implying that the number of magnets segmented should be limited. Therefore optimization variables must be limited during optimization process. These limitations are as follows: \(0.9 \leq w_{ib}(\text{mm}) \leq 3\), \(0.8 \leq t(\text{mm}) \leq 3\), \(19 \leq h_0(\text{mm}) \leq 29\), \(2 \leq \gamma \leq 7\), \(0.2 \leq d_1(\text{mm}) \leq 6\), and \(1 \leq d_0(\text{mm}) \leq 3\).

The Genetic Algorithm (GA) technique is employed as an optimization tool. The SIPMSM is analyzed by FEM, then the OF is computed by FEM and simplified magnetic circuit results. The outputs of genetic algorithm and its typical design are listed in Table 3. It is shown that the number of segmented PM “\(\gamma\)” after optimization using GA is increased to 5 and flux barrier width \(d_1\) has been decreased too. The magnet position “\(h_0\)” has been reduced due to increasing the number of PM segmented. The effect of these changes on inductances and rotor structure is illustrated in Figure 6 and Table 4. The output torque and other parameters are computed using commercial FEM Ansoft/Maxwell software. The optimized SIPMSM has higher torque, current angle and saliency ratio related to the typical design. Increasing the saliency ratio increases the reluctance torque component, increasing the output torque and power as a result. Increasing the \(d\) inductance in optimized design leads to a decrease in the air gap flux, decreasing the magnetic torque component. But the increase in the reluctance torque component is greater than the decrease in the magnetic torque component. As a result the total output torque increases by 11% compared to the typical design. The output torque of typical and optimized SIPMSM is illustrated in Figure 7. According to Figure 7 maximum speed of the optimized design in generation of output torque is higher than typical design. The characteristic current of optimized SIPMSM is decreased by 30% compared to the typical design, leading to an increase in

| Table 3. Design variables before and after optimization |
|---------------------------------|-----------------|-----------------|
| Parameter | Before optimization | After optimization |
| \(\gamma\) | 3 | 5 |
| \(\omega_{ib}\)(mm) | 1.8 | 1.07 |
| \(t\)(mm) | 2 | 1.63 |
| \(h_0\)(mm) | 27.82 | 22.98 |
| \(d_1\)(mm) | 2.86 | 2.06 |
| \(d_0\)(mm) | 5.94 | 1.4 |
Comparison of torque components which are obtained by typical and an optimized design is illustrated in Figure 10. This demonstrates that the electromagnetic torque component of optimized SIPMSM (Figure 10-a) in all current angle ranges is smaller than the typical design but the reluctance torque component of optimized design is higher than typical design in all ranges of the current angle (Figure 10-b). Finally, by addition of two torque components of optimized design which is equal to total output torque is higher than total output torque of typical design (Figure 10-c) excluding current angles lower than 15 degrees which are belong to light loads. This range is not important because nominal current angle operation of SIPMSM is at least out of this range.

### 4. CONCLUSION

In this paper, an optimal design of a segmented interior permanent magnet synchronous motor (SIPMSM) for increasing the flux weakening range based on minimization of characteristic current and saliency ratio...
is proposed. The new objective function is well defined using a combination of characteristic current minimization (for increasing the flux weakening range) and maximization of saliency ratio (for compensation of output torque drop during optimization process). In order to reduce calculations, magnet flux and dq inductances are calculated using the proposed simplified magnetic equivalent circuit instead of FEM analysis. Simulation results demonstrate that the optimized design has a good performance in increasing the flux weakening range and output torque related to the typical design.

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6. APPENDIX

\[ k_{1d} = \alpha + \frac{\sin(\alpha n)}{n} \]  
\[ k_{1d} = \frac{\sin(\alpha n/2)}{\alpha n/2} \]  
\[ k_1 = 4 \sin(\alpha n/2)/\alpha \]  
\[ \varphi_{ml} = \frac{2d}{\mu_isA_{ml}} = \frac{4d}{\mu_0k(h_1+h_2)} \]  
\[ \varphi_{mm} = \frac{2d+d_0}{\mu_is\varphi_{mm}} = \frac{2d+d_0}{\mu_0\varphi_{E}} \]  
\[ \varphi_{lb} = \frac{h_{lb}}{\mu_is\varphi_{lb}} = \frac{h_{lb}}{\mu_0\varphi_{LW}} \]  
\[ \varphi_{rxi} = B_iLW_{rxi} = B_iL \frac{w_m}{3} = \frac{\varphi_{r}}{3} \]