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Influence of asymmetries in stator back iron of PMS motors to the level of cogging torque components

Abstract. *A study presents a dependence of the level and harmonic structure of a cogging torque in PM motors to interlocks and notches in stator back iron, which are standard methods for stator lamination stacking. It has been established that technologies for stacking lamination packs are causing local saturation peaks in back iron which give rise to additional cogging torque harmonic components and consequently increase the total cogging torque. The estimation of the substitutive relative permeability of the interlock soft magnetic material is also discussed.*

Streszczenie. *Artykuł prezentuje zależność poziomu i struktury harmonicznej momentu bezprądowego w silnikach z magnesem trwałym i wycięciami w rdzeniu stojana ze wstecznym żelazem – są to standardowe metody dla składania warstwowego stojana. Trzeba dać sobie sprawę, że technologie składania blach. Powoduje to lokalne nasycenia, które w efekcie dają wzrost momentu bezprądowego. Przedyskutowano .zastępczą przenikalność magnetyczną. (**Wpływ asymetrii w silniku maszyny elektrycznej na składniki momentu bezprądowego**)*

Keywords: cogging torque, finite-element method, harmonic components, PM synchronous motor.
Słowa kluczowe: moment bezprądowy, metoda elementów skończonych, składowe harmoniczne silnik synchroniczny z magnesem trwałym

Introduction

High-performance drives in automotive applications require permanent magnet synchronous motors (PMSM) that produce smooth torque with a very low component of cogging torque. This is not easy to attain as improper design of PMSMs results in cogging torque that may be as high as 25 % of the rated torque. In many commercially available machines, it has typically a nominal value of 5 % ÷ 10 % of the rated torque [1]. A number of high-performance applications necessitate cogging torque not to exceed 1 % of the rated torque [2]. Therefore, methods for analysis and computation of the cogging torque are required to design machines that meet the required specifications. Minimization of cogging torque often becomes a challenging task, since it is composed of several harmonic components, which originate in combination of many design parameters and material or assembly imperfections [3, 4]. A parametric finite element method (FEM) was used to study the influence of notches and interlocks in the stator back iron of PMSM on the level of additional cogging torque components.

Cogging torque harmonic components

Cogging torque T_{cog} arises from the interactions between each edge of rotor permanent magnets (PM) as the source of the air-gap flux and stator slot openings as the source of the varying air-gap reluctance [1]. The air-gap reluctance varies periodically, thus causing the T_{cog} to be a periodical function composed of two main components [4]

$$T_{cog}(\alpha) = \sum_{i=1}^{\infty} A_{NHC\,i} \cdot \sin(N_{NHC\,i} \cdot \alpha + \varphi_{NHC\,i}) + \sum_{i=1}^{\infty} A_{AHC\,i} \cdot \sin(N_{AHC\,i} \cdot \alpha + \varphi_{AHC\,i}) \tag{1}$$

where: α - rotor angular position, NHC - array of native harmonic components, AHC - array of additional harmonic components, φ - phase shift, A - amplitude of harmonic component, N - order of harmonic component.

Native harmonic components NHC of cogging torque T_{cog} have orders defined as

$$N_{NHC\,i} = \mathrm{LCM}(Q, P) \cdot i \tag{2}$$

where: LCM - least common multiple, Q - number of stator slots, P - number of rotor magnetic poles, i – integer.

Native harmonic components of cogging torque NHC exist always, even in ideally manufactured motors, and can be efficiently evaluated by FEM calculations [2, 3]. A variety of methods are known to minimize NHC in PM motors. Theoretically, it is even possible to eliminate NHC, but in practice they can only be substantially minimized applying proper design methods [2, 5].

Additional harmonic components AHC of cogging torque T_{cog} appear only in PM motors with irregularities, which mostly result from mass-production like PM magnetic material inhomogeneity, variance in PM dimensions, PM and stator teeth misplacements due to assembly tolerances, magnetic asymmetries in stator lamination, additional notches or interlocks in stator lamination, etc. [4]. A sensitivity of PM motor designs to the phenomenon of AHC mostly depends on the motor design parameters [6].

Several parametric FEM models were analyzed in order to observe AHC due to stator lamination imperfections, which cannot be avoided in mass-production of PMSMs. The soft magnetic material used in stator lamination is not truly isotropic due to grain orientation and manufacturing process such as punching, stamping and laser cutting [3]. Additionally, methods of stacking up the lamination such as welding or interlocking can also considerably increase AHC [7]. Orders of AHC yielding from such effects are

$$N_{AHC\,E\,i} = \mathrm{LCM}(E, P) \cdot i \tag{3}$$

where E is the number of symmetrically distributed notches or interlocks in the stator back iron (Fig. 1). Notches on the stator lamination's outer diameter are necessary as indexing positions in the process of winding insertion and for welding joints. Another possibility to attain stiffness of the stator lamination is to make several interlocks in the stator back iron. Both, notches and interlocks introduce asymmetry of magnetic field distribution in the stator core, which leads to increased level of AHC having orders defined by (3).

Modeling of interlocks - FEM calculations and experimental results

A PM motor with Q = 27 and P = 6, which is manufactured in mass-production with a demand for an extremely low level of cogging torque T_{cog} (less than 6 mNm), has been modeled and tested to evaluate presented theoretical considerations.

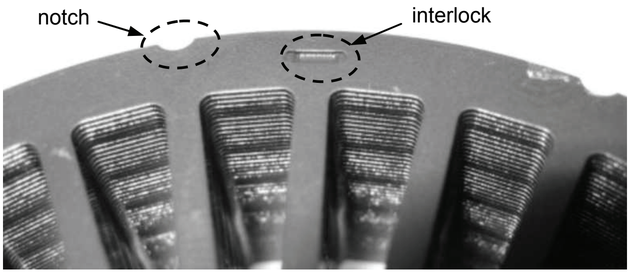

Fig.1. Stator lamination with notches and interlocks in the back iron

Initial stator lamination has no interlocks (E = 0) and 9 additional notches on the stator lamination's outer diameter (Fig. 3a). The additional harmonic component for this initial FEM model with 9 notches representing indexing positions needed in the process of winding insertion has an order $N_{AHC\,1}$ = 18 according to (3), the calculated amplitude is $A_{AHC\,1}$ = 0.42 mNm, and the measured one is 0.45 mNm (Table I, E = 0). Interlocks E are symmetrically punched in the stator lamellas due to manufacturing demands, but their number significantly influence on orders $N_{AHC\,i}$ and amplitudes $A_{AHC\,i}$ of the AHC [7]. A special stator lamination stack with glued lamellas was prepared to study this phenomenon (Fig. 3 and Fig. 4). The holes were drilled in the stator lamination equally to the positions in FEM models with the same diameter (2.3 mm).

In the model with E = 1 (Fig. 3b) there is one area having different magnetic properties in comparison to the others due to the interlock in the back iron (Fig. 2). Local saturations are clearly seen in the root of the affected tooth, resulting in slight magnetic field deformation near slot openings around these teeth in the air-gap region. A fast Fourier transform (FFT) of FEM computations reveals AHC components having orders $N_{AHC\,1}$ = 6, $N_{AHC\,2}$ = 12, and $N_{AHC\,3}$ = 18 according to (3) with corresponding simulated and measured amplitudes (Table I, E = 1).

When placing three interlocks (E = 3) in the stator lamination (Fig. 4a), the orders of AHC remained the same as in the case of E = 1, and the component $A_{AHC\,1}$ has nearly doubled due to more expressed magnetic asymmetry in the stator back iron. The component $N_{AHC\,3}$ = 18 of the amplitude $A_{AHC\,3}$ = 0.42 mNm is almost constant and exists owing to 9 notches on the stator lamination's outer diameter.

The last FEM model has E = 9 (Fig. 4b) and reveals the same orders of AHC as the initial model (Table I, E = 9). However, amplitude value of $N_{AHC\,1}$ = 18 has increased almost four times to $A_{AHC\,1}$ = 1.63 mNm in comparison to the model with E = 0. Notice that changing the number of symmetrically distributed interlocks from E = 3 to E = 9 has also modified harmonic spectrum of AHC components. The orders $N_{AHC\,i}$ and amplitudes $A_{AHC\,i}$ of this components depend on chosen number and positions of this stacking elements in stator back iron, thus the optimal number of interlocks must be selected in order to minimize the effect of AHCs [7]. Calculated and measured results presented in Table I are also shown in Fig. 5 in graphic form.

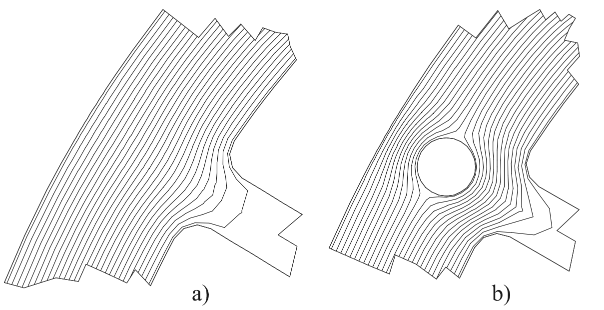

Fig. 2. Magnetic field distribution in stator back iron:
(a) without interlock, (b) with circular shape interlock

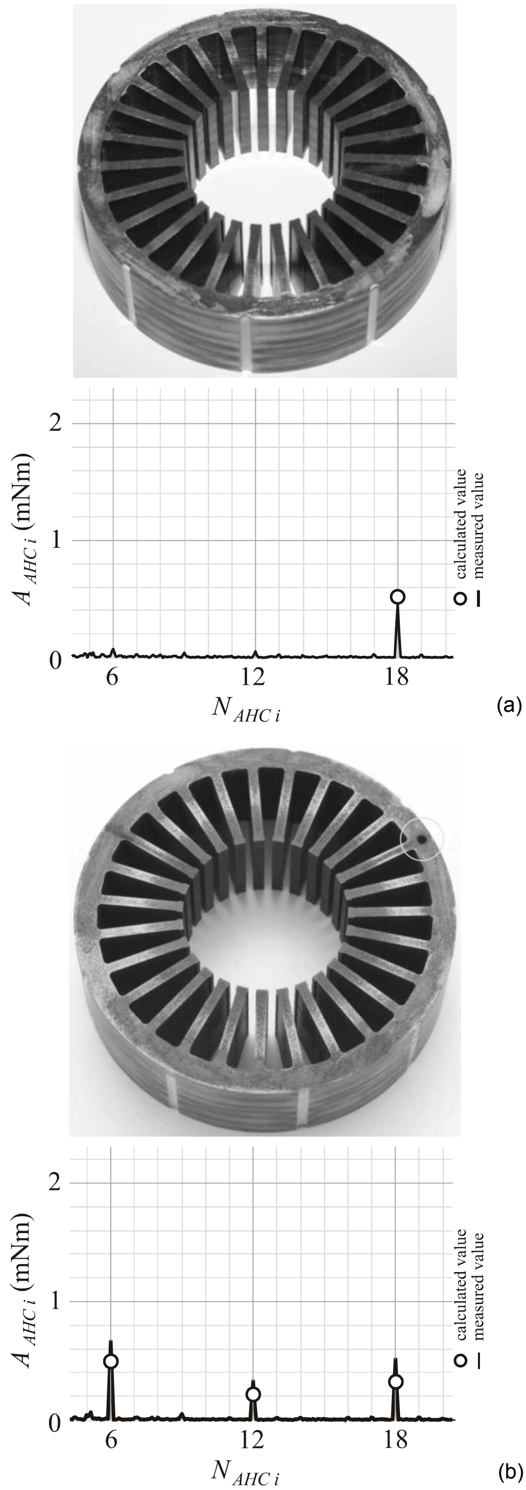

Fig. 3. Stator lamination of tested PMSM with Q = 27, P = 6 and interlocks in back iron with corresponding simulated and measured results of $N_{AHC\,i}$ and $A_{AHC\,i}$: (a) E = 0, (b) E = 1

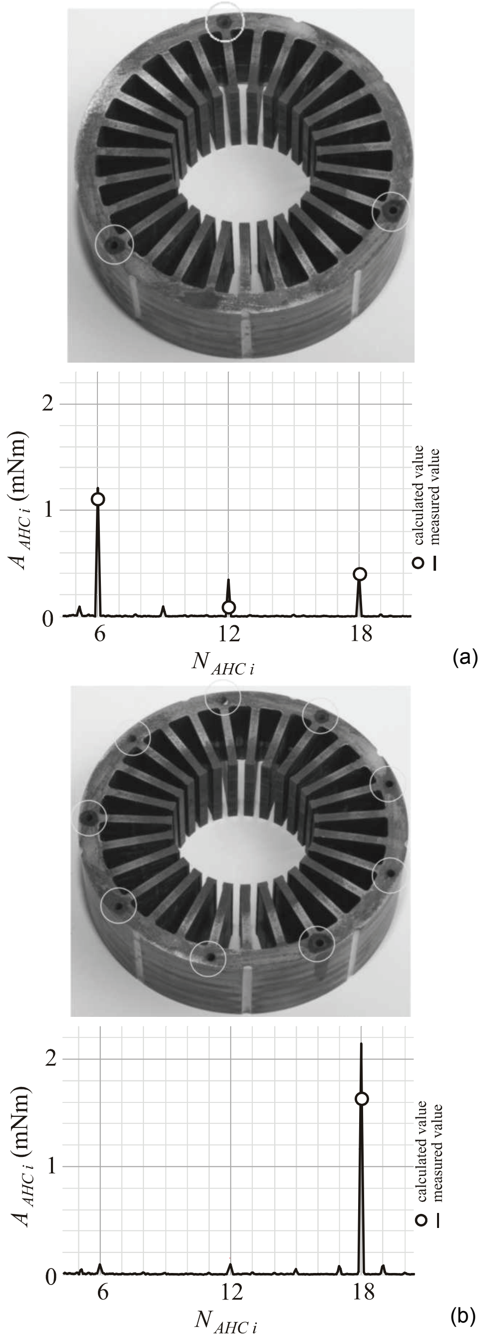

Fig. 4. Stator lamination of tested PMSM with Q = 27, P = 6 and interlocks in back iron with corresponding simulated and measured results of $N_{AHC\,i}$ and $A_{AHC\,i}$: (a) E = 3, (b) E = 9

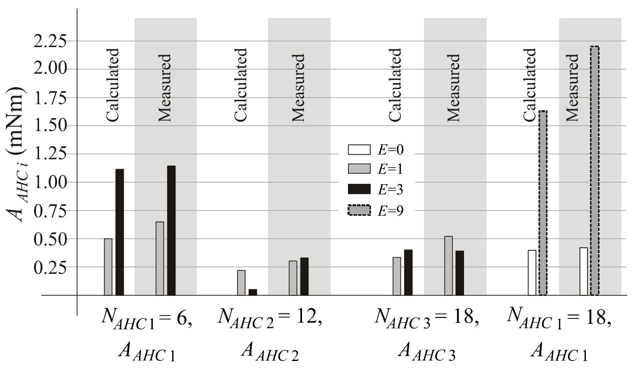

Fig. 5. Gathered results of cogging torque components for a model Q = 27, P = 6 and E = 0, E = 1, E = 3, and E = 9

Table I. Components $A_{AHC\,i}$ for a selected model of Q = 27, P = 6 and increasing number of interlocks E

Calculated $A_{AHC\,i}$ [mNm]			
Number of interlocks	$N_{AHC\,1}$ = 6 $A_{AHC\,1}$	$N_{AHC\,2}$ = 12 $A_{AHC\,2}$	$N_{AHC\,3}$ = 18 $A_{AHC\,3}$
E = 1	0.50	0.22	0.37
E = 3	1.15	0.05	0.42
			$N_{AHC\,1}$ =18 $A_{AHC\,1}$
E = 0	/	/	0.42
E = 9	/	/	1.64
Measured $A_{AHC\,i}$ [mNm]			
Number of interlocks	$N_{AHC\,1}$ = 6 $A_{AHC\,1}$	$N_{AHC\,2}$ = 12 $A_{AHC\,2}$	$N_{AHC\,3}$ = 18 $A_{AHC\,3}$
E = 1	0.68	0.32	0.51
E = 3	1.20	0.35	0.41
			$N_{AHC\,1}$ =18 $A_{AHC\,1}$
E = 0	/	/	0.45
E = 9	/	/	2.18

Determination of adequate relative permeability for interlocks

Interlocks in the stator lamination are formed during stamping by pressing material in such a way that on one side of the stator lamination there are hollows while on the other side there are pins (Fig. 6). Interlocks must be created very precisely in order to form a solid stator lamination by pressing several lamellas together. In sections, where interlocks are positioned, the lamination is heavily stretched and consecutively the relative permeability μ_r of the material is reduced.

Several authors simplify the modeling of interlocks by assigning them the relative permeability of air μ_r = 1 not taking into account that they are of soft magnetic material with only a reduced value of the relative permeability. For precise simulation of PMSM's cogging torque an exact estimation of interlocks' relative permeability has to be carried out.

The stator lamination stack of the model Q = 27, P = 6 with number of interlocks E = 9 and without 9 notches was analyzed. The μ_r in the parts of the lamination where interlocks are positioned were changed by steps from 1 to 3000 and amplitude values of $N_{AHC\,1}$ = 18 were calculated. When choosing the μ_r = 1, the amplitude value of $N_{AHC\,1}$ = 18 is $A_{AHC\,1}$ = 1.87 mNm (Fig. 7). By increasing the value of μ_r up to 1150, the amplitude values of $N_{AHC\,1}$ = 18 fall down to $A_{AHC\,1}$ = 0.00 mNm which means that the μ_r of the interlocks is equal to μ_r of the back iron in the stator lamination stack and no asymmetry is present. A further increase of μ_r arises the amplitude value of $N_{AHC\,1}$ = 18 once again as modeled areas with higher μ_r anew insert anomalies in the stator back iron.

In further analysis a real model Q = 27, P = 6 having 9 notches (shape of circular segment as shown in Fig. 1) and 9 interlocks (shaped rectangular as shown in Fig. 1 and Fig. 6) has been considered. A similar behavior of amplitude values of $N_{AHC\,1}$ = 18 can be observed since 9 notches have constant contribution to the amplitude value of $N_{AHC\,1}$ = 18. The curve minimum in this case is not at the same value of μ_r in comparison to the previous case due to the phase shift between notches and interlocks. The measured amplitude value for $N_{AHC\,1}$ = 18 is $A_{AHC\,1}$ = 0.55 mNm, consequently μ_r can be estimated around 220 for this particular PMSM model.

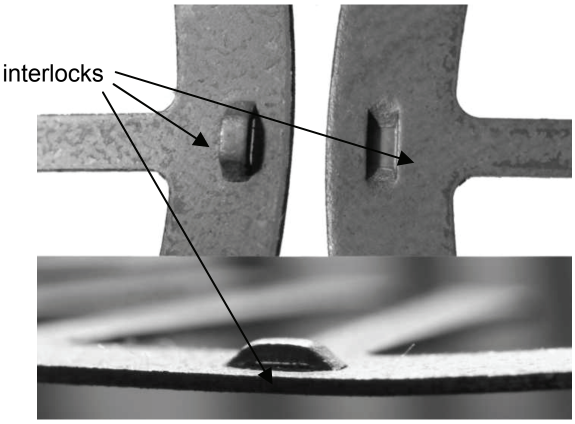

Fig. 6. Interlocks in the stator lamination

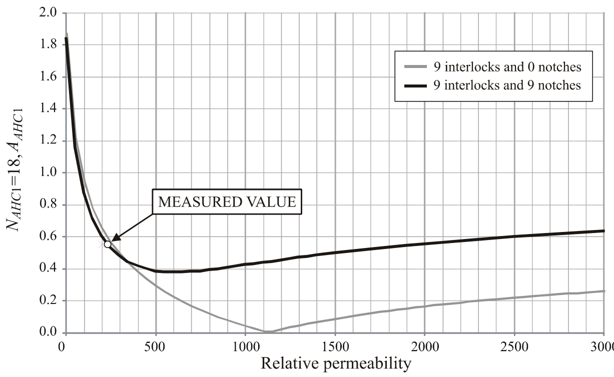

Fig. 7. Calculated amplitude values of $N_{AHC\,1}$ = 18 for determination of interlocks' relative permeability

Conclusions

FEM computations and FFT analysis along with experimental results have proved that notches and interlocks in stator lamination stack cause additional cogging torque components AHC. The orders and amplitudes of this components depend on chosen number and positions of this stacking elements in stator laminations. Considering the theory introduced, motor designers are able to predict and evaluate new harmonic components in T_{cog}. In this way the optimal stacking method can be selected in order to minimize the effect of AHC, thus fulfilling stringent demands for low cogging torque level in PMSMs.

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