International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 6, No. 4, December 2015, pp. 860~868
ISSN: 2088-8694

Electromagnetic Performance due to Tooth-tip Design in Fractional-slot PM Brushless Machines

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Article Info

Article history:

Received Aug 20, 2015
Revised Nov 15, 2015
Accepted Nov 28, 2015

Keyword:

Cogging Torque
Fractional-slot
Tooth Notch
Tooth-tip Asymmetry
Torque Ripple

ABSTRACT

Permanent Magnet (PM) machines are favorable as an alternative to other machine topologies due to simpler construction and high torque density. However, it may result hight torque ripple due to an influence of cogging torque and electronic commutation. In this paper, comparisons of phase back-emf, static torque and cogging torque due to influence of tooth-tip asymmetry in 12-slot/10-pole double-layer and 12-slot/10-pole single layer winding machines are carried out using 2D Finite-Element Analysis. At rated condition, the stator asymmetry has great influence on the torque performance as there is significant reduction of torque ripple in 12-slot/10-pole mahine equipped with single layer winding than one equipped with double layer winding machine. It si confirmed that an optimum torque performance is desirable via stator iron modification in PM machines.

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1. INTRODUCTION

PM brushless machines have been used in many applications due to the advantages of low copper loss [1], high winding factor [2]-[4], high torque density [1],[4]-[5], as well as simpler structure [6]. However, high torque ripple [8], high cogging torque [9],[10], large unbalanced magnetic pull [5] and high rotor loss [11] are some of the drawbacks which may causes of undesirable noise and vibration especially in small permanent magnet machines [12]. For high performance applications, these parasitic effects should be minimized as much as possible. In design stage, cogging torque minimization is needed especially for a low speed application. Previous researches have shown there are various effective techniques used for the cogging torque minimization that change the geometric shapes of the machine such as stator or rotor skewing [13], magnet pole shape [14],[15], pole arc coefficient [16], magnet shifting [17], stator teeth notching [18] and etc. It is also possible to combine two design optomization methods i.e. stator teeth notching and rotor magnet skewing in order to eliminate the cogging torque. Teeth notching helps to reduce skewing angle of rotor magnet that solve various manufacturing problem and retains the shape of back EMF waveform [19]-[21]. Many researchers as mentioned found that reduction in cogging torque inherently reduce the torque ripple as the cogging torque is one of the components of torque pulsation in principle. However in many cases, torque pulsation is still high even the cogging torque is significantly reduced. This is because due to no-load reluctance torque that exists during open-circuit, while the torque ripple at rated condition exists due discrepancy of back EMF and winding current [22]. Torque ripple in PM brushless machines also mainly due to harmonics in back-EMF, winding MMF, commutation of current and cogging torque [23] as well as saturation in magnetic circuit path of electric machine. The torque ripple is also can be reduced effectively which depends on other factors instead of cogging torque [21].

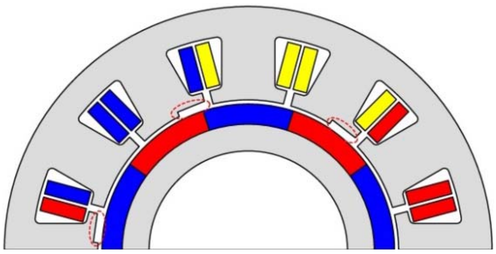
In this paper, further investigation is carried out by coupling the influence of tooth–notching with the influence of stator modification from previuos work [24] which main parameter is tabulated as in Table 1. These works are mainly focused on the output torque performance in single and double layers fractional slot surface mounted PM machines. Factors such as notch depth, notch width, notch numbers and notch position on stator tooth-tip are included in the investigation. All results are predicted by the Ansys Finite Element Analysis software. Significant findings in this research are discussed in the later sections.

Table 1. Design specifications for 12-slot/10-pole machine

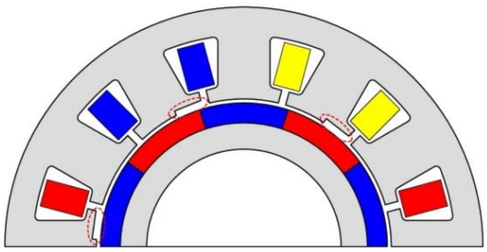
Parameter	Specifications
Supply voltage (V)	24
Rated torque (Nm)	10
Rated speed (rpm)	100
Stator outer diameter (mm)	120
Rotor outer diameter (mm)	72
Axial length (mm)	20
Magnet thickness (mm)	5
Airgap length	1
Slot Opening	1.9
Tooth tip thickness	3.3
Rated current (A)	10.8
Magnetization type	Parallel
Operating mode	BLDC

2. STATOR MODIFICATION

Symmetrical stator tooth-tip width is in relation to the stator slot opening. A winding process will be much easier when bigger space of copper winding is available. By increasing the slot opening width, a change on slot permeance results a bigger cogging torque. If a wider tooth-tip width is implemented, magnetic interaction between permanent magnet and slot permeance is minimized leading to a smaller cogging torque and eventually the torque ripple. Therefore, stator tooth-tip should be as close as possible to minimize the cogging torque and stator slot should be wide enough to accommodate copper windings. In this study, the first asymmetry stator is implemented by having strange tooth-tip geometry as marked with dashed circle in Figure 1.



a) double layer winding



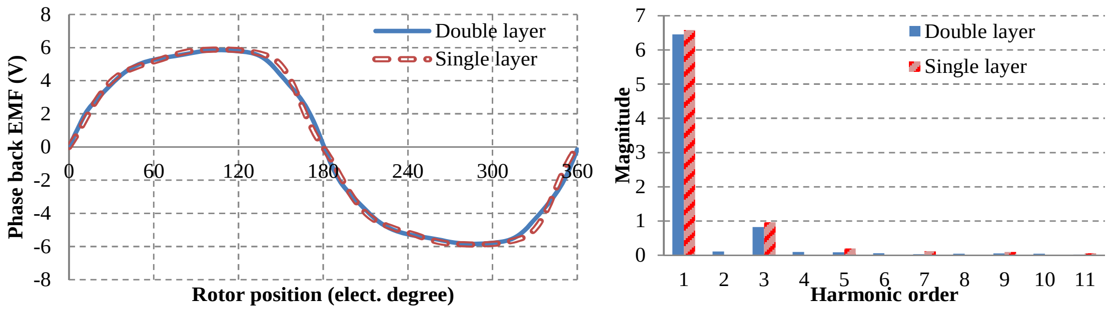
b) single layer winding

Figure 1. 12-slot/10-pole machine with alternate asymmetric tooth-tip [24]

2.1. Effect on Back EMF

The phase back-emfs of 12-slot/10-pole machines with the influence of different winding topologies and modification on alternate tooth-tip are compared in Figure 2. The modified stator distort developed stator magnetic path thus resulting an unsymmetrical phase back-emf. In other way, the developed stator magnetic path has been interfered by the localized flux due to the asymmetric geometry, leading to a severe saturation condition in the stator tooth-tip. The phenomena can be explained by the harmonics content as shown in Figure 2b). The modified stator – single layer winding has higher fundamental and 3rd order harmonics while at the same time boost the 5th and 7th order harmonics compare to modified stator – double layer winding. It is also shown that the modified stator – double layer winding has boost the 2nd order harmonics.

In general, the modified stator affects the phase back-emfs in both double layer and single layer winding machines.

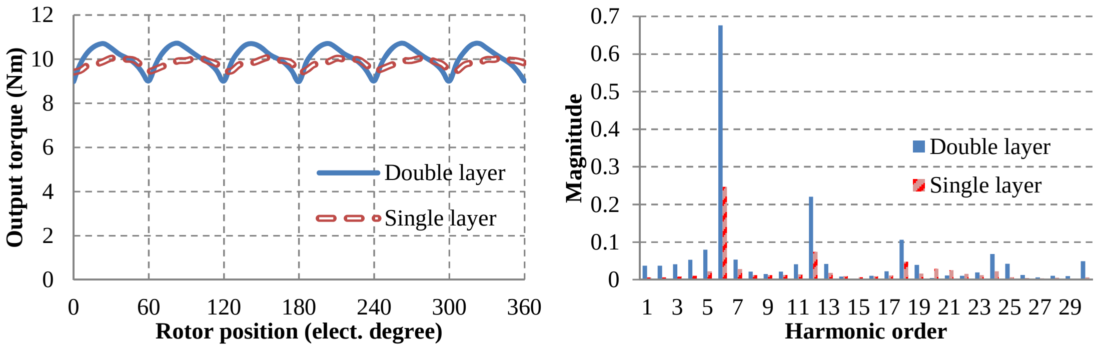


a) Phase back-emf b) Harmonics

Figure 2. Phase back-emf of 12-slot/10-pole machine with modified stator

2.2. Effect on Output Torque

Figure 3 compares the rated output torque in 12-slot/10-pole machines with the influence of different winding topologies and modification on stator tooth-tip. The modified machine that employs single layer winding results superior torque performance than the double layer winding as its torque ripple is only 6% while having similar average output torque. The modified machine that employs double layer winding results a bigger torque ripple i.e. 17.2% while maintaining average output torque of 10Nm. The harmonic content of output torque in all machines are shown in Figure 3b). The reduction of fundamental and higher multiple harmonics order corresponding to the torque files as shown in Figure 3a). The rise of other lower sub-harmonics order results in more dc from of torque in the single layer winding machine. This would results minimum noise and vibration. The average output torque and torque ripple in all respective machines are tabulated in Table 2.



a) Torque profile b) Harmonics

Figure 3. Output torque of 12-slot/10-pole machine with modified stator

Table 2. Rated output torque in 12-slot/10-pole machine with modified stator

Machines	Average torque (Nm)	Torque ripple (%)
Double layer	10	17.2
Single layer	9.8	6

2.3. Effect on Cogging Torque

Figure 4 compares the cogging torque in the respective machines. Theoretically, the 12-slot machines have identical cogging torque although they employ different winding configurations. However, machines that have modified stator result bigger cogging torques and new cogging torque cycles but their output torque ripple reduced [24].

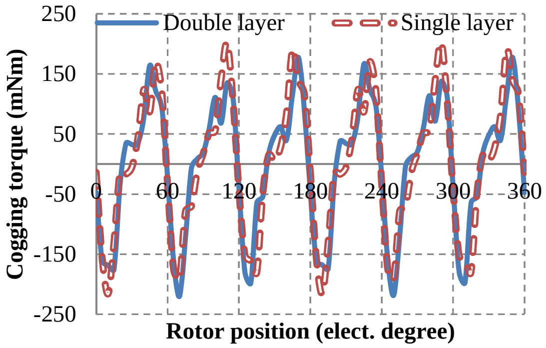
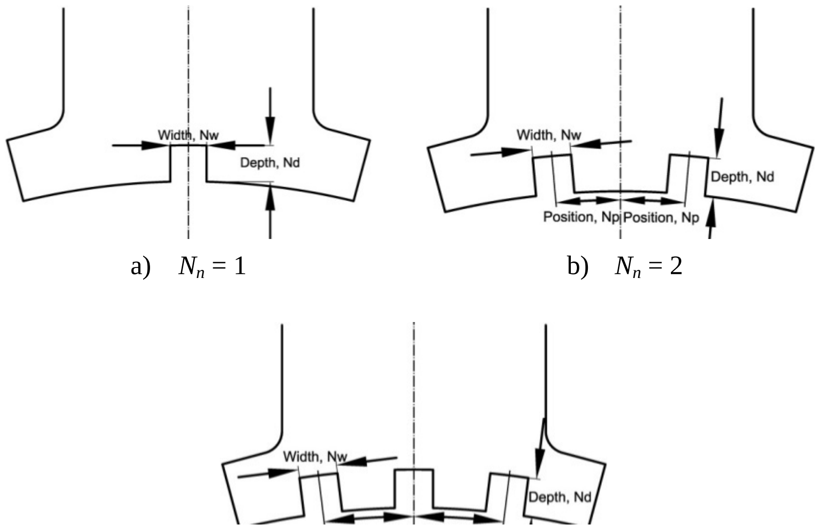


Figure 4. Cogging torque of 12-slot/10-pole machine with modified stator

3. TOOTH-TIP NOTCH

Further investigation of stator modification is followed by tooth notching. This technique is implemented by introducing auxiliary slots along the tooth tip periphery. In most cases, cogging torque can be effectively reduced when notches have same width as slot-opening. Fractional-slot machines in which slot per pole per phase, q is a fraction would be preferable instead of integral-slot type because notch numbers is pointless and does not affect the reduction of cogging torque when q is an integer. Suitable notch number, N_n must be carefully chosen for a minimum pulsating torque.

Figure 5 illustrates stator tooth notching with different numbers of notch at stator tooth-tip. Here, the notches are introduced at stator teeth that are alternately symmetric to the modified ones as marked with dashed circle in Figure 6. The machine equipped with singler layer winding is selected for further analysis of stator tooth-tip notch due to its performance in term of back EMF and less torque ripple. Tooth-tip notch may cause the magnetic flux distribution to depart from its ideal path as in turn changes the output performance of the motor. By varying the notch depth, N_d, notch width, N_w, notch position, N_p and suitable number of notches, N_p., the machine performance are analysed and compared with the machine equipped with single layer winding and having modified stator as shown in Figure 1.



a) $N_n = 1$ b) $N_n = 2$

c) $N_n = 3$

Figure 5. Stator tooth asymmetry

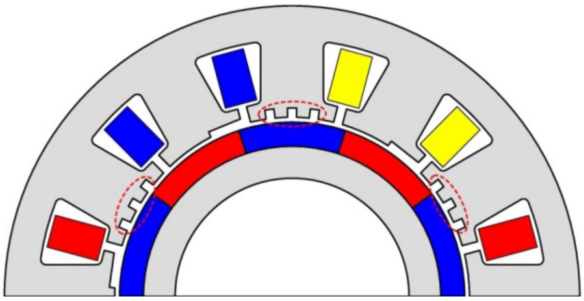


Figure 6. Stator tooth asymmetry

3.1. Notch Number and Notch Position

The influences of notch position on torque ripple are investigated for different notch numbers. Tooth notch with N_n = 1 are positioned on the center of the tooth-tip. However, tooth notch also can be positioned apart from tooth-tip center when it has N_n = 2 or N_n = 3. The influence of notch position is investigated by varying its positions from N_p = 4° up to N_p = 12° starting from the centre of the tooth-tip. It should be noted that tooth notches are relatively effective on cogging torque reduction when they have same width as winding slot opening. Thus, the notch dimension in this study resembles as winding slot opening which is 1.9 mm. Figure 7 shows torque ripple of different notch positions for N_n = 1, N_n = 2 and N_n = 3. A similar torque performance is obtained in two different conditions; when i) N_n = 1 and N_p = 0° and ii) N_n = 3 and N_p = 10°. It can be seen that torque ripple reaches it maximum at N_p = 6° and minimum when notches are positioned at N_p = 10° for both N_n = 2 and N_n = 3. It is also can be seen that stator with N_n = 3 results less torque ripple than when N_n = 2.

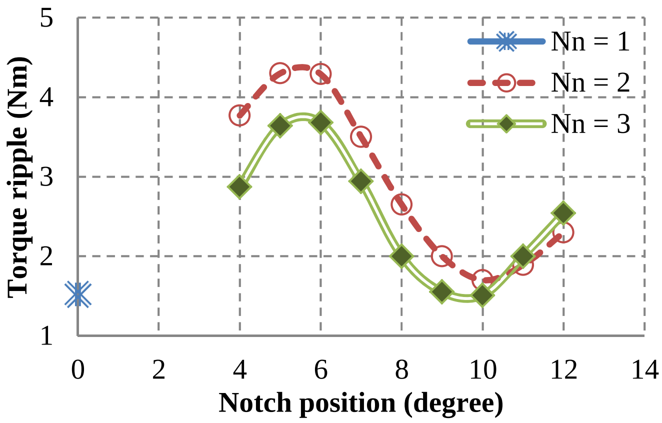


Figure 7. Torque ripple for different degree of notch position

3.2. Notch Depth and Notch Width

A compromise between the notch depth and notch width has to be considered to acheieve optimum torque i.e. higher average torque but less torque ripple. Figure 8 shows torque ripple due to various notch depth and notch width when N_n = 1. There is not much change of torque ripple when notch depth inreases. Notches in the stator tooth-tip change the behavior of magnetic field in the stator tooth body and hence affecting machine torque capability. The smallest torque ripple is obtained when N_w = 5 mm and N_d = 4 mm .

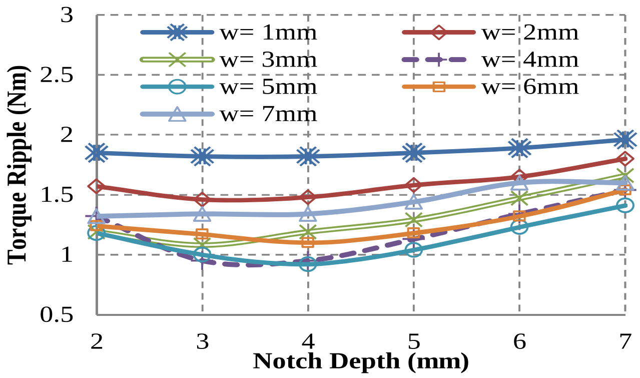
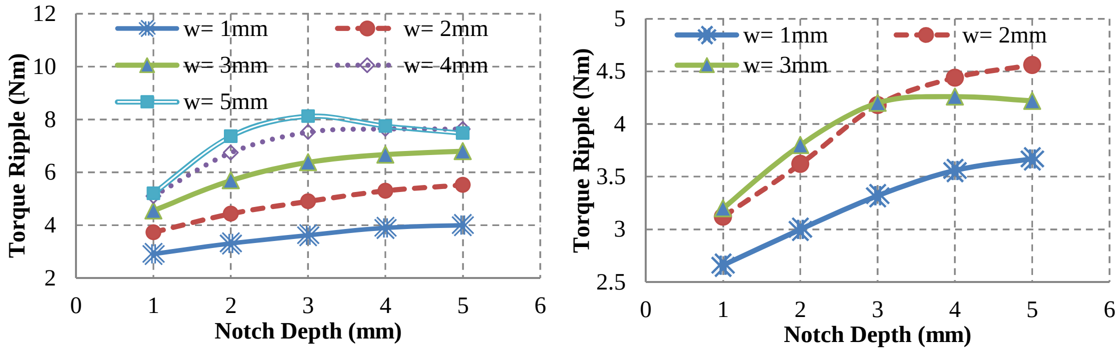


Figure 8. Torque ripple for various notch depth and notch width when N_n = 1

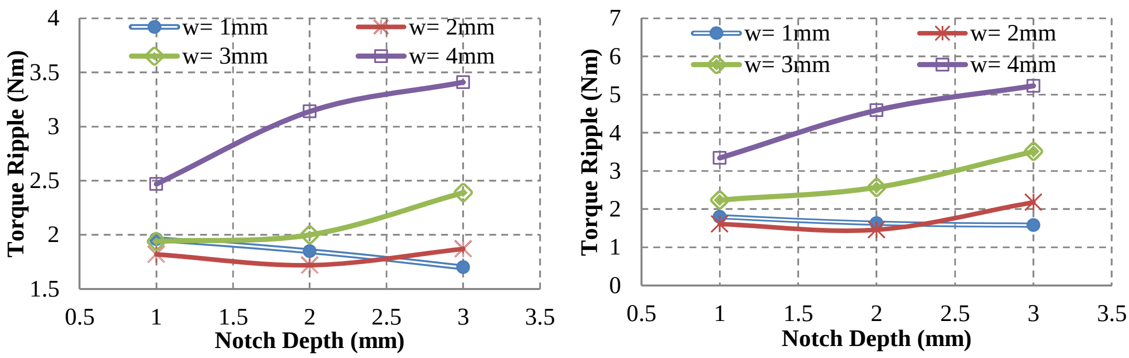
Investigation of torque ripple due to variation of notch depth and notch width for N_n = 2 and N_n = 3 are presented in Figure 9 and Figure 10 respectively. The investigation focus at two different position i.e. N_p = 5° and N_p = 10°. From Figure 9, there is similar trend i.e. the torque ripple increase as notches getting deeper and wider. Saturation in tooth body could be increased due to the bigger size of notch dimension, leading to a slight reduction of average torque but bigger torque ripple. This phenomenon is confirmed by Figure 9, when N_p = 5°.



a) N_n = 2 b) N_n = 3

Figure 9. Torque ripple due to different dimension of notch depth and notch width when N_p = 5°

Figure 10 shows a similar trend as in Figure 9 as the torque ripple increases when the notch depth and notch width are increased. Regardless of N_n = 2 or N_n = 3, a condition of N_w = 1mm results the smallest range of torque ripple and it relatively remains constant over various notch depth.

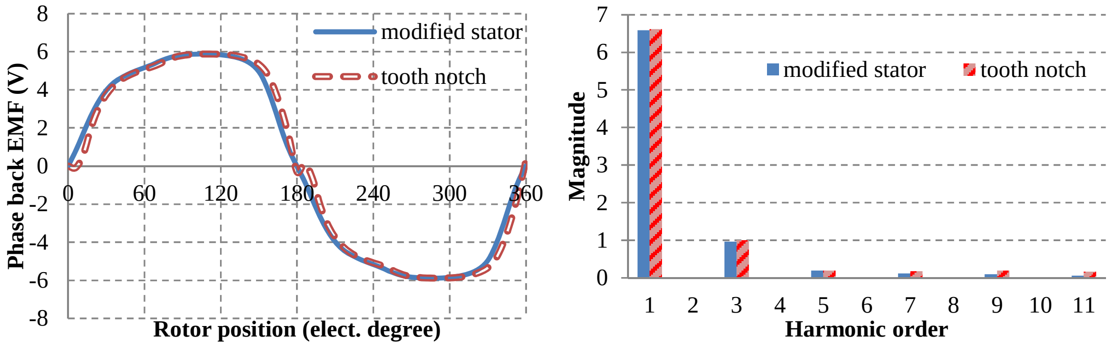


a) N_n = 2 b) N_n = 3

Figure 10. Torque ripple due to different dimension of notch depth and notch width when N_p = 10°

3.3. Effect on Back EMF

The phase back-emfs of 12-slot/10-pole, single-layer machines with the influence of stator modifications, i) asymmetric tooth-tips (M1); ii) asymmetric tooth-tips + alternate tooth notching (M2); are compared in Figure 11a). These auxiliary slot i.e. tooth notching distorts the developed stator magnetic path and establishes high localized magnetic flux saturation. For M2 stator, there is little mis-match between positive and negative portions of phase-back emf for every 180° elect. degree. However the M2 stator, results similar harmonics content with M1 stator as shown in Figure 11b).

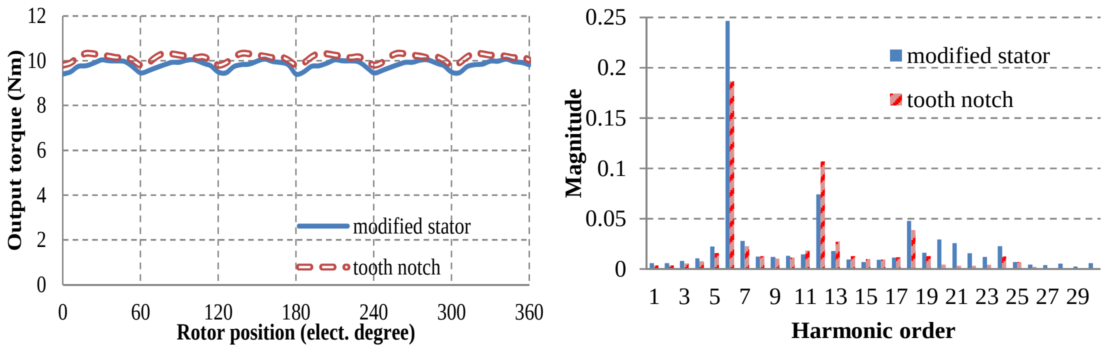


a) Phase back-emf b) Harmonics

Figure 11. Phase back-emfs due to asymmetric tooth tip in 12-slot/10-pole machines

3.4. Effect on Output Torque

In general, both M1 and M2 stator result similar torque performance, but M2 is slightly better than M1 as shown in Figure 12. The harmonic content of each respective models are illustrated in Figure 12 b),and it is shown that the fundamental and higher multiple harmonics orders of M2 are reduced. The average torque and torque ripple at rated condition is tabulated in Table 3.



a) Torque profile b) Harmonics

Figure 12. Output torque due to asymmetric tooth tip in 12-slot/10-pole machines

Table 1. Output torque of asymmetries stator 12-slot/10-pole machines

Machines	Average torque (Nm)	Torque ripple (%)
Modified stator	9.8	6
Tooth nooth	10	5.2

3.5. Effect on Cogging Torque

Figure 13 compares cogging torque between the two stator models. The M2 model has a slight increase of cogging torque than the M2 where the cogging torque cycle is unchanged. Although the tooth-notch is tiny, it results localized flux saturation due to interaction between rotor permanent magnet and the stator tooth. In general, non-uniform design of stator tooth may change cogging torque characteristics.

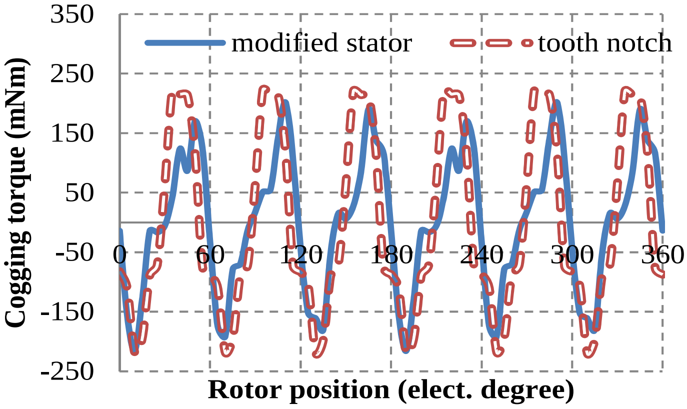


Figure 13. Cogging torque due to asymmetric tooth tip in 12-slot/10-pole machines

4. CONCLUSION

From the investigation, the stator asymmetry has great influence on the torque performance as there is significant reduction of torque ripple in 12-slot/10-pole single layer winding machine equipped than the ones equipped with double layer winding topology. Although a distorted back-emf exists when auxiliary notches and asymmetry stator tooth-tip are employed, an optimum torque performance i.e. less torque ripple is desirable.

ACKNOWLEDGEMENTS

The authors would like to thank Universiti Teknikal Malaysia Melaka (UTeM) for providing the research grant PJP/2012/CERIA/Y00002 for this research.

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