Study of the performance characteristics of a surface permanent magnet motor at various magnetization patterns

Lidija Petkovska and Goga Vladimir Cvetkovski
Faculty of Electrical Engineering and IT, Ss. Cyril and Methodius University, Skopje, Macedonia (FYROM), and
Paul Lefley
Department of Engineering, University of Leicester, Leicester, UK

Abstract

Purpose – In this paper the influence of the magnetization patterns of rotor magnets on the performance characteristics of a surface permanent magnet (SPM) motor has been investigated and presented. The purpose of this paper is to show how the electromagnetic and electromechanical characteristics of this type of motor can be significantly changed by applying various magnetization patterns of permanent magnets (PM) on the rotor surface.

Design/methodology/approach – First, a survey of possible and most frequently used magnetization patterns for PM motors is presented. The research was focused on the comparison of performance characteristics and was developed at three levels. The study started with the investigation of a conventional SPM motor having segmented PMs, and two magnetization patterns were considered: parallel and radial. As there was no significant difference in motor performance between parallel and radial magnetization, further investigations used radial only magnetization, being more conventional, was considered. In the second step, the counterparts of SPM with two new Halbach array magnet configurations, under the constraint of fixed magnet volume, were studied. Finally, detailed comparative analyses of the SPM for radial, Halbach 1, and Halbach 2 magnetization patterns are presented. The advantages and drawbacks of the suggested magnetic configurations are then discussed.

Findings – The authors have shown how the magnetization pattern of rotor PMs can have a substantial impact on the SPM motor performance characteristics. From the analysis of magnetic field properties for various types of magnetization, it is observed that both the shape and the characteristics, for radial magnetization and the Halbach 2 configuration, exhibit similar features. This is because the Halbach 2 array spreads the magnetic flux above the PMs – that is, it strengthens the magnetic field in the rotor, and enhances the coupling between the rotor and stator magnetic field. It is worth emphasizing that, because of less saturation of the magnetic core and lower iron loss with Halbach 1 and Halbach 2 magnetization, it is possible to increase the ampere-turns and consequently increase the electromagnetic torque. Also, being able to replace expensive rare-earth magnets with lower cost varieties is an important area for further research.

Originality/value – The paper presents an original comparative analysis of the performance characteristics of a surface permanent magnet motor for various magnetization patterns. The novelty of the paper is seen in the introduction of two new variations of Halbach magnetization arrays for the PMs, and improvement in the performance characteristics of SPM motors.

Keywords Surface permanent magnet (SPM) motor, Electromagnetic characteristics, Electromechanical characteristics, Halbach magnetization array, Magnetization pattern

Paper type Research paper.

Introduction

The demand for more compact and more effective electrical machines has attracted the attention of researchers and manufacturers towards permanent magnet machines. There is a tendency for conventional motors to be replaced by their permanent magnet counterparts with special structures that offer new features, making them more attractive for use in electrical drive systems. In fact, permanent magnet motors (PMMs) are being recommended increasingly for industrial applications, mainly because of the increased power density, higher efficiency, better dynamic performance, and higher values of torque per unit volume. Owing to their simpler design, increased life span, and easier maintenance, PM motors are highly advantageous. The new generation of high-performance PMs that are capable of providing strong magnetic fields has expanded the application range of magnets with new electric motor topologies and designs.

A Halbach magnet array is a specific arrangement of PMs. In this structure the magnetic field on one side of the array is augmented, whereas on the other side it is almost cancelled. This novel magnet pattern is commonly called a Halbach array. The Halbach array has been applied to various magnet systems for industrial applications: from magnetic bearings, brushless motors and magnetically levitating (maglev) systems, to high-tech applications such as wiggler magnets of particle accelerators as well as nuclear magnetic resonance devices.

Many authors have presented numerous arrangements, designs, and analyses of applications for Halbach PM arrays: Shute *et al.* (2000) presented an extensive mathematical analysis of one-sided flux paths in various magnetized structures. A very powerful and fast analytical method to compute Halbach magnetic interactions was presented by Allag *et al.* (2009), whereas Rovers *et al.* (2009) determined the static forces induced in Halbach arrays. Choi and Yoo (2008) determined the number of layers in Halbach magnets and Cha *et al.* (2008) studied the topology of eddy current couplings and brakes with Halbach magnets.

The general question is when and why one should use a Halbach PM array in the design of surface mounted PMMs. It is known that electric motors with Halbach PM arrays hold several attractive features, such as the following: almost sinusoidal air-gap field distribution and back-emf waveform; strong field intensity; low cogging torque; potentially high air-gap flux density; and avoidance of a rotor back-iron in some cases. Early research in this area by Marinescu and Marinescu (1992) presented a new concept of PM excitation using a Halbach magnetization pattern. An analysis of the torque production capabilities of Halbach and conventional magnet arrays under the constraints of fixed magnet volume was presented by Ofori-Tenkorang and Lang (1995). Halbach magnetized surface permanent magnet (SPM) motors are continuously attracting much research and development interest, resulting in extensive investigation into their design topologies and applications. Nowadays much research into the potentials of Halbach arrays is being undertaken by Mansson (2014, 2015a, b). By using the finite element method Fan and Wu (2012) optimized the Halbach magnet in PM synchronous motors. On the other hand, Zhu *et al.* (2002) compared the characteristics of brushless machines with discrete magnet segments and a single ring magnet. Kataoka *et al.* (2013) presented the analysis of three magnet array-type rotors in Vernier motors, whereas Winter *et al.* (2012) studied the shape of Halbach arrays in axial flux motors. The performance characteristics and features of a variety of devices using Halbach magnet arrays were analysed by finite element analysis (FEA) (Livadaru *et al.*, 2011; Ibtissam *et al.*, 2014; Jian and Chau, 2010). A procedure for minimizing torque pulsations in Halbach array PM machines was proposed by Sadeghi and Parsa (2012).

High-performance electric drives require a smooth static electromagnetic torque, and a high peak torque with a low component of cogging torque. In SPM motors, torque is a result of the interaction between the rotor PM field and the stator armature reaction field. Consequently, the magnetization pattern of the rotor magnets has an important influence on the torque characteristics of the motor. To obtain the best results we have to enhance this interaction.

In this paper the analysis shows how the magnetization pattern affects the magnetic field and torque production in SPM motors. The study shows a comparison between conventional surface PM synchronous motors and its counterparts designed with two new modifications of Halbach magnet array configuration. Thus, the influence of the magnetic configuration on the performance of surface mounted PMMs was analysed. Along with conventional magnetizations of PMs, two possible new Halbach magnetizing patterns produced by discrete arrangement of magnet segments were considered. The electromagnetic and electromechanical characteristics, when such magnetization patterns are employed in a surface PMM, were determined and analysed. A comparison between performance characteristics of a conventional surface PM motor and two Halbach array topologies is presented. The study consists of FEM based numerical experiments that highlight the properties of the static electromagnetic and cogging torque characteristics. In addition, electromagnetic features, such as electromagnetic field distribution in the motor, magnetic flux per pole, and components of the flux density in the air gap, are also analysed.

Halbach Magnetization Patterns

Several rotor topologies for PM machines are possible. This variety depends on the shape of the PMs and their arrangement in the rotor. Most PMMs use permanent magnets that are mounted on the rotor surface, but they can also be inset magnets, interior magnets, or buried magnets. The effect of the position of the PMs as well as their magnetization patterns on machine performance characteristics is significant.

In conventional surface PMMs, the magnet poles can be magnetized with constant direction – parallel magnetization – or with a slightly different magnetization direction depending on their position within the pole arc – radial magnetization. Halbach magnetized PM machines are novel and they offer many new and attractive features.

In 1973 when it was realized that when a planar structure, such as a flat plate or a disc, has varying in-plane and out-of-plane components of magnetization, all of the external fringing flux emerges below the structure, with identically zero flux appearing above. A paper published by Mallinson (1973) showed a previously unknown class of magnetization patterns in planar structures that had the unique property of all of the flux escaping from one surface with none leaving the other side. At the time, his discovery was considered a “magnetic curiosity”.

Almost simultaneously, and independently, Halbach showed that, by assembling blocks of uniformly magnetized PMs, for both two-dimensional and three-dimensional structures, significantly increased fringing flux could be produced. Consequently, a few years later a novel PM configuration was reported (Halbach, 1980), which was later named after its inventor. A Halbach array is a special arrangement of PMs that augment the magnetic field on one side of the array while almost cancelling the field on the other side. This is achieved by a spatially rotating pattern of linear magnetization. A continuously varying magnetization pattern, as presented in Figure 1(a), yields truly one-sided fluxes. The ideal linear Halbach array has a pure sinusoidal magnetic profile on the enhanced side of the array, while cancelling the field on the other side. The practical Halbach array is shown in Figure 1(b).

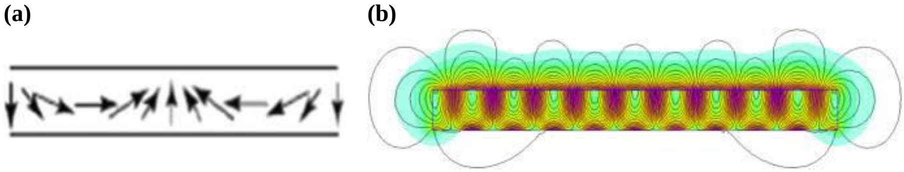
The idea of such a self-shielding property did not immediately gain widespread acceptance because of the difficulty in realization. Instead, an array of rectangular or square PMs was actually used. These non-ideal Halbach arrays do not provide a purely sinusoidal magnetic field on the enhanced side and a zero magnetic field on the cancelled side; however, they provide much better performance characteristics than simply using an array composed of alternating polarity magnets, magnetized by conventional patterns – parallel or radial.

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

Although promising, Halbach's research results, mainly due to the linear layout of the magnets, were not seen as a possible solution for rotating electrical machines. But it was only a matter of time until the radial design was proposed and was successfully implemented for the design of electric motors. To date, Halbach magnetized machines have generally been fabricated from pre-magnetized magnet segments with the appropriate magnetization orientations, which approximate the Halbach array. In addition, the existence of a self-shielded flux in the magnet poles could sometimes lead to abandonment of the rotor back-iron.

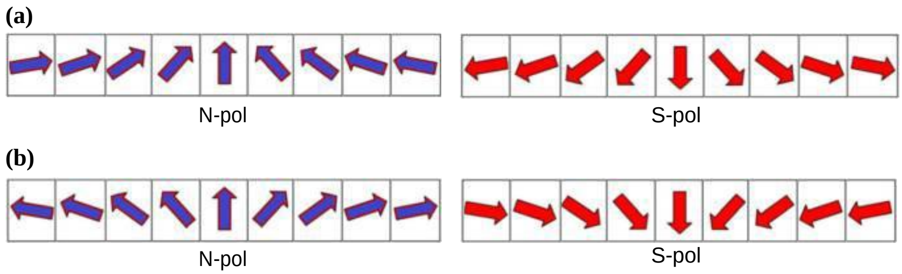
Case Study

An analytical model comprises a surface PMM with 18 A rated current, 0-10 Nm torque range, and 0-4,000 rpm speed range. Both rotor and stator are iron-cored structures. The stator lamination has 36 slots, where three single-layer stage windings are placed.



Notes: (a) Ideal; (b) practical

Figure 1. Illustration for linear Halbach array

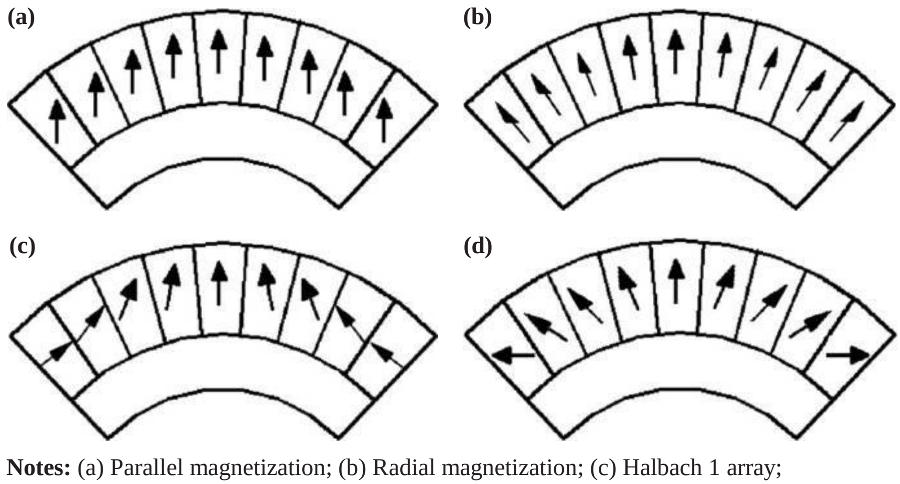


Notes: (a) Halbach array 1: magnetic field is cancelled below the permanent magnets; **(b)** Halbach array 2: magnetic field is cancelled above the permanent magnets

Figure 2. Practical nine-piece Halbach array magnetization patterns for a pair of poles

The drive is connected to a current-source inverter and is controlled by rectangular current waveforms. At each instance of time one winding is energized by a positive current wave +I, the other by negative −I, and the third winding remains unexcited. There are six surface mounted segmented $SmCo_5$ magnets on the rotor. The pole arc is 54° with nine segments arranged in a radial direction and 15 layers in 90 mm axial length. This segmented PM structure is convenient for investigating how various magnetization patterns affect the magnetic field distribution, torque production, and performance characteristics of SPM motors. Four different magnetization patterns, as presented in Figure 3, have been considered, and the respective performance characteristics are compared: parallel magnetization – with constant direction of the magnetic flux; radial magnetization – flux is directed normally across the air gap tangent; Halbach 1 array – magnetic flux is cancelled in the rotor core: i.e. below the PMs; and Halbach 2 array – magnetic flux is cancelled in the stator teeth: i.e. above the PMs. The study presented in this paper is mainly a simulation one. For analysis, software based on the finite element method was used, which enabled an investigation of the magnetic field properties in the SPM motor, as well as the derived electromagnetic and electromechanical quantities and characteristics. Usually, there are different tools that can be employed in numerical simulations and they depend on the state of the analysed system: i.e. steady state or transient operation. The focus was on the properties of the magnetic field created by the PMs; hence the magnetostatic analysis is relevant. It has to be pointed out that this FEM approach catches a given moment of the motor operation. Consequently, rotation, speed, or voltage/current variations are not considered; they are represented by scalar values corresponding to the particular moment that is analysed.

As the presented research has a comparative character, it is developed at three levels. Starting with a conventional SPM synchronous motor with segmented PMs; two magnetization patterns were considered: parallel and radial, as presented in Figures 3(a) and (b). Thereafter, the counterparts with two Halbach array configurations were studied: Halbach 1 and Halbach 2, shown in Figures 3(c) and (d) respectively. The FEM calculations were performed when only the PMs generated the magnetic field.



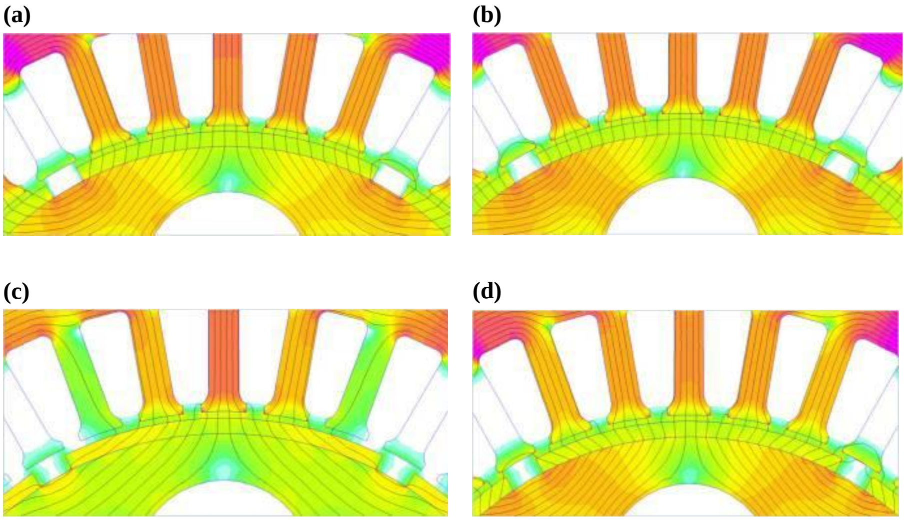
Notes: (a) Parallel magnetization; (b) Radial magnetization; (c) Halbach 1 array; (d) Halbach 2 array

Figure 3.
Four analysed magnetization patterns: an N-pole is depicted

A part of the magnetic field distribution spanning an N-pole pitch is shown in Figures 4(a)-(d).

The results have proved that there is no significant difference between motor characteristics for parallel and radial magnetization of the PMs. For example, the maximum value of magnetic flux per pole for parallel magnetization is 2.24 mVs, while for radial it is 2.31 mVs, which is ~3 per cent difference; at the same time the profiles of their characteristics, $\Phi_p = f(\theta)$, as shown in Figure 5, are almost identical. Hence, only radial magnetization (being more common in practice), Halbach 1 and Halbach 2 magnetizations were investigated.

Taking into consideration the radial magnetization and the two Halbach arrays, the performance analysis of the SPM motor was carried out. It is important to emphasize



Notes: (a) Parallel magnetization; (b) Radial magnetization; (c) Halbach 1 array; (d) Halbach 2 array

Figure 4. Magnetic field distribution for analysed PM magnetization patterns: no-load at $\theta = 0°$ rotor position

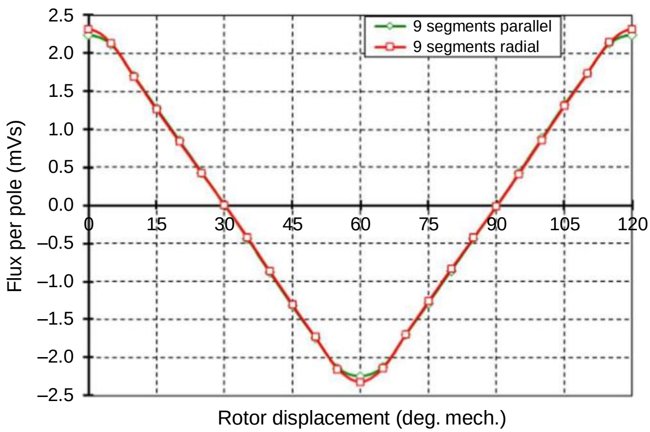


Figure 5. Flux characteristics Φ_p=f(θ) for conventional magnetizations (parallel and radial) at no-load

that, because of less saturation of the magnetic core and lower iron loss for Halbach 1 and 2 magnetization arrays, it is possible to increase the armature current and consequently increase the electromagnetic torque, which in turn will give an advantage to SPM motors with a Halbach array-type magnetization.

Computational Results

For prediction of the performance characteristics of the studied SPM motor 2D FEA was employed. The mesh of finite elements has more than 123,000 nodes and 245,000 elements. The selection of the relevant results is presented under the subsequent headings.

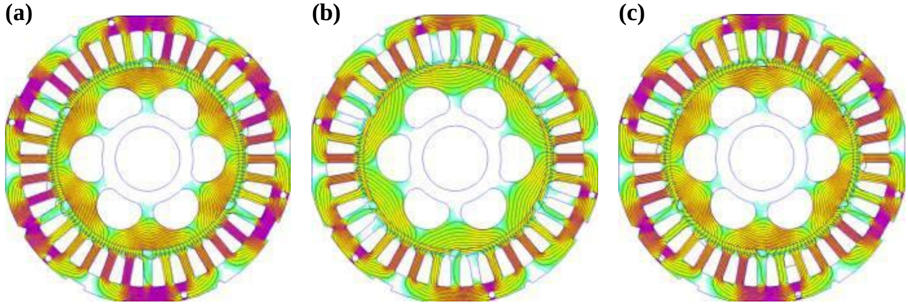
Magnetic field analysis

Figure 6 presents the magnetic flux density colour map and flux lines for rated current I_n =18 A and rotor position θ = 30° mech. = 90° el., for the analysed magnetization types of rotor magnets.

In order to obtain comparable views for all figures, the maximum value of the flux density was set at 1.7 T, whereas the number of flux lines is proportional to the respective value of the magnetic vector potential A_{max} (V/s). Thus, one can observe the saturation level and weak regions for the analysed magnetization patterns. Some interesting results are presented in Table I.

Electromagnetic characteristics

In Figure 7 are presented the characteristics of the air-gap flux per pole, Φ_p f(θ), at no-load and at rated load I_n 18 A; as expected, Halbach 1 array generated the lowest magnetic flux.



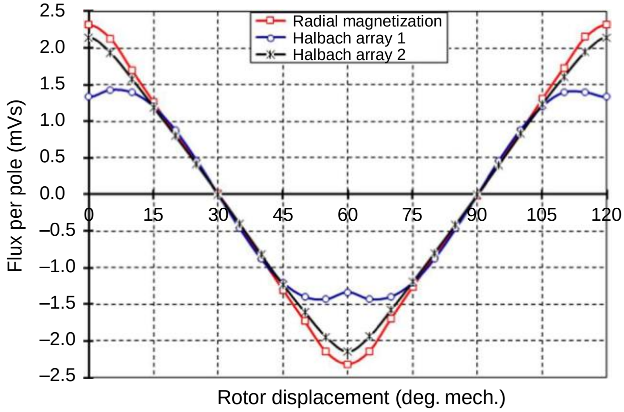
Notes: (a) Radial magnetization: 27 lines; (b) Halbach 1 array: 19 lines; (c) Halbach 2 array: 25 lines

Figure 6. Magnetic field plots at rated load I_n = 18 A and rotor position θ=90° el.

Table I. Magnetic field properties of SPM motor at various magnetization patterns

		No-load $I = 0$; $\theta = 0°$			Rated load $I_n = 18$A; $\theta = 0°$		
Description	Unit	Radial	Halbach 1	Halbach 2	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

(a)



(b)

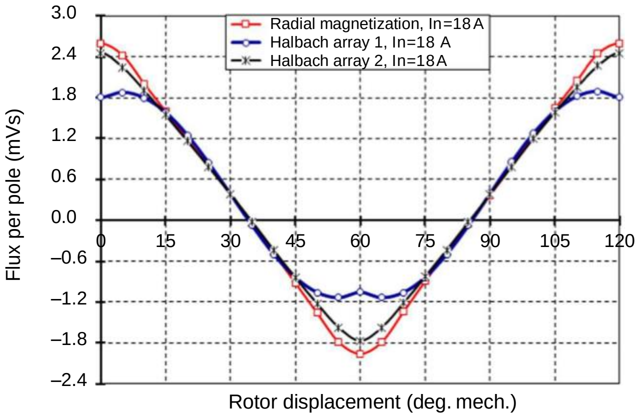


Figure 7. Comparative characteristics of the magnetic flux per pole, $\Phi_p = f(\theta)$

Notes: (a) No-load $I = 0$; (b) rated load $I_n = 18$ A

The spatial distribution of the magnetic flux density components, along the mid-gap line, is shown comparatively in Figure 8, for the normal field component and for the tangential component; the calculation was done when the magnetic field was generated by the permanent magnets only: i.e. for $I = 0$.

Electromechanical Characteristics

In this study, stress is placed on the cogging and static torque characteristics. The weighted stress tensor volume integral was used to calculate the torques. This approach greatly simplifies the computation of torques and gives the most accurate results when compared with line integration to calculate the Maxwell stress tensor, or with application of the energy concept and numerical differentiation of the air-gap magnetic co-energy. For closer estimation of torques, the mesh density in the air gap, where the Maxwell stress is the highest, is particularly refined (Petkovska *et al.*, 2015). The FEM simulations start at no-load, without current in stator windings, when the magnetic field is induced only by the PMs and the cogging torque is computed. For the static torque to be predicted, field computations continue at rated load operation.

Cogging torque

Cogging torque, T_{cog}, is probably the most annoying parasitic element in PM motors, because it is an undesired motor output, produced because of the interaction between the rotor magnet poles and slots of the stator: i.e. the stator saliency. Cogging torque is calculated at no-load, for all magnetization patterns, and the rotor is displaced along one pole pitch in the clockwise direction: i.e. for 60° mech., with a step of 1° mech. The cogging torque profile, $T_{cog} = f(\theta)$, is depicted in Figure 9.

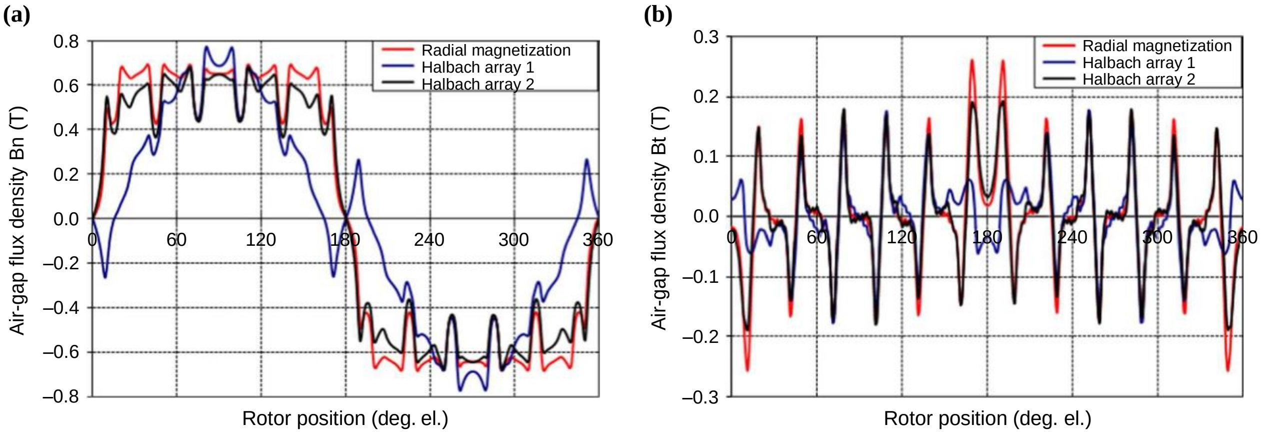
Parallel and radial magnetization do not show significant discrepancy. The Halbach 2 array exhibits a similar profile to radial magnetization, although the Halbach 1 array is more favourable, as the peak value is four times lower, although at double the frequency. In Figure 10 are displayed the cogging torque characteristics comparatively, in the same manner as done previously, by omitting the parallel magnetization pattern.

Static torque

To evaluate the operating performance of SPM synchronous motors at various loading conditions with different magnetization patterns, it is required to analyse the torque production and the respective static torque characteristics. Electromagnetic torque is a result of the interaction between the rotor PMs and the stator armature reaction field. All four different magnetization patterns were again analysed.

The rated operating mode is simulated by setting typical rectangular current waves in the stator windings, as follows: $I_A = +I_n$, $I_B = -I_n$; the phase winding, C, however, is not energized ($I_C = 0$). Such current distribution enables the use of 2D magnetostatic field simulations. Starting with the initial position when the rotor and stator fields are aligned, the rotor was displaced for 5° mech. in the clockwise direction.

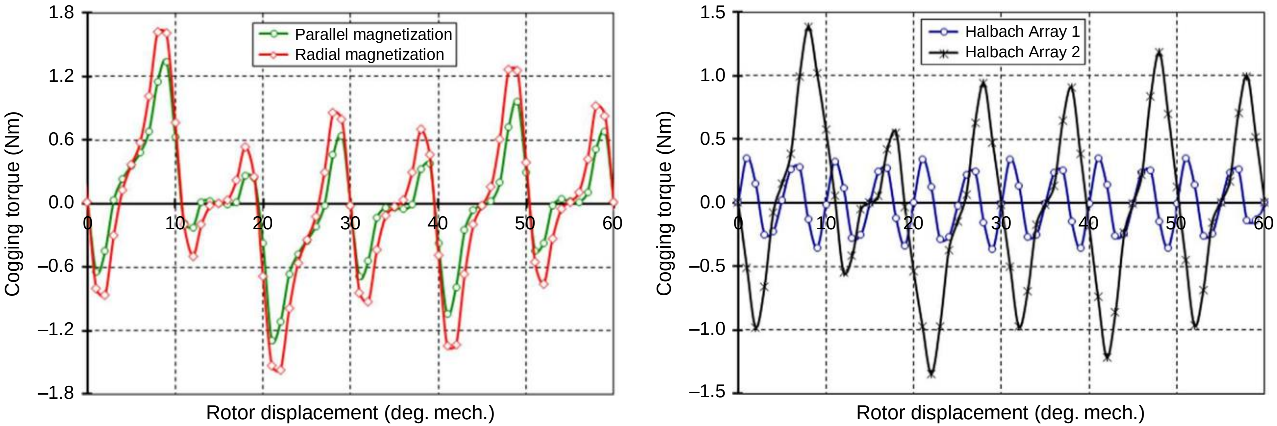
The static electromagnetic torque was computed, and the comparative characteristics, $T_{em} = f(\theta)$ for the analysed magnetization patterns, spanned along one full period of 120° mech., i.e. 360° el., are given in Figure 11. The computational results prove again that parallel and radial magnetization characteristics are very close and hence, as mentioned before, only the characteristic for radial magnetization has been considered. Emphasis is placed on the Halbach magnetization patterns – Halbach 1 and 2 arrays. From the static and cogging torque characteristics, it is evident that the Halbach 1 array exhibits a symmetrical profile, but with the lowest torque values and the



Notes: (a) Normal component B_n =f(ϑ); (b) tangential component B_t =f(ϑ)

Figure 8. Comparative characteristics of magnetic flux density in dependence of rotor position, at no-load

Figure 9.
Cogging torque characteristics at different PM magnetization patterns



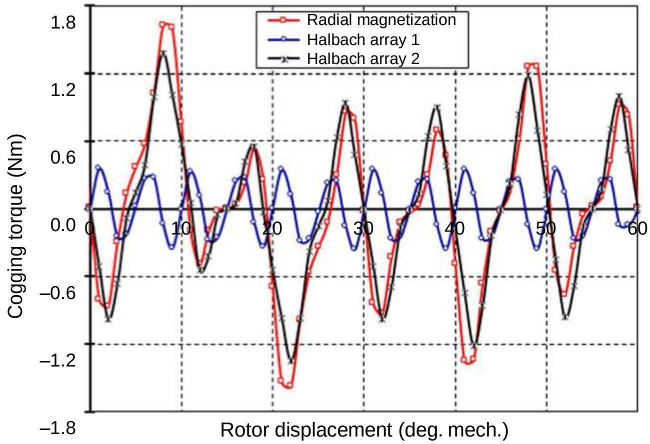


Figure 10. Comparative cogging torque characteristics

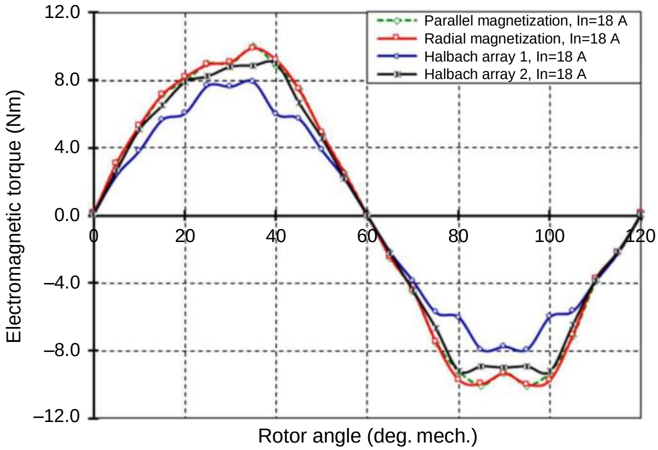


Figure 11. Comparative static torque characteristics, $T_{em} = f(\theta)$, at rated load $I_n = 18\,A$

largest ripple. However, the advantage of this magnetization pattern is for the lowest cogging torque, as seen in Figure 10. Although it should be emphasized that a possible drawback is the doubled frequency; namely, instead of six, there are 12 periodical changes of the profile. On the other hand, the Halbach 2 array pattern prevails over the radial magnetization because of the lower torque ripple level, and a lower cogging torque by up to ~15 per cent, but equal torque at rated operating load angles of 0-10° mech and for 50-60° mech The only drawback is a slightly lower peak static torque. However, because of a lower magnetic saturation in the stator teeth zone and hence lower iron loss, it is possible to increase the current in the stator windings; thus, the static electromagnetic torque can be increased and, accordingly, this disadvantage can be overcome.

Conclusions

In this paper the influence of magnetization patterns on the performance characteristics of surface PMMs has been analysed. The computational results obtained by 2D magnetostatic FEM were used for detailed performance analyses. Four different magnetization patterns have been considered: two conventional – parallel and radial – and two recently developed configurations – Halbach 1 and 2 arrays. Emphasis has been placed on motor torque characteristics. In addition, electromagnetic features such as electromagnetic field distribution of the motor, magnetic flux per pole, and components of the flux density in the air gap, were also analysed.

From the analysis of the FEM computational results and a review of the magnetic field properties of the magnetization patterns, one can conclude that both the values and shape of the characteristics for the radial magnetization and Halbach 2 configuration, exhibit similar features. It is due to the fact that the Halbach 2 array spreads the magnetic flux above the PMs – i.e. it strengthens the magnetic field in the rotor, and enhances the coupling between the rotor and stator magnetic field. On the other hand, the Halbach 1 array exhibits an overall weakened magnetic field, and consequently a less saturated machine with inadequate use of active material, which in turns leads to lower electromagnetic torque values with higher ripple. This result may be counter-intuitive when the pole flux appears to be much more concentrated. Ultimately the level of flux crossing the air gap is limited by local saturation effects. It should also be pointed out that in the case of the Halbach 1 array the cogging torque has the lowest value.

It is worth emphasizing that, because of less saturation of the stator magnetic core and lower iron loss in both Halbach 1 and 2 magnetization arrays, it is possible to increase the ampere-turns and thus increase the electromagnetic torque, which in turn will give an advantage to the SPM motors with a Halbach array. This fact could be a matter for further analysis especially with a view to replace expensive rare-earth magnets with lower cost varieties to achieve the same performance for SPM motors.

Future work could also involve an analysis of the induced back-EMF waveforms with different magnetization patterns of PMs. An analysis of the losses in the PMs as well as the overall losses and efficiency of the SPM motor by using the time-stepping finite element method could also be of interest. To this end, the present work will serve as a good guide to finding alternative lower cost magnet arrays for high performance motors.

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About the authors

Lidija Petkovska has received a BSc EE Degree from the Faculty of Electrical Engineering, University of Belgrade, and an MSc EE and a Doctoral Degree from the Faculty of Electrical Engineering, Ss. Cyril and Methodius University, Skopje, Macedonia. Her field of interest covers a wide area related to the problems in electrical machines and transformers, in particular, design, optimization, testing, simulations, and FEM calculations. Professor Lidija Petkovska has published more than 320 papers in scientific journals and conference proceedings. She is a Member of ISCs of prestigious conferences, acting as reviewer and chairing sessions. She is a

Senior Member of IEEE, Member of CIGRE International, the Chair of MAKO-Cigre B4 Committee Macedonia, the past Chair of ISEF'2013, and a founder and Chair of SAEM conferences. Lidija Petkovska is the corresponding author and can be contacted at: lidijap@feit.ukim.edu.mk

Goga Vladimir Cvetkovski received his BSc EE, MSc EE, and Doctoral degrees from the Faculty of Electrical Engineering and Information Technologies at the Ss. Cyril and Methodius University, Skopje, in 1992, 1994, and 2001. At present he is a Full Professor at the Department of Electrical Machines, Transformers and Apparatuses, giving lectures on electrical machines, power converters, and drives. His main field of interest covers various problems in electrical machines, in particular optimal design, control, simulations, and FEM calculations. Goga Cvetkovski has published more than 220 papers in scientific journals and conference proceedings. He is a Senior Member of IEEE and the Chair of the joint chapter of IES/IAS/PELS of the Republic of Macedonia IEEE Section.

Paul Lefley received his PhD from the University of Nottingham in 1989. He is a Lecturer in Power Electronics, Electrical Machines, and Drives in the Department of Engineering at the University of Leicester, UK. Dr Lefley has an international reputation on all of his research work, which is principally in three areas: novel electrical machines, drives and control, and application of power electronics and pulsed power. Paul Lefley is a Member of the UK IET with chartered status, a Member of the US IEEE, and also a Member of the Royal Institute. He is the past Chairman of the 34th UPEC. He sat on the Steering Committee of PEMD2008, and on the Scientific Committee of the International Symposium on EFEEA2010, in Ghardia.