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Shaping the Stator Poles of BLDCPM Motor for Cogging Torque Reduction

***Abstract**. Recently, the cogging torque in electric motors has been drastically decreased as designers and manufacturers have developed better understanding of the cogging phenomenon. The paper presents a design methodology for cogging torque reduction by an appropriate shaping of stator poles in a Brushless DC Permanent Magnet (BLDCPM) Motor. Cogging torque waveforms, along with other relevant characteristics are examined and a new stator poles design of the BLDCPM motor is proposed.*

***Streszczenie.** W artykule przedstawiono metodę projektowania bezszczotkowej maszyny DC z magnesami trwałymi (BLDCPM), z uwzględnieniem redukcji momentu zaczepowego poprzez odpowiednie ukształtowanie biegunów stojana. Analizie poddano charakterystyki samego momentu zaczepowego jak i innych, powiązanych z zagadnieniem parametrów. Zaproponowano także nowy projekt maszyny BLDCPM. (**Wpływ ukształtowania biegunów stojana na redukcję momentu zaczepowego w maszynie BLDCPM**).*

Keywords: Cogging torque, Motor design, Brushless DC Permanent Magnet (BLDCPM) Motor, Stator pole shaping
Słowa kluczowe: moment zaczepowy, projektowanie silnika, bezszczotkowy silnik DC z magnesami trwałymi, kształtowanie biegunów stojana.

Introduction

Permanent magnet motors have been used in high performance applications because of their high efficiency, high torque density, and power factor close to unity.

However, the vibration and noise caused by cogging torque and electromagnetic torque ripple seriously affects the motor performance. The main motor vibration sources are found in ball bearing roughness, cooling air turbulence, electrical commutation and iron core–magnet reluctance forces. Recently, both the electric motor designers and the motor manufacturers have developed better understanding of the cogging phenomenon.

This paper deals only with the magnetically generated forces known as *cogging*. These forces are usually large and can cause excessive motor vibrations if not properly controlled. An extensive variety of techniques for minimizing cogging torque of permanent magnet motors is documented in the literature. They can be categorized into two groups: sizing techniques and *shaping techniques*. In the paper a shaping technique of the stator poles design in a BLDCPM motor for reduction of the peak cogging torque is presented.

Problem Definition

For applications that require production of a favourable ripple-free torque, good cogging torque waveforms are necessary. However, at the design stage and before the prototype is made, it is often difficult to construct a motor that produces satisfactory cogging torque shape. Moreover, no specific criteria are found to determine the stator poles shapes for such cogging torque waveforms. Hence, in the paper, a shaping technique for the stator poles design is applied to solve the above mentioned problems in permanent magnet (PM) motors. A prototype of a BLDCPM motor is studied to demonstrate the developed technique.

Cogging torque occurs when saliency of the stator iron core, due to tooth–slot geometry or presence of the salient poles, interacts with the multiple permanent magnet (PM) poles on the rotor. Both of the stator geometries undergo cyclic force fluctuation as the rotor turns. The only difference is whether the stator teeth or stator poles are affected. These teeth or poles forces are displaced from each other in time, and they produce a torque. The sum of all the instantaneous individual torques is the total torque, which is in general with nonzero value. This torque is with cyclic pulsating pattern and is referred to as *cogging*.

Cogging torque is greatly affected by the geometry of the rotor and stator, as well as the air-gap profile.

Consequently, pulsating torque minimization can be performed by acting on: the geometry of the stator, the shape and magnetization direction of the permanent magnets along with the geometry of the rotor, as well as the profile of the air-gap. In continuation the stator pole shaping has been proposed to reduce the cogging torque, although a combination of the techniques can be considered as well.

The proposed method of shaping the stator poles for cogging torque reduction, is applied on a single phase BLDCPM prototype motor, and is focussed to finding feasible stator pole shapes.

Design Development of BLDCPM Motor

For the design simplicity, most single phase brushless DC permanent magnet (BLDCPM) motors have salient poles on the stator. First, a novel generic model of a single phase 4-pole surface mounted BLDCPM motor, with constant air gap and equal pole arcs has been developed [1]. The motor geometry is presented in Fig. 1. In the study, this motor model is taken as reference motor – M1.

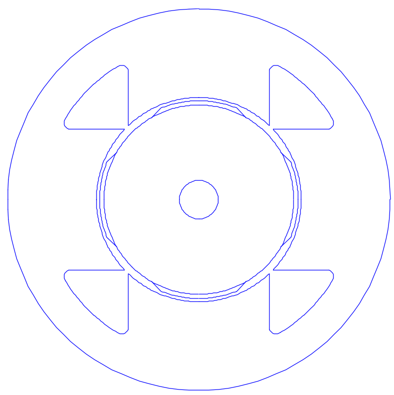


Fig. 1. Generic model of BLDCPM motor – M1

The performance analyses of the motor [2] have shown that this geometry causes considerable cogging created by the simultaneous alignment of the edges of the rotor magnets with the stator poles. Thus, starting from this generic model, and aiming to a cogging torque reduction, the new motor design has been developed.

Referring to the results of the previous investigations of the authors [3], it was found that the cogging torque can be significantly decreased if alternating stator poles are employed. The ratio 1:3, i.e. arc angles 45^0 and 135^0 for the *small* and *big* poles, respectively, has been proved as the best. The arc length of permanent magnets is the same as of the small poles; the geometry is shown in Fig. 2.

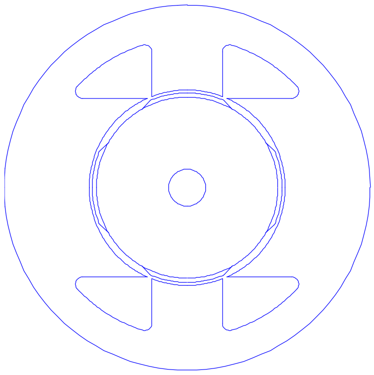


Fig. 2. Design development of BLDCPM motor: pole ratio 1:3 – M2

The novelty of the motor design lies in the combination of the asymmetrical stator poles with ratio 1:3, together with rotor magnets arc that coincide with the width of small stator poles. This motor topology is adopted to be motor model M2. The model has the benefit of a fractional slot motor in reducing the cogging torque, and develops both reluctance and electromagnetic alignment torque, which is usually higher than in conventional single phase BLDCPM motors.

Shaping the Stator Poles

Efficient utilization of iron requires avoiding waste of this active material and a reduction of the dimensions where possible and appropriate. Otherwise, the magnetic loading per volume of the large stator poles body will be rather low, while the specific electrical loading of the winding will be too high. The unique stator design of model M2, where the small stator poles arc is 1/3 of the width of the large stator poles arc, is used for further development of the new motor model M3. More details regarding development of the novel motor design can be found in [1]. In order to create more winding space, while keeping the pole arcs ratio to 1:3, some of the metal from the big stator poles body was removed to implement a pole shoe design as shown in Fig. 3. The target is to reach more efficient utilisation of iron and copper. The big stator poles are shaped to reach the same width of the pole body as the body of the small ones. It can be shown that this motor model, similar to the previous model, keeps both reluctance and electromagnetic alignment torque.

A particular interest has been put on the reduction of the volume of permanent magnets, as they are the most expensive part of a BLDCPM motors. Thus, it is accepted the rotor magnets to have the same arc length as the small stator poles, as well as the shape and dimensions as proposed in the previous stator design of the model M2.

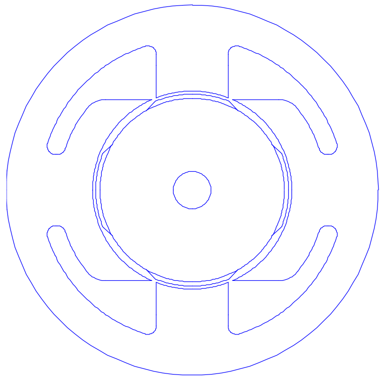


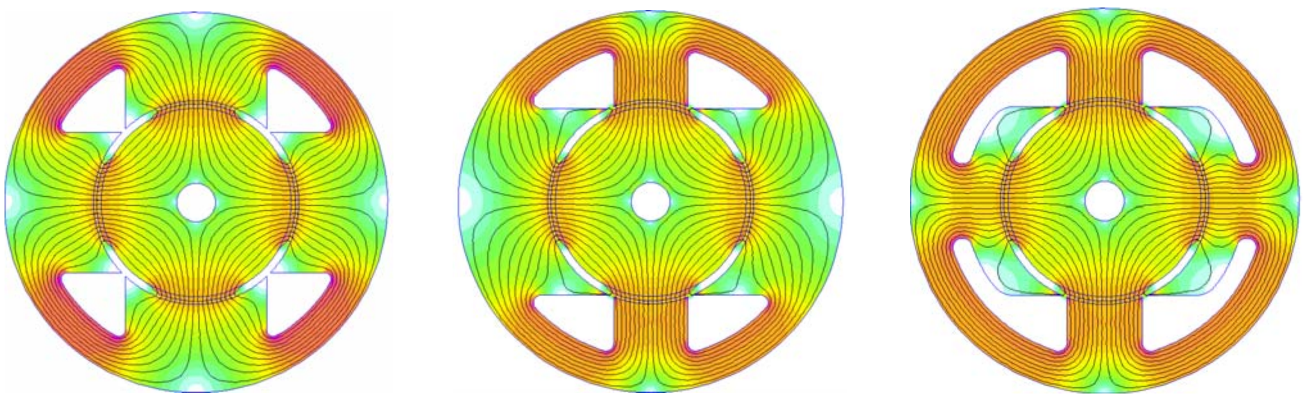
Fig. 3. Shaping the stator poles of BLDCPM motor – M3

In summary, the new motor model is novel because: • there are two pole pairs with different arc lengths – small and large; • the large stator pole arcs are 3 times the length of the small arcs; • the rotor magnets have the same arc length as the small stator pole arcs; • the large stator pole is designed with a pole shoe, thus creating more winding space; • these features when combined have been shown to reduce the cogging torque, while maintaining almost the ideal rectangular shape of the back EMF.

FEM Results

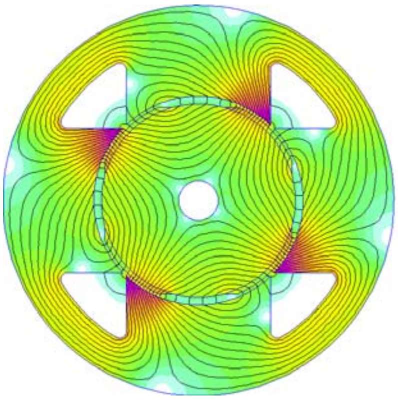
The 2D FEM was employed for electromagnetic field analysis of the three BLDCPM motor models. The nonlinear field solutions are obtained by running the FEM solver for every degree of rotor displacement. Graphical presentation and visualization of the FEM results show the magnetic flux distribution in the cross-section of the BLDCPM motor.

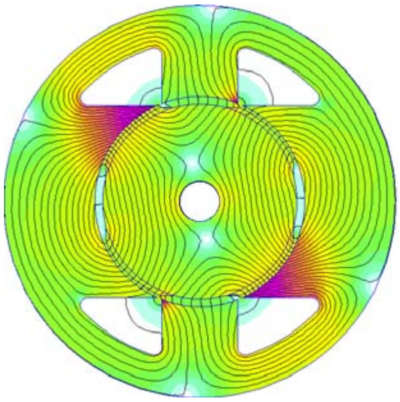
First, the referential stator and rotor axes are arbitrary selected. The rotor rotation is selected to be clockwise. The computations start with no-load, i.e. at zero current in the stator windings; in this regime, the magnetic field in the motor is obtained by the permanent magnets only. To show the effects of the stator current on the magnetic field distribution, the motor windings are excited with rated current. The following figures have been chosen to highlight interesting features from the results of the field calculations. The field distribution at no-load and 0^0 rotor position, as well as at rated current and 45^0 rotor position, are presented in Fig. 4 and Fig. 5, respectively. Derived models M1, M2 and M3 are presented successively as (a), (b) and (c). In order to compare the flux patterns and the magnetic flux density *B* distribution, the same scale has been selected; thus, in all these figures B_{max} is set to 1.5T, while the number of flux lines over the cross-section is selected to be 19 and 23.



(a) Model M1 (b) Model M2 (c) Model M3

Fig. 4. Field distribution in unexcited BLDCPM motor and 0^0 rotor position in the derived models M1, M2 and M3


(a) Model M1


(b) Model M2

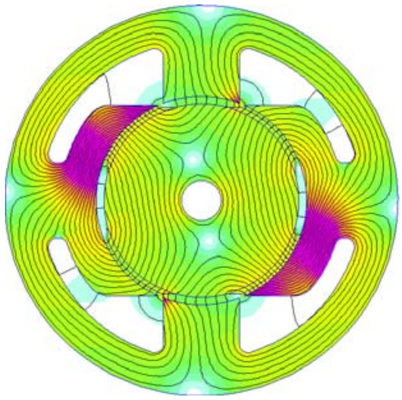
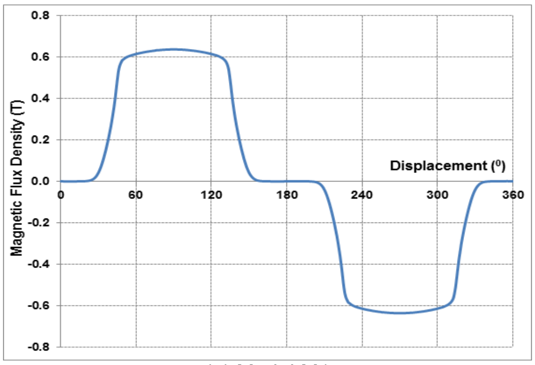

(c) Model M3

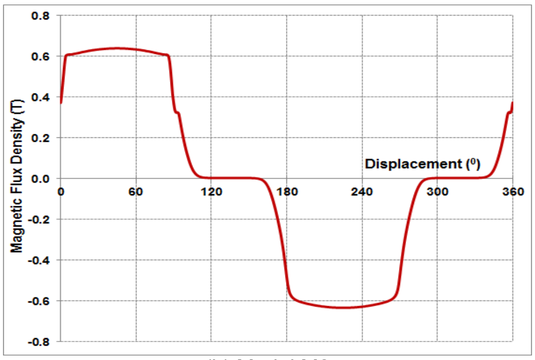
Fig. 5. Field distribution at rated current and 45^0 rotor position in the derived models of BLDCPM motor M1, M2 and M3

Air-gap Flux Density Profile

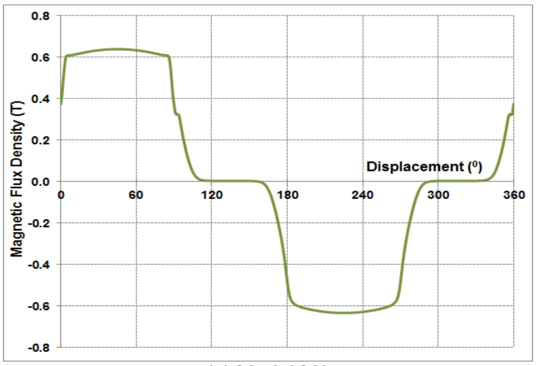
The FEM postprocessor enables presentation of spatial distribution of the magnetic flux density *B* at any arbitrary selected line. The results along the circumference of the mid-gap line at no-load for the same field calculations related to Fig. 4, are presented in Fig. 6.



(a) Model M1



(b) Model M2



(c) Model M3

Fig. 6. Spatial distribution of the magnetic flux density along the mid-gap circumference line, in all motor models at no-load

Analysing the magnetic field distribution in the derived models, presented in Fig. 4 and Fig. 5, and comparing the air-gap flux density profile of the new developments M2 and M3, one can easy notice the advantages of M3, because an important save of the iron, without significant magnetic field saturation, has been achieved. Fig. 6 (a) shows that M1 at alignment position is with zero flux, meaning that no starting torque is produced. On the other side, both M2 (b) and M3 (c) develop alignment torque. Taking into account that there is no difference in the spatial distribution of the magnetic flux density, due to the advantages of pole shaping in the model M3, it has been selected as the best one.

Cogging Torque

The cogging torque is generated by the tendency of the rotor magnets to align with the stator at positions where the reluctance of the magnetic circuit is minimised. In this study, the cogging torque of the BLDCPM motor is solved in the FEM post processor using an additional Laplace equation, and computing the *weighting function*. The stress tensor is then calculated by volume integration, and the results are displayed. For the generic model M1 the dependence of the cogging torque on the rotor position is presented in Fig. 7.

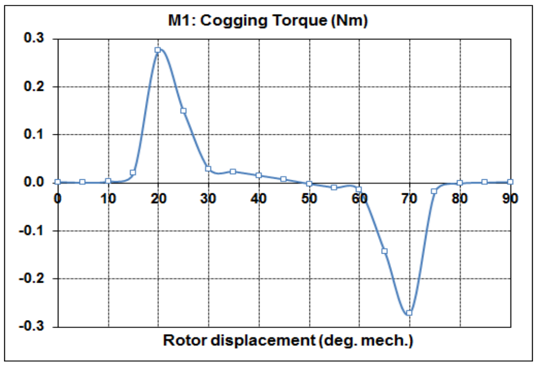


Fig. 7. Cogging torque of the generic model of BLDCPM motor–M1

Analyses of the cogging torque profile of the generic model M1 show rather big peak-value, and the need for the reduction is evident. The most effective solutions for the cogging torque reduction are adjustment of the magnet arc width relative to the stator geometry, as well as skewing. Other methods which have been proposed for reducing the cogging torque include the design issues. In the research, reduction of the cogging torque is formulated and solved as design problem, described before. The first derived model M2 shows significant improvement of the cogging torque, which is smaller for 10 times, as presented in Fig. 8. The cogging torque in the model M3, where stator poles are with ratio 1:3, but additionally shaped, is shown in Fig. 9.

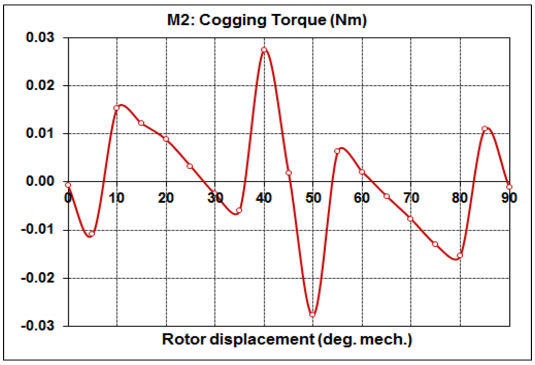


Fig. 8. Cogging torque of the model M2 – pole ratio 1:3

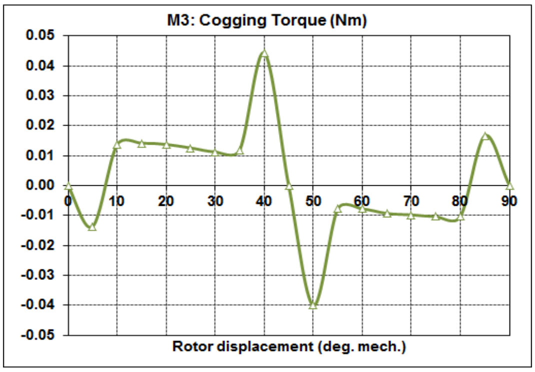


Fig. 9. Cogging torque of M3 – pole ratio 1:3 and shaped poles

Solution Analysis

From the brief analysis of the previous figures, a substantial improvement of the peak cogging torque in the model M2 is evident. However, the ripple is four times more frequent, which is not a negligible fact. In the model M3, compared to M2, the peak torque is obviously higher, but the ripple is twice smaller; also, it is still significantly lower than in the generic model M1. Hence, the stator pole shape of the model M3 is accepted to be the best. An investigative analysis of the characteristics of the BLDCPM motor model M3 is presented in continuation.

The postprocessor of the FEM package offers simple calculations of the most important electromagnetic and electromechanical quantities. First, the characteristic of the magnetic flux generated by permanent magnets is derived. For the proposed design solution M3 of the BLDCPM motor, it is shown in Fig. 10.

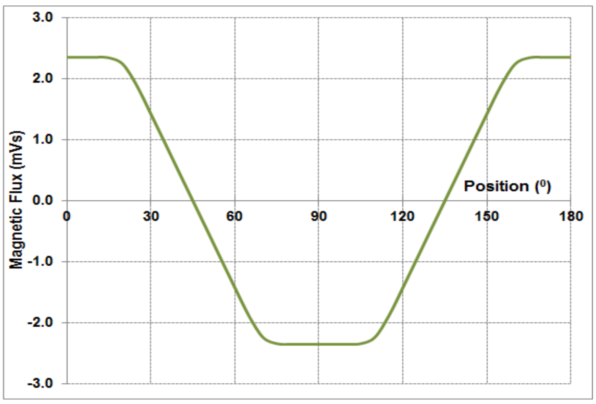


Fig. 10. Magnetic flux per pole of the model M3

As the rotor rotates, the permanent magnet flux ϕ linking N stator windings varies, and an electromotive force e is induced; the frequency of the emf e depends on the rotor speed, while the shape is determined by the waveform of the flux linkage that is coupled with the stator windings. The back EMF in the stator winding of the BLDCPM motor can be determined from the following expression [2]:

$$e = \frac{d\psi}{dt} = \frac{d\theta}{dt} \cdot \frac{d\psi}{d\theta} = \omega \cdot \frac{d\psi}{d\theta} \quad (1)$$

where: e is back EMF in (V), $\omega = d\theta/dt$ is the angular speed in (rad/s), while $\psi = N \cdot \phi$ is the flux linkage of stator windings with N turns per pole.

The back-emf waveform, at a rotor speed of 1500 rpm, is presented in Fig. 11. While the magnetic flux profile of stator windings is with almost trapezoidal shape, the back-emf profile is reasonably close to a rectangular one.

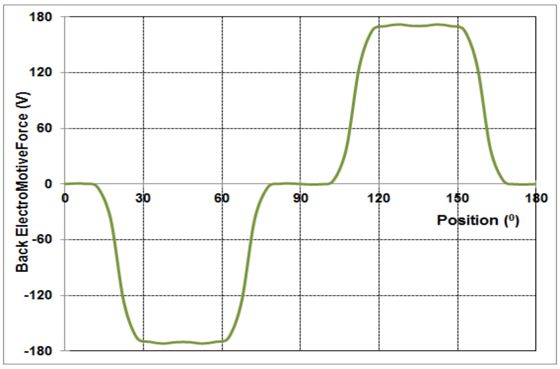


Fig. 11. Back-EMF profile of the motor model M3

Conclusion

The analyses presented in this work show that cogging torque can be effectively reduced by employing pole arc ratio of 1:3 and an asymmetrical stator pole topology; at the same time a good starting torque has been achieved. A significant saving of iron, when shaping stator poles as proposed, is not deteriorated with core saturation, the fact that is very important for the smooth control of the motor.

The notable features of the motor model M3 are cogging torque decreased for almost 7 times compared to generic model M1 and back EMF close to rectangular shape. The next foreseen task is to perform the dynamic analysis of the BLDCPM motor and to consider its dynamic behaviour. Additionally, further optimisation of the geometrical motor design might be necessary in order to achieve the desired dynamic characteristics.

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