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 elektronomotornim 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 zahtjev i izazov 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 osjetljive 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 components, but most of them consequently reduce the output torque as well. The presented paper among others discusses and quantifies native and additional cogging torque components of PM synchronous motors. For more clear interpretation, native harmonic components (NHC) and additional harmonic components (AHC) 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

\[ HC = NHC + AHC, \]

where NHC and AHC consist of vector arrays:

\[ NHC \left( A_{NHC}, N_{NHC}, \varphi_{NHC} \right), \]

\[ AHC \left( A_{AHC}, N_{AHC}, \varphi_{AHC} \right), \]

where \( A \) stands for an amplitude, \( N \) for a number of repetitions in mechanical revolution (order of harmonic component), \( \varphi \) for a phase shift, and \( i = 1, 2, 3, ... \) . Cogging torque \( T_{cogg} \) is a periodical function, which depends on rotor angular position \( \alpha \) and is composed of two components

\[ T_{cogg}(\alpha) = T_{NHC}(\alpha) + T_{AHC}(\alpha), \]

where \( T_{NHC} \) is a composed component of NHC contributions and \( T_{AHC} \) is a composed component of AHC contributions. For more clear interpretation, \( T_{NHC} \) and \( T_{AHC} \) can be represented as a sum of sine functions:

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

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

Native harmonic components \( NHC \) of cogging torque have orders defined by the following expression

\[ N_{NHC} = LCM(Q, P) \cdot i, \]

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

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

$$N_{AHC T_i} = P \cdot i,$$

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

$$N_{AHC R_i} = Q \cdot i,$$

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 $T_{cogg}$.

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 $\alpha_m$ (left), and flux distribution in model segment (right)](image)

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.

A similar optimization of $\alpha_m$ and $\gamma$ 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.
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 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
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 $R_{\text{notch}}$ for different magnet spans $\alpha_m$. Calculated results for one additional notch in stator teeth determine that this design technique is inefficient for 36-slot and 6-pole PMSM. Excessive $R_{\text{notch}}$ leads to the cogging torque increase (Fig. 10). Two additional notches in stator teeth are also inefficient and excessive $R_{\text{notch}}$ significantly reduces the output torque due to the saturation effect in stator teeth.

### Table 1. Torque results for certain rotor designs

| Design technique                                | $T_{\text{cog max}}$ (Nm) | $T_{\text{cog max}} / T_0$ | $T_0 / T_{\text{basic mod.}}$ |
|-------------------------------------------------|-----------------------------|-----------------------------|-------------------------------|
| Basic PMSM model ($\alpha_m=56^\circ$)         | 4.42                        | 0.1768                      | 1.00                          |
| Magnet span ($\alpha_m=40^\circ$)              | 2.10                        | 0.0937                      | 0.89                          |
| Magnet pole shifting with magnet span ($\gamma=56^\circ$, $\alpha_m=50^\circ$) | 0.99                        | 0.0404                      | 0.98                          |
| Bread loaf magnet shape                         | 0.024                       | 0.0011                      | 0.89                          |

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

![Fig. 9](image)

### 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 $\alpha_m=50^\circ$ and $\alpha_m=51^\circ$ 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. 10](image)

### Table 2. Torque results for certain stator designs

| Design technique                                | $T_{\text{cog max}}$ (Nm) | $T_{\text{cog max}} / T_0$ | $T_0 / T_{\text{basic mod.}}$ |
|-------------------------------------------------|-----------------------------|-----------------------------|-------------------------------|
| PMSM model ($\alpha_m=50^\circ$)                | 3.56                        | 0.146                       | 1.00                          |
| One additional notch ($\alpha_m=50^\circ$, $R_{\text{notch}}=0.75\text{ mm}$) | 3.59                        | 0.148                       | 0.99                          |
| Two additional notches ($\alpha_m=50^\circ$, $R_{\text{notch}}=0.75\text{ mm}$) | 3.86                        | 0.158                       | 0.99                          |
| Slot opening in stator lamin. ($\alpha_m=48^\circ$, slot opening 2.0 mm) | 2.81                        | 0.115                       | 0.97                          |

![Fig. 11](image)

### 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 length, 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 \( N_{NHC} \) 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 \( 1^\circ \). 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 \( P = 4, Q = 18 \).

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 \[ F = \frac{N_{NHC \, 1}}{Q}. \] (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.

### 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 \( F = 1 \).

### 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 \( N_{NHC} \), \( F \), \( T_{NHC} \), \( T_{AHC} \) for models of \( P = 4 \) and \( Q = 12, 18, 24, 30, 36 \)

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

stated the same irregularities on stator teeth and rotor PM were applied to all models. It can also be easily noticed that \( T_{AHC} \) are significantly increased in comparison to the \( T_{NHC} \) (Tab. 4, column 7) in the case of motor design with parameter \( F = 2 \). On the contrary, values of \( T_{AHC} \) are negligibly low compared to the \( T_{NHC} \) 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 \( N_{NHC} \), furthermore, even the ratio \( T_{AHC} \) / \( T_{NHC} \) is of the same range. Calculated \( T_{NHC} \) 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 \( T_{NHC} \) 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 \( T_{NHC} \) on models differ from 1 mNm to 436 mNm (Tab. 5, column 5) and is in tight correlation with \( F \) and \( N_{NHC} \) (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) \( T_{NHC} \) is decreasing, but on the other hand a rise of \( T_{AHC} \) is significant, which leads to high values of the ratio \( T_{AHC} / T_{NHC} \).

From Fig. 16 it is obvious that there exist two FEM models \( (Q = 12, Q = 24) \) which share the same \( N_{NHC} \) but differ in \( T_{NHC} \) 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 \( (Q = 18 \text{ and } Q = 36) \) sharing the same \( N_{NHC} = 72 \) but due to different sensitivity \( (F = 2 \text{ and } F = 4) \) the level of \( T_{NHC} \) and \( T_{AHC} \) 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
Table 5. Calculated parameters $N_{NHC}$, $F$, $T_{NHC\text{ max}}$, $T_{AHC\text{ max}}$, $T_{AHC\text{ max}}/F$, $N_{NHC}$, for models of $P = 8$ and $Q = 12$, 18, 24, 30, 36

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

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 $T_{cogg}$.

$$F = 1 \quad \rightarrow \quad T_{NHC} \quad \text{HIGH} \quad \rightarrow \quad T_{AHC} \quad \text{LOW}$$

Manufacturing assembly tolerances and material imperfections have low impact on increase $T_{cogg}$

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 $T_{cogg}$.

$$F > 1 \quad \rightarrow \quad T_{NHC} \quad \text{LOW} \quad \rightarrow \quad T_{AHC} \quad \text{HIGH}$$

Manufacturing assembly tolerances and material imperfections have high impact on increase $T_{cogg}$

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 CONCLUSION

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 predetermined 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.

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