Concentrated winding PM machines: a pre-design approach

Imen Abdennadher and Ahmed Masmoudi
Research Unit on Renewable Energies and Electric Vehicles, Sfax Engineering School, University of Sfax, Sfax, Tunisia, and
Ahmed Elantably
Allison Transmission Division of General Motors, Indianapolis, Indiana, USA

Abstract

Purpose – The purpose of this paper is to discuss the design of concentrated winding permanent magnet (PM) machines dedicated to propulsion applications considering both surface-mounted and flux-concentrating arrangements of the PMs.

Design/methodology/approach – Following the selection of a suitable distribution of the concentrated winding, a derivation of the machine inductances is carried out in order to highlight the increase in the flux-weakening range gained through the substitution of distributed windings by concentrated ones. Then, mmf and finite element analysis are carried out in order to investigate the air gap flux density and the torque production capability of both surface-mounted and flux-concentrating PM machines.

Findings – The paper finds that, although both machines provide almost the same average torque, the surface-mounted PM machine offers lower torque ripple with respect to the flux-concentrating arrangement: a crucial benefit in electric and hybrid propulsion systems.

Research limitations/implications – The research should be extended to the comparison of the obtained results related to the torque production capability with experimental measurements.

Practical implications – An increase in the efficiency associated with the extension of the flux-weakening range and a reduction of the volume make the concentrated winding PM machines interesting candidates, especially in large-scale production applications such as the automotive industry.

Originality/value – The paper proposes an approach to design and performance investigation of concentrated winding PM machines considering both surface-mounted and flux-concentrating arrangements of the PMs.

Keywords Surface mount technology, Flux density, Windings, Inductance, Finite element analysis, Torque

Paper type Research paper

1. Introduction

The integration of concentrated windings in permanent magnet (PM) machines represents a challenge alternative for conventional distributed winding PM machines (Cros and Viarouge, 2002; Magnussen and Sadarangani, 2003; El-Refaie and Jahns, 2004). Concentrated windings make it possible to significantly increase the machine inductance in order to reduce the characteristic current to the point of establishing equality with the rated current. This allows the possibility of extending the flux weakening range (El-Refaie and Jahns, 2004): a crucial requirement for electric and hybrid propulsion systems. Furthermore, the copper losses are minimized thanks to the resulting reduction of the end-windings. Moreover, as far as concentrated windings are

COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering
Vol. 27 No. 5, 2008
pp. 985-999

0332-1649
DOI 10.1108/03321640810890726

simply wound around teeth, their manufacturability turns to be simplified with respect to distributed ones (Magnussen and Sadarangani, 2003).

From a topological point of view, surface mounted PM machines, have generally been considered to be poor candidates for achieving wide ranges of constant power operation by means of flux weakening. The principal reason for this drawback is due to the fact that the inductance values of surface mounted PM machines are typically low with distributed armature winding. Such reduced inductances result from the increased value of the air gap caused by the PM arrangement. This drawback is relatively reduced in flux concentrating PM arrangement.

The present paper deals with the design of concentrated winding PM machines dedicated to propulsion applications. Following the selection of a suitable distribution of the concentrated winding, a derivation of the machine inductances is carried out inorder to highlight the increase in the flux weakening range. Then, a case study is treated where both surface mounted PM and flux concentrating PM machines are considered.

2. Concentrated winding selection

Referring to Abdennadher *et al.* (2006), it has been reported that many influent design parameters charactirize concentrated windings, especially:

- the slot per pole and per phase S_{pp}, whose selection greatly influences the remaining parameters;
- the winding factor K_w, which should be as high as possible in order to increase: the EMF generation and torque production capabilities. This issue has been widely treated in the literature (Cros and Viarouge, 2002; Magnussen and Sadarangani, 2003; Libert and Soulard, 2004) and is therefore skipped in this work;
- the direct inductance L_{dc}, which should be increased in order to extend the flux weakening range (El-Refaie and Jahns, 2004): a crucial requirement for propulsion applications;
- the lowest-common-multiple (LCM) of the number of stator slots N_s and the number of rotor poles $2p$, which should be as high as possible in order to reduce the cogging torque ripple amplitude (Magnussen and Sadarangani, 2003; El-Refaie and Jahns, 2004; Salminen *et al.*, 2004); and
- the difference between the number of stator slots N_s and the number of rotor poles $2p$, which should be different from one in the case of double layer winding and from two in the case of simple layer winding (Libert and Soulard, 2004; Skaar *et al.*, 2006).

Table I confirms the above-cited statements in a given range of S_{pp}.

Table I.
Variations of K_w, of L_{dc}/L_{dd} and of LCM in terms of S_{pp}

N_s	12	12	12	12	12	12	12
P	4	5	6	7	8	9	10
S_{pp}	1/2	2/5	Ø	2/7	1/4	Ø	2/10
K_w	0.866	0.933	Ø	0.933	0.866	Ø	0.5
L_{dc}/L_{dd}	13.928	9.147	Ø	5.002	4	Ø	2.844
LCM	24	60	Ø	84	96	Ø	120

Referring to Table I, one can notice that $S_{pp} = 2/5$ and $S_{pp} = 2/7$ are interesting candidates. However, the topology whose $S_{pp} = 2/5$ is much more interesting for propulsion applications as far as it provides wider speed weakening range.

3. Flux weakening range extension

It well known that the flux weakening range of conventional distributed winding surface mounted PM machines is relatively narrow. This is due to the fact that the direct inductance of conventional distributed winding surface mounted PM machines is relatively low. While in concentrated winding surface mounted PM machines, and referring to El-Refaie and Jahns (2004), the direct inductance could be increased so that the optimal flux weakening condition could be fulfilled by selecting suitable values of S_{pp}.

Giving the fact that in surface mounted PM machines, the characteristics current is inversely proportional to the direct-axis inductance, it is interesting to investigate this latter and especially its variation with respect to S_{pp}.

3.1 Inductance derivation

The self inductance L_a of a phase of the armature is expressed as follows:

$$L_a = \frac{\mu_0 L_s D_g}{2g} \int_0^{2\pi} \left(\frac{\mathscr{F}(\theta)}{I} \right)^2 d\theta \tag{1}$$

where $\mathscr{F}(\theta)$ is the produced mmf by the considered phase.

The mutuel inductance M_a between two phases of the armature is expressed as follows:

$$M_a = \frac{\mu_0 L_s D_g}{2g} \int_0^{2\pi} \frac{\mathscr{F}(\theta)\mathscr{F}(\theta - (2\pi/3))}{I^2} d\theta. \tag{2}$$

Then the direct and quadrature inductances, noted L_d and L_q, respectively, are derived:

$$\begin{cases} L_d = L_a + M_a \\ L_q = L_a - M_a \end{cases} \tag{3}$$

Accounting for the mmf spatial repartitions of both concentrated and distributed windings, the inductance expressions are derived as follows.

3.1.1 Case of concentrated windings. Let us consider the case of a concentrated winding made up of N_{co} coils including N_c turns each. The coils are connected in such a way that the produced mmf per phase is the one shown in Figure 1.

In this case, the inductance L_{ac} is expressed as follows (Abdennadher *et al.*, 2006):

$$L_{ac} = \frac{\mu_0 L_s D_g}{2g} \frac{2N_{co}}{q} \int_0^{\pi\beta/N_s} N_c^2 \, d\theta = \frac{\mu_0 L_s D_g}{2g} \frac{N_{co}}{g} \tau_s N_c^2 \tag{4}$$

where β is the ratio of the slot opening τ_s with respect to the slot pitch α. As far as $M_{ac} = 0$, one can write:

$$L_{dc} = L_{qc} = L_{ac} = \frac{\mu_0 L_s D_g}{2g} \frac{N_{co}}{q} \tau_s N_c^2. \tag{5}$$

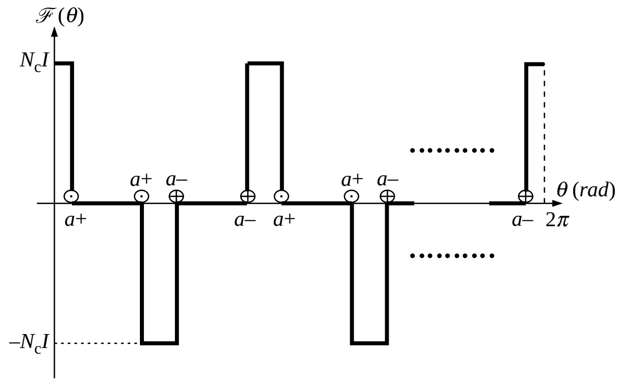

Figure 1.
MMF per phase of a concentrated winding

In the case of a double layer concentrated winding the number of coils is equals to N_s, therefore:

$$L_{dc} = \frac{\mu_0 L_s D_g}{2g} \tau_s P_r S_{pp} N_c^2 = \frac{\mu_0 L_s D_g}{2g} \beta \frac{\pi}{q} N_c^2 \tag{6}$$

3.1.2 Case of distributed windings. Let us consider the case of a basic distributed winding made up of a single coil including N_d turns and inserted in a pair of diametral slots, as shown in Figure 2.

The self inductance L_{ad} of the basic distributed winding is:

$$L_{ad} = \frac{\mu_0 L_s D_g}{2g} 2p \int_0^{\pi/p} \left(\frac{N_d}{2}\right)^2 d\theta = \frac{\mu_0 L_s D_g}{2g} \frac{\pi}{2} N_d^2. \tag{7}$$

The mutual inductance M_{ad} is expressed as:

$$M_{ad} = \frac{\mu_0 L_s D_g}{2g} 2p \left[\int_0^{2\pi/3p} \left(\frac{N_d}{2}\right)^2 d\theta - \int_{2\pi/3p}^{\pi/p} \left(\frac{N_d}{2}\right)^2 d\theta \right], \tag{8}$$

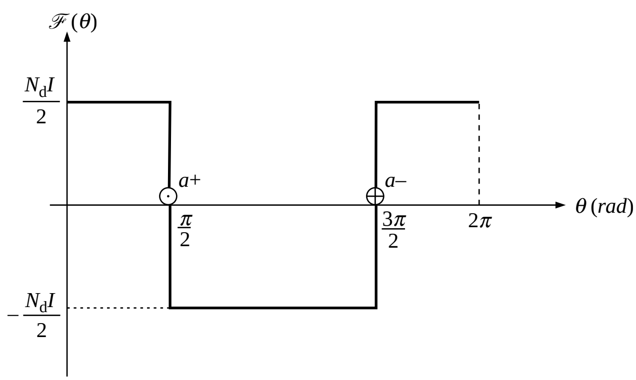

Figure 2.
MMF per phase of basic distributed winding

which leads to:

$$M_{ad} = \frac{\mu_0 L_s D_g}{2g}\ \frac{\pi}{6} N_d^2. \tag{9}$$

Then the direct and quadrature inductances of distributed windings, noted L_{dd} and L_{qd}, respectively, turn to be:

$$\begin{cases} L_{dd} &= \frac{\mu_0 L_s D_g}{2g}\ \frac{2\pi}{3} N_d^2 \\ L_{qd} &= \frac{\mu_0 L_s D_g}{2g}\ \frac{\pi}{3} N_d^2 \end{cases} \tag{10}$$

3.2 Stator-rotor flux linkage derivation

The flux linkage Φ between the PMs and a phase of the armature is expressed as follows:

$$\Phi = \frac{L_s D_g}{2} \int_0^{2\pi} \frac{\mathscr{F}(\theta)}{I} B_{pm}(\theta)\, d\theta. \tag{11}$$

Assuming that the PM arrangement presents a sinusoidal flux density B_{pm}, such that:

$$B_{pm}(\theta) = B_{pmax} \sin(p\theta). \tag{12}$$

Accounting for equation (12), the expression of the flux linkage Φ turns to be in the case of:

3.2.1 Case of concentrated windings:

$$\Phi_c = L_s \frac{D_g}{2} \frac{2N_{co}}{q} \int_0^{\pi\beta/N_s} N_c B_{pmax} \sin(p_r \theta)\, d\theta, \tag{13}$$

which leads to:

$$\Phi_c = \frac{L_s D_g B_{pmax} N_c}{2p_r}\ \frac{2N_{co}}{q} \left(1 - \cos\left(\frac{\pi\beta}{2qS_{pp}}\right)\right). \tag{14}$$

In the case of a double layer concentrated winding the number of coils is equals d to N_s, therefore:

$$\Phi_c = 2L_s D_g B_{pmax} N_c S_{pp} \left(1 - \cos\left(\frac{\pi\beta}{2qS_{pp}}\right)\right) \tag{15}$$

3.2.2 Case of distributed windings:

$$\Phi_d = L_s \frac{D_g}{2} 2p \int_0^{\pi/p} \frac{N_d}{2} B_{pmax} \sin(p\theta)\, d\theta, \tag{16}$$

which yields:

$$\Phi_d = L_s D_g B_{pmax} N_d \tag{17}$$

3.3 Inductance ratio
Referring to equations (15) and (17), one can establish the relation between N_d and N_c in order to obtain equality of Φ_d and Φ_c that is:

$$N_c = \frac{1}{2S_{pp}(1-\cos(\pi\beta/2qS_{pp}))} N_d. \tag{18}$$

Accounting for equation (18), the ratio of the direct-axis inductances turns to be:

$$\frac{L_{dc}}{L_{dd}} = \frac{(3/8)(\beta/q)}{(S_{pp}(1-\cos(\pi\beta/2qS_{pp})))^2}. \tag{19}$$

Referring to Figure 3, one can notice that the ratio L_{dc}/L_{dd} increases with S_{pp}. Therefore, it is possible to extend the flux weakening range with reasonable values of the characteristic current. This said, the increase of the ratio L_{dc}/L_{dd} should be limited as far as it is proportional to $(N_c/N_d)^2$, which leads to an increase of the copper losses, then a decrease of the efficiency.

4. Case study

In what follows, is considered the analysis of two concentrated winding PM machines:

(1) a surface mounted PM machine; and

(2) a flux concentrating PM machine.

Both machines have the same following sizing parameters:

- the stator outer diameter $D_s = 234$ mm;
- the air gap $g = 0.5$ mm;
- the active length $L_s = 70$ mm;
- the pole pair number in the rotor $p_r = 5$;

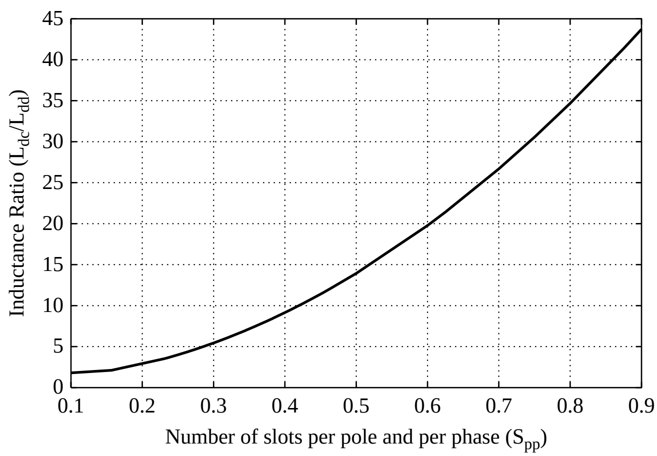

Figure 3.
Inductance ration L_{dc}/L_{dd} versus the slot per pole and per phase S_{pp}

- the number of slots in the armature $N_s = 12$;
- the number of phases $q = 3$; and
- the number of slot per pole and per phase $S_{pp} = 2/5$.

4.1 Surface mounted PM topology

4.1.1 MMF analysis. Regarding the fact that the length of the end winding is higher in the case of single-layer arrangement of the armature winding than in the case of double-layer one, we have been interested in the case where the windings are distributed around the air gap in double-layer slots. The armature winding, which is the same for both surface mounted and flux concentrating PM machines, is distributed considering the methodology presented in Cros and Viarouge (2002) and Libert and Soulard (2004), which yields the arrangement shown in Figure 4.

FEA carried out in order to investigate the waveform of the no-load phase flux per turn has led to the results shown in Figure 5. These clearly show that the machine would be suitably fed by sinusoidal currents.

Let us consider the case where the concentrated winding PM machine is fed by sinsoidal currents, with a maximum current/in phase a ($i_a = I$ and $i_b = i_c = -I/2$). In order to investigate the spatial distribution of the armature mmf, the surface mounted PM s in the rotor are supposed to be discarded.

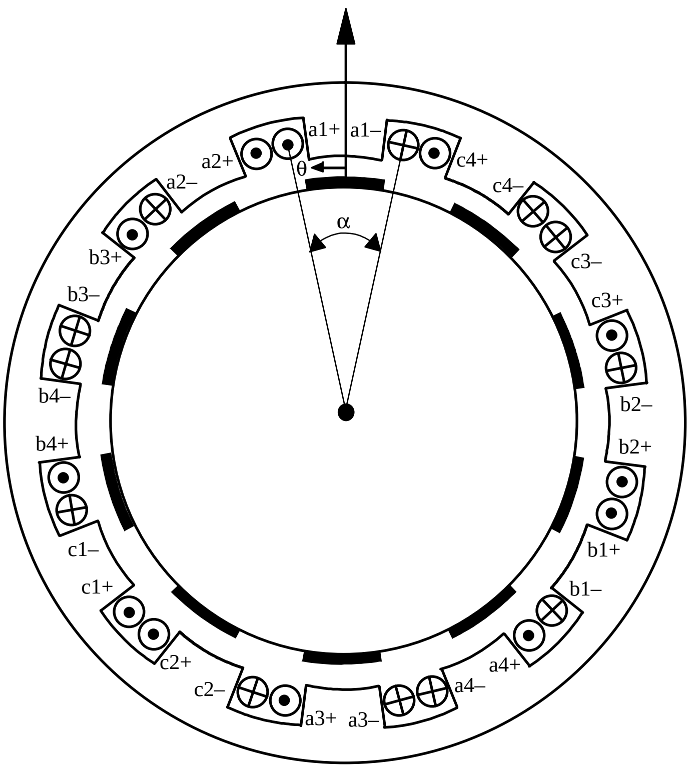

Figure 4.
Winding distribution in the case of two layer slots with $S_{pp} = 2/5$

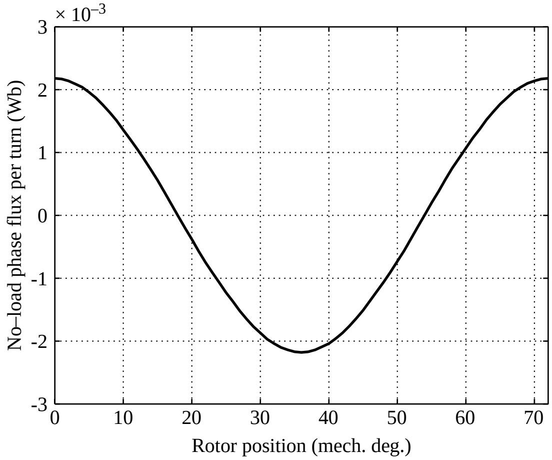

Figure 5.
No-load phase flux per turn versus the mechanical angle in the case of the surface mounted PM machine

Giving the fact that each phase is made up of N coils, the mmf F_{a1} produced by the one coil of phase a ($a1+/a1-$) is expressed as follows:

$$F_{a1} = \begin{cases} (2-\beta)(NI/8) & -(\alpha/2) \leq \theta \leq (\alpha/2) \\ -\beta(NI/8) & \text{elsewhere} \end{cases} \tag{20}$$

where α is shown in Figure 4, τ_p is the armature-pole pitch, and β is the coil pitch ratio, such that:

$$\beta = \frac{\alpha}{\tau_p}. \tag{21}$$

Taking into account the hypothesis which considers that the magnetic circuit is not saturated, one can apply the superposition theorem in order to obtain the mmf F_a of phase a. Then, the superposition of F_a, F_b and F_c has led to the spatial profile of the resulting armature mmf $F(\theta)$ shown in Figure 6.

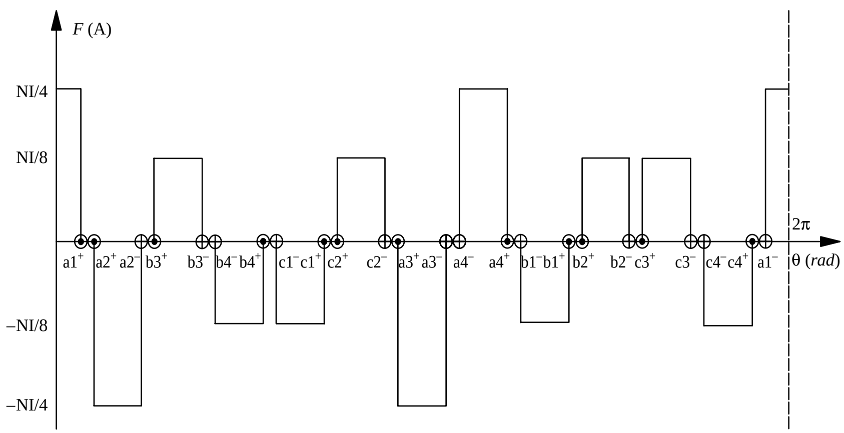

Figure 6.
Spatial repartition of the mmf resulting from feeding the armature by sinusoidal currents

The Fourrier transform of the spatial repartition of the resulting mmf has led to the following general term (Masmoudi *et al.*, 2008):

$$\mathscr{F}_n(\theta) = A_n \sin\left(n(\theta - (\pi/12))\right) \tag{22}$$

where:

$$A_n = \frac{NI}{\pi}\left(1 + (-1)^{(n+1)}\right)\left(\cos\frac{2\pi n}{3} - 1\right)\frac{\sin(n\beta(\pi/2))\sin(n\pi/12)}{n} \tag{23}$$

4.1.2 Finite element analysis. The computation of the no-load air gap flux density assuming slotless stator core has led to the results shown in Figure 7. Figure 8 shows the no-load air gap flux density where the stator slots are taken into account.

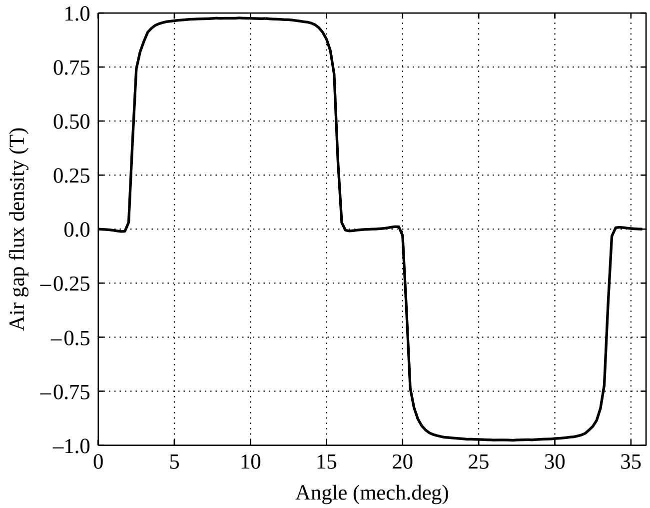

Figure 7.
No-load air gap flux density versus the mechanical angle obtained with PMs mounted on the rotor surface assuming a slotless stator core

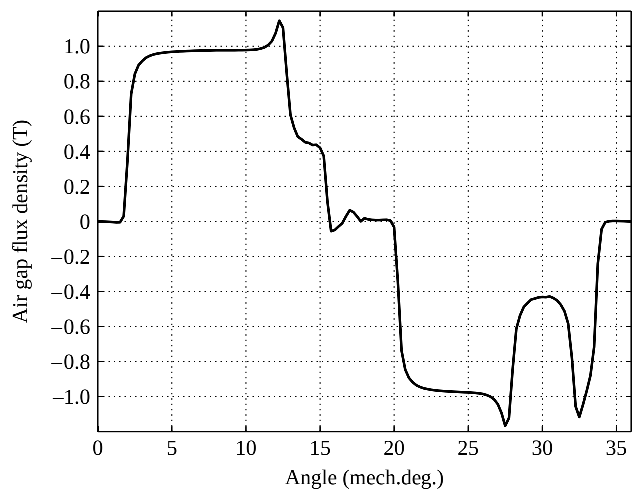

Figure 8.
No-load air gap flux density versus the mechanical angle obtained with PMs mounted on the rotor surface with the stator slotting effect taken into account

Figure 9 shows the computed electromagnetic torque considering a sinusoidal current supply with a current, density of 15 A/mm^2. One can notice that in the case of surface mounted PM machine, the average value of the torque is 118 Nm, with a peak-to-peak ripple of 7.59 per cent.

Figure 10 shows the flux line distribution of the surface mounted PM machine, considering a sinusoidal current supply with a maximum current I in phase a ($i_a = I$ and $i_b = i_c = -I/2$) and with a current density of 15 A/mm^2.

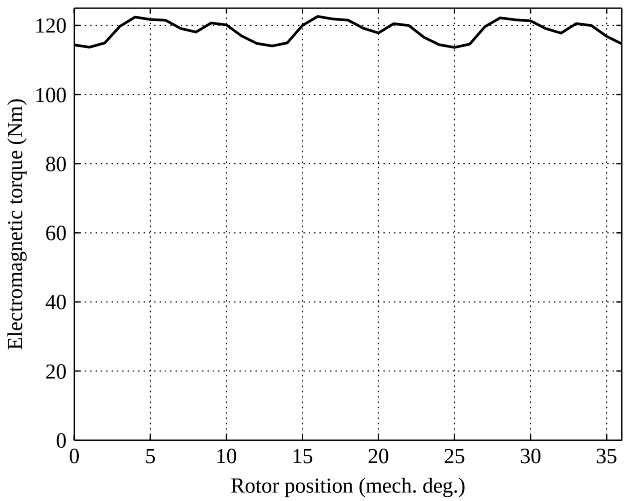

Figure 9.
Electromagnetic torque versus the mechanical angle of surface mounted PM machine considering a sinusoidal current supply with a current density of 15 A/mm^2

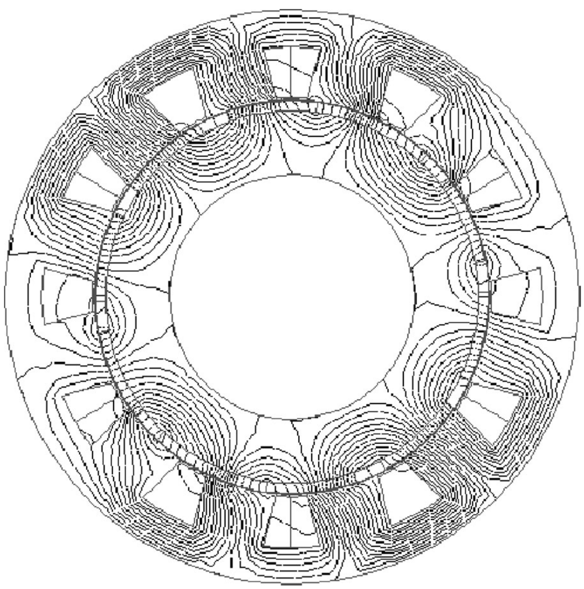

Figure 10.
Flux line distribution of surface mounted PM machine with the armature fed by sinusoidal current supply whose density is 15 A/mm^2

Note: Reproduced from the only available original

4.2 Flux concentrating PM topology

4.2.1 MMF analysis. FEA carried out in order to investigate the waveform of the no-load phase flux per turn has led to the results shown in Figure 11. These clearly show that, in the manner of the surface mounted PM machine, the flux concentrating PM one would be suitably fed by sinusoidal currents.

As far as both surface mounted PM and flux concentrating PM machines present the same stator winding distribution, the spatial repartition of the armature mmf obtained under sinusoidal current supply is the same for both machines, that is the one shown in Figure 6.

4.2.2 Finite element analysis. The computation of the no-load air gap flux density assuming slotless stator core has led to the results shown in Figure 12. Figure 13 shows the no-load air gap flux density where the stator slots are taken into account.

Figure 14 shows the computed electromagnetic torque considering a sinusoidal current supply with a current density of 15 A/mm^2. One can notice that in the case of flux concentrating PM machine, the average value of the torque is 116 Nm, with a peak-to-peak ripple of 11.7 per cent.

Figure 15 shows the flux line distribution of the flux concentrating PM machine, considering a sinusoidal current supply with a maximum current I in phase a ($i_a = I$ and $i_b = i_c = -I/2$) and with a current density of 15 A/mm^2.

5. Conclusion

The paper was devoted to the design of concentrated winding PM machines dedicated to propulsion applications. The selection of a suitable distribution of the concentrated winding is a crucial step in design procedure in an attempt to fulfill the propulsion application requirements. Of particular interest are a high winding factor and a large flux weakening range.

In a first step, a derivation of the machine inductances has been carried out in order to highlight the increase in the flux weakening range gained through the substitution of distributed windings by concentrated ones.

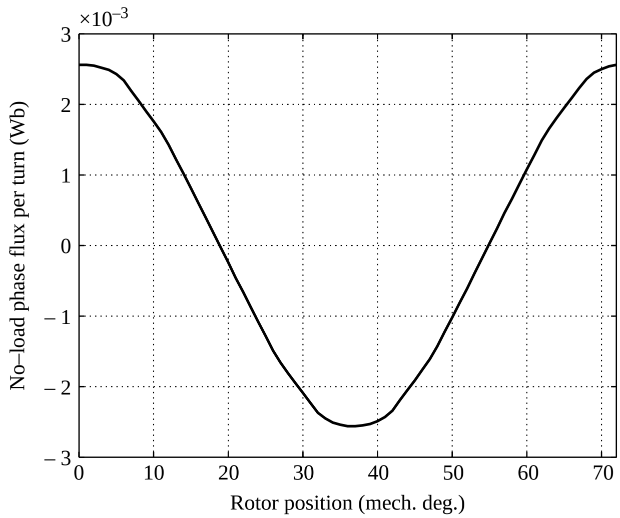

Figure 11.
No-load phase flux per turn versus the mechanical angle in the case of the flux concentrating PM machine

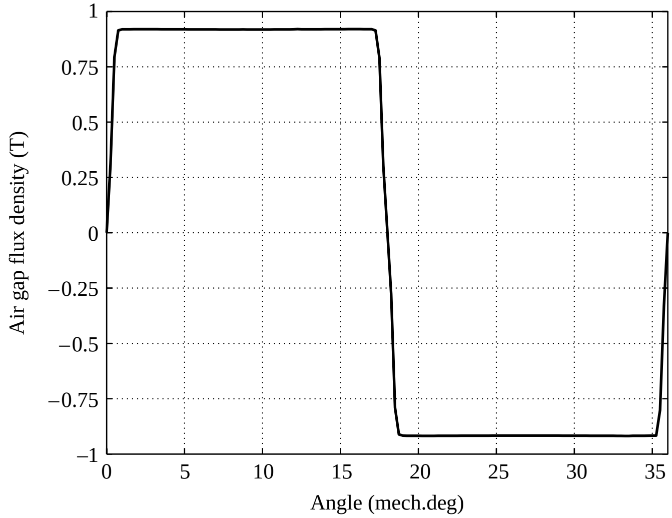

Figure 12.
No-load air gap flux density versus the mechanical angle obtained with flux concentrating PMs rotor assuming a slotless stator core

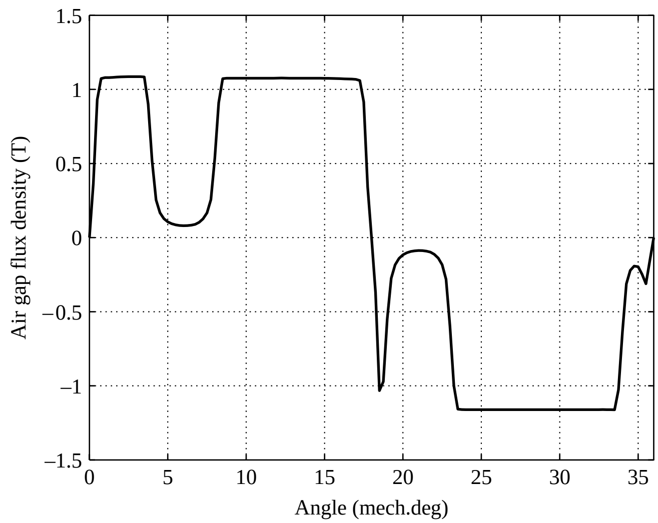

Figure 13.
No-load air gap flux density versus the mechanical angle obtained with flux concentrating PMs rotor with the stator slotting effect taken into account

Then, a case study has been treated where both surface mounted PM and flux concentrating PM machines have been considered. The study has been focused towards both mmf and finite element analysis. This latter allowed the investigation of the air gap flux density and the torque production capability of both machines.

It has been found that, although almost the same average torque is developed by both machines, the surface mounted PM one offers lower torque ripple compared to the flux concentrating PM machine one.

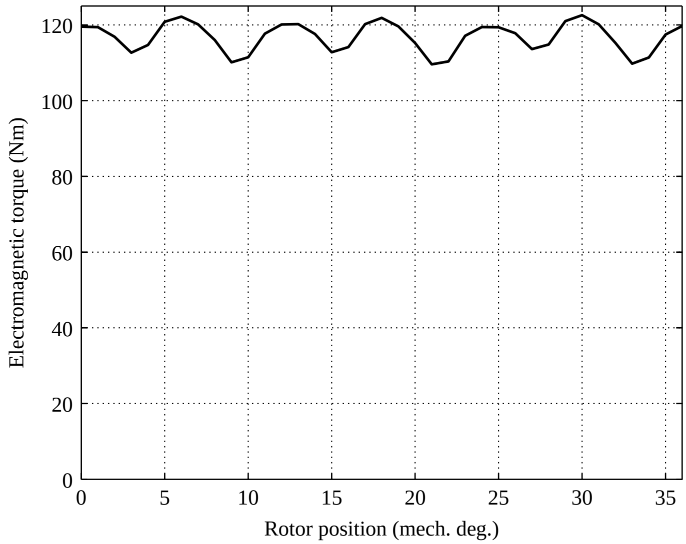

Figure 14. Electromagnetic torque versus the mechanical angle of flux concentrating PM machine considering a sinusoidal current supply with a current density of 15 A/mm^2

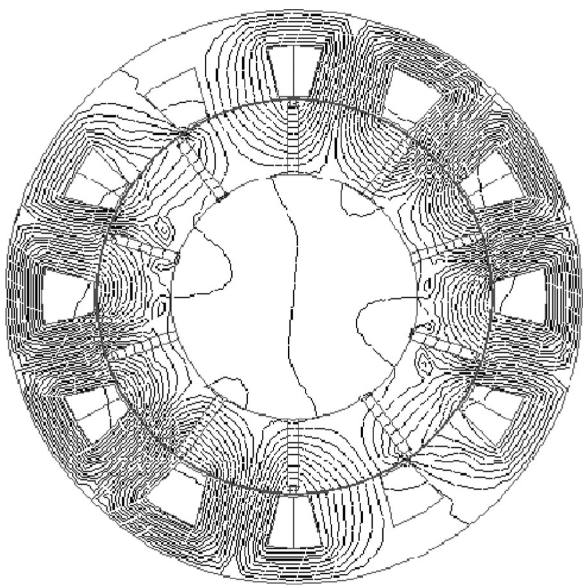

Figure 15. Flux line distribution of flux concentrating PM machine with the armature fed by sinusoidal current supply whose density is 15 A/mm^2

References

Abdennadher, I., Masmoudi, A. and Elantably, A. (2006), "An attempt to extend the flux weakening range of a single stator dual rotor PM machine", paper presented at International Conference on Electrical Machines (ICEM'06), CD-ROM.

Cros, J. and Viarouge, Ph. (2002), "Synthesis of high performance PM motors with conceentrated windings", *IEEE Transactions on Energy Conversion*, Vol. 17 No. 2, pp. 248-53.

El-Refaie, A.M. and Jahns, T.M. (2004), "Optimal flux weakening in surface PM machines using concentrated windings", paper presented at IEEE Industry Applications Society Annual Meeting, CD-ROM.

Libert, F. and Soulard, J. (2004), "Investigation on pole-slot combinations for permanent magnet machines with concentrated windings", paper presented at International Conference on Electrical Machines (ICEM'04), CD-ROM.

Magnussen, F. and Sadarangani, C. (2003), "Winding factors and joule losses of permanent magnet machines with concentrated windings", *Electric Machines and Drives Conference (IEMDC'03)*, Vol. 1, pp. 333-9.

Masmoudi, A., Ben Hamadou, G., Abdennadher, I. and Masmoudi, A. (2008), "FMM based investigation of the torque production capability of a class of concentrated winding brushless synchronous machines", paper presented at the 3rd International Conference on Ecological Vehicles and Renewable Energies, CD-ROM.

Salminen, P., Niemel, M., Pyrhnen, J. and Mantere, J. (2004), "Performance analysis of fractional slot wound PM-motors for low speed applications", paper presented at IEEE Industry Applications Society Annual Meeting, CD-ROM.

Skaar, S.E., Krovel, O. and Nilssen, R. (2006), "Distribution, coil-span and winding factors for PM machines with concentrated windings", paper presented at International Conference on Electrical Machines (ICEM'06), CD-ROM.

About the authors

Imen Abdennadher received the BS in Electromechanical Engineering in 2005 and the Master in Electric Machine Analysis and Control in 2006, both from Sfax Engineering School, University of Sfax, Tunisia. She is a Member of the Research Unit on Renewable Energies and Electric Vehicles (RELEV) of the University of Sfax. She is a Member of the Organizing Committee of the International Conference on Power Electrical Systems scheduled within the International Multiconference on Systems, Signals and Devices (SSD). She is a Member of the Organizing Committee of the International Workshop on Electric and Hybrid Automotive Technologies (WAT): a biannual workshop organized and supported by the RELEV, since 2003. She is currently preparing her PhD dealing with the design of concentrated winding surface mounted permanent magnet machines.

Ahmed Masmoudi received the BS degree from Sfax Engineering School (SES), University of Sfax, Tunisia, in 1984, the PhD from University Pierre and Marie Curie, France, in 1994, and the Research Management Ability degree from SES, in 2001, all in Electrical Engineering. He joined Schlumberger Ltd, Paris, France, in 1984 as a Field Engineer, then the Tunisian Official Press as the Manager of the Phototypesetting Department, in 1985. In April 1988, he joined the Tunisian University where he held different positions involved in both education and research activities. He is currently a Professor of Electric Power Engineering at SES. He is the Manager of the Research Unit on Renewable Energies and Electric Vehicles of the University of Sfax. He is the general Co-chairman of the IEEE International Conference on SSD. He is an Associate Researcher with Allison Transmission Division of General Motors, Indianapolis, Indiana, USA. He is a Senior Member of IEEE. His current interests include the design of emergent converter-fed machines and the implementation of advanced control strategies in machine drives, applied in automotive as well as in renewable energy systems. Ahmed Masmoudi is the corresponding author and can be contacted at: a.masmoudi@enis.rnu.tn

Ahmed Elantably received the BS Electrical Engineering from Cairo University (Egypt) in 1968, the MS in Control Engineering, and the PhD in Electrical Engineering, both from Sussex University, UK, in 1975 and 1980, respectively. He has been with Westinghouse Electric Corporation, USA from 1980 to 1989. He joined Delphi Energy and Engine Management Systems, General Motors Corporation, in 1989. He has designed the induction motor used in the electric vehicle EV1 manufactured by General Motors, and several larger motor; up to 250 kW used in hybrid application cars, buses, and trucks. In 1998, he moved to Allison Transmission Division of General Motors, where he is currently involved the development of novel motor technologies for hybrid propulsion applications. He is the inventer of many patents, and the author of several papers. He is a Senior Member of IEEE. He is a Member of the Editorial Board of the international journal *Electric Power Components and Systems*. He is the Member of the Scientific Committee of many international conferences.