Reducing Cogging Torque in Flux Switching Motors with Segmented Rotor

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Flux switching machine with a segmented rotor is an attractive alternative for driving high torque density and high speed applications. However motor doubly salient structure causes torque ripples as well as acoustic noise and vibrations. In this paper cogging torque of the motor is analyzed and reduced by imposing notches into the segments. Different numbers and shapes of notch are considered and their effects on the motor cogging torque, developed torque and back EMF are investigated analytically. After optimization of motor cogging torque, the suitable notch number and shape are introduced. Finite element analysis is employed to confirm the analytical results. Also, the finite element results are compared with the presented experimental results.

Index Terms— Flux Switching Motors, Cogging Torque, Finite Element Method

I. INTRODUCTION

Flux switching (FS) machines are attractive to high torque density, high efficiency and high power factor applications in a vast field including home appliance [1], automotive [2] and aerospace [3]. A FS machine can be regarded as a combination of an inductor alternator and a switched reluctance (SR) motor; so it inherits the high torque capability of a PM motor and the robustness of rotor structure of a SR machine [4]. In order to avoid the risk of demagnetization in FS machines, the permanent magnet poles are placed in stator structure so that both the excitation and the armature windings are accommodated within the motor stator. By this combination, a better thermal management of PM is also achieved [5]. Air gap excitation field can be controlled by replacing the permanent magnets by concentrated field windings [6]. A similar rotor topology to the one used in segmented rotor SR motor [7], is employed in a different FS motor structure. The developed torque in this structure is comparable with that of SR motors of same class [6].

FS machines generally suffer from higher torque ripples than other commonly used machines. It is essential to minimize torque fluctuations caused by a high air gap flux density and the interaction between mmf harmonics and air gap permeance harmonics. Under dynamic conditions, torque ripples can be transmitted via the rotor shaft to the load, causing difficulty in position and speed control. Also, torque ripples may cause vibration, acoustic noise and structural resonance in the motor stator. In a segmented rotor flux switching (SRFS) motor the main problem is the torque ripples that reach up to 50 percent of average developed torque in high armature and field currents. Different methods are employed to minimize torque ripples in electric machines. Some researchers focus on driving methods of motors [8] while others work on rotor or stator tooth shaping including fractional number of slot per pole [9], slot skewing [10], notches or teeth and pole arc optimization [11-12]. While these methods are more or less effective in reducing torque ripples, they are concerned with other machine types. The specific structural and operational characteristics of SRFS machines require that the existing methods of ripples reduction are examined on this type of machine in order to apply appropriate modifications.

In this paper torque fluctuations of a 12/8 segmented rotor wound field FS motor is analyzed. Using an analytical approach, it is shown that the changes in air gap permeance lead to changes in the motor cogging torque profile. Since a change in the stator tooth shape is cumbersome, the rotor segments shape is modified. This is carried out by providing notches in rotor segments. Finite element (FE) method is employed to model the motor and approve analytical findings. Firstly, the effects of notches location and dimensions on the average developed torque and its ripples are evaluated. Then by optimization, the best number, location and dimensions of notches for maximum ripple suppression are extracted. Next, in order to minimize the reduction of average value of torque, the shape of the best selected notch is modified. At the end, a test motor is modeled in FE environment and its performance is compared with the experimental results to confirm the effectiveness of the cogging torque reduction method [13].

II. MODELING SRFS

There are different choices for a SRFS motor topology especially in terms of rotor segments and stator teeth numbers. These topologies have different output characteristics, particularly in terms of average value of developed torque and its ripple contents. It is required that adjacent stator teeth are wounds alternatively with one field winding and one armature winding. Also, the polarization of each field winding should be opposite to the one of the adjacent winding. Each slot is filled by one armature phase winding and field winding. Therefore, half of the total slots are filled by each of the armature or field winding. Therefore, the minimum number of stator slots for a three phase topology is 12 and other topologies may be built with its integer multiple number of slots.

In a 12 stator teeth configuration, it is anticipated that a
rotor with odd number of segments develops an unbalanced magnetic force. Segment spans are limited by their separating spans provided to prevent any significant flux crossing to adjacent segments. Besides, the number of segments on the rotor, controls segment pitches. Different topologies are evaluated and it is found out that a 12/8 topology have the highest torque capability with a reasonable back EMF waveform [15]. A SRFS motor schematic view with a 12/8 stator teeth and rotor segments is illustrated in Fig. 1.

![SRFS Motor Schematic](image)

The SRFS motor develops a torque on the rotor which is derived by [13]:

\[
T = i_f i_a \frac{dM_{fa}}{d\alpha} \tag{1}
\]

where \(i_f\), \(i_a\), \(M_{fa}\) and \(\alpha\) are field current, armature current, mutual inductance between adjacent field and armature windings and circumferential coordinate angle of rotor respectively. The torque can also be given as:

\[
T = T_{avg} + T_{cog} \tag{2}
\]

where \(T_{avg}\) is the average developed torque and \(T_{cog}\) is the related cogging torque. The latter torque is the result of energy variations within the motor caused by the rotation of rotor. Since the variation of energy in iron parts are negligible compared to its variation in the air, the cogging torque resulted from magnetostatic energy variation is obtained as [14]:

\[
T_{cog}(\alpha) = -\frac{\partial W(\alpha)}{\partial \alpha}_{\text{airgap}} \tag{3}
\]

\[
= -\frac{\partial}{\partial \alpha} \left( \frac{1}{2\mu_0} L_s \frac{1}{2} (R_2^2 - R_1^2) \right) \frac{\pi^2}{2} G^2(\theta) B^2(\theta, \alpha) d\theta
\]

where \(L_s, R_2, R_1, G(\theta), B(\theta, \alpha)\), \(\theta\) are the stack length, stator inner radius, rotor outer radius, normalized air gap permeance, flux density function and displacement angle of rotor respectively.

For this motor the rotor segments and stator slots are evenly spaced so that, the Fourier expansion of \(G^2(\theta)\) and \(B^2(\theta, \alpha)\) can be written as:

\[
G^2(\theta) = \sum_{n=0}^{\infty} C_{nN_s} \cos nN_s \theta \tag{4}
\]

\[
B^2(\theta, \alpha) = \sum_{n=0}^{\infty} A_{nN_s} \cos nN_s (\theta + \alpha) \tag{5}
\]

where \(N_r, N_s, C_{nN_s}\) and \(A_{nN_s}\) are rotor segment number, stator teeth number and the corresponding \(n\)th harmonic Fourier coefficient of air gap permeance and airgap flux density respectively. In order to extract the cogging torque expression, (4) and (5) are substituted in (3) in order to yield:

\[
T_{cog}(\alpha) = T_c \sum_{n=1}^{\infty} nC_{nN_L} A_{nN_s} \sin nN_s \alpha \tag{6}
\]

\[
T_c = N_L \left( R_2^2 - R_1^2 \right) \frac{L_s \pi}{4\mu_0} \tag{7}
\]

\[
t_{cog} = \frac{120\pi}{n_r N_L} \tag{8}
\]

where \(n_r\) is rotor speed in radians per minute, \(t_{cog}\) is the cogging torque period and \(N_c\) is the least common multiple of \(N_r\) and \(N_s\). Therefore, design techniques are required to control these parameters in order to reduce cogging torque by increasing \(t_{cog}\) and decreasing cogging torque amplitude. From (6) and (7) it is found out that cogging torque is directly dependant on motor general dimensions that is not reasonable to be changed since it affects motor performance seriously including \(T_{avg}\). Also (6) indicates that the cogging torque can be reduced by controlling \(N_s, C_{nN_s}, A_{nN_s}\).

Fig. 2 shows the ideal airgap flux density caused by one rotor segment when the stator is slotless and the intersegment fringing effect is neglected. In this figure \(S_t\) is defined as the segment length to segment pitch ratio. Therefore, the Fourier

![Airgap Flux Density](image)
coefficient $A_{nnL}$ of $B(\alpha, \theta)$ is revealed:

$$A_{nnL} = \frac{N_r}{\pi} \int_{-\frac{\pi}{N_r}}^{\frac{\pi}{N_r}} B_0^2 \cos(nN_L \alpha') d\alpha' =$$

$$= \frac{2N_r}{nN_L} B_0^2 \sin(nN_L \frac{\pi}{N_r})$$

where $B_0$ is the maximum flux density shown in Fig. 2. Change of this parameter is not reasonable since it affects the motor performance seriously. Airgap permeance function reduces with a reduction of the motor performance seriously. Airgap permeance function index directly depends on the permeance function variations. So, it is required to change the profile of permeance function from what is used in the main model. It means that there is a sudden change from a minimum to a maximum value of permeance function in the main structure. As so, in order to decrease this attractive force, it is required to decrease the circumferential component of attractive force attempts to maintain alignment between stator teeth and rotor segments. In order to decrease this attractive force, it is required to decrease the effect of permeance function variations. So, it is required to change the profile of permeance function from what is shown in Fig. 3. Since the exact permeance function of this motor is very hard to reach, the analytical derivation of segments design for zero cogging torque is not easy. Although, Fig. 3 is a simple model of permeance function, its variation profile is same as the main model. It means that there is a sudden change from a minimum to a maximum value of the permeance function in the main structure. So, in order to manage cogging torque, a smooth change of permeance should be achieved in each segment rotation.

and the corresponding normalized permeance function for each segment represented by:

$$C = \begin{cases} 1 : & \beta_1 < \alpha < \beta_1, \beta_2 < \alpha < \beta_2 \\ \varepsilon(\alpha) : & \beta_{\alpha 1} < \alpha < \beta_{\alpha 2} \\ 0 < \varepsilon(\alpha) < 1 \\ \end{cases}$$

that $\varepsilon(\alpha)$ is a function of $f(\alpha)$. The Fourier expansion of $C_{nnL}$ for a machine with a notched segment as in Fig. 4 becomes:

$$C_{nnL} = \frac{N_r}{\pi} \int_{-\frac{\pi}{N_r}}^{\frac{\pi}{N_r}} B_0^2 \cos(nN_L \alpha') d\alpha' =$$

$$= \int_{\beta_{\alpha 1}}^{\beta_{\alpha 2}} C_{nnL} \cos nN_L \alpha' d\alpha'$$

$$+ \left[ \frac{\beta_2}{2} \cos nN_L \alpha' d\alpha' \right]$$

then, (13) to (15) imply that:

$$C_{nnL} = \text{function}(N_r, N_L, \beta_1, \beta_2, \beta_{\alpha 1}, \beta_{\alpha 2}, \varepsilon(\alpha))$$

III. DESIGN MODIFICATION

Magnetic cogging torque in this machine is produced by interaction of rotor segments and stator teeth. The circumferential component of attractive force attempts to maintain alignment between stator teeth and rotor segments. In order to decrease this attractive force, it is required to decrease the effect of permeance function variations. So, it is required to change the profile of permeance function from what is shown in Fig. 3. Since the exact permeance function of this motor is very hard to reach, the analytical derivation of segments design for zero cogging torque is not easy. Although, Fig. 3 is a simple model of permeance function, its variation profile is same as the main model. It means that there is a sudden change from a minimum to a maximum value of the permeance function in the main structure. So, in order to manage cogging torque, a smooth change of permeance should be achieved in each segment rotation.

Fig. 4 depicts the rotor segment of Fig. 3 with a notch extended from $\beta_{\alpha 1}$ to $\beta_{\alpha 2}$ on each rotor segment. The segment outer radius defined as:

$$R = \begin{cases} R_1 : & \beta_1 < \alpha < \beta_{\alpha 1}, \beta_2 < \alpha < \beta_2 \\ f(\alpha) : & \beta_{\alpha 1} < \alpha < \beta_{\alpha 2} \\ \end{cases}$$

and the corresponding normalized permeance function for each segment represented by:

$$C = \begin{cases} 1 : & \beta_1 < \alpha < \beta_{\alpha 1}, \beta_2 < \alpha < \beta_2 \\ \varepsilon(\alpha) : & \beta_{\alpha 1} < \alpha < \beta_{\alpha 2} \\ 0 < \varepsilon(\alpha) < 1 \\ \end{cases}$$

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$$+ \left[ \frac{\beta_2}{2} \cos nN_L \alpha' d\alpha' \right]$$

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leads to a decrease in permeance function and cogging torque. It is approved by (10) that notches in rotor segments decrease $C_{cog}$. However, it is found out from (7), (8) and (15) that $N_t$ in the numerator is cancelled out by $N_t$ in the denominator of the permeance function. Therefore, it is resulted that this effect should cause by other terms like segment span.

Although, an exact formulation for $C_{cog}$ of notched segments is not extracted in (15), it is shown that the Fourier coefficients of the permeance function depends on $\beta_1, \beta_2, \beta_{n1}, \beta_{n2}$ and $f(\alpha)$. These terms are mapped into the rotor segment span, notch angle, notch start angle, notch height and its variation profile. It is resulted that the permeance function and as a result, cogging torque is managed with proper selection of notch quantity, location, dimensions and variation profile.

The relation between notch span and notch height is introduced as following:

$$\alpha_n = \eta \frac{h_n}{R_1} \quad (17)$$

where $\alpha_n$ is notch span, $h_n$ is notch height and $\eta$ is notching coefficient that varies between 1 to 50. Besides, a notch start angle is indicated as $\gamma$. These parameters are shown in Fig. 5.

### Table I

**Motor Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator back iron depth</td>
<td>11mm</td>
</tr>
<tr>
<td>Stator outer diameter</td>
<td>150mm</td>
</tr>
<tr>
<td>Stator tooth width</td>
<td>12.5mm</td>
</tr>
<tr>
<td>Stator tooth tip span</td>
<td>25°</td>
</tr>
<tr>
<td>Slot opening span</td>
<td>5°</td>
</tr>
<tr>
<td>Rotor Diameter</td>
<td>90.6mm</td>
</tr>
<tr>
<td>stack length</td>
<td>150mm</td>
</tr>
<tr>
<td>Airgap length</td>
<td>0.3mm</td>
</tr>
<tr>
<td>Segment maximum depth</td>
<td>14mm</td>
</tr>
<tr>
<td>Segment span</td>
<td>41°</td>
</tr>
<tr>
<td>Number of turn per field tooth coil</td>
<td>44</td>
</tr>
<tr>
<td>Number of turn per armature tooth coil</td>
<td>44</td>
</tr>
<tr>
<td>Conductor wire diameter</td>
<td>1.4mm</td>
</tr>
</tbody>
</table>

The effect of the parameters on the output cogging and average torque of a 12/8 SRFS motor are analyzed by changing the parameters one at a time. A set of a prototype motor parameters are presented in Table I. In the analysis $\alpha_n$, $\gamma$ and $h_n$ are changed from 1 to 6, 13 to 17 and 0.1mm to 0.8mm respectively. Their effects are shown in Fig. 6 (a) to (f). It is seen that with an increase in the notching angle, the notch start angle and the notch height, the average torque decreases gradually while the torque ripple decreases first and increases at the end.

Since the main target of this work is to find out the proper design of motor with minimum cogging torque and acceptable value of average torque, different notch designs should be considered. Therefore, five different notches are designed and applied to the rotor segments of the prototype motor. The parameters of these five notches are selected based on results obtained from Fig. 6. They are presented in Table II by N1 to N5. The average and cogging torques of the motor with these different notches on the rotor segments are evaluated. In order to study the effects of these modifications, numerical methods are employed. FE analysis of this motor with different rotor segment designs is carried out at 500 rpm, 14A field current and 14A armature winding RMS current.

![Table II](https://example.com/table2.png)

* S.: Segment span; **: They are calculated in relation to $\gamma$ in Fig. 5

In the first design, N1, three notches are applied to each segment. Two symmetric notches are located at the beginning and at the end of the segments while the third one at the center of each segment (Fig. 5). From simulation it is found out that the developed torque of the motor is deteriorated with three notches on each segment of rotor. So, the center notch is canceled and two notches with same height and symmetric location as in N1 are applied to each rotor segment in N2. From what is depicted in Fig. 6, it is found out that torque ripples are locally minimized by a segment span of about 6 degree so $\alpha_n$ is set to this value. Two notch locations on the rotor segment with locally minimum torque ripples are selected from Fig. 6 (d). The value of $h_n$ is changed in N3 as it causes a decrease in cogging torque and a desirable increase in average torque. In N4, $\alpha_n$ is changed and in N5 the notch location varies but there is not any serious improvement in cogging and average torque.
Since the gradual change in permeance is desired for better management of cogging torque, notches with exponential variation profile is considered on rotor segments as in Fig. 7. The values of $\alpha_n$, $h_n$ and $\gamma$ in N6 are same as N5 but the variation profiles are different. So, N6 design is modeled and the results show that in comparison to N4 model, the average torque increases by $4.65\%$ while torque ripple decreases by $5.78\%$. Based on findings from Fig. 6 (e) and (f), N6 model is modified to N7 by changing $\eta$ to 15.8. This should lead to a better compensation of cogging torque and improvement of average torque as will be evaluated in more details in the next section.

IV. EVALUATION

A prototype motor with the notched segments, specified as N7 in Table II, is implemented in finite element modeling environment and the motor performance are evaluated for the mentioned conditions at different rotor positions.

It is found out from simulation that a decrease in $h_n$ leads to a modification of average torque in N7. Also, in comparison to N6 model, the average torque is improved by $12.48\%$ while torque ripple increases by $12.68\%$. Although, the purpose of this work is to reduce torque ripples, it is also intended to keep average torque close to its original value (untouched rotor segment). The N7 design suits reasonably well with its desired specifications. Magnetic flux density of one segment of the prototype motor of N7 design is shown in Fig. 8. It is derived that the magnetic flux density in trails of segments increases by the notching that increase the risk of saturation.

The developed torque at aforementioned conditions for 3 main notch designs and the original model is depicted in Fig. 9, showing decrease of cogging torque due to provision of notches. Corresponding cogging torque values are shown in Fig. 10 along with average torque values. As it is predicted although the cogging torque in N3 and N4 is suppressed favorably, the average torque is attenuated undesirably. This is improved in N6 and N7 designs by shape modification of notches.

The evaluated armature winding back EMF waveforms for N3, N7 and original design are depicted in Fig. 11 and their harmonic content is shown in Fig. 12. From these two figures it is found out that the THD of back EMF for N3, N7 and the original design are $10.88\%$, $19.45\%$ and $28.34\%$ respectively. It is seen that the highest percentage is due to the original design and the lowest is due to N3 one. It approves a high reduction value of torque ripple in N3 which is shown in Fig. 9 and Fig. 10. Besides, it is shown in Fig. 11 and Fig. 12 that the back EMF fundamental component decreases in N7 and N3, leading to a decrease in average torque in the motor with modified rotor segments.

In order to verify the method, prototype motor without any segment modification is modeled in FE environment at 500 rpm, 14A DC excitation field current and 15A armature current. The results are compared with the experimental ones [13] and are depicted in Fig. 13. It is seen that the simulation results match with the experimental ones with acceptable accuracy.
In this paper the cogging torque of a 12/8 topology wound field flux switching prototype motor with segmented rotor is studied. Analytical and 2D FE models of the motor with notches on segments are analyzed. It is found out that an increase in notches number, height and span decreases the average torque and cogging torque by different degrees. However, the cogging torque increases with extra increase of the parameters, providing an opportunity for finding the best values of the parameters. FEM is employed to evaluate the findings of analytical models. Also, the results are compared with those obtained from experiments and acceptable accuracy of the motor modeling is confirmed.

It is revealed that the notches effectively reduce torque ripples, but the average torque decreases as well. In order to have a maximum average torque with minimum ripple content, notches with exponential variation profile are imposed. As a result the torque ripple reduces by 30% while average torque reduces by 11.8% only. In order to reduce noises due to notchting, the notches should be filled with a nonmagnetic material.

Accurate model of permeance function and cogging torque are desired and remained to be addressed in future research.

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