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# A New Approach for Cogging Torque Suppression in Interior Permanent Magnet Machines

**Amin Nobahari**[1], **and Abolfazl Vahedi**[1], *Senior Member, IEEE*

[1]School of Electrical Engineering, Iran University of Science and Technology, Tehran,
amin.nobahari@gmail.com

**Abstract**

In this paper, a new design and fabrication approach is proposed for cogging torque alleviation in interior permanent magnet machines. The paper mainly aims to introduce the main concept of the new design. In this regard, an interior permanent magnet machine with flat-shaped permanent magnets is examined as a case study. The methodology is based on a novel fabrication in which different segments are assembled along the axis. Finite elements model is used to evaluate the results.

**Keywords:** Interior permanent magnet machine, cogging torque reduction, axially segmented design

## Introduction

One of the remarkable challenges associated with the permanent magnet (PM) machines is the existing cogging torque that can affect their performance from various perspectives. The cogging torque contributes to the total pulsating torque under loading conditions, which leads to mechanical vibrations and acoustic noise. Besides, it affects the machine's starting, which is important in many applications such as wind generators. Furthermore, the cogging torque deteriorates the performance of the servo designs, especially where the position control is the main task, such as robots. Hence, one can find several studies deal with reducing this undesirable phenomenon in different kinds of PM machines.

One of the most known solutions for cogging torque reduction is to skew either the PM poles or the stator teeth [1, 2]. This approach has been assessed for surface mounted PM rotors [3, 4], interior PM rotors [5, 6], axial air-gap [7, 8] and transverse flux configurations [9, 10], as well as stator permanent magnet machines [11]. It can see that if the task is to skew the PM-included parts, the step-skew scheme is usually preferred to regular continuous skewing due to its relative easiness. In fact, PMs shaping is regularly ignored to avoid difficult and costly manufacturing. Although skewing has been found an effective method for cogging torque reduction, it always results in losing a portion of the machine's flux linkage, and hence reduces the torque production capability. Thus, other solutions have also been introduced by researches.

It was illustrated in [12] that the pole ratio (pole arc to pole pitch ratio) considerably affects the level of cogging torque, hence it can be optimally determined subject to the minimum cogging torque. Similar effects have been observed by various geometrical parameters such as slot opening width and the combination of the slot-pole number [1, 13]. Other structural modifications have also been proposed, such as modified PMs arrangements [14] and magnetization pattern [15], rotor notching [16], asymmetric rotor poles [17, 18], auxiliary stator slots [19], and pole shaping [20, 21].

In this paper, a new approach is proposed to significantly reduce the cogging torque in interior permanent magnet machines. The new design is based on a structural modification named "axially segmented" structure. The paper aims to demonstrate the methodology fundamentals, therefore, after an introduction to the basic concept, a typical interior permanent magnet machine (IPM) is considered as a case study. Then Finite Elements (FE) model is employed to analyze and design the axially segmented IPM and to verify the results.

## Introduction to the concept

The cogging torque is produced by the interaction of PMs magnetic field and the variable permeance of the air-gap mainly due to the slots presence. Its amplitude varies at different conditions (i.e. different loads and operating points), however, by ignoring the effects of magnetic saturation, it can be mathematically described at zero current condition, as:

$$T_C = -\frac{\partial}{\partial \theta}\left(\int_V \frac{1}{2\mu_0} B_{PM}^2 \, dV\right) \tag{1}$$

in which the PMs magnetic flux density (BPM) is the result of their MMF (FPM) and air-gap permeance function ( $\Lambda_{PM}$ ) multiplication

$$B_{PM}(\theta) = F_{PM}(\theta) \times \Lambda_{PM}(\theta) \tag{2}$$

In the above equations $\theta$ is the rotor position, $\mu_0$ is the vacuum permeability, and $V$ denotes the magnetic circuit volume (air-gap volume can be approximately replaced). Surveying all the previous reduction efforts, one can conclude that the designers have tried to reduce the cogging amplitude by reducing the derivation term of equation (1), by defining either proper $F_{PM}$, or $\Lambda_{PM}$ functions. Also, it can observe that the cogging torque waveform has not received attention independently, and only the maximum amplitude has been of interest.

The main concept of this study for cogging torque reduction is to use its waveform features that include the amplitude, too. In other words, the cogging torque maximum point solely does not matter, and the aim is to create specific torque waveforms rather than merely the amplitude reduction. The new approach will be applied through two key concepts: (1) torque waveform sensitive parameters, and (2) axially segmented fabrication.

*(a) Torque waveform sensitive parameters (TWSP)*
There are several geometrical parameters for design of different parts of the magnetic circuit of a PM machine. Figure 1 shows a typical set of design variables of an IPM. These design variables include stator core, rotor core, and PMs. Among all, it can find some parameters that significantly affect the cogging torque waveform characteristics, i.e. the cogging torque waveform changes considerably by a small variation of the parameter. These parameters are named TWSPs in this paper. As the first step, at least one TWSP must be determined, which can be performed via a pre-study on various parameters.

*(b) Axially segmented fabrication*
The proposed cogging torque reduction is based on a new fabrication scheme that is named axially segmented structure. Figure 2 illustrates a schematic view of an axially segmented machine with three segments. As can see, the magnetic core of the machine is constructed by at least two segments that are assembled along the axis. All the design parameters of the segments are exactly equal, but the value of pre-defined TWSP(s) and their axial length. It is worth noting that some constraints should be taken into account while selecting the TWSP. According to the illustrated proposed structure, the TWSP must be selected so that its change can be practical in the axially assembled segments. For instance, the stator slot width can bot be a good selection since it will result in vacant space in some slot regions. Also if the slot opening width is selected as the TWSP, the winding fabrication process could be too difficult. It seems that it would be better to choose the TWSP among the rotor structure of the PM machines.

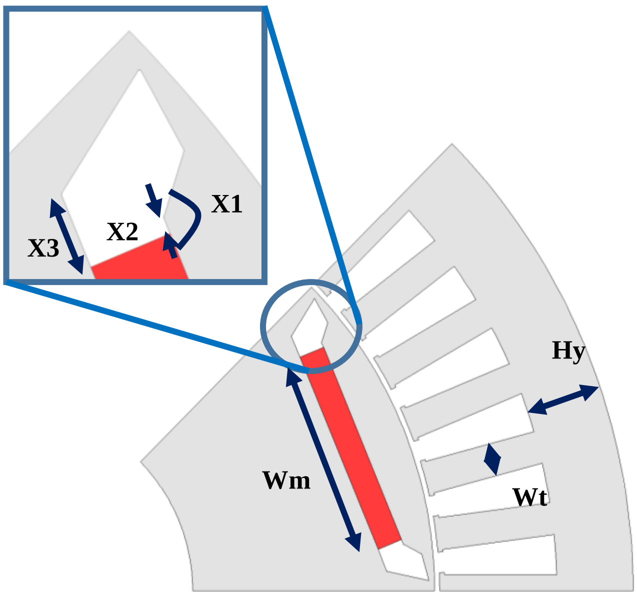


Figure1: Typical design variables of an IPM

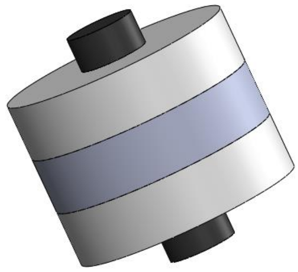


Figure 2: Schematic illustration of an axially segmented fabrication with three segments

The cogging torque waveform for the *i*th segment can be expressed generally by the following equation

$$T_{Ci} = \sum_{n} T_{i,n} \sin(nN_c\theta + \alpha_{i,n}) \; ; n = 1,2,3,... \qquad (3)$$

where $T_{i,n}$ and $\alpha_{i,n}$ are respectively the amplitude and phase of *n*th torque order, and $N_c$ is the smallest common multiple between slot number ($Q$) and pole number ($P$). Assuming $I$ segments that are assembled axially along the shaft, and by ignoring the axial magnetic coupling between the segments, the total cogging will be:

$$T_{CTotal} = \sum_{i=1}^{I} \sum_{n} T_{i,n} \sin(nN_c\theta + \alpha_{i,n}) \qquad (4)$$

According to equation (4), regardless of the amplitude of the cogging torque for each segment, the total cogging can be ideally eliminated if each harmonic component are canceled, i.e.:

$$\sum_{i=1}^{I} T_{Ci} = \sum_{i=1}^{I} T_{i,n} \cos(nN_c\theta + \alpha_{i,n}) = 0 \;\; ; \; \forall n = 1,3,... \qquad (5)$$

And for instance in the case of a two-segment design ($I$=2):

$$T_{1,n} = T_{2,n} \;\; \& \;\; \alpha_{1,n} = \pi + \alpha_{2,n} \;\; ; \;\; \forall n = 1,3,... \qquad (6)$$

In summary, the TWSP of each segment is chosen so that the phase conditions are fulfilled and the axial length of each segment is determined so that the amplitudes condition is satisfied. It should be noted that the total stack length of the machine must be unchanged so that its total rating is constant.

**Studied machine**
In this paper, a flat-shaped pole IPM (Figure 3) is assumed as a case study to investigate the proposed design method. The specification of the studied IPM is presented in Table 1. In the next section, the discussed procedure will be applied on the case study and the results will be illustrated.

Table 1: Rated specification of the studied IPM

| Parameter | Value | Unit |
|---|---|---|
| Rated power | 12 | *kW* |
| Rated torque | 65 | *N.m* |
| Pole number | 8 | - |
| Slot number | 48 | - |

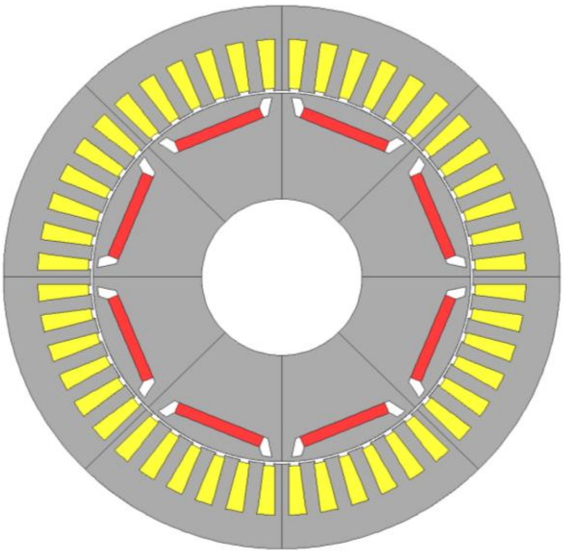


Figure 3: 2D cross section view of the studied IPM

**Results and discussion**

As mentioned earlier, the TWSPs should be selected among the rotor design variables so that the final design will be practically manufactured. The performed investigations have proven that a set of three variables corresponding to the rotor flux barriers is a proper candidate for the studied IPM. Assuming the values proposed in table 2, the resultant cogging torque of 24 designs are shown in Figure 4. These results are calculated via 2D finite elements (FE) analysis of the studied IPM. It can see that the selected variables can be considered a set of proper TWSPs according to the previously proposed definition for TWSP.

In order to design a two-segment IPM, two schemes that are highlighted in Figure 4 are selected (i.e. No. 6 & No. 24). Figure 5 illustrates the selected schemes as well as the developed 2D FE models for each one.

Table 2: The evaluated values for the TWSP set

| Parameter | values | Unit |
|---|---|---|
| X1 | [130, 140, 150] | *degree* |
| X1 | [0.1, 1] | *mm* |
| X2 | [2, 3, 4, 4.5] | *mm* |

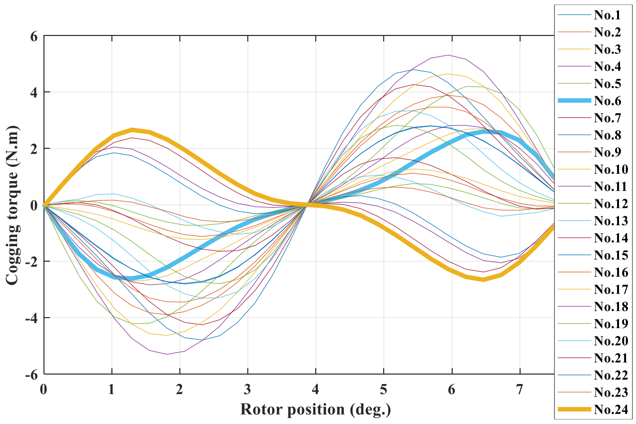
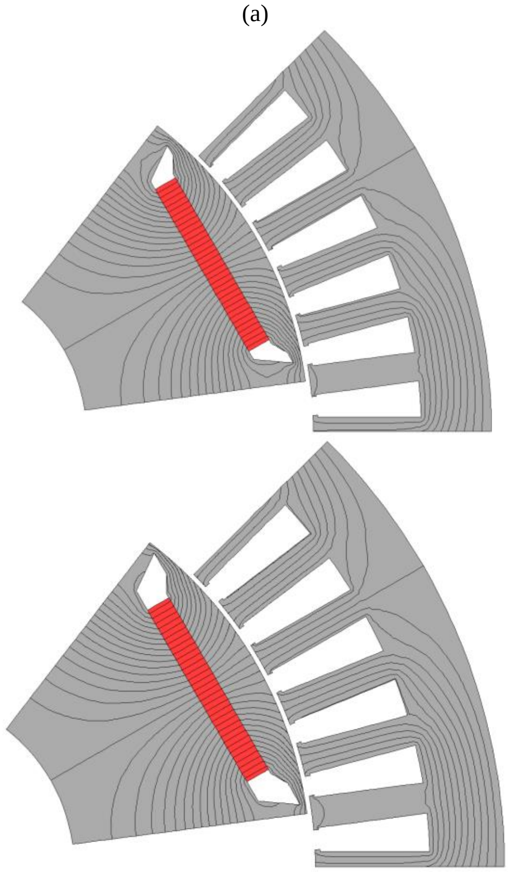
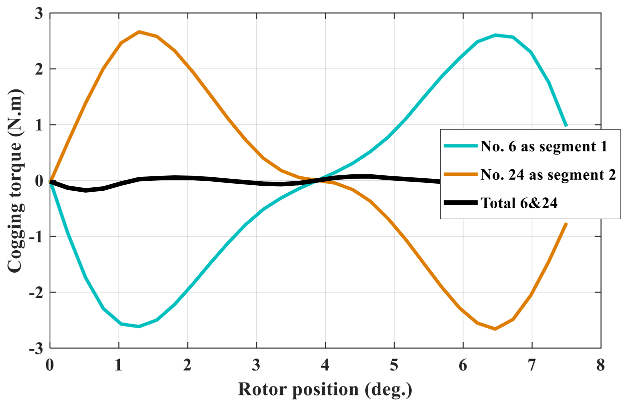



Figure 4: Calculated cogging torque of 24 schemes

(a)



(b)




(c)

Figure 5: Selected schemes to be adopted for new design segments. (a): rotor barriers shape, (b) flux lines distribution, (c) predicted modified result

Table 3: Cogging torque of schemes 6 and 24, and their combination

| Scheme | Cogging torque amp. (*N.m*) |
|---|---|
| Scheme No.6 | 2.60 |
| Scheme No.24 | 2.66 |
| Axially segmented | 0.18 |

Assuming equal length for both segments (i.e. 50%-50% combination) the total cogging torque can be estimated by:

$$T_{C6\&24} = 0.5T_6 + 0.5T_{24} \tag{7}$$

This is an estimation via the calculated 2D FE models that is shown in Figure 5(c) in comparison with designs No. 6 and No. 24. Indeed, a simplifying assumption is considered at this step that the axial magnetic coupling between the segments is ignored. Due to the near geometrical features of two adjacent segments (see Figure 5(a)) the magnetic potential difference between the segments in the junction region is negligible. Therefore the mentioned assumption is possible.
As mentioned earlier, the length of each segment can be adjusted in a manner that the most modification is achieved.

**Conclusions**

A new approach for cogging torque suppression in IPMs was proposed base on the concept named “axially segmented structure”. The main goal of the paper was to demonstrate the new concept, and in this regard a flat shaped IPM was considered as the case study. Without any optimization, it was observed that the methodology is capable to effectively reduce the cogging torque. Moreover, it can predict that more improvements may be achieved if the proposed method is applied through an optimization problem, which will be performed in the future studies.

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