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Magnetic Field Analysis of Halbach Permanent Magnetic Synchronous Machine

Bouloukza Ibtissam, Mordjaoui Mourad, Medoued Ammar & Guerboussa Fouzi
Department of Electrical Engineering, University of 20 August 1955 –Skikda, Skikda, Algeria
Boulekza_ibtm@yahoo.fr; Mordjaoui_mourad@yahoo.fr; amedoud@yahoo.fr

Abstract— **A numerical study of PMSM based on finite element method for estimating the airgap magnetic field distribution considering stator slots effect is presented both for traditional radial magnet structure and Halbach magnet array topology. Magnetic field, flux, torque and the induction in the air gap are presented. The two machines structures performances were compared which put in view the modifications brought by these structures.. According to numerical calculations, and harmonic analysis, the PMSM with Halbach magnet array provides a higher torque and better performance than the classical radial PMSM.**

Index Terms— **Halbach array configuration; permanent magnet synchronous machine; FEM analysis; magnetic induction; magnetic flux density.**

Introduction

During the last decade, the demand for more compact and more effective electric machinery drew all attention of the industrialists and the researchers towards the permanent magnet machines. However, the conventional machines are replaced more and more by the synchronous permanent magnet machines with special structures which offer several features that make it attractive for use in electric drive systems. In fact, the synchronous permanent magnet machines (PMSM) are recommended in the industrial world. This is due to the increased power density, higher efficiency, excellent acoustic performance when compared to DC and induction motors, better dynamic performance and a higher torque per volume values. Thus, their construction is simpler since: they do not have mechanical switches; consequently this increases their life time and avoids a permanent maintenance. However, high-performance bonded NdFeB magnets are capable to provide strong-enough fields.

The analysis of the electrical machines is conditional to power source and the circuit where they are connected. As a result, we can classify them into two main groups, those with trapezoidal back-emf (brushless DC motors) [1] and those with a sinusoidal back-emf (permanent magnet synchronous machines) [2-8]. However the choice of one both machines is based on technico-economic criteria. Indeed, the BDCM is advantageous by the simplicity of its command which just requires a position sensor while the PMSM requires a resolver or encoder attached to the shaft of the machine whose cost can be higher than the machine itself. In return, in spite of the economic advantages of the BDCM, the PMSM is better indicated in the precision trainings.

Several structures of rotor of synchronous permanent magnet machines are possible. This diversity depends on the magnets shape and theirs arrangement in the rotor. Most permanent magnetic machines utilize permanents magnets which are mounted on the rotor surface [4-6], surface-inset magnet [7-8], interior magnet, and buried magnet.

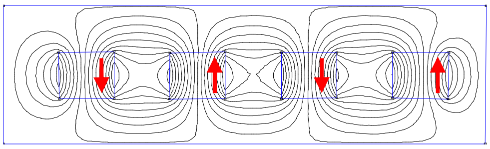
The air-gap magnetic field is rather trapezoidal then sinusoidal and, as consequence, significant high order harmonics with negative effects inhabit the air-gap magnetic field spectrum. A Halbach array is a special arrangement of permanent magnets that augments the magnetic field on one side of the array while cancelling the field to near zero on the other side (capable to inherently ensure a sinusoidal wave) [9]. Although the effect was discovered by John C. Mallinson in 1973, with "one-sided flux" were initially described by him as a "curiosity"[10]. Indeed, such authors have been applied in various magnet systems from industrial applications as: magnetic bearings [11] and a brushless ac motor [12], a nuclear magnetic resonance (NMR) device [13], and a magnetically levitating (maglev) system [14]. The preferred method for analyzing the Halbach arrays effects has been the analytical method [6, 8, 15], which will be refined by numerical simulation such as the finite-element (FEM) method [4, 16-18].

In this paper, a comparison between a regular PM motor and a Halbach array topology is presented. The study consists in a FEM based analysis, which put in view the difference of certain magnetic parameters as field, flux densities, induction, high order harmonics and torque.

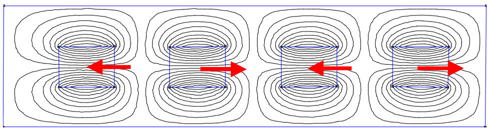
Theory Foundations

The concept of the Halbach array is first presented by the physicist Klaus Halbach of Livermore national laboratory in California. In the 1980's, it was successfully used in the new particle accelerator, synchrotron radiation device, etc. In recent years, the application of Halbach array in the high performance motor becomes more and more concerned, In the traditional design, the arrangement of the PMs is to be radial direction or azimuth direction. The Halbach array of the PMs is the combination of the radial and azimuth PM array, the result of this combination is that the magnetic flux density in one side of the PMs is weakened and the magnetic flux density in the other side is strengthened.

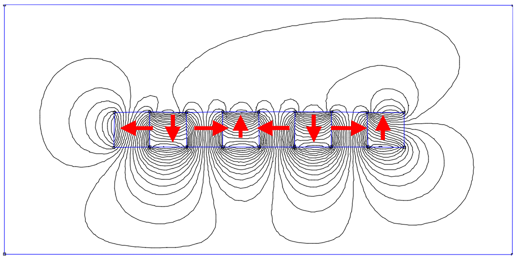
We can arrive at flux distribution by the addition of the flux distributions of the radial and azimuth structures, shown in figures 4.3 and 4.4. A final diagram of the flux of with eight segments Halbach magnets is shown in figure 4.5, illustrating that the diagrams simplified of flux corresponds enough to reality. There are some lines of flux seen at the top of the magnetic structure but they are very small compared with the number of the lines of flux at the base of the magnetic structure.



a. Radial structure;



b. Azimuth structural;



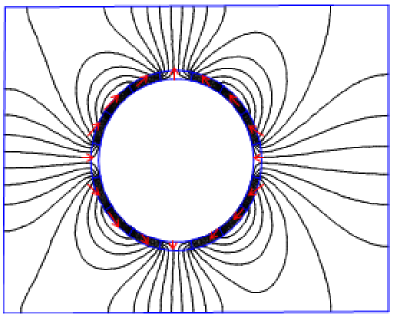
c. Halbach array.

Fig.1. Comparison of classical and Halbach array

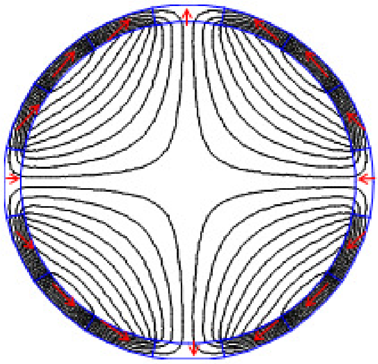
In the flux distribution of this structure, we can make the following observations:

- There is almost no flux in the upper part of the magnets, which implies that the iron of return is not necessary for this ideal structure of Halbach.
- The flux is more concentrated than that of the radial magnetic structure, and can be concentrated in import direction depending on the magnetizing of magnets and of number of the segments that pole can produce.
- The flux is at below (internal) or at the top (external) dependent on the orientation of the segments of Halbach magnet.

The Halbach structure corresponding to the case 3 is shown in the fig 2. There is very rare flux lines in inside/outside magnets and all the flux lines are concentrated respectively in inside (fig2.a) and external (fig 2.b) of rotor.



Flux lines distribution in inside Halbach magnets



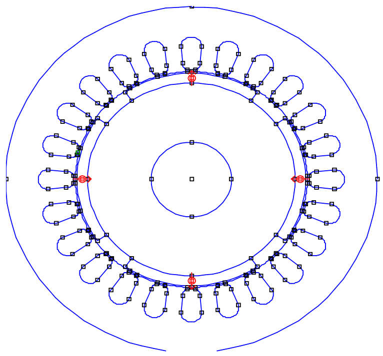
Flux lines distribution in outside Halbach magnets.

Fig.2. Comparison of inside/outside Halbach magnets

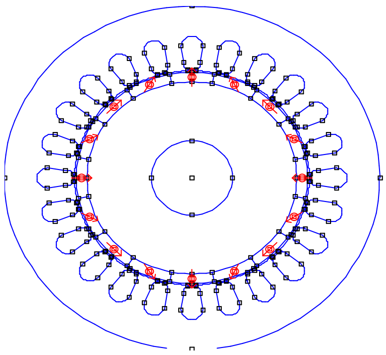
FINITE ELEMENT ANALYSIS AND RESULTS

In the last years the calculation by FEM is widely developed to the big improvement in the informatics domain. The study presented in this paper is signally a simulation one based on FEM, which is one of the most numerical methods used for the calculation of the magnetic field in the electric machines. In this study finite element FEMM free software is used for analysis of the PMSM. Since the presented study has a comparative character, between PM synchronous motor, and its counterparts with Halbach array configuration.

The regular three-phase PM machine has 4 poles and rare-earth permanent magnets, sintered NdFeB – HS-38AV type. Both rotor and stator are iron cored structures. Two different magnetization patterns (radial and Halbach) have been considered and their results compared with each other. For the Halbach array configuration, the magnets are segmented into 16 segments. As it can be observed, the number of magnet segments in the Halbach array configuration is not equal to the number of magnetic poles of the machine. This number depends on the magnetization pattern, which has to ensure the wished number of magnetic poles and an air-gap field wave as sinusoidal as possible.

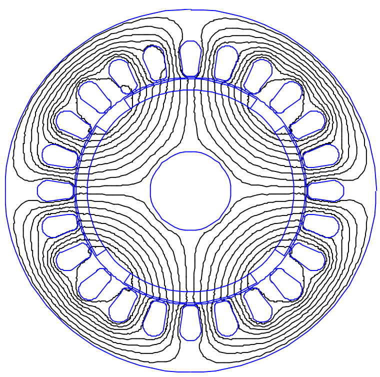


Radial magnetization (4 PMs)

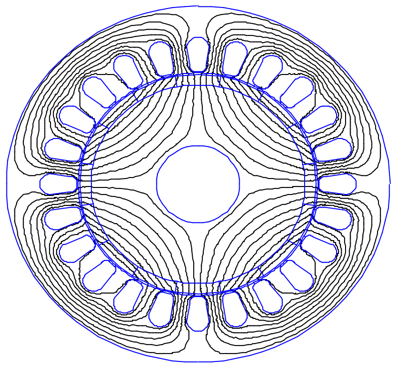


Halbach array with 90°-45° magnetization (16 PMs)

Fig.3. PM Configuration (4 global magnetic poles):



radial structure



Halbach structures

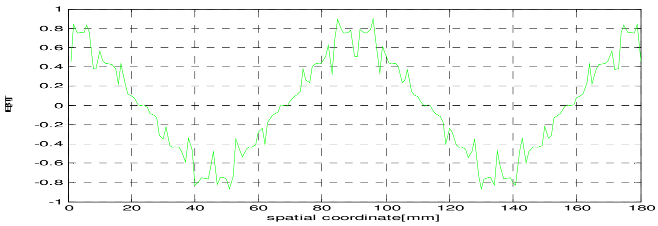
Fig.4. Flux lines distribution

Figure 4 show the flux lines distribution in both machines in the same condition for two magnetization patterns (Halbach, and radial). In the first the flux lines always pass in magnets while in the second case the field is worthless in certain magnets

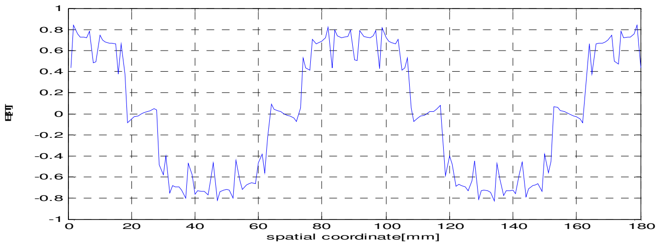
Figure 5 presents, air-gap magnetic induction curve and content in high order harmonics for two periods electric in the case of radial/Halbach structure. We observe that the air-gap induction amplitude is slightly reduced for Halbach configuration with same period. In fact, the magnetic induction shape of the regular PM machine is trapezoidal (Fig. 5.a) with a rich content in high order harmonics (the greatest is the third, ninth and the seventh are very important). Were the fundamental harmonic has a normalized amplitude by 70 for standard PM machine and 62 for Halbach configuration. It is interesting to notice and to state as well that lower harmonics amplitude are in Halbach configuration which generate a more sinusoidal air-gap magnetic induction curve. This leads to predict that the better qualities of the magnetic induction will be requires a higher number of magnet segments per pole.

A second interesting presents the flux density map distribution in two configuration machine (Fig.7). The maximal values of the flux density are for the magnet segments 1.61 T, and 1.33 for radial structure. There is a much lower loading of the rotor magnetic circuit in the Halbach topology. None the less that the rotor has a ferromagnetic core, an important amount of the flux lines tracks the permanent magnets Of high importance in the evaluation of the PM system of a synchronous machine is the shape of the phase flux density for both machine studies on 360° mechanic. The results are presented in Fig. 8. It is again obvious that the amplitude of the flux density of segmented PM machine is lower than standard machine (9.74×10^{-6} [Wb] against 1.16×10^{-5} [Wb]).

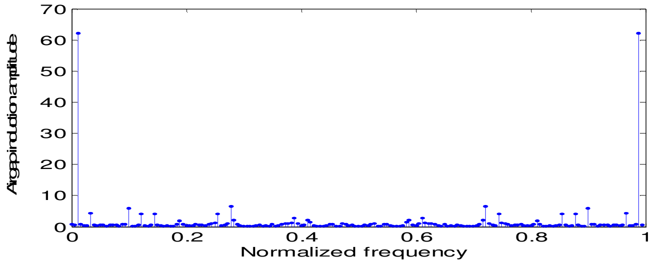
For the both structures, another study is evaluated by comparison of the torque variation in accordance with the change of rotor position, where the period is 15° mechanic corresponding *to* step winding as explained in Fig. 9.



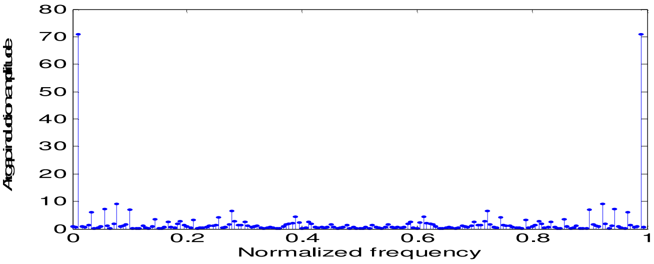
Halbach structure



Radial Structure



Halbach Structure



Radial Structure

Fig. 5. Air-gap magnetic induction curve and High order harmonics content.

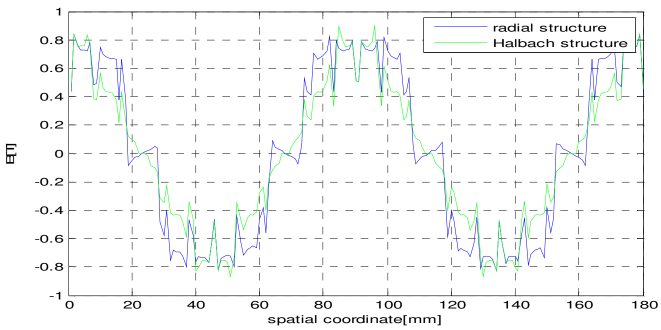
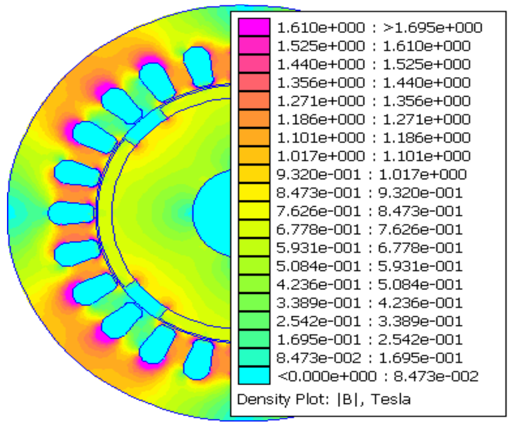
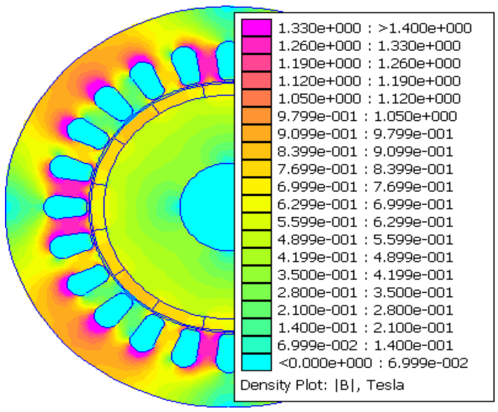


Fig.6. Comparison of magnetic induction curve for radial and Halbach structure

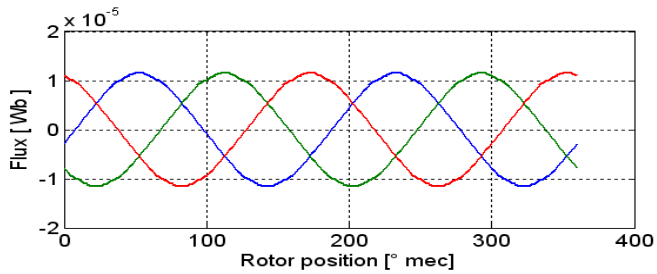


Radial structure

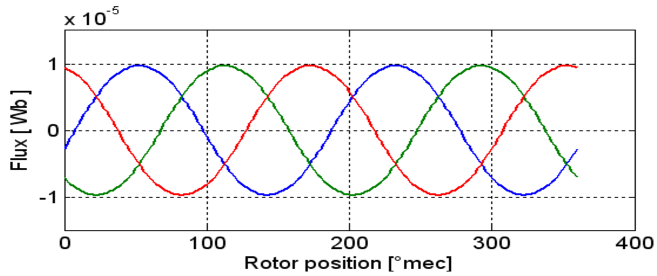


Halbach structure

Fig. 7. Flux density color map

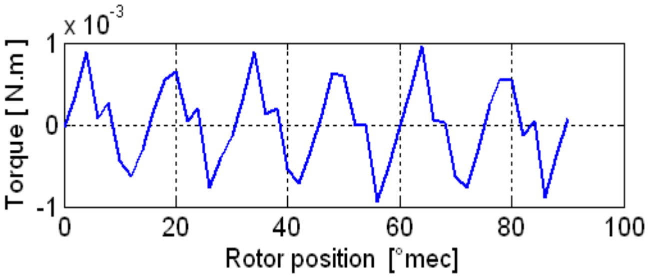


Radial Structure

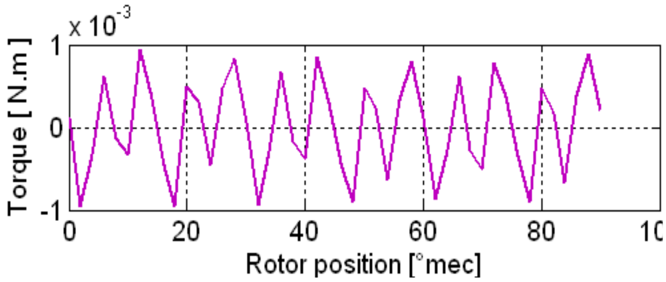


Halbach Structure

Fig.8. Variation of airgap flux for radial and Halbach structure



Radial structure



Halbach structure

Fig.9. Torque variation for rotor position of two PM machines

CONCLUSION

In this paper, a FEM analysis for reduction a high order harmonics in permanent magnet synchronous is presented. Two machines are compared with two magnetization patterns (radial/Halbach) for certain magnetic parameters (induction; flux density; torque in the air-gap). As results, the air-gap magnetic field can be brought to a quasi sinusoidal shape by means of a carefully magnetization of the segments. As consequence the high order harmonics are limited in Halbach array configuration.

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