ELEKTRYKA 2010
Zeszyt 4 (216) Rok LVI

Marcin KOWOL, Adrian MŁOT, Marian ŁUKANISZYN, Krzysztof LATAWIEC
Instytut Układów Elektromechanicznych i Elektroniki Przemysłowej, Politechnika Opolska

# APPLICATIONS OF AN EVOLUTIONARY ALGORITHM IN CONSTRUCTION OPTIMIZATION OF ELECTRICAL MOTORS

**Summary.** This paper deals with evolutionary optimization of construction parameters for brushless DC permanent magnet (BLDC) and transverse flux (TFM) motors. For a BLDC motor permanent magnets shape parameters are optimized to provide a minimum cogging torque. It is shown that the cogging torque in the motor with the multipolar excitation of permanent magnets is reduced six times as compared with the conventional BLDC motor. For a TFM, magnetic circuit construction parameters are optimized to compromise between the high electromagnetic torque and low torque pulsations. For both motors, the evolutionary optimization algorithm is coupled with a 3D FEM program employed for precise modeling of the electromagnetic field.

**Keywords:** Brushless DC motor, Transverse Flux Motor, electromagnetic torque, evolutionary optimization, 3D field modeling, ripple/cogging torque

# ZASTOSOWANIE ALGORYTMU EWOLUCYJNEGO DO OPTYMALIZACJI KONSTRUKCJI SILNIKÓW ELEKTRYCZNYCH

**Streszczenie.** W artykule przedstawiono optymalizację parametrów obwodu magnetycznego bezszczotkowych silników prądu stałego z magnesami trwałymi (BLDC) oraz silnika reluktancyjnego przełączalnego z zewnętrznym wirnikiem i ze strumieniem poprzecznym (transverse flux motor – TFM). W silniku BLDC optymalizowano wymiary magnesu trwałego, aby otrzymać minimalną wartość momentu od zębów (tzw. momentu zaczepowego). W pracy pokazano, że przy zastosowaniu magnesów trwałych ze zmiennym kierunkiem wektora magnetyzacji moment zaczepowy może być zredukowany sześciokrotnie, w stosunku do silnika z magnesami o radialnym kierunku wektora magnetyzacji. W przypadku silnika TFM zadanie optymalizacji sprowadzało się do zmiany wymiarów zębów wirnika, aby otrzymać maksymalny moment elektromagnetyczny przy stosunkowo niskich jego pulsacjach. W obu zadaniach optymalizacji algorytm ewolucyjny współpracował z programem opartym na trójwymiarowej metodzie elementów skończonych (FEM), w celu dokładnego modelowania pola magnetycznego w silnikach.

**Słowa kluczowe:** bezszczotkowe silniki prądu stałego, silniki ze strumieniem poprzecznym, moment elektromagnetyczny, algorytmy ewolucyjne, pulsacje momentu

## 1. INTRODUCTION

Nowadays, brushless direct current motors with permanent magnets (BLDC motors) and transverse flux motors (TFMs) are extensively used in a variety of industrial drives [1,2,6,8,9,12]. Usually, these drives are characterized by relatively high torque pulsations. Cogging torque reduction is an essential requirement in a wide range of high-performance motion control applications. Cogging torque is produced by the circumferential component of attractive forces between the magnet and the stator teeth [2,3]. Many applications like servodrives or hard disk drive micromotors do not tolerate cogging torque of any level. Reduction of the ripple/cogging torque is certainly welcome in the above high-torque implementations, but it is vital in modern control and robotics applications [7]. Simultaneous maximization of the average electromagnetic torque and minimization of the ripple/cogging torque is a contradicting task which can only be solved in a compromise way for a specific motor construction.

This paper presents two examples of the application of an evolutionary algorithm (EA) to optimization of BLDC and TFM motors. The main task is reducing of the cogging torque in a small brushless motor with permanent magnet excitation by shape optimization of permanent magnets and distribution of the magnetization vector [1,2,3].

A prerequisite for an optimal design of the ele-ctromagnetic field distribution in special-construction motors like TFMs is the availability of an accurate, numerical, necessarily 3D model of the field [1,2,3]. An effective tool for the purpose is the 3D FEM and an adequate modeling environment is the Flux3D program. The program is coupled with the Matlab package which provides means for the development of the evolutionary optimization algorithm [4,5].

## 2. OPTIMIZATION OF BLDC MOTOR

Calculations are performed for BLDC motors with radial permanent magnet magnetization with various widths of the magnets and for various distributions of the magnetization vector (Fig. 1). Using the multipolar excitation of PMs allows for reducing of the cogging effect and increasing the average electromagnetic torque, much better than for the conventional motor with radial magnetization [4, 5]. The motor pole structures are shown schematically in Fig. 1. In the motor with multipolar excitation, each pole in the rotor is subdivided into three segments with various arc-pole widths described by the parameters $\gamma$ and $\beta$ (the angle of magnetization vector is equal to 45°).

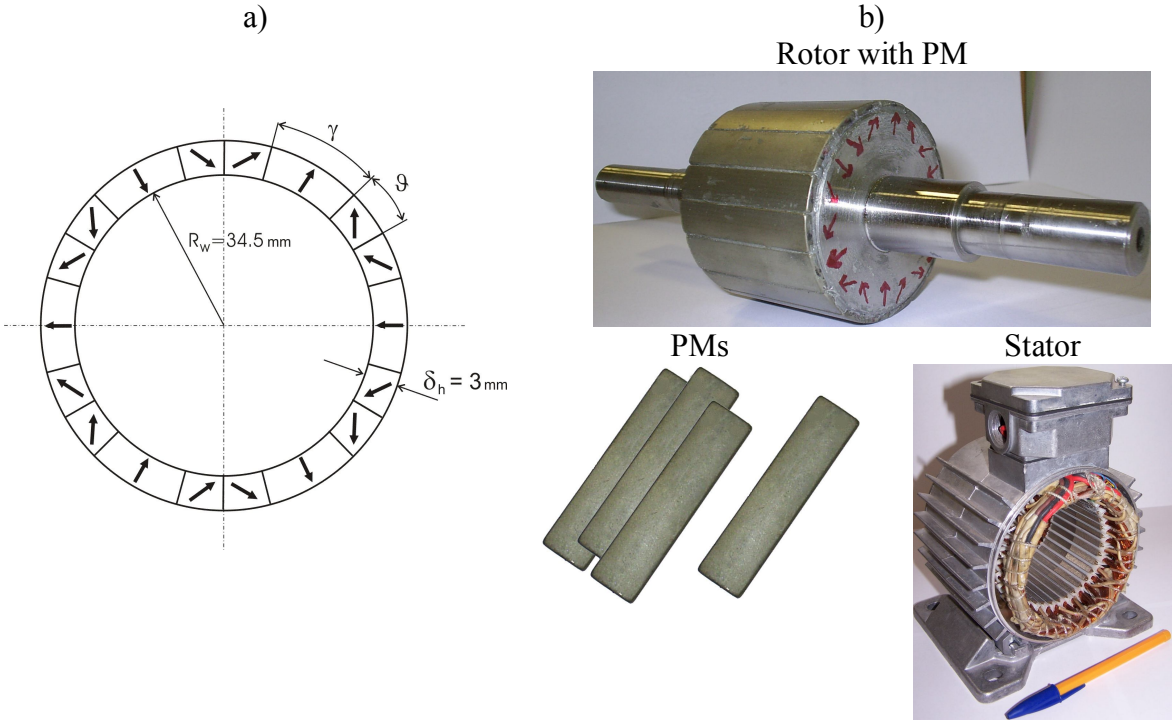



Fig. 1. Cross-section of BLDC motor with multipolar magnetization (a) and the prototype of the motor (b)
Rys.1. Silnik BLDC ze zmiennym wektorem magnetyzacji: przekrój poprzeczny (a), prototyp silnika (b)

The common parameters of BLDC PM motor prototypes with radial magnetization of PMs (prototype A) and with multipolar excitation of arrays (prototype B) are: $I$=10 A, $U$<45 V, $n$=1500 rpm.

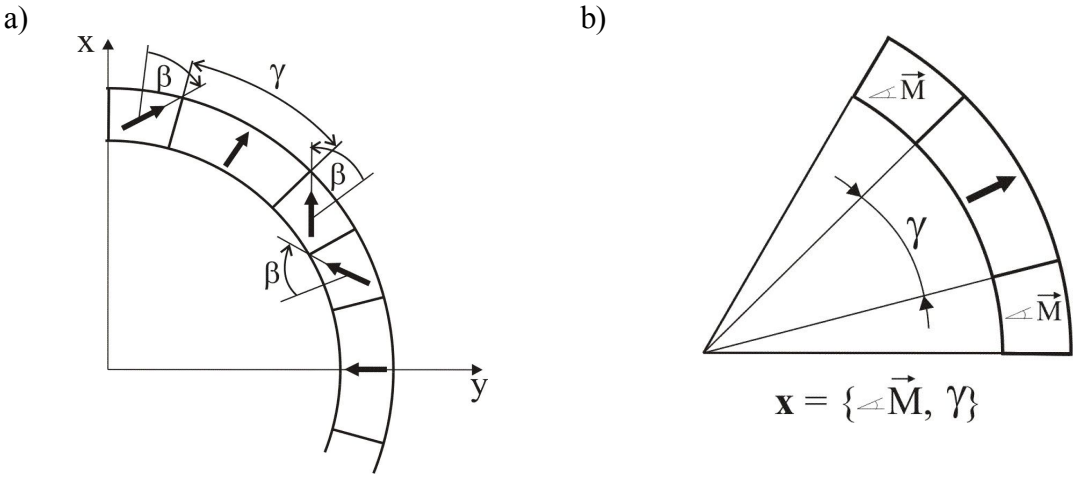



Fig. 2. Multipolar magnetization of PMs (a) and definition of decision variables for the optimization algorithm (b)
Rys. 2. Parametry magnesów ze zmiennym wektorem magnetyzacji (a) oraz zmienne decyzyjne (b)

The mathematical model of the motor for calculation of 3D magnetic field has been presented in details in [4,5]. The calculation of the electromagnetic torque developed by the motor is performed making use of the virtual work method. To ensure high accuracy in evaluation of the parameters of a BLDC motor while solving an optimization problem, the quasi-nonlinear 3D model of a BLDC motor is used. A 3D model is considered for magnetic field evaluation. In Fig. 2, decision variables for optimization algorithm are shown.

The objective function is defined in the form:

$$\min_{\mathbf{x}}\left(T_{cogg\cdot\max}\right) \tag{1}$$

where: $T_{cogg\ max}$ – maximum value of the cogging torque.

Table 1 shows the results from EA. In the optimized prototype B, the maximum cogging torque is reduced by sixteen times whereas in the non-optimized prototype B only a six-times reduction is obtained in comparison with prototype A. The torque ripple factor $\varepsilon$ was defined by Nakata at al. [6].

$$\varepsilon = \frac{T_{\max} - T_{\min}}{T_{av}} \cdot 100\% \tag{2}$$

where: $T_{max}$, $T_{min}$, and $T_{av}$ are the maximal, minimal and average values of the torque, respectively.

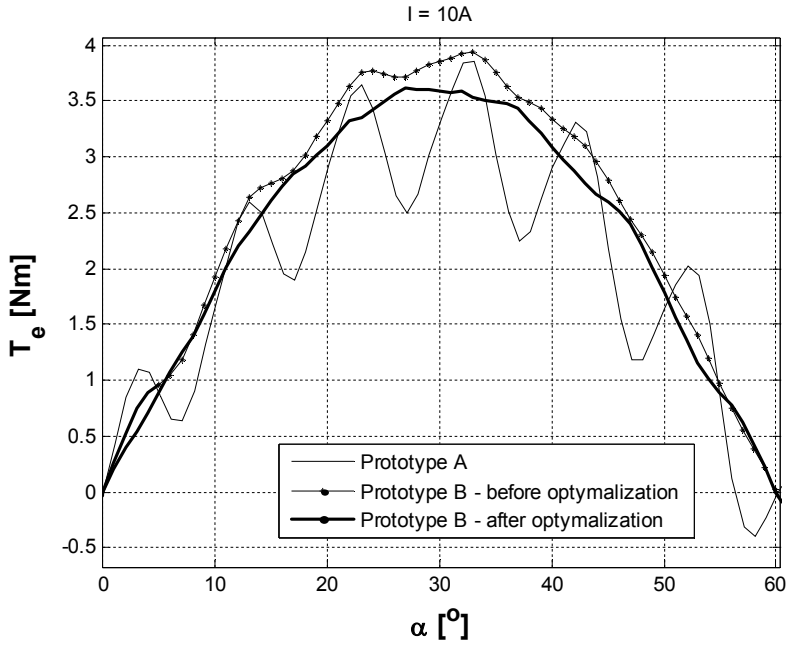
Table 1

Comparison of torques for the prototypes of BLDC motor for $I$=10A
dla $I$=10A

| Prototypes of BLDC motor | Parameter [°] | | $T_{\text{cogg_max}}$ [Nm] | | $T_{\text{emax}}$ [Nm] | $T_{\text{e av}}$ [Nm] | $\varepsilon$ [%] |
|---|---|---|---|---|---|---|---|
| | $\beta$ | $\gamma$ | Calcu-lated | Meas-ured | | | |
| B – before opt. | 45 | 22 | 0.11 | 0.11 | 3.94 | 3.67 | 16.89 |
| B – after opt. | 48 | 32 | 0.04 | - | 3.65 | 3.60 | 15.28 |
| A | 0 | 47 | 0.67 | 0.7 | 4.50 | 3.41 | 76.26 |

Using the multipolar excitation of PMs allows for reduction of the cogging effect much better than for prototype A (see Table 1). The main advantage is a higher average value of the electromagnetic torque. In addition, comparing the prototype B before optimization and the motor version after optimization, it can be observed that, for the latter, the average torque is lower by some 2%, but the relative ripple cogging torque is over 63% lower. The simulation results for the torques developed by the selected motor versions are illustrated in Fig. 3.

a)




b)

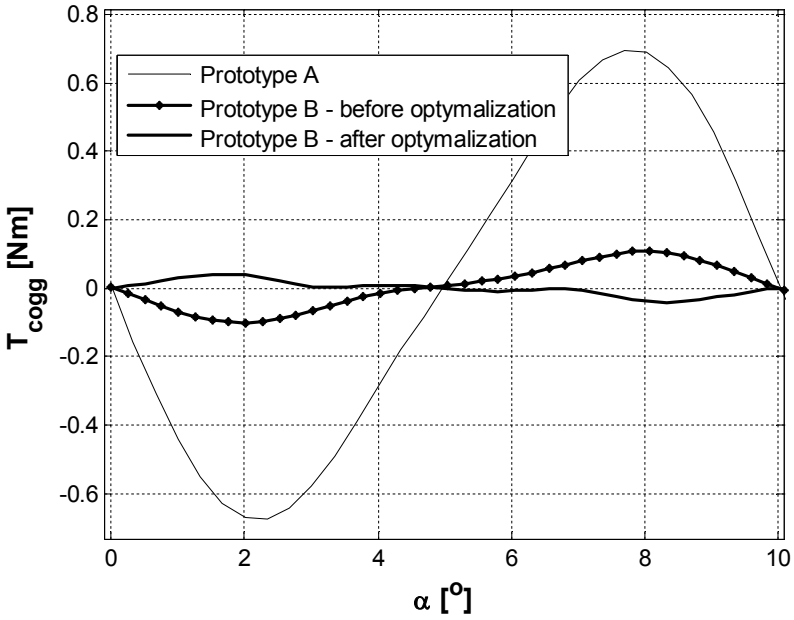



Fig. 3. Electromagnetic torque (a) and cogging torque (b) versus angular position for prototype B (before and after optimization) and motor version A

Rys. 3. Charakterystyki momentu elektromagnetycznego wytwarzanego przez silnik (a) oraz momentu od zębów w funkcji kąta dla rozpatrywanych wersji silnika (b)

## 3. OPTIMIZATION OF TFM PROTOTYPE

The basic motor prototype to be optimized (Fig. 4) consists of three equal modules, with the rotor sectors shifted between each other by ten mechanical degrees. Three stator modules

are centered along the motor shaft. Each sector has twelve teeth and contains one phase belt. The modules are separated from each other with nonmagnetic inserts. The main specifications for the motor are: $U$=24V, $I$=12A, $n$=300rpm [9,10].

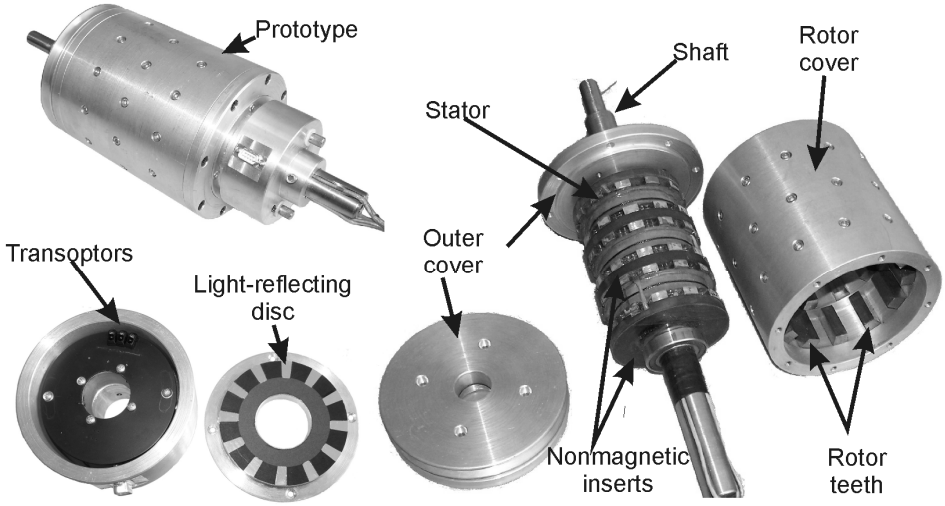



Fig. 4. Schematic of a basic TFM prototype
Rys. 4. Prototyp silnika ze strumieniem osiowym- TFM

The motor is supplied from a DC source through a three-pulse electric inverter. Control of the motor reduces to supplying the phases with a rectangular current waveform according to the sequence A,B,C,A.

A numerical, FEM-based model of the basic motor has been developed in Flux3D [11].

a) b)

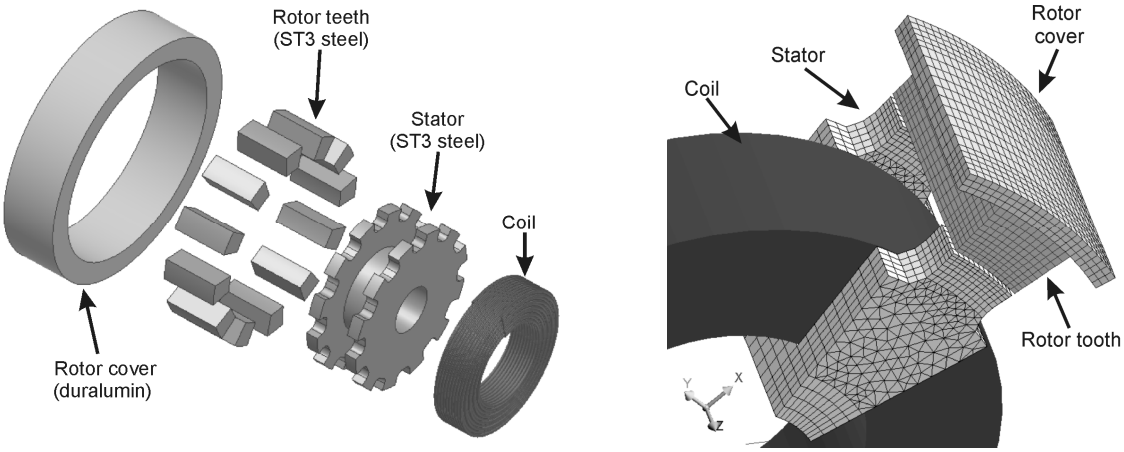



Fig. 5. TFM module: a) structure; b) discretization mesh
Rys. 5. a) Struktura modułu silnika TF, b) z siatką dyskretyzacyjną

The 3D magnetostatic field was described using the method of scalar magnetic potentials. A simplifying assumption is introduced in the calculations that no magnetic couplings occur between the modules, which is justified by separation of the modules with the nonmagnetic

inserts of an appropriate width. The assumption enables to limit the calculations to a single module only, and taking additionally account for the symmetry conditions in the motor, to 1/36 of the motor volume, which is called a calculation segment or just a segment. A structure of the motor module and a discretization mesh for the numerical model are depicted in Fig. 5.

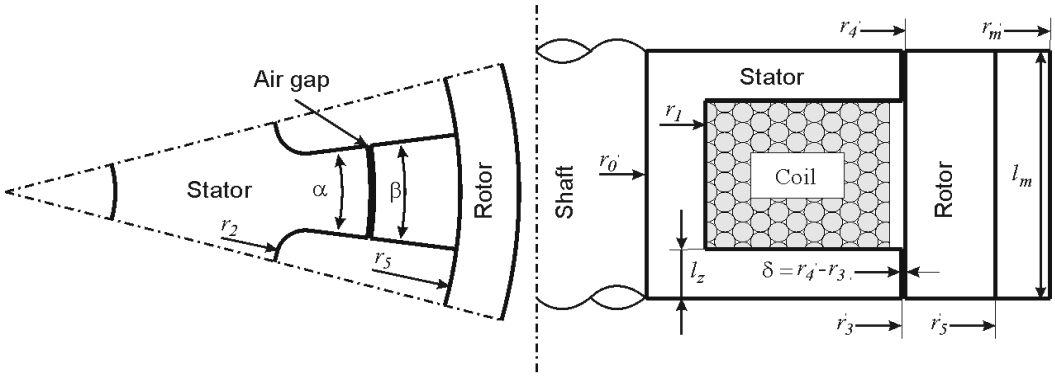



Fig. 6. Cross-section of the TFM segment
Rys. 6. Przekrój poprzeczny segmentu silnika TF z przyjętymi parametrami do optymalizacji

The influence of construction parameters on electromechanical parameters is analyzed for the machine with numbers of teeth in the stator and rotor being equal to 12, which has been comparatively found most reasonable for constructional reasons [10]. As a result of the above pre-optimization analysis, certain construction parameters are assessed to have only minor influence on the integral parameters of the TFM, so they are omitted in the optimum design. Finally, a vector of the decision variables is selected as $\underline{x}^T$=[ $r_1$, $r_2$, $r_3$, $l_z$, $\alpha$, $\beta$ ] (see Fig. 6) and variation ranges for each decision variable are specified. A 'reasonable' air gap is determined to be $\delta$=0.5 mm.

Use of various, fitness-related optimization criteria has been analyzed in detail in Refs. [9,11]. Both high-torque and low-pulsation criteria have been examined and specific criterion functions have been recommended in specific TFM applications. Based on that analysis, a flexible criterion function has been introduced in Ref. [9], which is now extended to a new, more general, EA-related criterion

$$\min_{\underline{x}\in X}\left\{\xi(\underline{x}) = \left[C(i) + k\left(T_{av}/T_b\right)^2 + (1-k)(1-\varepsilon/100)^2\right]^{-1}\right\} \tag{3}$$

where: $T_b$ is the average electromagnetic torque for the basic (unoptimized) motor, $k\in[0.0, 1.0]$ is the weighting coefficient, $C(i)$ is the variable weighting factor controlling the selective pressure of EA, with i being the successive number of EA generations, and $X\in R^6$ is a subspace of admissible solutions related to variation ranges for the decision variables.

We propose to use the exponential weighting function $C(i)=c_0(1-\lambda^{N-i})$, where $c_0$ is the user-selected initial value (we use $c_0$=1.0), $N$ is the total number of EA generations ($i$=1,…,$N$) and the exponential weighting coefficient $\lambda\in(0.0, 1.0)$ is typically selected close to 1.0 (we

use $\lambda$=0.96). The objective/fitness function (3) provides a simple realization of the evolutionary design in multicriterial optimization.

The above three optimal solutions, that is for $k$ equal to 1.0, 0.0 and 0.5, are now additionally compared in terms of plots of Fig. 7 of the electromagnetic torque vs. rotor rotation angle.

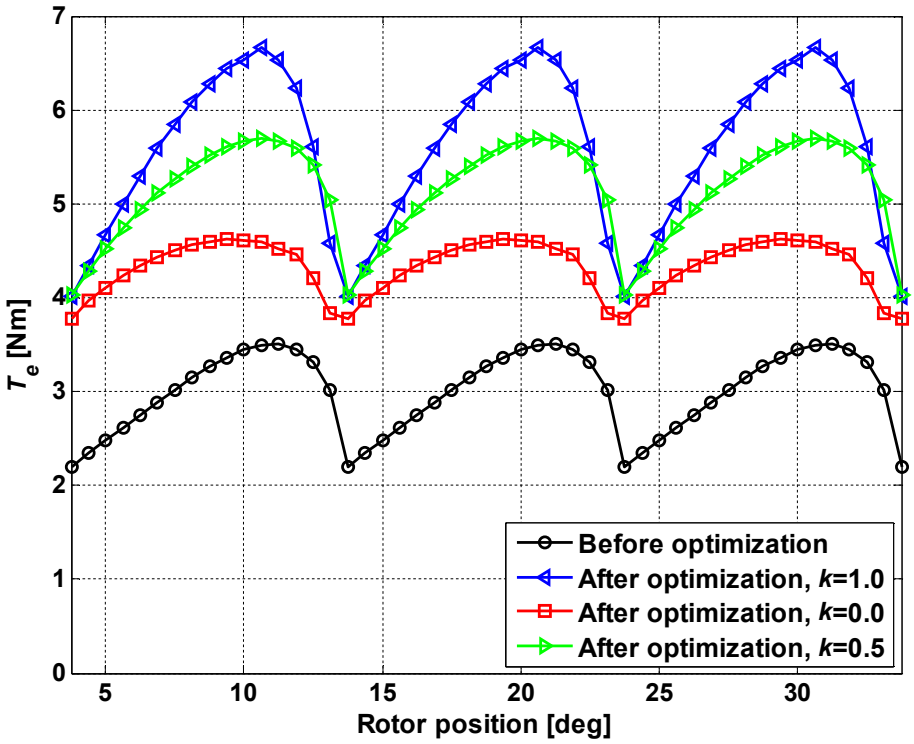



Fig. 7. Electromagnetic torque vs. rotor rotation angle
Rys. 7. Charakterystyki momentu elektromagnetycznego wytwarzanego przez silnik w funkcji kąta dla rozpatrywanych wersji silnika

The criterion (3) can serve a plethora of TFM construction optimization tasks, ranging from the maximum-torque ($k$=1.0) to the minimum-pulsation ($k$=0.0) designs. Depending on a specific application of TFM the designer can select the weighting coefficient to cover either high-torque or low-pulsation solutions, or to compromise between the two. The impressive results on construction parameters vs. integral parameters in Table 2 are self-explanatory. This illustrates the power of our new design approach and of the criterion (3) in the construction optimization of the TFM.

Table 2

Construction parameters and integral parameters for TFM before and after optimization acc. to (3)

| | $r_1$ [mm] | $r_2$ [mm] | $r_3$ [mm] | $l_z$ [mm] | $\alpha$ [°] | $\beta$ [°] | $T_{max}$ [N·m] | $T_{min}$ [N·m] | $T_{av}$ [N·m] | $\varepsilon$ [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| Before optimization | 23 | 42.5 | 49.75 | 6 | 15 | 15 | 3.45 | 2.17 | 2.99 | 42.84 |
| After optimization | 27 | 43.5 | 51.75 | 7.5 | 15 | 12.5 | 5.66 | 4.03 | 5.18 | 31.37 |
| Change [%] | +18 | +2.4 | +2.5 | +25 | 0 | -17 | +64 | +86 | +**73** | -**27** |

## 4. CONCLUSIONS

In this paper, two impressive examples of application of evolutionary construction optimization for BLDC and TF motors have been presented. Firstly, minimization of the cogging torque by shape optimization of permanent magnets and distribution of the magnetization vector for the BLDC motor has been approached. An effective model of BLDC motor for field evaluation has been developed and successfully applied for optimization using an evolutionary algorithm. The measurement results from prototype motors are well-compared with calculations. This confirms the usefulness of the computational approach presented for modeling of the BLDC PM motor performance.

The impact of inhomogeneous magnetization vector of PM and various pole width of rotor on the torque pulsations has been investigated. Results of the calculations clearly show the existence of an optimal direction of the magnetization vector and an optimal division of rotor poles, at which the average torque remains high and pulsations are considerably reduced. The cost is a bit more complicated rotor structure, with a number of sleeves cut for the construction of the segments.

Secondly, an effective solution to the problem of optimization of TFM construction parameters making use of a combination of a 3D FEM and an evolutionary algorithm has been offered. An optimum design enables to determine optimal construction parameters aiming at improved electromechanical parameters of the motor, which are represented here by high average electromagnetic torque and/or low ripple torque pulsations. The optimum construction design has been effectively applied in a new prototype TFM. Electromechanical parameters of the optimized prototype motor have been found very close to the theoretically calculated figures and much better than those for the basic, unoptimized prototype used as a reference.

**BIBLIOGRAPHY**

1. Łukaniszyn M., Jagieła M., Wróbel R.: Optimization of permanent magnet shape for minimum cogging torque using a genetic algorithm. "IEEE Trans. Magn." 2004, Vol. 40, No. 2, p. 1228-1231.
2. Borghi C.A., Casadei D., Cristofolinii A., Fabbri M., Serra G.: Application of a multiobjective minimization technique for reducing the torque ripple in permanent magnet motors. "IEEE Trans. Magn." 1999, Vol. 35, No. 5, p. 4238-4246.
3. Zhu Z.Q., Howe D.: Influence of design parameters on cogging torque in permanent magnet machines. "IEEE Trans. Energy Conversion" 2000, Vol. 15, No. 4, p. 407-412.
4. Łukaniszyn M., Młot A.: Influence of the inhomoge-neous magnetization vector on the cogging torque in a brushless DC motor (in polish). XLII International Symposium on Electrical Machines SME'06, Kraków 2006, p. 111-115.
5. Łukaniszyn M., Młot A.: Torque characteristics of a BLDC motor with multipolar excitation. ISTET, Szczecin 2007.
6. Nakata T., Takahashi N., Uehara K.: Analysis of magnetic characteristics of brushless DC motor taking into account the distribution of magnetization. "IEEE Trans. Magn." 1986, Vol. 22, p. 1084-1086.
7. Babazadeh A., Parspour N., Hanifi A.: Transverse flux machine for direct drive robots: Modelling and analysis. IEEE Conference on Robotics, Automation and Mechatronics, Singapore 2004, Vol. 1, p. 376-380.
8. Kastinger G.: Design of a novel transverse flux machine. ICEM 2002, Brugge, August 2002.
9. Kowol M.: Performance Analysis of an Outer-rotor Switched Reluctance Motor for Light Vehicles (in Polish). Ph.D. thesis, Opole University of Technolo-gy, Opole 2008.
10. Łukaniszyn M., Kowol M.: Influence of construction modification on the electromechanical parameters of the modular reluctance motor with outer rotor, (in Polish). "Przegląd Elektrotechniczny" 2006, R. 82, No. 11, p.43-45.
11. Łukaniszyn M., Kowol M.: Optimization of magnetic circuit of a modular reluctance motor with an outer rotor. Poznań University of Technology Academic Journals, Electrical Engineering 2007, p.157-166.
12. Wang X., Du J., Ren N., Liu Z., Tang R.: Optimization of Stator Structure of Transverse Flux Motor. "Journal of Iron and Steel Research International" 2006, Vol. 13 Supplement 1, p. 466-470.

Recenzent: Prof. dr hab. inż. Dariusz Spałek

Wpłynęło do Redakcji dnia 6 listopada 2010 r.

**Omówienie**

W ostatnim czasie projektowanie przetworników elektromechanicznych sprowadza się zazwyczaj do zadania optymalizacji, w celu osiągnięcia specyficznych założeń projektowych, takich jak np. uzyskanie jak największej wartości średniej momentu elektromagnetycznego, redukcję momentu zaczepowego itp. W tym celu stosuje się różne metody optymalizacji oraz różne kryteria oceny funkcji celu. W artykule przedstawiono optymalizację parametrów obwodu magnetycznego bezszczotkowych silników prądu stałego z magnesami trwałymi (BLDC – rys.1) oraz silnika reluktancyjnego przełączalnego z zewnętrznym wirnikiem i ze strumieniem poprzecznym (transverse flux motor TFM – rys.4). Do minimalizacji funkcji celu zastosowano algorytm ewolucyjny (AE), będący uogólnieniem algorytmu genetycznego, dostępny w bibliotece programu Matlab. Do projektowania obwodu magnetycznego zastosowano natomiast program do obliczeń polowych metodą elementów skończonych Flux3D. Ze względu na to, że modele polowe charakteryzują się dużym kosztem obliczeń, w szczególności przy zastosowaniu trójwymiarowej metody elementów skończonych, algorytm optymalizacyjny został rozbudowany dodatkowo o bazę danych.

W silniku BLDC optymalizowano wymiary magnesu trwałego (rys. 2), aby otrzymać minimalną wartość momentu od zębów (tzw. momentu zaczepowego). Funkcję celu opisano zależnością (2). Rozpatrywano silnik BLDC ze zmiennym wektorem magnetyzacji (rys.1a). W pracy pokazano, że przy zastosowaniu magnesów trwałych ze zmiennym kierunkiem wektora magnetyzacji i odpowiednim doborze kąta wektora magnetyzacji magnesów trwałych, moment zaczepowy może być zredukowany sześciokrotnie, w stosunku do silnika z magnesami o radialnym kierunku wektora magnetyzacji (tabela 1). Współczynnik pulsacji opisano zależnością (2). Na rysunku 3 zamieszczono charakterystyki momentu elektromagnetycznego wytwarzanego przez silnik oraz momentu od zębów w funkcji kąta dla rozpatrywanych wersji silnika.

W przypadku silnika TFM zadanie optymalizacji sprowadzało się do zmiany wymiarów geometrycznych stojana i wirnika, aby otrzymać maksymalny moment elektromagnetyczny przy stosunkowo niskich jego pulsacjach. Na rysunkach 5 i 6 pokazano strukturę modułu silnika TF z siatką dyskretyzacyjną oraz przekrój poprzeczny z przyjętymi parametrami do optymalizacji. Postać funkcji celu przedstawia zależność (3). Wyniki obliczeń parametrów całkowych silnika zamieszczono w tabeli 2, natomiast na rysunku 7 pokazano charakterystyki momentu w funkcji kąta obrotu dla rozpatrywanych funkcji celu. Na podstawie obliczeń został wykonany nowy prototyp silnika, a przeprowadzone pomiary wykazały dobrą zgodność z obliczeniami.

Przeprowadzona analiza pozwala na określenie optymalnych wymiarów obwodu magnetycznego, które w efekcie dają najlepsze rozwiązanie pod kątem poprawy wartości parametrów elektromechanicznych silników już na etapie projektowania. Prezentowana metoda optymalizacyjna jest względnie prostym i skutecznym narzędziem do poszukiwania optymalnych parametrów konstrukcyjnych modeli numerycznych.