Performance Evaluation of Flux-Switching Permanent Magnet with Modifications to Stator and Rotor

Mohammad Hussein Barzegari Bafghi1, Abolfazl Vahedi1*, Arta Mohammad-Alikhani1
1Center of Excellence for Power System Automation and Operation, Department of Electrical Engineering, Iran University of Science & Technology, Tehran, Iran
*avahedi@iust.ac.ir

Abstract. A flux-switching motor is a synchronous electric motor in which both field and armature coils are placed on the stator. There are thus three different stator structure types with regard to field excitation: permanent magnet, direct current field excitation, and hybrid. The rotor structure of the motor in this study reflected two types: integrated and multi-piece structure. The permanent magnet flux switching motor with integrated rotor structure offers more advantages and more attention has been paid to this as compared to other electric motors in various industries. The major advantages of this type are high torque density, ease of manufacture, high reliability, and robustness of rotor. However, these flux switching motors have relatively high cogging torque, and while work has been done on reducing the cogging torque and some literature published, most such works have focused on modifying the rotor tooth, skewing the rotor. These works study the effect of rotor shaping on motor performance, while in this paper, new rotor shapes are also considered. Finally, a method is introduced to minimise the cogging torque that has least adverse effect on other effective parameters such as torque density. Using the results of other papers, the finite element method is used to find the best method of rotor shaping in this paper.

1. Introduction
Flux-switching permanent magnet (FSPM) machines were introduced in 1955 for the first time [1]. In FSPM machines, permanent magnets (PMs) and armature windings are placed on the stator [2] to improve thermal control as compared to that seen in other structures [3], [4], [5]. Some structures use a DC excitation instead of PMs or combine the two approaches (hybrid excitation) [6]. The rotor structure is then similar to the switched reluctance rotor [7]. A sample of the traditional FSPM structure is illustrated in figure 1; as seen in this figure, the rotor has an integrated structure and is thus more robust than other rotor types [8], [9]. FSPM motors also have other advantages, including high power density, high efficiency, and ease of cooling [10], [11], [12].

Although the FSPM motor has many advantages, it also has some disadvantages, most of which are caused by its large cogging torque [13], [14], [15]. The relatively large torque ripple causes speed ripple, vibration, and noise problems in the motor [16], leading to several works investigating methods to reduce the cogging torque in FSPM motors. In this paper, some of this literature is thus reviewed and a finite element simulation of the resulting solutions presented.
**2. Cogging Torque calculation**

Energy variation occurs within a motor as the rotor rotates when there is no current in the coils causing cogging torque. The energy variation in the magnets and iron compared with the airgap is negligible for a conventional FSPM. Therefore, the cogging torque can be calculated as: [18] [19]

\[
T(\alpha) = -\frac{\partial W(\alpha)}{\partial \alpha}_{\text{airgap}} = \frac{L_s \pi}{4 \mu_0} \left( R_s^2 - R_m^2 \right) \sum nN_L G_{nN_L} B_{nN_L} \sin(nN_L \alpha) \]

where \( L_s, \mu_0, R_s, R_m, \) and \( \alpha \) are the stack length, air permeability, stator bore radius, magnet outer radius and rotation angle of rotor, respectively; \( G_{nN_L} \) and \( B_{nN_L} \) are the corresponding Fourier coefficients of the relative airgap permeance function and flux density function; and \( N_L \) is the least common multiple of the number of magnets and the number of slots. The fundamental cycle of the cogging torque is thus \( \frac{2\pi}{N_L} \) [18].

**3. Other Works Review about cogging torque reduction**

In [17] four structures for stator lamination were studied. These structures all have a bridge in the stator lamination and a short magnet structure to reduce cogging torque. The four structures are called the (a) Inner-inner structure, (b) Inner-outer structure, (c) Outer-inner structure, and (d) Outer-outer structure, as shown in Figure 2.
The examined work investigated the effect of these four structures on a motor for which the parameters are represented in table 1.

The output torque comparison of the four structures with different magnet lengths and the ratios between output torque and magnet length are illustrated in figures 3 and 4 respectively. Figure 3 shows that the output torque is largest in the outer-inner structure while the smallest output torque is seen in the inner-outer structure. As can be seen in figure 4, the cogging torque amplitude of all structures is almost the same when the magnet length is 19 mm. On shortening the magnet length, the peak-peak cogging torque reduction effect is most obvious in the inner-outer structure, however, being smallest in the inner-inner structure [17].

Table 1 Motor parameters for investigating the effect of stator lamination and reduction of magnet length [17]

| Parameters                        | Values       |
|-----------------------------------|--------------|
| Rated voltage (V)                 | 400          |
| Rate speed (r/min)                | 1500         |
| Stator/Rotor poles number         | 12/10        |
| Number of phases                  | 3            |
| Outer diameter of stator (mm)     | 102          |
| Air gap length (mm)               | 0.5          |
| Outer diameter of rotor (mm)      | 61           |
| Stator tooth width (mm)           | 4            |
| PM thickness (mm)                 | 4            |
| Rotor pole width (mm)             | 4            |
| Stator back-iron thickness (mm)   | 4            |
| Inner diameter of rotor           | 25           |
| Axial length (mm)                 | 60           |
In [18] five methods were used to reduce the cogging torque: rotor tooth-notch, rotor tooth-chamfering, rotor teeth-pairing, rotor-skewing, and magnet thickness optimisation. Rotor tooth-notch is illustrated in Figure 5; this causes the air gap to change, thus reducing cogging torque effectively where proper notching numbers and depth are applied. Rotor tooth-chamfering is presented in Figure 6. This method also changes the air gap and can thus reduce the cogging torque; it also causes the magnetic flux in the air-gap to become smoother [18].

Rotor teeth pairing is based on changing the phase of the cogging torque. When two adjacent poles have opposite phases, it can reduce the cogging torque most effectively. In [18] two types of rotor teeth with different widths, $\beta_r = 8^\circ$ and $\beta_r = 11^\circ$, were alternatively employed, as seen in Figure 7. In [18], rotor skewing and thinner magnets were also investigated in terms of reducing cogging torque. These methods were verified by FEM in [18]. The cogging torque curves and the electromagnetic torque for these methods are illustrated in Figures 8 and 9, respectively. The cogging torque and electromagnetic torques under these methods are compared in Tables 2 and 3 respectively, and the results show that skewing is the most effective method to reduce cogging torque.
Figure 7 Rotor teeth-pairing [18]

Figure 8 Cogging torque reduction with various methods [18]

Figure 9 Electromagnetic torque variation under various methods [18]

Table 2 Effectiveness of cogging torque reduction of various methods [18]

| Design Methods                     | Cogging Torque (Peak-to-Peak) (Nm) | Percentage to Original |
|-----------------------------------|-----------------------------------|------------------------|
| Original                          | 1.12                              | 100 %                  |
| Rotor tooth-notch                 | 0.19                              | 17 %                   |
| Rotor tooth-chamfering            | 0.23                              | 20 %                   |
| Rotor teeth-pairing               | 0.15                              | 13 %                   |
| Rotor-skewing by 6 mech-deg       | 0.056                             | 5 %                    |
| Thinner magnets                   | 0.4                               | 36 %                   |
Table 3 Comparison of back-EMF and average torque under various methods [18]

| Design Methods                  | Back-EMF amplitude (V) | Average EM-Torque (N.m) |
|---------------------------------|------------------------|-------------------------|
| Original                        | 31.3                   | 1.38                    |
| Rotor tooth-notching            | 29.7                   | 1.37                    |
| Rotor tooth-chamfering          | 27.6                   | 1.26                    |
| Rotor teeth-pairing             | 28.1                   | 1.23                    |
| Rotor-skewing by 6 mech-deg     | 32.5                   | 1.42                    |
| Thinner magnets                 | 30.6                   | 1.39                    |

In [20], the rotor skewing was applied to the rotor using a new method of step skewing along the rotor. The results for cogging torque and electromagnetic torque produced are presented in figures 10 and 11 respectively. As shown, step skewing can reduce the cogging torque effectively, but when the step increases by more than three steps, the reduction of cogging torque is not tangible.

4. Simulation and Results

In the current, three rotor tooth shapes are considered, and rotor step skewing is also investigated. The three rotor shapes selected are the headless rotor tooth, circle head rotor tooth, and conic rotor tooth as illustrated in figures 12, 13, and 14, respectively. Step skewing is studied for seven states: four states have three steps with different ranges (3.6°, 2.7°, 1.8°, and 0.9°) and 5 steps with 1.8° of change for each step, while the seven step and nine step states change by 0.9° each step. The motor specifications used in the simulation are presented in Table 4.

Table 4 Motor specifications in simulations

| Parameter                      | Value       | Parameter                      | Value       |
|--------------------------------|-------------|--------------------------------|-------------|
| Stator poles number            | 12          | Rotor tooth width (mm)         | 0.3606      |
| Rotor poles number             | 14          | Inner stator diameter (mm)     | 98.8        |
| Motor Length (m)               | 1.1         | Rotor yoke thick (mm)          | 3.6         |
| Outer stator diameter (m)      | 0.18        | Stator yoke thick (mm)         | 3.3         |
| Shaft diameter (mm)            | 34          | Permanent magnet width (mm)    | 0.0985      |
| Air gap (mm)                   | 0.65        | Stator tooth width (mm)        | 0.2613      |
| Coils turn number              | 46          | -                              | -           |
The rotor tooth shapes were simulated in finite element software (Flux 10.3) and the electromagnetic torque and ripple torque are presented in figures 15 and 16, respectively. As shown, the greatest reduction of ripple torque occurred when the circle head rotor tooth was used, and this method caused the most reduction in the electromagnetic torque as well. The conic shape causes some reduction in ripple torque and a small increment in electromagnetic torque; the electromagnetic torque for the three step states and states with more than three steps are illustrated in figures 17 and 18, respectively. In the three steps states, when the step is larger, the ripple torque and electromagnetic torque are reduced. In states with more than three steps, this remains true if the total angle is considered. The summary of results is presented in Table 5, with the percentage of torque ripple shown as a fraction of the peak-to-peak value of torque to the torque average at the steady-state (equation (2)).

\[
\frac{T_{\text{max}} - T_{\text{min}}}{T_{\text{avg}}}
\]  

(2)
Figure 16 Ripple torque of different rotor tooth shapes

Figure 17 Electromagnetic torque of step skewing for three step states

Figure 18 Electromagnetic torque of step skewing for more than three step states
Table 5 Summary of results for rotor tooth shape and step skewing

| State                              | Electromagnetic torque (N-m) | Ripple Torque (%) |
|------------------------------------|-----------------------------|------------------|
| Original                           | 300.2                       | 13.6             |
| Conic rotor tooth                  | 304.6                       | 12.4             |
| Circle head rotor tooth            | 229.3                       | 2.65             |
| Headless rotor tooth               | 278                         | 10.53            |
| 3 steps (each step=0.9°)           | 295.7                       | 5.4              |
| 3 steps (each step=1.8°)           | 282.2                       | 3.8              |
| 3 steps (each step=2.7°)           | 259.5                       | 4.4              |
| 3 steps (each step=3.6°)           | 234                         | 2.88             |
| 5 steps (each step=1.8°)           | 246.3                       | 3                |
| 7 steps (each step=0.9°)           | 273                         | 3.4              |
| 9 steps (each step=0.9°)           | 255.25                      | 3                |

5. Conclusion
In this paper, several methods to reduce ripple torque were reviewed and some methods investigated in more detail. The selected methods were rotor tooth-notching, rotor tooth-chamfering, rotor teeth-pairing, thinner magnets, conic rotor tooth, circle head rotor tooth, headless rotor tooth, and step skewing with varying numbers of steps and skewing angles. All of these were found to reduce the cogging torque, though the most effective method is the circle head rotor tooth, though this can only reduce the electromagnetic torque so much. This means that it cannot be confirmed as the best method overall. The step skewing effect depends on step number and skewing angle; where the step number and skewing angle are larger, the cogging torque is lower, and the electromagnetic torque is reduced. Of the investigated methods, only the conic rotor tooth and the thinner permanent magnet increase the electromagnetic torque while reducing the cogging torque. These methods can thus be used to reduce cogging torque, but other methods would be required to reduce electromagnetic torque, creating a necessary trade-off between electromagnetic torque reduction and ripple torque reduction.

6. References
[1] S. E. Rauch and L. J. Johnson, "Design principles of flux-switching alternators," *AIEE Trans., Power Apparatus Syst. Part III*, 74, 3, 1261-68, Jan. 1955.
[2] A. Thomas, Z. Q. Zhu, G. W. Jewell and D. Howe, "Flux-switching PM brushless machines with alternative stator and rotor pole combinations," *Journal of Asian Electric Vehicles*, 6, 1, 1103-10, 2008.
[3] L. E. Somesan and I. A. Viorel, "Permanent magnet flux-switching machine, optimal design and performance analysis," *Power Engineering and Electrical Engineering*, 11, 2, 46-53, 2013.
[4] B. Sarlioglu, Y. F. Zhao and T. A. Lipo, "A novel doubly saliency single phase permanent magnet generator," *Industry Application Society Annual Meeting*, 9-15, 1994.
[5] H. E., A. H. Ben-Ahmed and J. Lucidarme, "Switching flux permanent magnet polyphased synchronous machines," *7th European Conference on Power Electronics and Application*, 903-08, 1997.
[6] E.Sulaiman, M. F. M. Teridi, Z. A. Husin, M. Z. Ahmad and T. Kosaka, "Investigation on flux characteristics of field excitation flux switching machine with single FEC polarity," in *4th International Conference on Electrical Engineering and Informatics (ICEEI 2013)*, 2013.
[7] H. Wei, M. Cheng, Z. Q. Zhu and D. Howe, "Analysis and optimization of back-EMF waveform of a novel flux-switching permanent magnet motor," *Electric Machines & Drives Conference*, 2, 1025–30, May 2007.
[8] R. Deodhar, S. Andersson, I. Boldea and T. Miller, "The flux-reversal machine: a new brushless doubly-salient permanent-magnet machine," *IEEE Transactions on Industry Applications*, **33**, 4, 925-34, Jul/Aug 1997.

[9] Z. Q. Zhu and J. T. Chen, "Advanced flux-switching permanent magnet brushless machines," *IEEE Transactions on Magnetics*, **46**, 6, 1447-53, June 2010.

[10] Z. Q. Zhu, X. Chen and J. Chen, "Novel linear flux-switching permanent magnet machines," *Proceedings of ICEMS Conference*, 2948-53, Oct. 2008.

[11] Y. Du, K. T. Chau, M. Cheng, Y. Fan, Y. Wang, W. Hua and Z. Wang, "Design and analysis of linear stator permanent magnet vernier machines," *IEEE Transactions on Magnetics*, **47**, 10, 4219-22, 2011.

[12] Y. Du, K. T. Chau, M. Cheng, Y. Fan, W. Zhao and F. Li, "A linear stator permanent magnet vernier HTS machine for wave energy conversion," *IEEE Trans. Appl. Supercond.*, **22**, 3, 502-05, 2012.

[13] X. Zhu, L. Quan, D. Chen, M. Cheng, W. Hua and X. Sun, "Electromagnetic performance analysis of a new stator-permanent magnet doubly salient flux memory motor using a piecewise-linear hysteresis model," *IEEE Transactions on Magnetics*, **47**, 5, 1106-09, 2011.

[14] C. Sikder, I. Husain and W. Ouyang, "Cogging torque reduction in flux-switching permanent-magnet machines by rotor pole shaping," *IEEE Transactions on Industry Applications*, **51**, 5, 3609-19, 2015.

[15] M. Cheng and X. Y. Zhu, "Electromagnetic performance analysis and vector control of a flux controllable stator permanent magnet brushless motor with skewed rotor," *The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, **30**, 1, 62-71, 2011.

[16] R. Cao, M. Cheng, C. Mi, W. Hua and W. Zhao, "A linear doubly salient permanent-magnet motor with modular and complementary structure," *IEEE Transactions on Magnetics*, **47**, 12, 4809-21, 2011.

[17] M. Shen, J. Wu, C. Gan, Y. Hu and W. Cao, "Cogging torque reduction in FSPM machines with short magnets and stator lamination bridge structure," in *IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society*, Florence, Italy, 23-26 Oct. 2016.

[18] Y. Wang, J. Shen, W. Fei and Z. Fang, "Reduction of cogging torque in permanent magnet flux-switching machines," *J. Electromagnetic Analysis & Applications*, **1**, 11-14, 2009.

[19] S. M. Hwang, J. B. Eom, G. B. Hwang, W. B. Jeong and Y. H. Jung, "Cogging torque and acoustic noise reduction in permanent magnet motors by teeth pairing," *IEEE Transactions Magnetics*, **36**, 5, 3144–3146, Sep 2000.

[20] W. Fei, P. C. K. Luk and J. Shen, "Torque analysis of permanent magnet flux switching machines with rotor step skewing," *IEEE Transactions on Magnetics*, **48**, 10, 2664-73, 2012.