ISSN 0005-1144
ATKAFF 51(2), 157–165(2010)

Andrej Černigoj, Lovrenc Gašparin, Rastko Fišer

Native and Additional Cogging Torque Components of PM Synchronous Motors – Evaluation and Reduction

UDK 621.313.32.073.1
IFAC 5.5.4; 3.1.1

Original scientific paper

High performance motor drive applications require permanent–magnet synchronous motors that produce smooth torque with very low components of cogging torque. To fulfil such demands a variety of design techniques can be used to reduce or even eliminate cogging torque components. Rotor design techniques are in comparison to the stator ones much more effective, but their effectiveness depend considerably on the motor design parameters. Calculations have shown that the cogging torque can be significantly reduced while maintaining the output torque at the same level by the appropriate use of two or more presented techniques. However, the detailed analysis of cogging torque components has revealed that besides well-know native cogging torque components also additional cogging torque components exist which are provoked by assembly tolerances in mass–production. Since these two groups of cogging torque components are concerning design techniques mostly in contradiction, a minimization of the total cogging torque becomes a challenging task. A finite element method and Fast Fourier transformation were used to study the sensitivity of several motor simulation models with regard to manufacturing tolerances and assembly imperfections. On the bases of numerous simulations and analyses, it follows that manufacturing assembly tolerances and material imperfections cause the phenomena of additional cogging torque harmonic components, which are not present in the case of a perfect motor. The ascertainment that some permanent–magnet motor designs are more sensitive to the phenomenon of additional harmonic components in cogging torque than the others is an important fact for the producers of such motors, which must be seriously considered in the process of motor design optimization.

Key words: Cogging torque, Design optimization, Magnetic field, Permanent–Magnet motors

Prirodne i dodatne komponente pulsirajućeg momenta zbog ozubljenja kod sinkronog motora s permanentnim magnetima – procjena i njihovo smanjenje . Za sinkrone motore s permanentnim magnetima koji se primjenjuju u elektromotornim pogonima s visokim zahtjevima na radne karakteristike, mora se osigurati niska razina komponenata pulsirajućeg momenta nastalog zbog ozubljenja statora. Za ispunjenje toga zahtjeva koriste se razne. Tehnike izvedbe rotora u usporedbi s tehnikama izvedbe statora mnogo su efikasnije, međutim efikasnost u značajnoj mjeri ovisi o izvedbenim parametrima rotora. Proračuni su pokazali da se uz zadržavanje iznosa izlaznog momenta stroja, pulsirajući moment može značajno smanjiti primjenom dviju ili više tehnika prezentiranih u radu. Međutim, detaljna je analiza komponenata pulsirajućeg toka pokazala da se pored komponenata tzv. prirodnog pulsirajućeg momenta zbog ozubljenja, pojavljuju i dodatne komponente koje su rezultat slaganja dijelova stroja u masovnoj industrijskoj proizvodnji. Budući da eliminacija tih dviju grupa pulsirajućeg momenta zbog ozubljenja rezultira kontradiktornim zahtjevima na tehnološku izvedbu stroja, eliminacija ukupnog pulsirajućeg momenta zbog ozubljenja predstavlja zahtjevan i izazovan zadatak za projektanta. U radu se koriste metoda konačnih elemenata i brza Fourierova transformacija za analizu osjetljivosti izabranih simulacijskih modela s obzirom na tolerancije u proizvodnji i na nesavršenosti pri sklapanju dijelova stroja. Na osnovi brojnih simulacija i analiza pokazano je da tolerancije u proizvodnji i tolerancije u samim dijelovima stroja rezultiraju dodatnim harmoničkim komponentama pulsirajućeg toka, koje nisu prisutne u idealnom stroju. Činjenica da su neke izvedbe motora osjetljivije od drugih s obzirom na fenomen dodatnog pulsirajućeg momenta, proizvođačima je važna činjenica koja se mora uzeti u obzir u fazi projektiranja motora.

Ključne riječi: optimiranje dizajna, pulsirajući moment zbog ozubljenja, magnetsko polje, motor s permanentnim magnetima

1 INTRODUCTION

Permanent–magnet synchronous motors (PMSM) are widely used in industrial drives for high performance applications due to high torque density, high efficiency, easy speed control, low noise and vibration in comparison to other types of electric motors. In PMSM, inherent cogging torque exists that creates torque ripple and prevents smooth rotation of the motor. Cogging torque results from the interaction of permanent magnet (PM) *mmf* harmonics and air–gap permeance harmonics due to stator slotting. It manifests itself by the tendency of a rotor to align in a number of stable positions even when the motor is unexcited. Produced cogging torque does not contribute to an output torque of the motor, thus its minimization becomes necessary.

In the past, numerous methods have been developed and presented by many authors to reduce this problem of PM motors [1]–[7]. This proves a high importance of cogging torque minimization not only in top quality PMSM drives but also in a mass–production of PMSMs. Several well-known design techniques [2]–[7] can be used to minimize this parasitic harmonic torque components, but most of them consequently reduce the output torque as well. The presented paper among others discusses and quantifies compromises among reducing the cogging torque in connection with preserving the main output torque at a high value in order to optimize the PMSM design for a specific drive application.

Our research and experiences from mass–production show that this well–know methods for cogging torque reduction are often not working as expected in practice. Even more, on some PM motor designs a cogging torque can be enhanced by implementation of such methods. Frequently, PM motors produced in the same batch may have significantly different value of the cogging torque. It was found out and proved that assembly tolerances in mass–production give rise to additional cogging torque components, therefore a minimization of cogging torque becomes a challenging task [8]–[10]. The other but more complicated option for cogging torque reduction is to introduce advanced control methods of the drive [11].

2 COGGING TORQUE COMPONENTS

Cogging torque is a periodical function and can be considered as a sum of interactions between each edge of rotor PM and stator slot openings, thus a study of cogging torque can be based on analysis of these interactions. Harmonic components of cogging torque (*HC*) depend on design parameters, assembly tolerances and/or PM imperfections [7]–[10]. For a clearer interpretation *HC* should be separated and examined with regard to the cause of existence:

1. *Native harmonic components* (*NHC)* of cogging torque are the consequence of motor design parameters and exist always, even in ideally manufactured motors, and can be easily calculated and evaluated by finite element method (FEM) simulations. A variety of methods are known to reduce *NHC* in PM motors [2]–[7].

2. *Additional harmonic components* (*AHC)* of cogging torque appear only in PM motors with irregularities, which are common in mass–produced motors (PM and stator teeth misplacements and/or PM width and thickness variations). To observe *AHC* several parametric FEM models were applied to simulate such faults [8]–[10].

Harmonic component of cogging torque can be considered as a sum of

$$HC = NHC + AHC, \tag{1}$$

where *NHC* and *AHC* consist of vector arrays:

$$NHC\ (A_{NHC\ i}\ ,\ N_{NHC\ i}\ ,\ \varphi_{NHC\ i}), \tag{2}$$

$$AHC\ (A_{AHC\ i}\ ,\ N_{AHC\ i}\ ,\ \varphi_{AHC\ i}), \tag{3}$$

where *A* stands for an amplitude, *N* for a number of repetitions in mechanical revolution (order of harmonic component), φ for a phase shift, and *i* = 1, 2, 3, ... Cogging torque *Tcogg* is a periodical function, which depends on rotor angular position α and is composed of two components

$$T_{cogg}(\alpha) = T_{NHC}(\alpha) + T_{AHC}(\alpha), \tag{4}$$

where *TNHC* is a composed component of *NHC* contributions and *TAHC* is a composed component of *AHC* contributions. For more clear interpretation, *TNHC* and *TAHC* can be represented as a sum of sine functions:

$$T_{NHC}(\alpha) = \sum_{i=1}^{\infty} A_{NHC\ i} \cdot \sin(N_{NHC\ i} \cdot \alpha + \varphi_{NHC\ i}), \tag{5}$$

$$T_{AHC}(\alpha) = \sum_{i=1}^{\infty} A_{AHC\ i} \cdot \sin(N_{AHC\ i} \cdot \alpha + \varphi_{AHC\ i}). \tag{6}$$

Native harmonic components *NHC* of cogging torque have orders defined by the following expression

$$N_{NHC\ i} = LCM(Q,P) \cdot i, \tag{7}$$

where LCM stands for the least common multiple, *Q* is the number of stator slots, *P* is the number of rotor magnetic poles and *i* = 1, 2, 3, ... for a motor with ideally distributed PM and equally spaced teeth on the stator [2].

Additional harmonic components *AHC* of cogging torque originate from several possible stator and rotor assembly and material imperfections. Their orders are defined as

$$N_{AHC\ T\ i} = P \cdot i, \tag{8}$$

$$N_{AHC\ E\ i} = LCM(E, P) \cdot i, \tag{9}$$

$$N_{AHC\ R\ i} = Q \cdot i, \tag{10}$$

where components $N_{AHC\ T\ i}$ are caused by stator teeth misplacements, $N_{AHC\ E\ i}$ are the consequence of interlocks in stator back-iron, *E* is the number of symmetrically distributed interlocks, and $N_{AHC\ R\ i}$ are due to rotor PM misplacements and/or width and thickness variations, respectively. Their detailed explanations and analyses are in [8]-[10]. Fig. 1 shows the complex structure of harmonic components *HC* in the total cogging torque T_{cogg}.

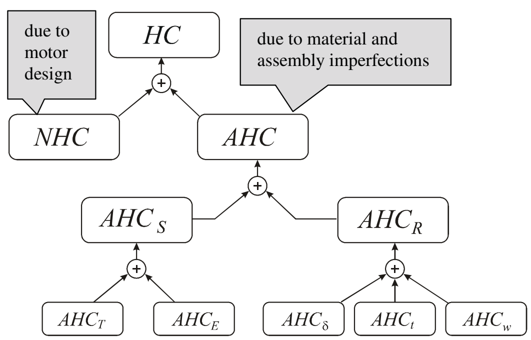

Fig. 1. Cogging torque harmonic components

3 DESIGN TECHNIQUES FOR REDUCTION OF NATIVE HARMONIC COMPONENTS

For effective reduction of *NHC* and consecutively T_{cogg}, while keeping the output torque T_0 at the same level, the proper slot/pole combination has to be selected. Beside this, for a given motor, the following design techniques should be considered:

1. magnet span variation,
2. magnet pole shifting,
3. selection of magnet shape and magnetization pattern,
4. step skew or skewing of magnets,
5. variation of slot opening in stator lamination, additional notches in stator teeth.

Because of the complexity of the given task, the full parametric FEM model of 36-slot and 6-pole PMSM was chosen (Fig. 2). Due to a slot/pole combination basic design will express a significant cogging torque, thus the cogging torque reduction using and combining aforementioned design techniques can be observed [7].

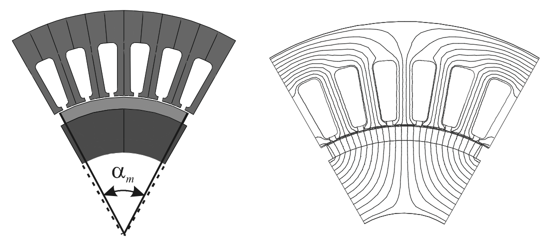

Fig. 2. FEM model segment with marked magnet span α_m (left), and flux distribution in model segment (right)

3.1 Rotor design techniques – selection of magnet span with magnet pole shifting

Effective way to reduce the cogging torque while maintaining the output torque T_0 is to optimize the magnet span α_m and shift magnet poles angle γ, as shown in Fig. 3. For the sake of simplicity, only the maximum of cogging torque versus magnet pole shift angle γ for different magnet spans α_m are shown in Fig. 4. The minimal cogging torque values appear around the shift angle γ = 56° and they are two to three times smaller than in the case of symmetrical magnet pole distribution (γ = 60°). The influence of magnet span αm on cogging torque values can also be observed and it is obvious that the minimum appears at α_m= 50°.

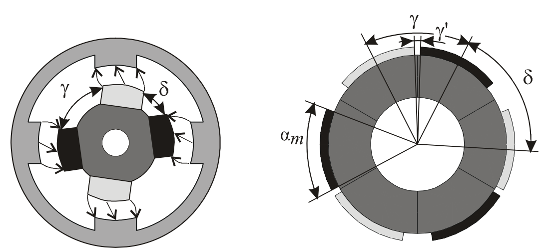

Fig. 3. Principle of shifted magnet poles, $\gamma \neq \delta$ (left), and shifted magnet poles on the rotor in FEM model (right)

A similar optimization of α_m and γ but for different model of 27-slot and 6-pole PMSM is shown in Fig. 5. It can be noticed that motor design parameters have significant influence on the sensitivity of this cogging torque reduction technique.

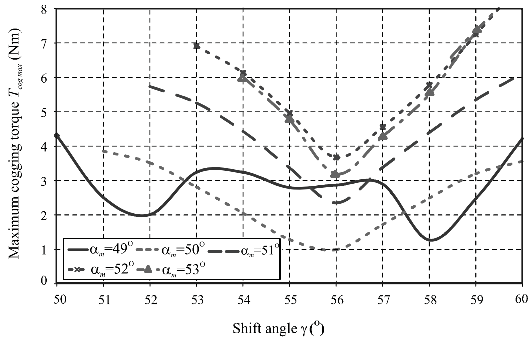

Fig. 4. Maximal cogging torque versus magnet pole shift γ (36/6 model)

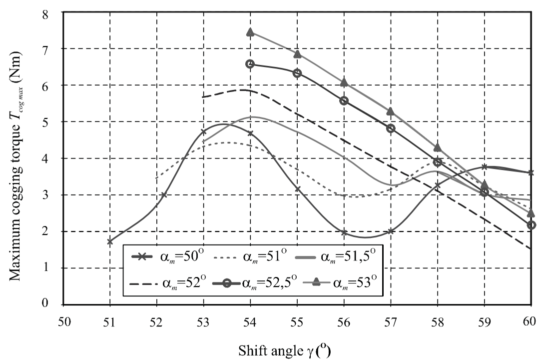

Fig. 5. Maximal cogging torque versus magnet pole shift γ (27/6 model)

3.2 Rotor design techniques – PM shape and magnetization pattern

Air-gap flux density distribution is strongly dictated by the shape and the magnetization pattern of applied PMs. Furthermore, this has a substantial influence on cogging torque, harmonic contents and magnetic saturation. Fig. 6 shows various shapes and magnetization patterns of arc magnets that are usually used for surface mounted PMSMs.

The influence of shape and magnetization pattern on the air-gap flux density distribution is presented in Fig 7. It is obvious that a "bread loaf" magnet shape flux density distribution is the closest to the desired sinusoidal distribution. The analysis of shape and magnetization pattern influence on cogging torque was carried out for all three shapes of PMs. Using a "bread loaf" magnet shape a minimal value of the cogging torque compared to the constant component of output torque T_0 is achieved, but the output torque is considerably reduced, as shown in Fig. 8. The shifted magnet poles with the selection of magnet span at the same time results in an efficient reduction of cogging

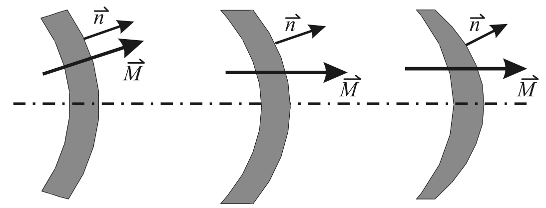

Fig. 6. Various shapes and magnetization patterns of PMs: surface radial (left), surface paralel (middle) and bread loaf (right)

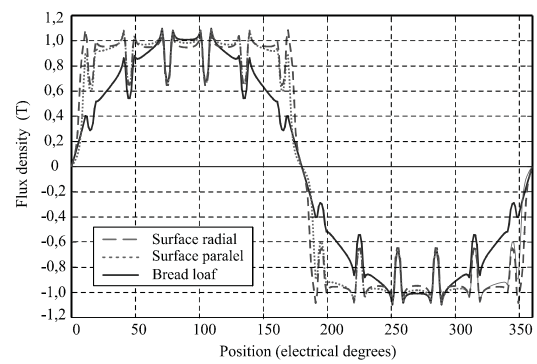

Fig. 7. Flux density along the center of the air-gap

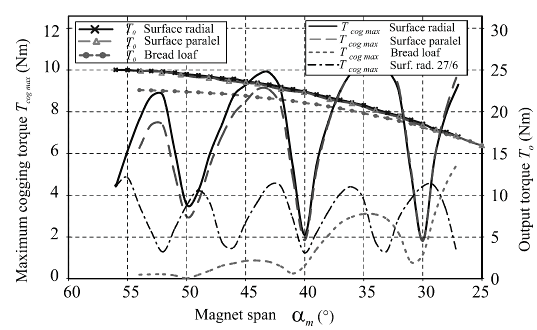

Fig. 8. Maximal cogging torque and output torque for various shapes and magnetization patterns of PMs versus magnet span α_m

torque and maintaining the level of the output torque T_0 (Table 1).

3.3 Stator design techniques – additional notches in stator teeth

Frequently used design technique for reducing the cogging torque is an introduction of additional notches in stator teeth (Fig. 9). Equally spaced notches result in an

Table 1. Torque results for certain rotor designs

Design technique	$T_{cog\,max}$ (Nm)	$T_{cog\,max}$ / T_0	T_0 / $T_{0\,basic\ mod.}$
Basic PMSM model (α_m=56°)	4,42	0,1768	1,00
Magnet span (α_m=40°)	2,10	0,0937	0,89
Magnet pole shifting with magnet span (γ =56°, α_m=50°)	0,99	0,0404	0,98
Bread loaf magnet shape	0,024	0,0011	0,89

increased number of interactions between rotor PMs and stator slots and consecutive in a reduced value of cogging torque. The number of additional notches must be respected in order to achieve effective reduction [3]. The influence of one and two semi-circle shaped additional notches in stator teeth was examined by changing the notch radius R_{notch} for different magnet spans α_m. Calculated results for one additional notch in stator teeth determine that this design technique is inefficient for 36-slot and 6-pole PMSM. Excessive R_{notch} leads to the cogging torque increase (Fig. 10). Two additional notches in stator teeth are also inefficient and excessive R_{notch} significantly reduces the output torque due to the saturation effect in stator teeth.

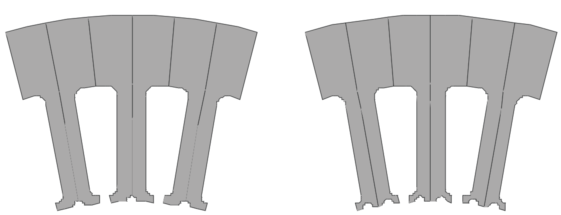

Fig. 9. FEM model segment with additional notches in stator teeth: one notch (left), two notches (right)

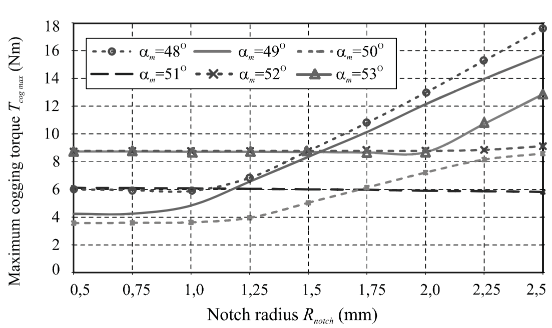

Fig. 10. Maximal cogging torque for one notch versus notch radius Rnotch and magnet span α_m

3.4 Stator design techniques – slot opening in stator lamination

The stator slot opening can have a significant effect on the level of the cogging torque. Generally, the amplitude of the cogging torque becomes smaller as the slot opening decreases [2]. In reality, each scenario may be different since it depends on the interaction of each edge of PM with the slot opening. The analysis shows that a decrease of slot opening reduces the cogging torque only in some cases. On the contrary, for magnet spans α_m= 50° and α_m= 51° the increase of slot opening reduces the cogging torque, as shown in Fig. 11. A decrease in output torque has been observed due to higher stator leakage at smaller slot openings. Stator design techniques are not as effective as the rotor ones. The results are displayed in Table 2.

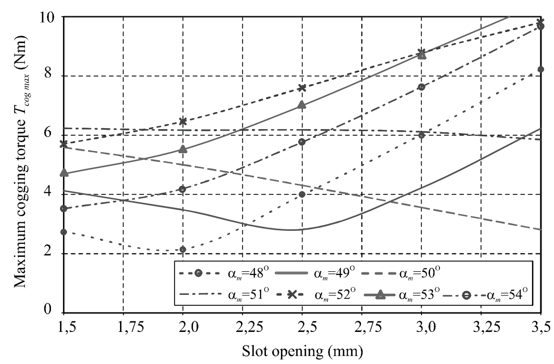

Fig. 11. Maximal cogging torque versus slot opening and magnet span α_m

Table 2. Torque results for certain stator designs

Design technique	$T_{cog\,max}$ (Nm)	$T_{cog\,max}$ / T_0	T_0 / $T_{0\,basic\ mod.}$
PMSM model (α_m=50°)	3,56	0,146	1,00
One additional notch (α_m=50°, R_{notch}=0,75 mm)	3,59	0,148	0,99
Two additional notches (α_m=50°, R_{notch}=0,75 mm)	3,86	0,158	0,99
Slot opening in stator lamin. (α_m=48°, slot opening 2,0 mm)	2,81	0,115	0,97

4 SENSITIVITY TO ADDITIONAL HARMONIC COMPONENTS OF COGGING TORQUE

Various parametric FEM models were developed also to study sensitivity of different PM motor designs to assembly tolerances and/or permanent–magnet imperfections, which cause *AHC* (see Fig. 1). To all parametric FEM models presented in the research were applied the same geometrical dimension like stator and rotor outer diameter, motor length and PM thickness. All other motor dimensions, for example stator teeth width and lenght, PM and back iron width, were optimized according to a particular chosen *P*, *Q* combination. One such example of a motor design is shown in Fig. 12.

Harmonic components of orders $N_{NHC\ 1}$ and amplitudes $T_{NHC\ max}$ has been calculated for symmetrical PM motor models having *P* (4, 6, 8) combined with different values of *Q* (12, 18, 24, 27, 30, 36). Only those combinations were considered, which can be wound with three phase winding and none of several well–know methods for reducing the amplitude of cogging torque [4] has been applied in presented simulations.

Most common assembly faults in mass–produced motors are PM and stator teeth misplacements. In favor of adequate comparison it has to be pointed out that for all presented FEM models and cogging torque computations were applied the same geometrical faults – one stator tooth shifted for 0.5 mm and one PM misplaced for 1°. Several additional harmonic components *AHC* of cogging torque T_{cogg} have been observed in all simulation results. For each case, $T_{AHC\ max}$ has been calculated and compared to the value of $T_{NHC\ max}$. Fig. 13 shows T_{cogg} and its components for a model *P* = 4 and *Q* = 18.

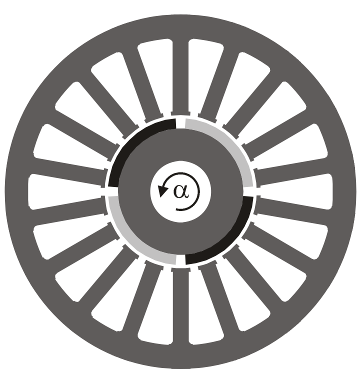

Fig. 12. FEM model P = 4, Q = 18

The sensitivity of PM motor designs to the phenomena of *AHC* of cogging torque due to assembly tolerances and/or PM imperfections is in close correlation with the number of cogging cycles per slot pitch [2]

$$F = \frac{N_{NHC\ 1}}{Q}. \qquad (11)$$

Parameter *F* of different motor designs influences strongly on the level of *AHC* and *NHC* components, which is demonstrated by following simulation results for various motor *P* and *Q* combinations.

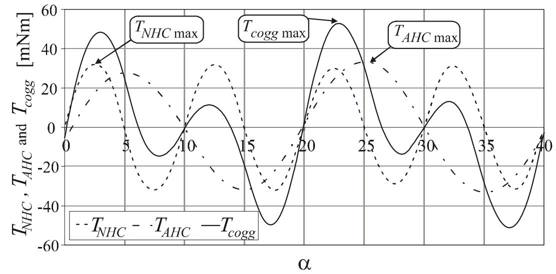

Fig. 13. Calculated signals T_{NHC}, T_{AHC}, and T_{cogg} for a model P = 4, Q = 18

4.1 PM model with *P* = 4

Calculated torques $T_{NHC\ max}$ (Tab. 3, column 5) seem to be in tight correlation with $N_{NHC\ 1}$ (Tab. 3, column 3) – the higher the value of $N_{NHC\ 1}$, the lower the value of $T_{NHC\ max}$ (Fig. 14). Calculated peak values of additional harmonic components $T_{AHC\ max}$ are presented in Tab. 3 (column 6). It can be easily noticed that $T_{AHC\ max}$ values are significantly increased in comparison to the $T_{NHC\ max}$ values (Tab. 3, column 7) in cases of motors having parameter *F* = 2 (*P* = 4, *Q* = 18 and *P* = 4, *Q* = 24). On the contrary, $T_{AHC\ max}$ values are negligibly low compared to the $T_{NHC\ max}$ for motors with *F* = 1. Models with *P* = 4, *Q* = 18 and *Q* = 36 have $N_{NHC\ 1}$ and also $T_{NHC\ max}$ of the same range. Sensitivity *F* differs between these two models. Model with *P* = 4, *Q* = 18 has sensitivity *F* = 2 and shows a significant raise of *AHC* compared to the model *P* = 4, *Q* = 36 having sensitivity *F* = 1.

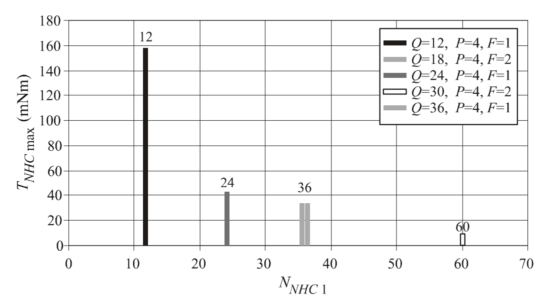

Fig. 14. Calculated T_{NHC} max related to N_{NHC} 1 for a PM motor model P = 4 and Q = 12, 18, 24, 30, 36

4.2 PM model with *P* = 6

FEM models with *P* = 6 can be divided into two groups regarding the $T_{NHC\ max}$ – the first group with high $T_{NHC\ max}$ values and the second group which has shown minimal $T_{NHC\ max}$ (Tab. 4, column 5, and Fig. 15). As

Table 3. Calculated parameters N_{NHC1}, F, T_{NHCmax}, $T_{AHC\ max}$ for models of P = 4 and Q = 12, 18, 24, 30, 36

P	Q	$N_{NHC\,1}$	F	$T_{NHC\,\max}$ [mNm]	$T_{AHC\,\max}$ [mNm]	$T_{AHC\,\max}$ / $T_{NHC\,\max}$ [%]
4	12	12	1	156	1	0.6
4	18	36	2	32	34	106
4	24	24	1	43	2	4.6
4	30	60	2	10	14	140
4	36	36	1	35	1	2.8

Table 4. Calculated parameters $N_{NHC\ 1}$, F, $T_{NHC\ max}$, $T_{AHC\ max}$, for models of P = 6 and Q = 18, 24, 27, 36

P	Q	$N_{NHC\,1}$	F	$T_{NHC\,\max}$ [mNm]	$T_{AHC\,\max}$ [mNm]	$T_{AHC\,\max}$ / $T_{NHC\,\max}$ [%]
6	18	18	1	185	6	3.2
6	24	24	1	75	3	4.0
6	27	54	2	1	6	600
6	36	36	1	135	15	11

stated the same irregularities on stator teeth and rotor PM were applied to all models. It can also be easily noticed that T_{AHC} max are significantly increased in comparison to the $T_{NHC\ max}$ (Tab. 4, column 7) in the case of motor design with parameter *F* = 2. On the contrary, values of $T_{AHC\ max}$ are negligibly low compared to the $T_{NHC\ max}$ for motor designs with *F* = 1.

Detailed observation of FEM models with *P* = 6, *Q* = 24 and *P* = 4, *Q* = 24 reveal that both share *F* = 1 and have the same $N_{NHC\ 1}$, furthermore, even the ratio $T_{AHC\ max}$ / $T_{NHC\ max}$ is of the same range. Calculated $T_{NHC\ max}$ for a model with *P* = 6 is higher than in case of a model with *P* = 4. As already mentioned, cogging torque may be considered as the sum of interactions between each edge of the rotor PM and stator slot openings, thus the study of cogging torque can be based on analysis of these interactions. In the case of *P* = 6 three edges of PM are passing the stator teeth compared to the two edges of PM in the case of *P* = 4. It can be expected that $T_{NHC\ max}$ will raise according to the increasing number of magnetic poles in the case of sensitivity *F* = 1.

4.3 PM model with *P* = 8

FEM models with *P* = 8 are especially interesting because of different possible sensitivities *F* = 1, *F* = 2 and *F* = 4 (Tab. 5, column 4). Calculated $T_{NHC\ max}$ on models differ from 1 mNm to 436 mNm (Tab. 5, column 5) and is in tight correlation with *F* and $N_{NHC\ 1}$ (Fig. 16). Considering the knowledge gained from earlier examples with *P* = 4 and *P* = 6, it is not a surprise that at higher values of sensitivity *F* (Tab. 5, column 4) $T_{NHC\ max}$ is decreasing, but on the other hand a rise of $T_{AHC\ max}$ is significant, which leads to high values of the ratio $T_{AHC\ max}$ / $T_{NHC\ max}$.

From Fig. 16 it is obvious that there exist two FEM models (*Q* = 12, *Q* = 24) which share the same $N_{NHC\ 1}$ but differ in $T_{NHC\ max}$ values for approximately 56 %. Sensitivity for the FEM model with *Q* = 12 is *F* = 2, on the contrary the FEM model with *Q* = 24 has *F* = 1. A careful reader can notice in Tab. 5 (column 3) and Fig. 16 that there is another pair (*Q* = 18 and *Q* = 36) sharing the same $N_{NHC\ 1}$ = 72 but due to different sensitivity (*F* = 2 and *F* = 4) the level of T_{NHC} max and T_{AHC} max also vary.

5 DISCUSSION AND RECOMMENDATIONS

The sensitivity of PM motor designs is in close correlation with the number of cogging cycles per slot pitch *F*, therefore PM motors can be divided in two groups.

In the first group with *F* = 1 the amplitude of T_{NHC} is typically high (Fig. 17). Manufacturing assembly tolerances and material imperfections have low influence on increasing amplitude value of T_{AHC} and do not contribute

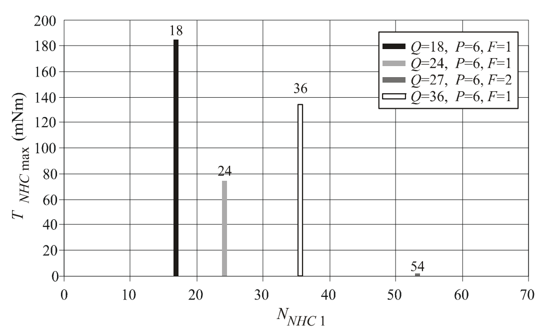

Fig. 15. Calculated $T_{NHC\ max}$ related to $N_{NHC\ 1}$ for a PM motor model P = 6 and Q = 18, 24, 27, 36

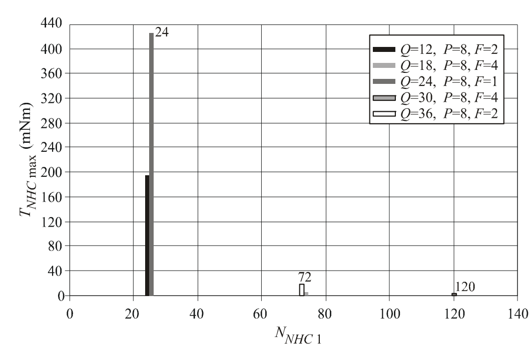

Fig. 16. Calculated $T_{NHC\ max}$ related to $N_{NHC\ 1}$ for a PM motor model P = 8 and Q = 12, 18, 24, 30, 36

Table 5. Calculated parameters $N_{NHC\ 1}$, F, $T_{NHC\ max}$, $T_{AHC\ max}$, for models of P = 8 and Q = 12, 18, 24, 30, 36

P	Q	$N_{NHC\ 1}$	F	$T_{NHC\ max}$ [mNm]	$T_{AHC\ max}$ [mNm]	$T_{AHC\ max}$ / $T_{NHC\ max}$ [%]
8	12	24	2	190	25	13
8	18	72	4	6	43	717
8	24	24	1	436	11	2.5
8	30	120	4	1	40	4000
8	36	72	2	15	28	187

significantly to the total value of cogging torque T_{cogg}. PM motor designs with F = 1 are not sensitive to phenomena of additional cogging torque harmonic components. Well–known methods to reduce cogging torque are working as expected on these PM motor designs and PM motors produced in the same batch have mostly very comparable values of the T_{cogg}.

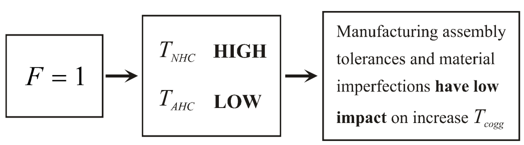

Fig. 17. The relationship between T_{NHC} and T_{AHC} for PM motor designs having the sensitivity F = 1

In the second group there are PM motors with $F > 1$ (Fig. 18), where the amplitude of T_{NHC} and consequently value of cogging torque T_{cogg} is low in cases of perfect PM motors without manufacturing imperfections. Even more, a higher value of F results in a lower amplitude value of T_{cogg}.

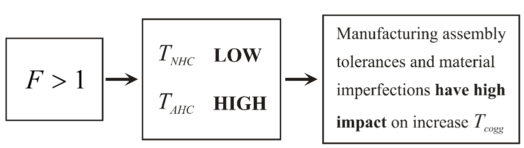

Fig. 18. The relationship between T_{NHC} and T_{AHC} for PM motor designs having the sensitivity $F > 1$

Therefore, some designers of PM motors are often misled by expectation for a very low T_{cogg} by selecting PM motors with $F > 1$ not knowing that manufacturing assembly tolerances and material imperfections will cause high impact on amplitude values of T_{AHC} resulting in significant increase of T_{cogg}, although they have managed to reduce T_{NHC} components. With such design choice they achieve just the opposite effect as desired. Furthermore, some of well–known methods to reduce the cogging torque [7] are not working as expected in PM motor designs having $F > 1$. It is often observed that PM motors fabricated in the same batch or mass–production have very diverse values of T_{cogg}. This phenomenon is intensified by increasing the value of F as shown in the presented research (Table 5).

In modern high performance PM motors low value of cogging torque is a very important parameter but designers should also satisfy other requirements as low torque ripple and reduced values of induced voltage low order harmonic components. PM motor designs with $F > 1$ are therefore most proper choice to meet such constraints, but without considering the phenomena of additional cogging torque harmonic components *AHC* motor producers are frequently surprised and disappointed once PM motors are manufactured and tested at output control. Our detailed research and experiences from mass–production show that PM motor designs having $F = 2$ and properly prescribed manufacturing tolerances can be effectively produced in mass–production resulting in a low amplitude level of T_{AHC} and T_{cogg}. On the contrary, PM motor designs with $F > 2$ and stringent demands for low amplitude level of T_{cogg} are less appropriate for high quality mass-production due to high impact of manufacturing tolerances on the amplitude level of T_{AHC} and consecutive on the level of T_{cogg}.

6 CONLCUSION

The paper presents the classification of cogging torque components, which are basically divided into *NHC* and *AHC* with regard to their origin. The research is focused on various design techniques for *NHC* elimination. Rotor design techniques are in comparison to the stator ones much more effective, but their effectiveness depends considerably on the motor design parameters.

Manufacturing assembly tolerances and material imperfections cause the phenomena of *AHC*, which are not present in the case of a perfect motor. Considering introduced theory motor designers are able to predict the entire cogging torque harmonic spectrum, thus predetermine required manufacturing tolerances to minimize cogging torque and fulfil the stringent market demands. The ascertainment that PM motor designs with higher F values are more sensitive to the phenomenon of *AHC* in cogging torque than the ones with lower values of parameter F is an important fact for the producers of PM motors, which must be seriously considered in the process of motor design optimization.

REFERENCES

[1] J. Gieras, M. Wing, *Permanent–Magnet Motor Technology – Design and Applications*, New York, Marcel Dekker, 2002.

[2] S. Islam, S. Mir, T. Sebastian, "Issues in Reducing the Cogging Torque of Mass–Produced Permanent–Magnet Brushless DC Motor," *IEEE Transactions on Industry Applications*, vol. 40, no. 3, pp. 813–820, May/June 2004.

[3] N. Bianchi, S. Bolognani, "Design Techniques for Reducing the Cogging Torque in Surface–Mounted PM Motors," *IEEE Transactions on Industry Applications*, vol. 38, no. 5, pp. 1259–1265, Sept/Oct. 2002.

[4] L. Dosiek, P. Pillay, "Cogging Torque Reduction in Permanent Magnet Machines," *IEEE Transactions on Industry Applications*, vol. 43, no. 6, pp. 1565–1571, Nov./Dec. 2007.

[5] R. Lateb, N. Takorabet, F. Meibody–Tabar, J. Enon, A. Sarribouete, "Design Technique for Reducing the Cogging Torque in Large Surface Mounted Magnet Motors," in *Proceedings of 16th ICEM* (CD), (Krakow, Poland), Sept 2004.

[6] D. Miljavec, and B. Zidarič, "Eddy current losses in permanent magnets of the BLDC machine," *Compel*, vol. 26, no. 4, pp. 1095–1104, 2007.

[7] A. Černigoj, L. Gašparin, R. Fišer, "Evaluation of Design Techniques for Reducing Cogging Torque of Permanent Magnet Synchronous Motor," in *Proceedings of. 16th Compumag*, (Aachen, Germany), pp. 1077–1078, June 2007.

[8] L. Gašparin, R. Fišer, "Detection and analysis of additional cogging torque harmonic components in permanent–magnet synchronous motors," *Electrotechnical Review*, vol. 75, no. 3, pp. 129–135, 2008.

[9] L. Gašparin, A. Černigoj, S. Markič, R. Fišer, "Additional cogging torque components in permanent magnet motors due to manufacturing imperfections," *IEEE Transactions on Magnetics*, vol. 45, no. 3, pp. 1210–1213, March 2009.

[10] L. Gašparin, R. Fišer, "Phenomena of Additional Cogging Torque Components Influenced by Stator Lamination Stacking Methods in PM motors," *Compel*, vol. 28, no. 3, pp. 682–690, 2009.

[11] M. Nemec, K. Drobnič, D. Nedeljković, V. Ambrožič, "Direct Current Control of a Synchronous Machine in Field Coordinates," *IEEE Trans. Industrial Electronics*, vol. 56, no. 10, pp. 4052–4061, Oct. 2009.

Andrej Černigoj received the B.Sc. and M.Sc. degrees from the Faculty of Electrical Engineering, University of Ljubljana, Slovenia, in 1999 and 2006, respectively. Since 1999 he is a Project Engineer in Institute for Electric Rotary Systems in Iskra Avtoelektrika d.d. His research interests include finite-element modeling, electromagnetic design optimization of electrical machines, torque ripple and cogging torque minimization. He has been involved in several research projects on the development of modern permanent-magnet machines for automotive and marine industry applications, like permanent-magnet motor and generator for hybrid boat propulsion. Current research projects are focused on optimization of axial flux permanent magnet machines with concentrated winding.

Lovrenc Gašparin received the B.Sc., M.Sc., and Ph.D degrees from the Faculty of Electrical Engineering, University of Ljubljana, Slovenia, in 2000, 2003, and 2009, respectively. Currently he is a Research Engineer in Institute for Electric Rotary Systems in Iskra Avtoelektrika d.d. His main research interests are in the areas of finite-element modeling, design and optimization of electrical machines and related issues on cogging torque minimization. He has been involved in several research and development projects on modern permanent-magnet machines for automotive industry applications, like electric power steering and permanent-magnet motors/generators for hybrid vehicles. He is the author of several technical papers focusing on cogging torque issues in permanent-magnet machine designs.

Rastko Fišer received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from the Faculty of Electrical Engineering, University of Ljubljana, Slovenia, in 1984, 1989 and 1998, respectively. In 1986, he joined the Faculty of Electrical Engineering, Laboratory of Electrical Drives, University of Ljubljana, first as a Junior Researcher, then Assistant, Assistant Professor, and since 2009, an Associate Professor at the Department of Mechatronics. He lectures on electrical machines, electrical drives and power electronics in undergraduate and postgraduate Ph.D. studies at University of Ljubljana. Prof. Fišer currently leads the Laboratory of Electrical Drives. His main research interests include condition monitoring, diagnostics and supervision of electrical drives, modeling, simulation, testing and control of electrical machines, power electronic converters, and electrical traction systems. He is a member of the IEEE Industry Applications, Industrial Electronics, Power Electronics, and Power Engineering Societies.

AUTHORS' ADDRESSES

Andrej Černigoj, M.Sc.
Lovrenc Gašparin, Ph.D.
Iskra Avtoeletrika d.d.
Polje 15, 5290 Šempeter pri Gorici, Slovenia
email: Andrej.Cernigoj@iskra-ae.com,
Lovrenc.Gasparin@iskra-ae.com

Prof. Rastko Fišer, Ph.D
University of Ljubljana,
Faculty of Electrical Engineering,
Tržaška cesta 25, 1000 Ljubljana, Slovenia
email: Rastko.Fiser@fe.uni-lj.si

Received: 2009-11-13
Accepted: 2010-02-24