Performance analysis of brushless motors with segmented cores considering manufacturing constraints

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Abstract

Brushless servomotors are widely used in industry and in all domains that require precise and easy position/speed/torque control. To further improve the performance of these motors, the segmentation of the stator core is taken into account. This approach to core construction provides a high slot fill factor, compact design and efficient use of materials. This paper aims to present that the manufacturing constraints and tolerances of this particular core construction can increase unwanted effects in brushless motors, like cogging torque, torque ripple and their influence regarding the back-EMF.Two models for a 12slots-10 pole configuration, one with segmented core and one with standard laminated core are compared and analyzed using the FEA (Finite Element Analysis) method. The influence of the additional air gaps that occur in such constructions is investigated to provide an overview for the design of segmented motors. Various lenghts for air gaps between the segments of the core are taken into consideration and non-uniform distribution of such gaps. The paper also provides further steps that must be taken in order to verify/validate the studied model's impact on motor design.

Keywords: brushless motors, segmented core, surface permanent magnets, manufacturing tolerances, performance degradation, finite element analysis

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1. Introduction

Brushless servomotors with permanent magnets are well known for their torque capabilities, concentrated windings and simplicity of control [1]. There is a constant interest to improve the performance of these machines. One way to improve the machine overall performance is to use segmented cores together with concentrated windings for a compact design. One design possibility for this combination is shown in Figure 1.

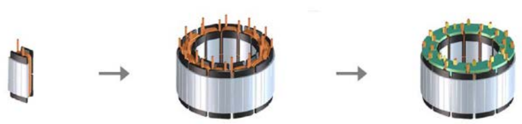

Figure 1. Segmented motor core design pattern

Concentrated windings are used in a wide power range, from few W to kW. This type of winding is attractive due to it's short end-windings and low torque ripple that can be achieved [2]. Also, from a manufacturing point of view, these windings are also non-overlapping windings, which makes the winding process simpler compared to the process needed for the distributed windings[3][4].

Segmented cores can be produced by various means, as presented in [5]. Most common are riveting, interlocking and bonding. Segmented cores can also be mass-produced and offer the best use of the electrical steel, with minimum material loss [4].

Segmented cores are used in conjunction with concentrated windings for an improved slot fill factor. This approach allows a simple process of winding, reducing winding time and also reducing wire stress [3].

Although segmented cores used in brushless motors offer some advantages, there are drawbacks that must be taken into consideration.

It is well known that segmenting the stator of a brushless machine can lead to various problems, some including constraints imposed by the manufacturing tolerances of the segments [6][7]. There are articles in the literature that presented the effects of segmenting the core on flux leakage [8]-[11], cogging torque [12]-[15] and a possible alteration of the back-EMF harmonic content [16].

Many models for were investigated in [14][17] to give an analytical formulae that can be used to determine the cogging torque amplitude since the beginning of the design process. Unfortunately, as stated in [17], most models can offer a good guess only about the periodicity of the cogging torque, it's amplitude being hard to evaluate in the design phase with just analytical methods. For a more accurate analysis of the cogging torque in these machines a FEA model is necessary.

The back-EMF in segmented core was investigated in [18] and led to the conclusion that additional air gaps in the structure due to mechanical tolerances can lead to a increase in the THD (Total Harmonic Distortion) factor of the back-EMF in sinewave brushless motors.

This paper intends to study the main parameters of a brushless motor with segmented core and to compare them with an equivalent that uses the common laminated core. The comparison is used to analyze the main problems that appear with the brushless motor when some mechanical parameters that are specific to the manufacturing process were not taken into consideration during the design process.

2. Machine model and analysis

2.1 The motor model

The proposed machine for analyis is a 12 slots-10 poles brushless motor with surface permanent magnets.Two different stator models are studied.

The rotor is identical for both models and is made out of solid magnetic steel with magnets on the surface. Those magnets are sintered NdFeB magnets for high temperature. The magnets have a parallel magnetization pattern with a pole arc to pole pitch ration of 0.907. The magnets' grade and dimensions are provided in Table 1.

The stator for the segmented model has 12 slots and is made out of 12 identical segments made from steel laminations with a thickness of 0.5mm. . The winding is a double layer 12/10p configuration with a winding factor of 0.933 for the fundamental harmonic. The model is presented in Figure 2.

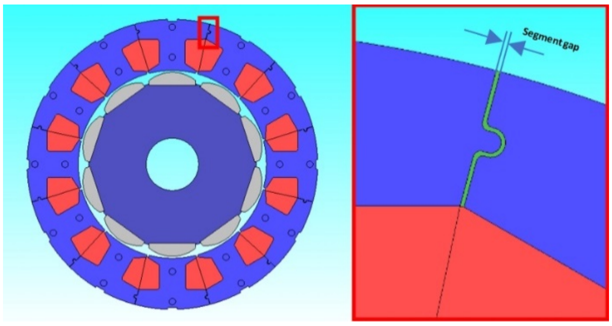

Figure 2. Segmented motor configuration

The stator for the reference model has 12 slots and is made out of laminations of 0.5mm thickness. The winding is in single layer 12/10p configuration with a winding factor of of 0.966 for the fundamental harmonic. The model geometry is presented in Figure 3.

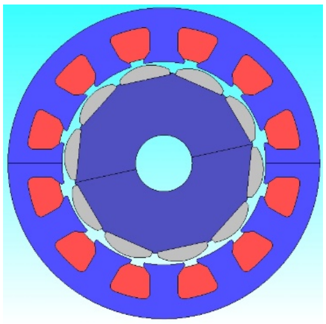

Figure 3. Reference model configuration

Table 1. Proposed machines main parameters

Parameters	Segmented motor model	Reference model
Stator outer diameter [mm]	111	111
Rotor outer diameter [mm]	70.4	70.4
Stack length [mm]	90	90
Air gap length [mm]	0.7	0.7
Magnet thickness [mm]	5	5
Magnet radius [mm]	14	14
Magnet length [mm]	30	30
Magnet grade	N45SH	N45SH
Winding type	double layer	single layer
Turns/coil	40	39
Slot fill factor	0.5	0.32

2.2. Analysis method

For the motor analysis, a FEA model was made using the software JMag [20]. Both the reference motor and the segmented motor were studied in the same manner.

For the segmented motor, the analysis takes into consideration the geometric features of a segmented motor core (the air gaps between segments). This model was used to study the machines' cogging torque, back-EMF and torque ripple for various segment gaps. For that, 5 cases that take into consideration various gaps between segments were created for finite element analysis.

The first case assumes that the core of the motor has no gaps between segments, hence it is an ideal model (*Ideal model* = segment gap of *0mm*). This model was made to put into perspective the peformance of the considered ideal machine.

The next three models are considered to have uniform segment gaps of *0.05mm*, *0.07mm* and *0.1mm* between each segment

The last model takes into consideration a scenario where there is only one segment slightly shifted for the *0.1mm* segment gap case model, thus resulting in a model with one asymetric gap. This model was made to take into consideration the worst case scenario where only one segment is not properly aligned and breaks the symetry of the motor (*Uneven* gap model).

For torque ripple analysis the segmented motor was fed with 3 phase sine currents with a RMS value of *6.3A*.

For the reference model, because of the winding that is rated for another voltage, the same torque is obtained at 12.5A RMS.

The FEA model analysis for the first 4 cases of the segmented motor and for the reference motor was carried out using the motor symmetry and taking into account the periodicity of the 12/10p motor. This allowed for a reduction of the calculation domain in half and also a reduction in the calculation time.

For the *Uneven* gap case, the motor has no symmetry and a full domain model was required.

2.3 Cogging torque models

In the machine design literature there are many models that deal with the evaluation of the cogging torque. One of these models is the energy method.

According to this model, the cogging torque has the following expression:

$$T_{cgg} = -\frac{\partial W(\alpha)}{\partial \alpha} \quad (1)$$

where W is the magnetic energy of the machine and α is the position angle of the machine[zhu2009].

$$W(\alpha) = \frac{1}{2\mu}\int_V B \cdot dV \quad (2)$$

where B is the magnetic flux density in various parts of the machine, and μ is the magnetic permeability of the corresponding parts.

The period of the cogging torque that coresponds to this model is given by [14] as following:

$$P_{cgg} = \frac{360°}{LCM\{Ns,Np\}} \quad (3)$$

where *Ns* is the number of slots of the machine, *Np* is the number of poles of the machine and *LCM* stands for the least common multiple.

According to equation (2) and with respect to [20], the cogging torque expression is:

$$T_{cgg} = \frac{L}{g \cdot \mu_o}\int_S r \cdot B_n \cdot B_t \, dS \quad (4)$$

where L is the stack length, g is the air gap length, μ_0 is the air gap magnetic permeability, B_n is the normal component of the magnetic flux density, B_t is the tangential component of the magnetic flux density respectively, and r is the radius from the centre of the rotor to the center of the air gap.

3. Results

3.1 Cogging torque and Back-EMF

The no-load FEA analysis provided the cogging torque waveform as well as the back-EMF for the studied models. All cases were simulated for one electrical period at 1000 rpm to obtain directly the back EMF constant. Since in the simulation does not take into consideration any mechanical aspects (like rotor inertia or any kind of friction), in the same study the cogging torque can be obtained The cogging torque waveform is presented in Figure 4.

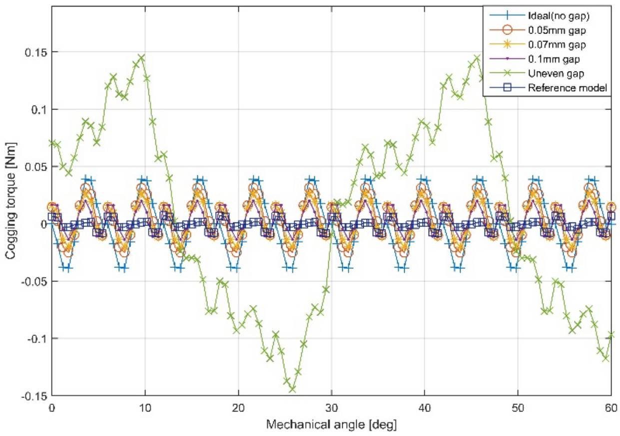

Figure 4. Cogging torque waveform

The cogging torque parameters were computed and are presented in Table 2.

Table 2. Cogging torque parameters

Case	Peak-peak cogging torque [Nm]	Percentage of rated torque [%]
Ideal	0.077	0.26
0.05mm gap	0.056	0.21
0.07mm gap	0.046	0.18
0.1mm gap	0.034	0.14
Uneven gap	0.289	1.03
Reference model	0.015	0.05

The back EMF waveform for the segmented model was obtained from FEA for one period and is displayed in Figure 5.

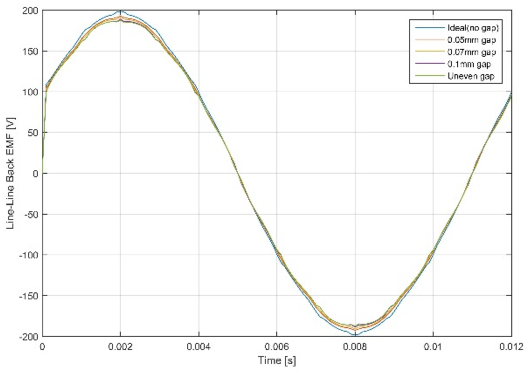

Figure 5. Segmented motor Back EMF waveform

Back EMF parameters for the segmented motor are computed and displayed in Table 3.

The THD factor definition is given as:

$$THD[\%] = \frac{\sqrt{\sum_{i=2}^{n} V_i^2}}{V_1} \cdot 100 \quad (5)$$

where V_i is the RMS voltage corresponding to the harmonic i, and V_1 is the RMS voltage corresponding to the fundamental frequency.

For the proposed motor with the 12 slots-10 pole configuration, rotating with 1000 rpm, the fundamental frequency is 83.333 Hz. The Fourrier analysis used to determine the amplitude and the RMS value of the other harmonics was carried for frequencies up to 3 kHz.

Table 3. Back EMF parameters

Case	Back EMF constant [V/krpm]	THD Factor [%]
Ideal	138.06	0.89
0.05mm gap	134.75	0.91
0.07mm gap	133.68	0.92
0.1mm gap	132.13	0.91
Uneven gap	131.80	1.2

3.2 Torque waveform

The torque analysis was carried out in FEA to obtain the average rated torque. All 5 cases of the segmented model were fed with the same 3 phase sine current of 6.3 A RMS, while the reference model was fed with 12.5 A RMS because of it's winding that is rated for another voltage. The torque for all the models is presented in Figure 6.

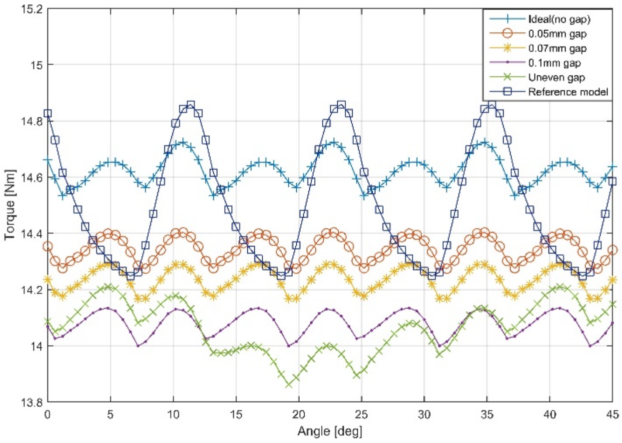

Figure 6. Torque waveform

Torque parameters were computed using the following formulae:

$$T_{Avg} = \frac{T_{Max} - T_{Min}}{2} \quad (6)$$

where T_{Avg} is the average torque, T_{Max} is the maximum torque and T_{Min} is the minimum torque obtained from the graph in Figure 5.

$$T_{ripple} = \frac{T_{Max} - T_{Min}}{T_{Avg}} \cdot 100 \quad (7)$$

The torque parameters calculated with (6) and (7) are presented in Table 3 for the studied cases.

Table 4. Torque parameters

Case	Average Torque [Nm]	Torque ripple [%]
Ideal	14.62	1.23
0.05mm gap	14.34	0.89
0.07mm gap	14.23	0.86
0.1mm gap	14.08	0.95
Uneven gap	14.04	2.47
Reference model	14.51	4.2

4. Discussion

For the studied segmented motor model, according to the cogging torque waveform, presented in Figure 4, the peak cogging torque decreases slightly as the air gap between segments increases. This decrease of cogging torque is accompanied by a decrease in the back-EMF constant, which means that the flux leakage was increased due to those air gaps. This is an expected result, since the additional air gaps increase the reluctance of the magnetic circuit.

This increased flux leakage is supported by the other results, since the back-EMF decrease and also the torque, as it can be observed in Figure 5 and Figure 6

The main reason for which the cogging torque decreases is the fact that the air gap segments are all the same and evenly distributed. In reality, this is most likely never the case, as the air gap between segments can be different for each segment gap. Using the cogging torque period equation (3), for the 12 slots 10 pole configuration, the period of the cogging torque is 6 mechanical degrees, which is confirmed by FEA, as seen in Figure 4. This further enforces that the gaps do not break the magnetic's circuit symmetry.

On the other hand, the Uneven Gap scenario showcases the significant impact that one different segment gap can have on the cogging torque. Not only that the cogging torque does not keep it's periodicity, it also increases it's amplitude significantly. The peak-peak cogging torque for the Uneven Gap case is 0.289 Nm, compared with the 0.1mm gap model where the amplitude of the cogging torque is 0.034 Nm.

In similar studies, the cogging torque usually increases as the segment air gaps increase. The main reason for which in the studied segmented model this does not happen is because the magnets used are round magnets, designed to reduce the tangential component of the magnetic flux density. Since the cogging torque is proportional with the product between normal and tangential component of the magnetic flux density, and also because the segment gaps reduce the normal component, the cogging torque decreases. This type of magnet produces an uneven air gap, compared to the constant air gap created by magnets with constant thickness that are used in other studies. This reason highlights the importance of the magnet shape and air gap distribution of the magnetic flux density when designing segmented core motors. The choice of magnet shape and magnetization pattern influences significantly the cogging torque.

Another important aspect regarding the cogging torque can be seen from the comparison of the reference model with the ideal segmented model. Although the segmented model (in it's ideal form with no airgaps) has a bigger cogging torque amplitude compared with the reference model. Segmented core motor allow for a significant decrease in the slot opening, since this opening is no longer a problem for the placement of the winding inside the slot. It can be seen that a small slot opening can affect the segmented motor's cogging torque,and small slot openings do no necessarly mean a significant decrease in the cogging torque. For this reason, it is necessary to optimize this slot opening for each motor, especially for motor with segmented cores.

In Figure 6, the torque waveform analysis provides valuable information regarding the segment gap influence on torque parameters. As it can be observed in Table 4, evenly distributed and uniform segment gaps do not increase the torque ripple. The major torque ripple increase is present when the segment air gaps are no longer uniform. The Uneven Gap model has a torque ripple of 2.47% compared to the 0.1mm uniform segment gap model which has a torque ripple of just 0.95%. This is a significant increase of about 150% of the torque ripple for only one non-uniform segment gap.

The torque ripple present in the torque waveform for the reference model is given mainly the different slot opening configuration, due to manufacturability constraints regarding the insertion of the coils into the slot. The segmented motor allow the use of a double layer winding with a greater slot fill factor that also reduces the torque ripple. It can be stated that in segmented core motors, double layer winding is of preferable use , because the lower winding factor of the double layer winding can be compensated by the increased slot fill factor that a segmented motor core construction can provide.

The last aspect that concerns the study made in this paper is the harmonic content and the THD factor of the back EMF. In Figure 5 are presented the waveforms of the back EMF for the segmented motor with the studied cases of various segment gaps. Those waveforms are for the Line-Line back-EMF. The winding has a star connection configuration for both the segmented motor and the reference motor. The Line-Line back-EMF does not contain many harmonics mainly because the phase back EMF is filtered by the star connection. Even in this case, it can be seen that the segment gaps that are present in the segmented motor core construction can influence the THD factor, but it's value remains low, under 1.5% as it is defined by equation (5). Even for the Uneven Gap model, the back EMF is not affected in a significant way by the assymetry of the magnetic circuit. As expected, the harmonic content of the back EMF will not be greatly affected by the segment gaps.

5. Conclusions

In this paper, the main parameters of influence in segmented motors were investigated. The air gaps that appear between the segments of the motor because of the manufacturing tolerances were taken into consideration and their influence on machine parameters like cogging torque, back EMF and torque ripple were presented.

Segmented cores used in the construction of brushless motors offer increased torque capability, high slot fill factor, compact design and also ease in manufacturing once the line of production is set.

If the manufacturing tolerances and constraints that are present in the segmented core motors are properly investigated and understood, the design process can take into account and overcome the problems presented in this paper and in literature concerning segmented core motors.

The future research will study the experimental model of this segmented motor and compare it with the FEA results. This will help to validate the FEA model or will give hints about what needs to be added in FEA model so that it can provide more accurate results for this type of motor core construction.

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