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Comparative Analysis of Magnetic Field in Surface Permanent Magnet Motor at Various Types of Rotor Magnetization

***Abstract**. In this paper the influence of magnetization pattern on the magnetic field features and characteristics in a surface mounted permanent magnet motor is analysed. A comparative analysis of performance characteristics for a conventional surface PM motor with Halbach array topologies is presented. The study is based on FEM field computations that enable ″the visibility″ of the magnetic properties and characteristics. The emphasis is put on electromagnetic field distribution, magnetic flux per pole profile and components of the flux density in the air gap.*

***Streszczenie.** W artykule przeprowadzono analizę wpływu sposobu magnetyzacji na właściwości pola magnetycznego I charakterystyki w silniku z powierzchniowym magnesem trwałym. Przedstawiona została analiza porównawcza charakterystyki działania dla konwencjonalnego silnika z powierzchniowym magnesem trwałym w układzie Halbacha. Badania zostały oparte na metodzie elementów skończonych, która umożliwia „widzenie" właściwości magnetycznych i charakterystyk. Nacisk położono na rozkład pola elektromagnetycznego, strumień magnetyczny w profilu i składowe indukcji magnetycznej w szczelinie powietrznej. (**Analiza porównawcza pola magnetycznego przy różnych typach magnetyzacji wirnika w silniku z powierzchniowym magnesem trwałym**).*

Keywords: rotor magnetization patterns, Halbach array, surface permanent magnet motor
Słowa kluczowe: sposoby magnesowania wirnika, układ Halbacha, silnik z powierzchniowym magnesem trwałym.

Introduction

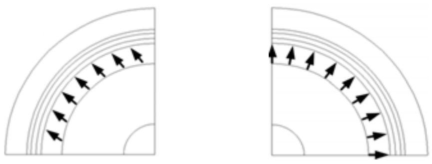
The demand for more compact and more effective electric machines attracted the attention of researchers and manufacturers towards permanent magnet machines. This is due to increased power density, higher efficiency, better dynamic performance and higher torque per volume. There is an evident tendency the conventional motors to be replaced by their permanent magnet counterparts with special structures that offer new features, making them more attractive for use in electric drive systems.

Several rotor topologies of permanent magnet machines are possible. This variety depends on magnet shape and their layout in the rotor. Most PM motors use permanent magnets which are mounted on the rotor surface, but they can be also inset magnets, interior magnets or buried magnets. The effect of magnetization patterns on machine performance can be significant, i.e. the rotor magnetization has an important influence on the motor characteristics.

In the paper we analyse how the magnetization pattern affects the magnetic field distribution and magnetic characteristics of Surface Permanent Magnet (SPM) motors. The FEM field computations are used as numerical tool of analysis. Accurate results can be obtained by including the precise magnetization direction in the FE simulations. The presented study has a comparative character, between conventional surface PM synchronous motor, and its counterparts designed with Halbach magnet array configurations.

Conventional Rotor Magnetization

In conventional surface permanent magnet (SPM) motors, magnet pole parts can be magnetized with constant direction – *parallel magnetization*, or with slightly different magnetization depending on their position within the pole arc, where the direction is directly pointed across the air gap – *radial magnetization*, as presented in Fig. 1 (a) and (b), respectively.



(a) parallel (b) radial

Fig. 1. Conventional magnetization of permanent magnets

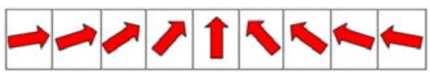
Halbach Array

Halbach magnetized permanent magnet machines are novel and they offer many attractive features. It is known that electric motors with Halbach PM arrays hold several attractive features, as: almost sinusoidal airgap field distribution and back-emf waveform, strong field intensity, potentially high airgap flux density and low cogging torque. Hence, SPM motors with Halbach magnetization patterns have recently attracted much research and development interest, resulting in an extensive investigation for their applications [1-6].

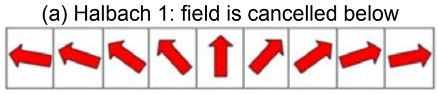
All it started back to the year 1973 when the effect of ″one-sided flux″ has been discovered and published [7] by J. C. Mallinson. However, the idea of such self-shielding property did not immediately gain widespread acceptance because of the difficulty in realization. Few years after, K. Halbach in 1980 reported a novel PM configuration [8], which later has been denoted by his name.

The ideal Halbach array has pure sinus magnetic profile, but it is impractical to fabricate. Instead, an array of rectangular or square permanent magnets (PM) segments is actually used. These non-ideal Halbach arrays do not provide the zero magnetic field on the cancelled side and the purely sinusoidal magnetic field on the enhanced side, but they still provide better performance characteristics than conventional magnetization of magnets – parallel or radial.

An approximated continuously varying magnetization array is achieved by using a number of segmented magnets with varied magnetization angles; such novel construction of a permanent magnet is named *Halbach array* hereafter. Basically, the topology has magnet segments with distinct magnetization direction, as presented in Fig. 2. (a) when magnetic flux is cancelled below the magnets – *Halbach 1*, and Fig. 2. (b) for the magnetic field cancelled above the permanent magnets – *Halbach 2*.



(a) Halbach 1: field is cancelled below



(b) Halbach 2: field is cancelled above

Fig. 2. Halbach magnetization arrays

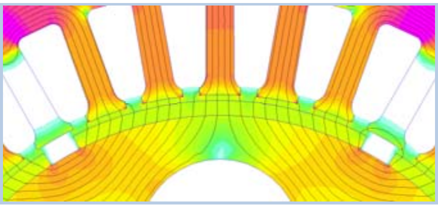
SPM Configuration

The use of Halbach array configuration in manufacture of SPM motors represents a relatively new solution, which has the main intention to improve their magnetic circuit features. The FEM-based analyses put in view the modifications brought by these structures on the magnetic parameters, as magnetic field distribution, magnetic flux and flux density.

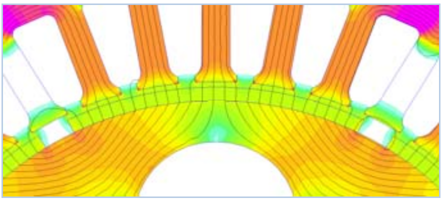
The analysis model is a surface permanent magnet (SPM) motor, 18 A rated current, 0–10 Nm torque control, and 0–4000 rpm speed control. The stator lamination is with 36 slots, where 3 single-layer phase windings are placed. Both rotor and stator are iron cored structures. There are 6 surface mounted segmented SmCo5 magnets on the rotor. The pole arc is spanned over 54^0 with 9 segments arranged in radial direction and 15 layers in axial direction. This segmented PM structure is convenient to investigate how various magnetization patterns, *parallel*, *radial*, *Halbach1* and *Halbach2*, as presented in Fig. 1 and Fig. 2, influence the magnetic field distribution and electromagnetic performance characteristics of the SPM motor.

FEA Results

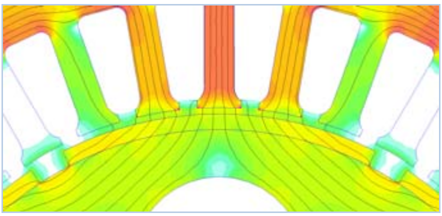
The two-dimensional Finite Element Analysis (FEA) is used for prediction performance characteristics of the studied SPM motor [9]. The mesh of finite elements has more than 123,000 nodes and 245,000 elements. The calculations start with no-load, i.e. without current in the armature windings, when the magnetic field is produced only by the permanent magnets. A part of magnetic flux distribution, spanned to an N-pole for the four magnetization patterns which are analysed, is shown in Fig. 3 (a) – (d).



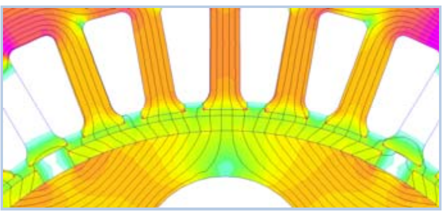
(a) parallel magnetization



(b) radial magnetization



(c) Halbach array 1



(d) Halbach array 2

Fig. 3. Magnetic field at no-load for various types of magnetization

The study presented in this paper is mainly a simulation one. Usually, there are different FEM ways that can be employed in numerical simulations and they depend on the state of the analysed system, i.e. steady state or transient operation. We intend to focus on the properties of the magnetic field created by permanent magnets; hence the magnetostatic analysis is relevant. It has to be pointed out that this FEM approach catches a given moment of the motor operation; thus, rotation, speed or voltage/current variations are not considered.

Magnetic flux per pole and its shape is an important parameter that determines the performance of the surface permanent magnet motor. Since the presented research has a comparative character, it is developed into three levels. It is started with a conventional SPM synchronous motor with segmented permanent magnets. Two types of magnetization patterns are considered: parallel and radial. Afterwards, their counterparts with two Halbach array configurations are studied: Halbach 1 and Halbach 2, as have been shown in Fig. 2 (a) and (b), respectively.

From the FEM field calculations, for conventional magnetizing of the permanent magnets, the characteristic $\Phi_p=f(\theta)$ at no-load is determined and presented in Fig. 4.

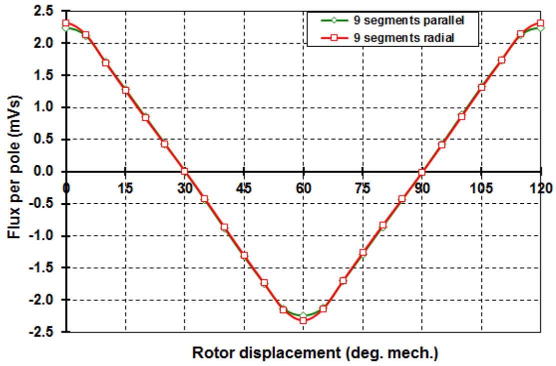


Fig. 4 Flux characteristics for conventional magnetization at no-load

From the above figure it is evident that there is no significant difference between the motor characteristics at parallel and radial conventional magnetization of the permanent magnets. As an example can serve the maximum value of magnetic flux per pole, which is for parallel 2.24 mVs, while for radial magnetization it is 2.31 mVs, i.e. ~3% difference; at the same time, the profiles of their characteristics $\Phi_p=f(\theta)$ are identical. In continuation only radial, as more common, and two Halbach magnetization arrays will be analysed. Thence, in Fig. 5 are shown comparative characteristics of the magnetic flux per pole $\Phi_p=f(\theta)$ at no-load.

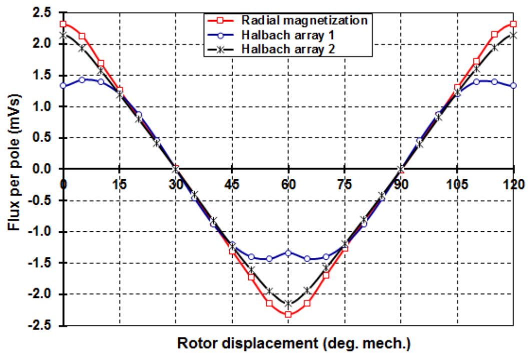


Fig. 5. Comparative characteristics of the magnetic flux per pole $\Phi_p=f(\theta)$ at no-load

The distribution of the normal component for the air-gap magnetic flux density at no-load is presented in Fig. 6, while the tangential component is given in Fig. 7.

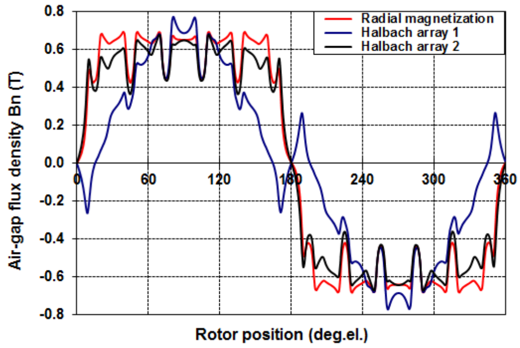


Fig. 6. Comparative characteristics of the normal component distribution for the air-gap magnetic flux density at no-load

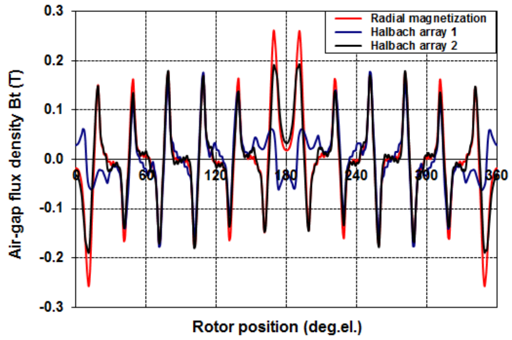


Fig. 7. Comparative characteristics of the tangential component distribution for the air-gap magnetic flux density at no-load

The FEM computations continue at rated current I_n=18A. The performance characteristics of the analysed surface permanent magnet motor, when Halbach1 and Halbach 2 magnetization patterns are employed, are compared with those that are obtained when the magnetic field is induced with conventional radially magnetized magnet segments. In Fig. 8 are presented comparative characteristics of the magnetic flux per pole $\Phi_p=f(\theta)$ at rated current.

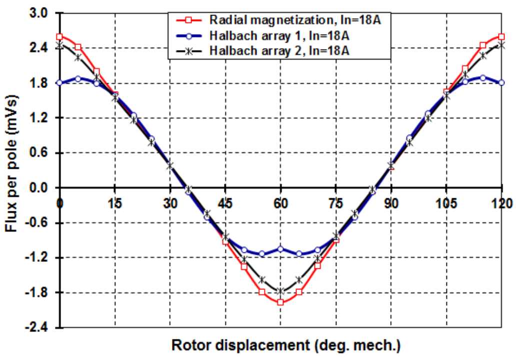
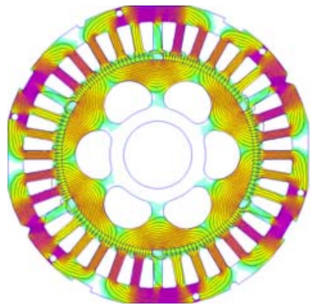


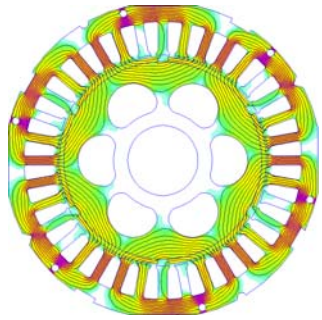
Fig. 8. Flux characteristics $\Phi_p=f(\theta)$ at rated load I_n=18 A

In Fig. 9 (a), (b) and (c) are presented the magnetic flux density colour maps and flux lines at rated current I_n = 18 A, when the rotor position is θ = 30^0 mech. = 90^0 el., for the analysed types of magnetization: radial, Halbach 1 array and Halbach 2 array, respectively.

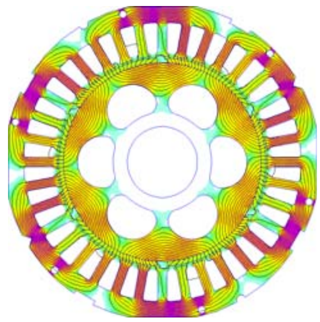
In order to get comparable views, for all figures the maximum value of the flux density is set on 1.7 T, while the number of flux lines is proportional to the respective value for the magnetic vector potential A_{max} (V/s). A selection of more interesting results, obtained from FEM calculations, is presented in Table 1.



(a) radial magnetization; 27 lines



(b) Halbach 1 array; 19 lines



(c) Halbach 2 array; 25 lines

Fig. 9. Magnetic field plots at rated load I_n=18 A and for rotor position θ=90^0 el.

Table 1 Magnetic field properties of SPM motor at various magnetization patterns

Description	Unit	No-load I = 0; θ = 0^0			Rated load I_n = 18 A; θ = 0^0		
		Radial	Halbach1	Halbach2	Radial	Halbach1	Halbach2
Magnetic vector potential A_{max}	V/s	0.01334	0.00854	0.01264	0.01496	0.01103	0.01453
Magnetic flux per pole Φ_p	mVs	2.31405	1.33240	2.14514	2.59865	1.80858	2.45885
Magnetic flux density B_m	T	0.55052	0.34437	0.51033	0.61823	0.43027	0.58497

Magnetic field distributions in Fig. 9 show less saturation of the stator magnetic core, when Halbach 1 and Halbach 2 patterns are used for magnetization of permanent magnets. Consequently, the iron loss is lower and it is possible to increase the armature winding currents, thus enhancing the electromagnetic characteristics, which in turn will give the advantage to the surface permanent magnet motors with this type of magnetization.

From the review of the magnetic field properties at studied magnetization patterns, one can conclude that values of the magnetic characteristics, for the radial magnetization and Halbach 2 configuration, exhibit similar features. In addition, the presented charts for the electromagnetic characteristics in the previous figures show the same shape for radial and Halbach 2 magnetization, while Halbach 1 array exhibits somehow weird behaviour. It is due to the fact that Halbach 2 array cancels magnetic flux above the permanent magnets, i.e. strengthens the magnetic field in the rotor, and enhances the coupling between the rotor and stator magnetic field.

On the other hand, Halbach 1 array magnetization, cancelling the magnetic flux below the permanent magnets, leads to a weakened magnetic field and consequently, less saturated machine with not enough effective use of the active materials. Also, PMs with Halbach 1 array generate lower magnetic field strength, thus giving the advantage to Halbach array 2.

Conclusions

In the present paper the influence of magnetization patterns on the performance of surface permanent magnet motor has been analysed. The 2D magnetostatic FEM computational results are used as powerful numerical tool for performance analyses, enabling ″the visibility″ of the magnetic characteristics features.

At the beginning, four different magnetization types have been considered: two conventional patterns – parallel and radial, and two recently developed configurations – Halbach 1 array and Halbach 2 array. The particular emphasis has been put on electromagnetic characteristics, such as electromagnetic field distribution in the motor, magnetic flux per pole and components of the flux density in the air gap.

It is worth to emphasise, that due to less saturation of the magnetic core and lower iron loss at Halbach 1 and Halbach 2 magnetization array, it is possible to increase the armature current and consequently to increase the electromagnetic field strength, which in turn will give the advantage to the SPM motor with Halbach arrays magnetization. This fact is interesting for further analyses.

The next task will be to analyse the induced back-EMF waveforms at different magnetization patterns of permanent magnets. An analysis of the losses in permanent magnets, as well as overall losses and efficiency of the SPM motor, by using the time-stepping method could also be of interest. This work could serve as a good guide.

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