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Cogging Torque Reduction Analysis of Radial Field Excitation Coil Flux Switching Motor Using JMAG-Designer Software

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Abstract: Hybrid excitation flux switching machines (HEFSM) is an attractive topic of research and development in recent decades, especially for electric vehicle applications. The HEFSM design proposed a lower permanent magnet consumption, a higher torque density, and a higher efficiency. However, cogging torque is one of the factors which affect the motor in terms of vibration and non-audible noise that become a serious issue in flux switching machines. It is mandatory for every motor to have low cogging torque because having low cogging torque enhances the control based on the positioning of the motor in an electric vehicle drive application. The purpose of this project is to do cogging torque reduction analysis and evaluates the output performances of HESFM with FEC in a radial direction based on the finite element method. The JMAG-Designer version 16 software is used as a two-dimensional (2D) finite element solver. The machine's performances in terms of cogging torque, back EMF, flux linkage, flux distribution and output torque are also evaluated. Various rotor technique configurations such as notching (NOT) and chamfering (C.H), were examined. Then a new technique has been proposed and compared using a combination of NOT and C.H for reduction of cogging torque. Initially, techniques based on NOT and C.H reduced the cogging torque by 58% and 54% respectively of the original value of 9.6Nm. Then, the proposed technique by combining NOT and C.H has reduced almost 62% of the initial result simultaneously. This result is considered the best-reduced technique for the reduction of cogging torque of HEFSM. The combined technique has successfully reduced the cogging torque which improves motor performance.

Keywords: Hybrid Flux Switching Motor, Notching, Cogging Torque, Chamfering

1. Introduction

An electric motor is a machine that converts electrical energy into mechanical energy. The principle of the flux switch motor (FSM) was invented by electric motors in the mid-1950s [1]. In addition, FSM topologies have been developed for a variety of applications such as low-cost

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appliances, automobiles, and wind power [2]. FEC provides variable flux control functions related to conditions that strengthen or weaken the field. There are three types of FSM: permanent magnet (PMFSM), field excitation (FEFSM), and hybrid excitation (HEFSM) [3]. HEFSM combines with FEC and permanent magnet. Meanwhile, both the PMFSM and FEFSM have permanent magnets and FEC as their main flux sources [4].

The design structure of HEFSM is very simple and easy to develop. Generally, high air-gap flux density and doubly salient structure of HEFSM developed magnetic saturations in the machine`s teeth which leads to producing high torque ripple [5]. As a result, HEFSM has a significant torque ripple in comparison with rotor PM machines which is mainly caused by the cogging torque [6]. Minimizing cogging torque is important when designing HEFSM for high-performance applications, as torque ripple can cause mechanical vibration and acoustic noise and affect machine performance [5]-[7]. The purpose of this project is to redesign HESFM using radial FEC and perform output power analysis based on the finite element method. Then use chamfering and notch improvement techniques to reduce the cogging torque of the motor. Motor structural parameters are introduced by adjusting the stator width, rotor width, and armature coil to test the output.

2. Methodology

The design methodology of the proposed cogging torque reduction technique by using JMAG-Geometry and JMAG-Designer ver.16 software as a finite element solver for simulating and designing a hybrid excitation flux switching machine. The JMAG-Geometry Editor is used in designing the motor components of the rotor, stator, PM, armature coil, and FEC. Then, the design will be updated into the JMAG-Designer to do the analysis process of the machine's operating principle, back-emf, cogging torque and output torque.

2.1 Parameter and Specification of Initial design HEFSM

The specification and limit for the salient rotor 12S-14P HEFSM are proposed as listed in Table 1. The outer stator's outside diameter is 134.5mm and the radius of the rotor is 97.25mm with a rotor angle of 12.8571°. The PM weight is fixed at 1 kg.

The analyses performance is divided into the no-load and loaded analysis. The no-load performance will analyze in terms of cogging torque, back EMF, flux linkage, and flux distribution. While the load performance torque Ja at various Je and torque Je at various Ja are to be analyzed by using JMAG Designer as a finite element solver. The related restriction for electrical of maximum 650V DC bus voltage and maximum 360A current defined. The armature current density, Ja, and the FEC current density, Je is fixed at 30 A/mm^2. Figure 1 shows an initial design of 12S-14P HEFSM.

Table 1: Design parameter of HEFSM

Parameter	Quantity
Number of phases	3
Shaft radius (mm)	30
Outer Stator outside diameter (mm)	134.5
Radius of rotor, R1 (mm)	97.25
Rotor pole length, R2 (mm)	18.3
Rotor pole width, R3 (mm)	8.333
PM length, R4 (mm)	17.775

FEC width, R5 (mm)	14.99
FEC height, R6 (mm)	7.676
Width armature coil, R7 (mm)	6.46
Length of armature coil, R8 (mm)	26.006
Armature coil no. of turns	7
FEC no. of turns	57

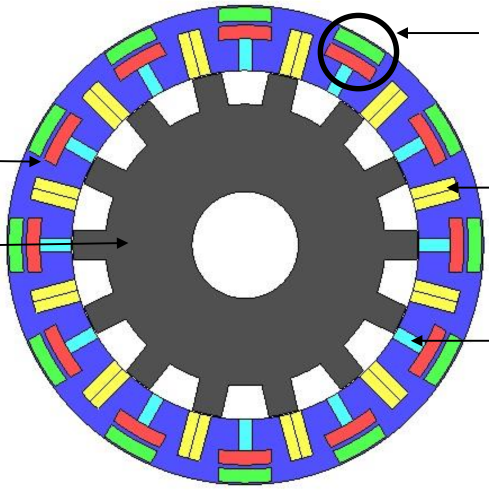

Figure 1: Initial design of 12S-14P HEFSM

2.2 Cogging Torque Reduction Technique for Rotor

Hybrid excitation flux switching machines focus on the design modification to study the cogging torque minimization. Therefore, the techniques to reduce the effect of cogging torque are determined by the terms of easy implementation with minimal cost and machine performance. The optimal rotor shape of the 12S-14P HEFSM was designed in this study. An analytical method is used to determine the design parameters, and the rotor shape is optimised using the finite element method. This study used a conventional 12S-14P HEFSM with techniques to reduce the cogging torque effect. The techniques are as follows:

i. Chamfering (C.H)
ii. Notching (Not)
iii. Combination of chamfering (C.H) and notching (Not)

i. Chamfering (C.H)

Chamfering technique has been designed on the rotor for the reduction of cogging torque. Figure 2 shows the flowchart of chamfering. It can be used to smooth the variation of air-gap permeance between rotor and stator in HEFSM in results suppressing the amplitude of cogging torque. Initially, the rotor is varied step by step to reduce the cogging torque, the procedure will be repeated until the cogging torque is reduced, the variation in chamfering from 0.8mm, 1mm and 2mm is shown in Figure 3.

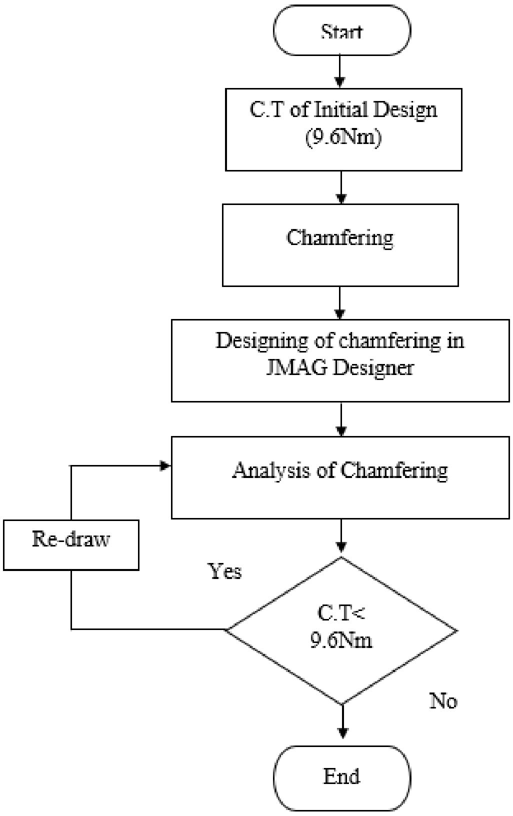

Figure 2: Flowchart of Chamfering

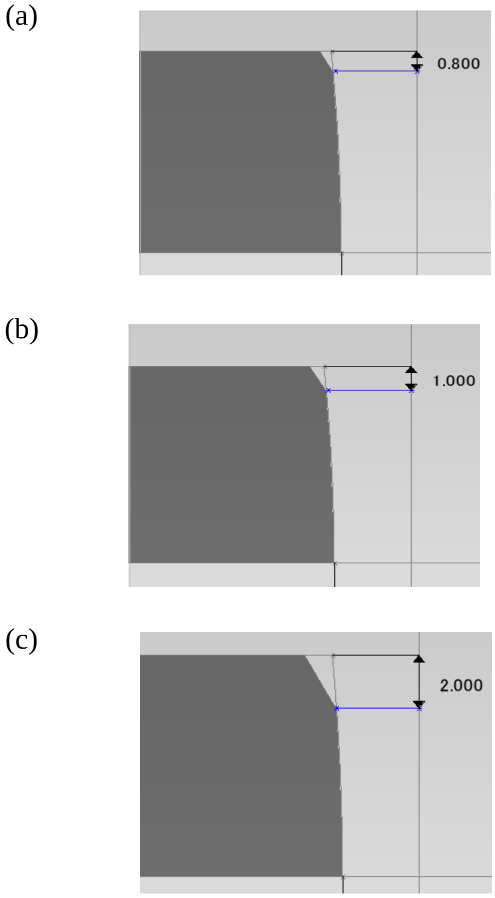

Figure 3: Variation of chamfering at the rotor (a) 0.8mm (b) 1mm (c) 2mm

ii. Notching (Not)

Nothing technique has been designed on the rotor for reduction of cogging torque. Mainly the notches have shaped dummy slots in either rotor or stator in the machine. The notching technique is applied to the outer radius of the rotor by designing the notches (tooth). Basically, notches are creating the distance between the tooth increasing the air gap between the rotor and stator side, thus reducing the cogging torque. There are two methods in which the whole procedure of notching has executed based on length is 1mm and width as shown in Figure 4.

Figure 4: (a) Method 1 and (b) method2 of Notching

Figure 5 shows the flowchart for the notching technique.

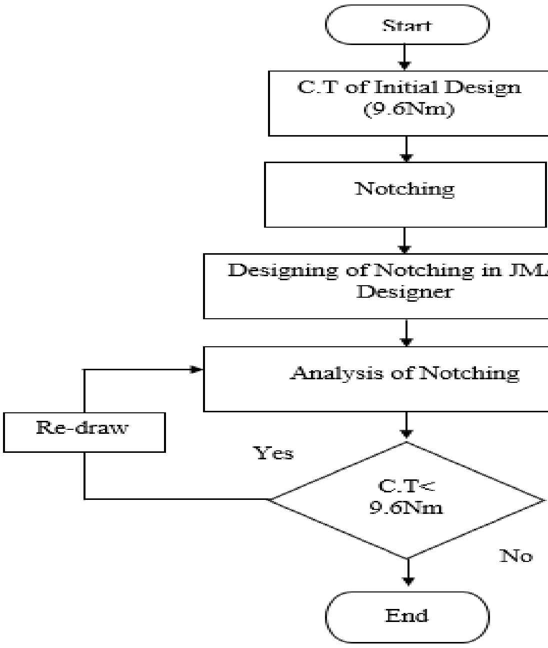

Figure 5: Flowchart for the notching

iii. Combination of Techniques for Cogging Torque Reduction

In order to achieve the best design for reducing the cogging torque, a combined method of NOT and C.H has been introduced. Firstly, the technique based on notching and chamfering is applied to the outer rotor for reducing the cogging torque as discussed in i and ii, as the minimum cogging torque is achieved from both the technique individually, then the combined method will be implemented on the rotor. This combined method is repeated until the further reduction in cogging torque. The proposed design of the combined method is shown in Figure 6. Figure 7 shows the flow diagram of the combined NOT & C.H Techniques.

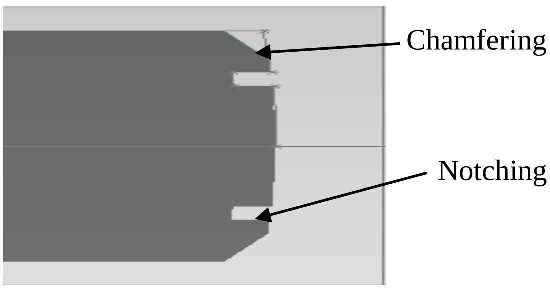

Figure 6: Combined NOT and C.H design of rotor

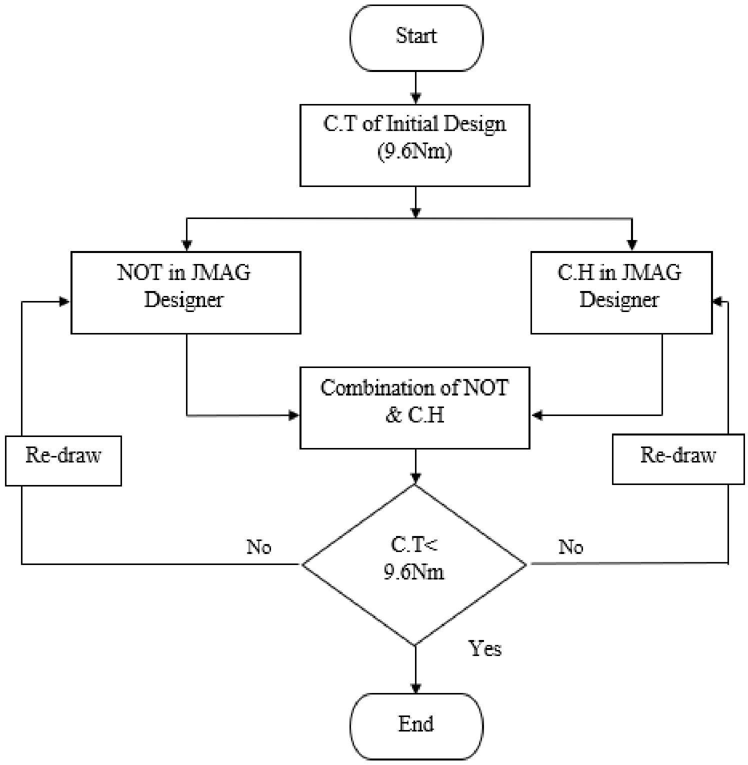

Figure 7: Flow diagram of combined NOT & C.H Technique

3. Results and Discussion

The cogging torque reduction, different techniques have been executed on the improved HEFSM rotor for reducing the cogging torque. At the initial position, the cogging torque of the initial HEFSM rotor was calculated at 9.6Nm, however using various methods for improving the performance of the initial HEFSM increase the cogging torque which can be affected by the motor. Thus, the techniques of reducing the cogging torque such as notching (Not), chamfering (C.H) and their combination will be applied to reduce the cogging torque effect.

3.1 Chamfering (C.H)

Chamfering is another technique for reducing the cogging torque. Basically, in HEFSM rotor chamfering has been done on the rotor as discussed in the previous section. The variation of the rotor as changes, and the cogging torque keeps reducing as shown in Figure 8.

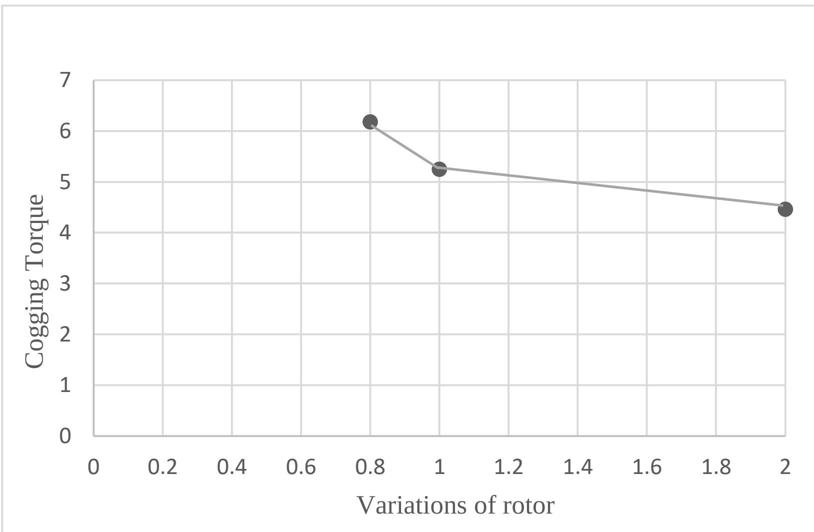

Figure 8: Variations on the rotor

By using the technique based on chamfering, the 2(mm) parameter shows the lowest cogging torque value among the other parameters and almost 54% of the original cogging torque is shown in Figure 9.

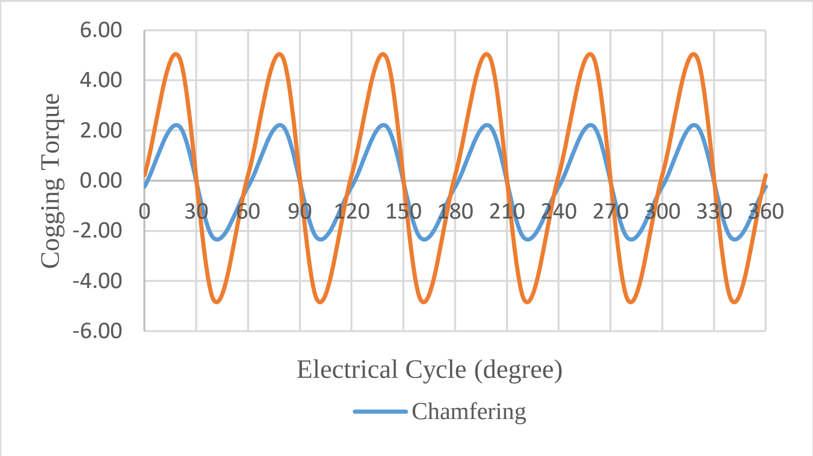

Figure 9: Waveform of Cogging Torque using Chamfering technique

3.2 Notching (Not)

The notching technique is used for reducing the cogging torque either on the rotor or stator. As discussed in Section 2.2 (ii), the method notches design is applied on the rotor to reduce cogging torque. The process of notching is applied as two methods with notches of length and width shown in Table 2.

Table 2: Method 1 and 2 in Notching

Method 1		Method 2	
Notch	Cogging Torque (Nm)	Notch	Cogging Torque (Nm)
1	5.78	2	4.05
3	9.90	4	9.74
5	11.42	6	11.31
7	12.68	8	12.38

The best result is 2 notches because it shows the lowest cogging torque value among the others. However, the notching technique reduces the 58% of cogging torque as compared with the initial cogging torque which is shown in Figure 10.

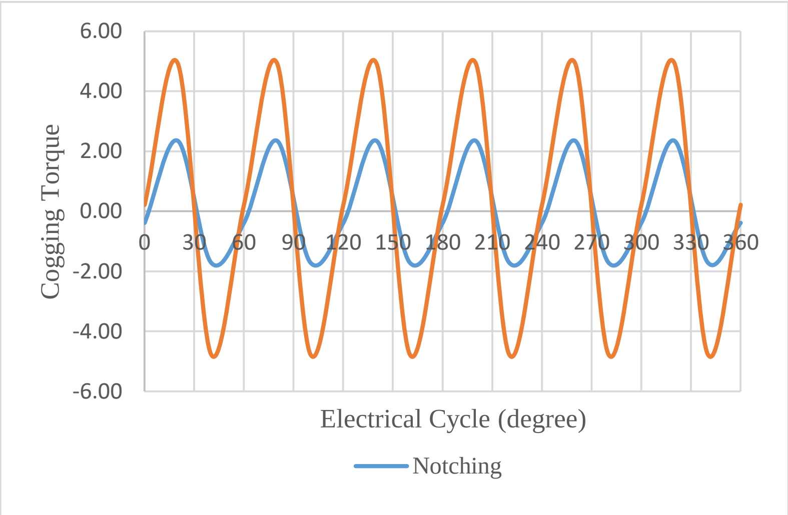

Figure 10: Waveform of cogging torque Notching techniques

3.3 Combination of NOT and C.H

Conventional or basic design configuration has the highest peak-to-peak cogging torque value approximately at 9.6Nm. For Notching, the cogging torque has been reduced 4.05Nm and for chamfering technique, the cogging torque is reduced 4.46Nm. Therefore, the combined technique of Notching and Chamfering maintained the low cogging torque effect of 62% reduction. Figure 11 shows a waveform of cogging torque combination notching and chamfering.

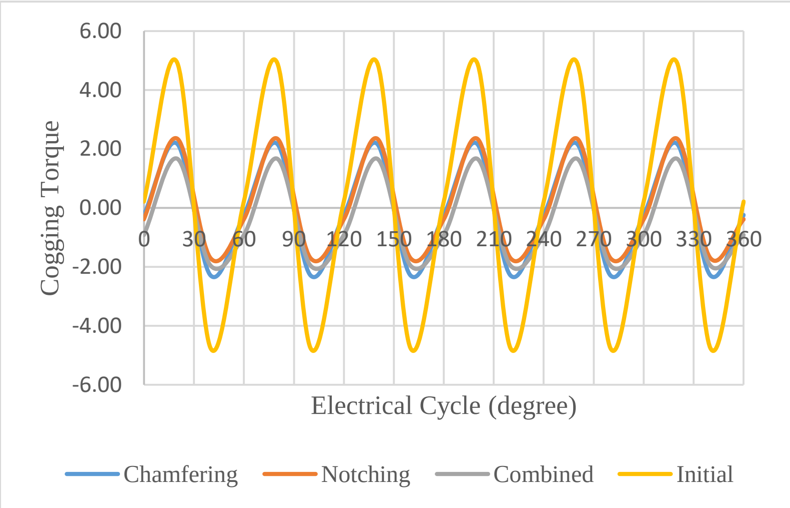

Figure 11: Waveform of cogging torque combination notching and chamfering

Various motor technique has been discussed for improving the performance of the initial HEFSM design. After those different techniques for the reduction of cogging torque have been discussed and the new proposed design of the new technique as well. Table 3 shows the overall performance of improved, notching, chamfering and combined techniques.

Table 3: Overall performance of improved, notching, chamfering and combined technique

Model	Cogging Torque (Nm)	Percentages Reduction %
Initial Design	9.6	-
Chamfering (C.H)	4.46	54
Notching (Not)	4.05	58
Combined (C.H & Not)	3.61	62

3.4 The induced voltage

The induced voltage generated conventional design HEFSM at 1200 r/min as illustrated in Figure 12. From the graph, the maximum value for the induced voltage of the initial design is 54.92V. After using technique reduction, the induced voltage for chamfering and notching techniques design was decreased which is 53.69V and 54.25. The combined technique of NOT and C.H reduces to 51.66V.

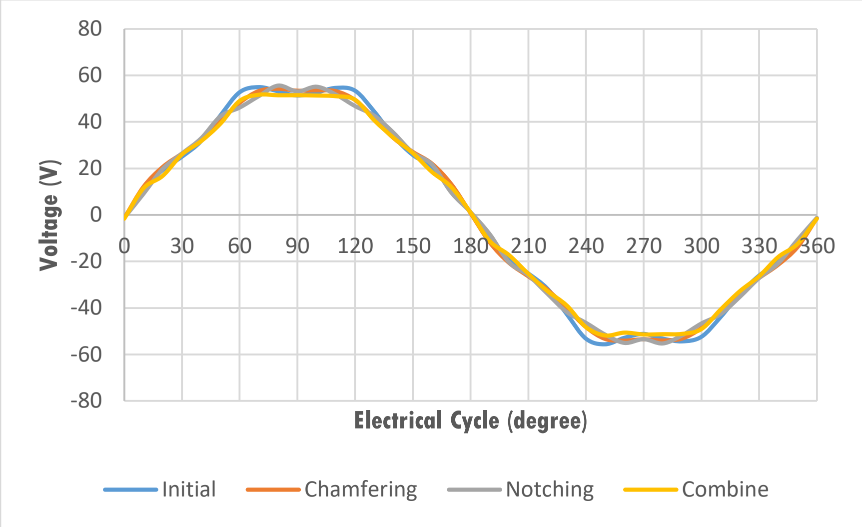

Figure 12: The Waveform of induced voltage

3.5 Torque Performance at various armature current density, J_a and FEC current density, J_e

For load analysis, the performances of the machine at maximum Ja and Je are analyzed. To investigate this issue, the torque versus field excitation current densities Je, at various armature current densities Ja is plotted as depicted in Figure 13. The graph shows it is obvious that the torque is increased when Je is applied. When Je and Ja are $0\mathrm{A/mm}^2$ the torque result obtained is approximately 0Nm and constant until Je $30\mathrm{A/mm}^2$ because no current is injected into Je and Ja only depending on PM. However, when Ja is set between $5\mathrm{A/mm}^2$ to $20\mathrm{A/mm}^2$, the output torque is maintained constant for Je greater than $25\mathrm{A/mm}^2$. For Ja at $25\mathrm{A/mm}^2$ and $30\mathrm{A/mm}^2$, the maximum torque obtained are 278.88Nm and 295.26Nm respectively. From the graph, it is also clear for the Je of $30\mathrm{A/mm}^2$ where much FEC flux is generated and the torque is increased it shows that there is no any magnetic saturation or flux cancellation.

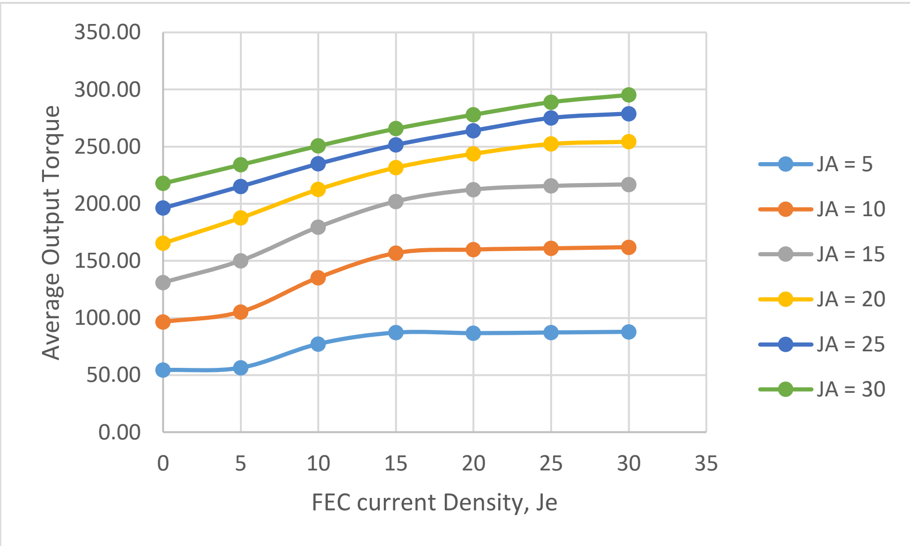

Figure 13: Torque versus J_e at various J_a

4. Conclusion

In conclusion, the cogging torque effect has been reduced by using various techniques such as notching (Not) and chamfering (C.H) and finally, the combined method has been applied to the rotor configuration at no load condition and compared with the initial design. The combined technique of

NOT and C.H reduces almost 62% of the reduction of the original value. Finally, the proposed design successfully achieving in getting low cogging torque and high performance than the initial design for the conventional salient rotor HEFSM design.

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References

[1] M. F. Omar, E. Sulaiman, H. A. Soomro, F. Amin, L. I. Jusoh, and E. I. Mbadiwe, "Optimal design of single-phase 12S-6P FEFSM using segmental rotor and nonoverlap windings*," Indones. J. Electr. Eng. Comput. Sci*., vol. 14, no. 2, pp. 735–743, 2019, doi: 10.11591/ijeecs.v14.i2.pp735-743.

[2] M. F. Omar, E. Sulaiman, F. Khan, G. M. Romalan, and Z. A. Husin, "Comparison between single-phase and three-phase FEFSM with non-overlap windings and salient rotor," vol. 10, pp. 8595–8600, Jan. 2015.

[3] S. K. Rahimi, M. Z. Ahmad, E. Sulaiman, S. M. N. S. Othman, and H. A. Soomro, "Preliminary studies of 12S-8P and 12S-14P Hybrid-Excited Flux Switching Machine with FEC in radial direction by using JMAG-designer software*," Int. J. Eng. Technol*., vol. 7, no. 4.30, p. 479, 2018, doi: 10.14419/ijet.v7i4.30.22373.

[4] M. F. M. Ab Halim, E. Sulaiman, and R. N. F. K. R. Othman, "Flux switching machine: Design variation review*," Int. J. Adv. Trends Comput. Sci. Eng*., vol. 9, no. 2, pp. 2422–2430, 2020, doi: 10.30534/ijatcse/2020/228922020.

[5] W. Fei, P. C. K. Luk, and J. Shen, "Torque analysis of permanentmagnet flux switching machines with rotor step skewing," *IEEE Transactions on Magnetics*, vol. 48, pp. 2664-2673, 2012

[6] M.-J. Jin, Y. Wang, J.-X. Shen, P. C.-K. Luk, W.-Z. Fei, and C. Wang, "Cogging torque suppression in a permanent-magnet fluxswitching integrated-starter-generator," *IET electric power applications*, vol. 4, pp. 647-656, 2010.

[7] 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,* vol. 51, pp. 3609-3619, 2015.