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Research Article

The Effects of the Unequal Rotor Slot Arc on Cogging Torque for Flux Switching Permanent Magnet Machines

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Abstract : Many of electric machine researchers are studying the flux switching permanent magnet machines. The cogging torque is one of the most unwanted parameters for highly sensitive electric machine applications. In this study, the configuration of the unequal rotor slot arc (URSA) to see the effects of the asymmetry for three phase FSPM machine has been studied. The proposed asymmetry presents different arc angled rotor poles and analyzes the torque performance of them by utilizing the 2D finite element method (2D-FEM). 12 stator poles and 10 rotor poles (12s/10p) FSPM machine topology have been chosen for the design. Results proved that the unequal rotor slot arc proposition demonstrates good performance in comparison to the symmetric design. Inequalities on the rotor slots were simulated by using parametric analysis to minimize the cogging torque. The suggested design indicates a substantial reduction in cogging torque, achieving a conspicuous minimization. Consequently, the suggested use of unequal rotor slot arc for FSPM machines has reasonable outcomes.

Keywords : Flux switching machines, rotor permeance, cogging torque, asymmetric rotor, permanent-magnet machines, unequal rotor slot arc.

1 Introduction

Flux-switching permanent magnet (FSPM) machines generally have salient rotor poles and permanent magnets embedded within the stator core (Figure 1). 12s/10p structure is commonly used in the literature. 12s/10p FSPM machine has distinction on the magnetic flux patterns related to the coppers of each phase [1, 2]. This differentiation results in canceling the harmonics of the back EMF results of windings. So that the sinus-shaped back EMF is created as the result [3, 2]. A parametric minimization is researched by performing lumped parameters with the electromagnetic circuit model of a 12s/10p FSPM machine [3]. The saliency of the stator and the rotor have impacts on torque production. However, the PM excitation mainly causes electromagnetic torque. The reluctance torque can be ignored in comparison to the torque of the PM excitation [3].

The cogging torque minimization is a problem to solve for FSPMs that's why it is subjected to many studies such as [4, 5, 6, 7]. The cogging torque (CT) is explained for the produced FSPMs in [4]. One of the techniques is to reduce the interplay between the stator and rotor to diminish the CT [5]. The skewed segments of the rotor side constructed with notches inside mitigate the cogging torque as analytically investigated in [6]. PHEV applications with FSPMs are studied in [7] in contrast to the cogging torque.

In this paper, the unequal rotor slot arcs are investigated to mitigate the cogging torque. In fact, the asymmetry methods, including stator teeth, windings, and rotor eccentricity for performance enhancement are researched in the literature [8, 9, 10, 11]. Torque ripple reduction is achieved by using the asymmetric stator teeth for interior permanence magnet (IPM) machines [8]. The vibration of the spoke-type permanent-magnet (PM) machine with an asymmetric rotor considering the modulation effect of the stator teeth has been studied in [9]. According to this study, the equivalent minimum nonzero-order harmonic should be determined for the asymmetric rotor design for minimization of the vibration and the noise. Asymmetric stator poles are suggested for gathering higher torque density in [10]. The obtained design is validated experimentally by a prototype machine and experimental results proved a higher torque density. Xiu et al. tried to reduce cogging torque for a 6s/4p FSPM machine by chamfering and flanging the rotor pole. They are proposed to mitigate the cogging torque of the machine without skewing teeth. The proposition has been verified by simulation and experimental outcomes [11]. Inverse cosine rotor flange shaping, eccentric circular, multi-step shaping techniques are suggested for variable flux reluctance machines [12]. The shifting rotor teeth with two different designs and stepped skewing rotor parts are recommended for cogging torque diminution of FSPMs [13]. Rotor

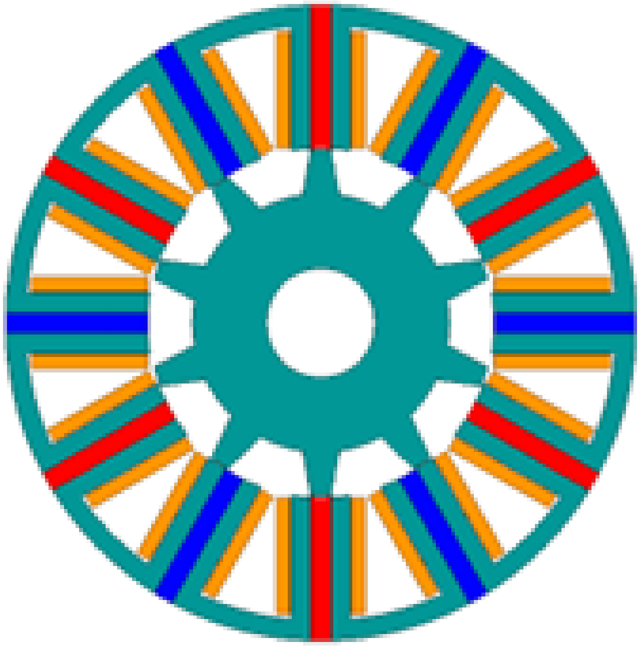


Figure 1: The cross-section of the 12s/10p equal rotor slot arc FSPM Machine

Table 1: Parameters of the FSPM machine

Parameters	Unit	Value
Phase number	-	3
Stator slot/Rotor pole Number	-	12s/10p
Peak current	A	3.8
Rated speed	rpm	1200
Stator outer diameter	mm	128
Stator inner diameter	mm	70.4
Rotor outer diameter	mm	69.8
Rotor inner diameter	mm	22
Stack length	mm	75
Number of turns per phase	-	280
PM Remanence	T	1.2
PM Relative Permeability	T	1.05
PM coercivity	kA/m	-909.46
Stator tooth/Rotor pole width ratio	-	1

pole teeth optimization is explored in [14] for electrically supplied FSPMs. Forming the rotor teeth is even to mitigate the EM impact pulse (which causes vibration) during the operation [15].

Briefly, these studies are given to achieve the optimum torque performance. This paper represents a reducing technique of cogging torque of the FSPMs by changing the rotor pole slots' arc angle. The main justification is the permeance modification which is a well-known method for FSPMs in literature [16]. Thus, the airgap permeance impacts on the electromagnetic torque mechanism by the rotor teeth have been objected to in this paper. 12s/10p variation is chosen which can be seen in Figure 1. The parameters of the FSPM machine are given in Table 1. A parametric analysis is performed within the 2D-FEA simulation by using the finite element analysis method.

This paper is constructed as follows. In stage II, the mathematical expressions of the cogging torque for the FSPM machines are given. In section III, the cogging torque reduction technique URSA is introduced. Then, the parametric simulation outcomes are given. Results are expressed clearly for the conclusion in section IV.

2 Analytical Procedure of the CT and URSA effect

CT is one of the most challenging problems for FSPM machines. It's one of the unwanted torque profile parameters. In summarizing, the main sources of the undesired torque ripples are [13] firstly, the interactions between the steel cores and the magnets cause to CT, secondly, the harmonics occur in phase back EMF because of the windings and the phase armature currents, thirdly, the time-varying reluctance torque because of the changing of dq axes inductances.

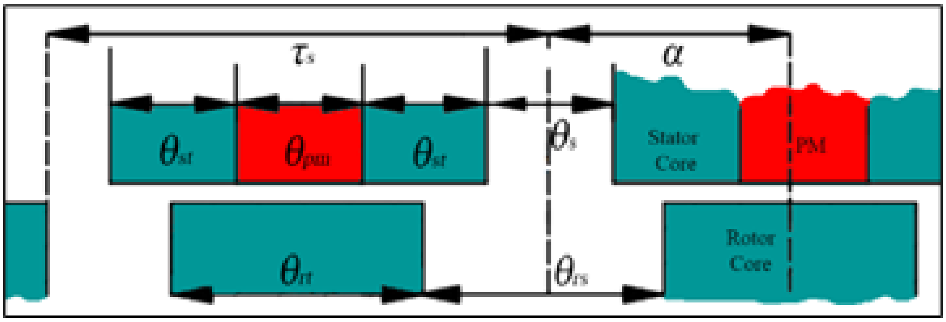


Figure 2: Dimensional parameters of the FSPM machine

Due to this knowledge, this study is dedicated to the mitigation of the CT by using the URSA method. The study was started by the modification of the CT expression for the FSPM machine. There have been implemented two different slot arcs for the parametric study as θ_{rs1} and θ_{rs2}. These arc angles are changed during the parametric study under physical and analytical constraints.

First of all, the airgap flux-density distributions in of 12s/10p FSPM machine related to the magnets are calculated by the MMF-permeance model [17, 18].

$$B(\theta,\alpha) = F_{\text{pm}}(\theta)\Lambda(\theta,\alpha) \tag{1}$$

So that the difference rate of the total airgap energy can be analytically derived as the cogging torque as given in the following expression:

$$T_{\text{cogg}}(\alpha) = \frac{\partial}{\partial\alpha}\left(\frac{1}{2\mu_0}\int F_{pm}^2(\theta)\Lambda^2(\theta,\alpha)dV\right) \tag{2}$$

If the following assumptions are accepted, the permeability of the steel core is infinite, the permanent magnet flux leakage is zero and the magnetic field distribution is smooth or a variation only exists in radial direction, the cogging torque equation becomes

$$T_{\text{cog}}(\alpha) = \frac{\left(R_2^2 - R_1^2\right) L_a N_r \pi}{4\mu_0}\sum_{m=1}^{\infty} mF_{pm}\Lambda_m \sin\left(mN_r\alpha\right) \tag{3}$$

where F_{pm2} and Λ_2 are substituted, m and k are defined as

$$m = \frac{kN_s}{GCD\left(N_s, N_r\right)}, k = 1, 2, 3, \ldots \tag{4}$$

Here, R_1 is the rotor outer radius, R_2 is the stator inner radius, L_a is the effective stack length, N_s is the number of stator slots, N_r is the number of rotor slots, θ_{rt} is the teeth width of the rotor, and GCM is the greatest common divisor.

In this paper, an unequal rotor slot arc approach is implemented to reduce the cogging torque. This method is usually an effective technique to mitigate the cogging torque, especially for FSPMs due to the relatively simple structure of the rotor without magnets or windings. Figure 3 depicts the configuration of the unequal rotor slot arcs of the FSPM machine.

Taking the asymmetry effect into consideration and assuming that the unequal rotor slot arc angles are θ_{rs1} and θ_{rs2}, permeance distribution becomes as given in Figure 4. Due to this permeance waveform, the expression for Λ_2 is;

$$\Lambda^2\left(\theta,\alpha\right) = \Lambda_0 + \sum_{m_1=1}^{\infty \sum\left(\frac{m_1 N_r}{2}\right)} \Lambda_{m_1} cos \tag{5}$$

Here,

$$\Lambda_0 = \frac{N_r\Lambda^2\theta_{rt}}{2\pi}, m_1 = \frac{2kN_s}{GCD\left(2N_s, N_r\right)} and k = 1, 2, 3, \ldots \tag{6}$$

In general, the fundamental component of the cogging torque is dominant. So that, k is set to be 1 in Equation (6). After mathematical derivations, when the studied FSPM machine has a 12s/10p structure, Λ_{m1} can be written as follows:

$$\Lambda_{m1} = \frac{8\Lambda^2}{m_1\pi} sin\left(\frac{m_1 N_r\theta_{rt}}{4}\right) cos\left(\frac{m_1 N_r\left(\theta_{rs1} + \theta_{rs2} + 2\theta_{rt}\right)}{8}\right) cos\left(\frac{m_1 N_r\left(\theta_{rs1} - \theta_{rs2}\right)}{8}\right) \tag{7}$$

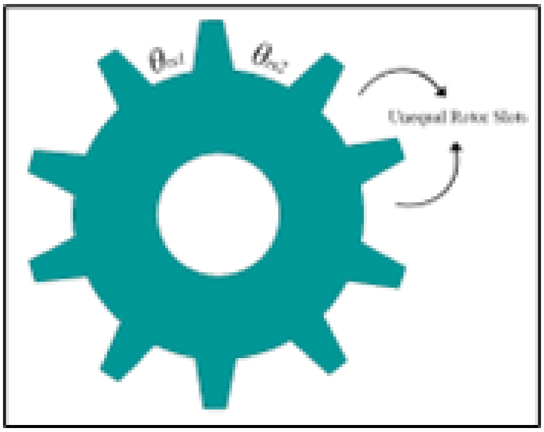


Figure 3: Unequal rotor slot arc angle parameters of the FSPM machine

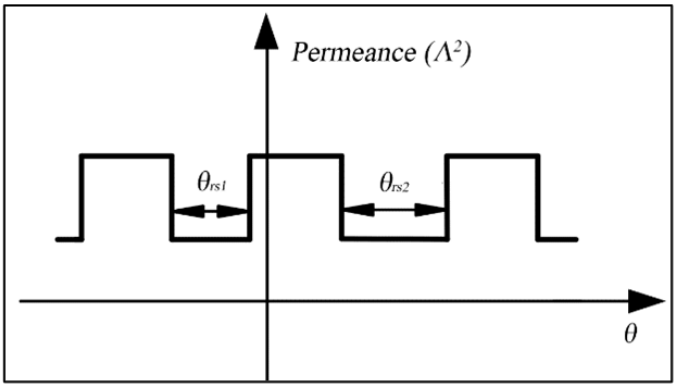


Figure 4: Permeance variations of the unequal rotor slot arc

where,

$$\begin{cases} \theta_{rs1} = \frac{2k_1\pi+2k_2\pi}{\mathrm{LCM}(2N_s,N_r)} - \theta_{rt} \\ \theta_{rs2} = \frac{2k_1\pi-2k_2\pi}{\mathrm{LCM}(2N_s,N_r)} - \theta_{rt} \end{cases} k_1 > k_2 = 1,3,5\dots \tag{8}$$

here LCM is the least common multiple.

3 Simulations and Results of the Proposed Design

To evaluate the simulation, consecutive teeth of the rotor have been adjusted by θ_a and θ_b. The designed and simulated 12s/10p machine has 10° teeth arc and 26° rotor slot arc as an equal FSPM machine. Also, θ_{st} and θ_{pm} have both 10° arc angles too. Simulation has been set to change the equality by the moving angles θ_a and θ_b as given in Fig.5. The main aim is to have unequal slot arcs consecutively. To obtain that, each consecutive tooth has been moved under the constraint of plus and minus two degrees as given in Fig.5. θ_a and θ_b parameters are used to change the slot arc angles θ_{rs1} and θ_{rs2} between +2° and -2° by 0.5° motion steps in parametric analysis. Rotor teeth arc length was kept constant in all simulation stages for making a fair comparison for basic design (equal rotor slot arc FSPMs) and proposed URSA FSPMs.

Table 2: Average torque and Torque ripple key results of the parametric analysis

θ_a	θ_b	T_{ripple}	T_{avg}
-1,5	1	0,28	8,82
-0,5	2	0,35	8,39
1,5	-1,5	0,49	8,67
1	-0,5	0,63	8,74
-1,5	**2**	**0,75**	**8,48**
-0,5	0,5	0,82	8,86
0	0	0,97	8,88
2	2	1,12	7,67

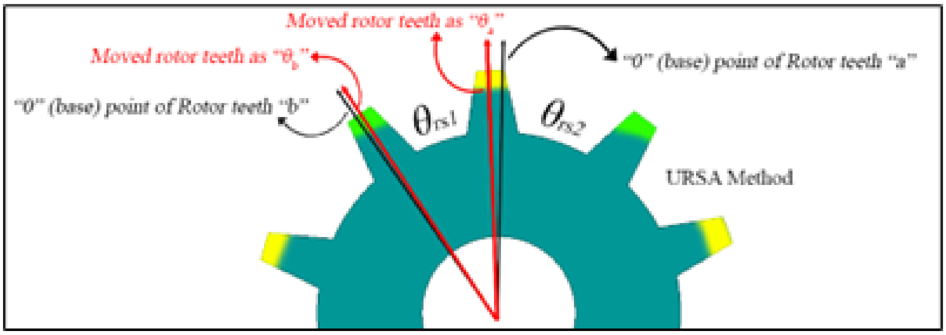


Figure 5: URSA method simulation parameters

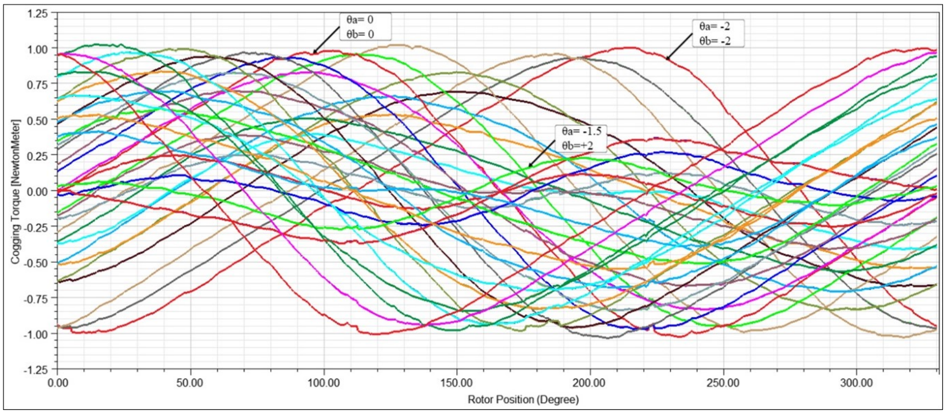


Figure 6: The cogging torque results of the parametric analysis

Figure 9 demonstrates the spectral analysis of the back EMF for the proposed design. Since the back EMF amplitude is 435 V peak-to-peak, the 1st harmonic of the design is lower than 150 V. And harmonics can be ignored after the seventh, which becomes nearly zero further.

Magnetic field distribution is simulated for the proposed design where $\theta_a = -1.5$ and $\theta_b = +2$ as given in Figure 10. Here, the legend shows the rating of the magnetic flux density distribution in Tesla between 0 to 2.5 in Figure 10a. The other legend depicts magnetic flux lines in Wb/m in Figure 10b. As can be seen from Figure 10a, the proposed design does have reasonable saturation fields. Also, Figure 10b indicates that magnetic flux lines have a smooth distribution on the rotor and stator core, which is crucial for efficiency.

The proposed URSA method has potential on mitigation of the CT, as seen in Figure 6. Also, URSA method has the potential on torque ripple reduction as given in Figure 7. While improving the performance on CT and torque ripple for FSPMs, the back EMF wave is pretty sinusoidal as depicted in Figure 8. The best results for CT reduction were obtained when parametric angles $\theta_a = -1.5$ and $\theta_a = -1.5$. This means that unequal rotor slot arcs change consecutively as 26-1.5=24.5 and 26+2=28 degrees. The rotor teeth arc was kept still during the simulation to compare the basic design (equal rotor slot arc FSPMs) and

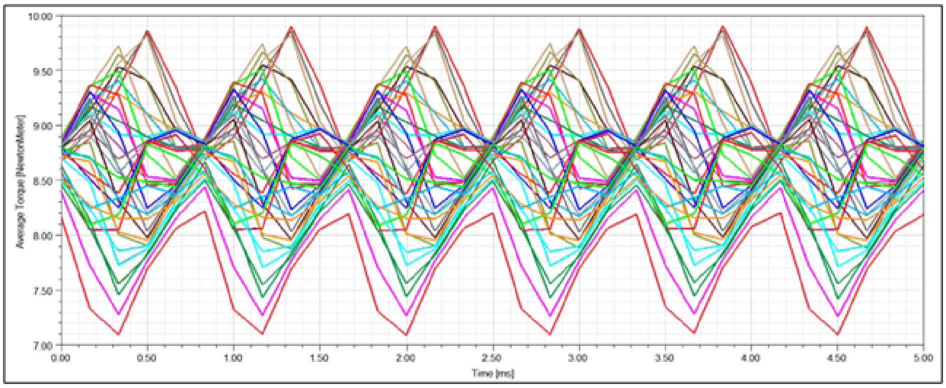


Figure 7: Average torque and Torque ripple results of the parametric analysis

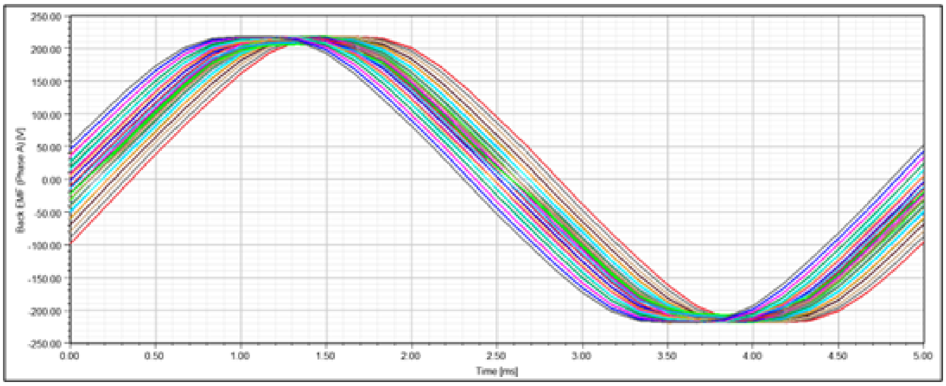


Figure 8: Back EMF results of the parametric analysis

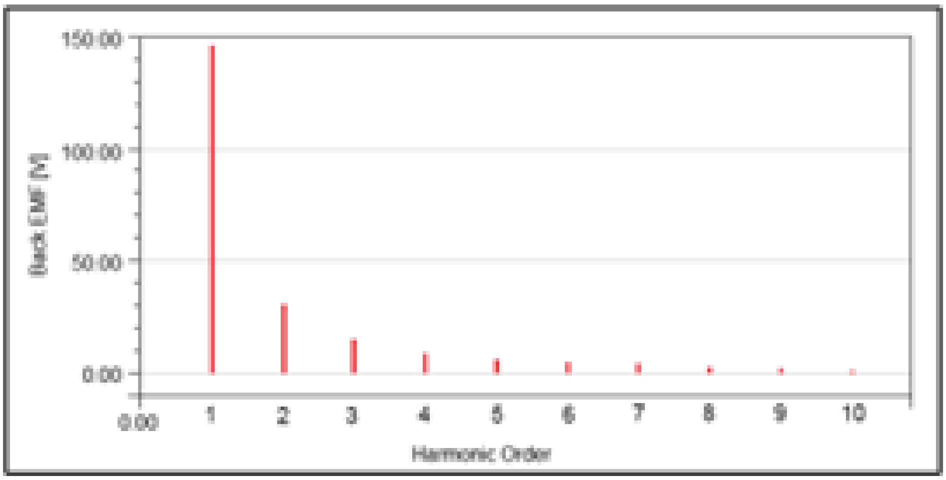
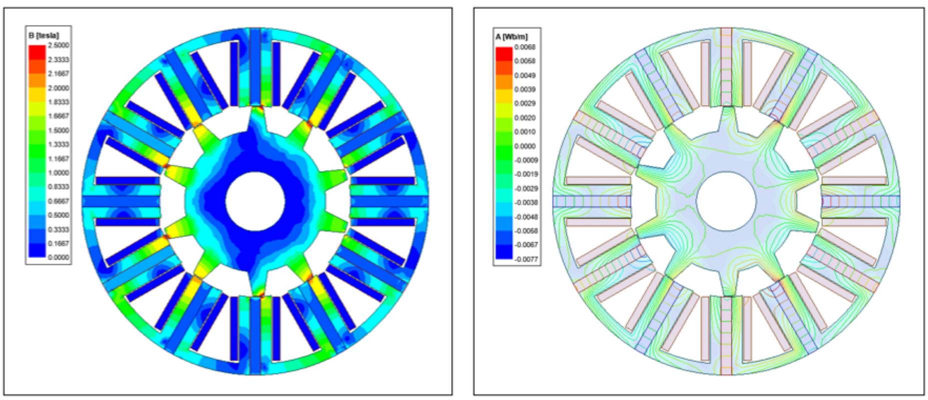


Figure 9: Spectral analysis of the back EMF



(a) Electromagnetic field distribution **(b)** Magnetic flux distribution

Figure 10: Magnetic distribution of the proposed design where $\theta_a = -1.5$ and $\theta_b = +2$

Table 3: Parameters of the FSPM machine

	Basic Design (Equal Slots)	Proposed Design with $\theta_a = -1.5$ and $\theta_b = +2$	Difference (%)
Average Torque (AT) (Nm)	8.88	8.48	-4,5
Torque Ripple (TR) (%)	10.8	8.8	-2
Cogging Torque (CT) (Nm)	2.03	0.501	-300

proposed URSA FSPMs. The electromagnetic field distribution and magnetic flux distribution for the proposed URSA design with $\theta_a = -1.5$ and $\theta_b = +2$. Finally, the comparison table is given in Table 3 which gives comparative information proposed and basic designs.

4 Conclusions

FSPM machines are one of the most studied electric machines for the last decade. Due to the usage of the permanent magnets, occurs cogging torque. Thus, CT is one of the problems that needs to be solved. There are many challenges to mitigate the CT for FSPMs. Average torque loss is an expected outcome of CT mitigation studies. But Torque ripple reduction and CT mitigation rate are very crucial for the sensitive application of the FSPMs. CT reduction is targeted for this study first. But while mitigating the CT, average torque, torque ripple, back EMF, magnetic flux distribution, and electromagnetic field distribution have been taken into account.

After all simulations of parametric analysis, the results are promising. CT is reduced to 0.5 N.m from 2.03 N.m. There has been an 8.8% reduction in the torque ripple while reasonable difference in average torque. This study proves that the URSA method has promising outcomes for further studies.

Authors' Contributions

EC performed all of the study of the paper and has read and approved the final manuscript.

Competing Interests

The author declares that they have no competing interests.

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