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ANALYSIS OF CRITERION FUNCTIONS IN OPTIMIZATION OF THE MAGNETIC CIRCUIT FOR TFM

ABSTRACT *The paper presents an optimal design of the magnetic circuit for a modular reluctance TFM. A numerical model of the motor developed in the Flux3D program is coupled with a Matlab-based evolutionary algorithm for optimization of construction parameters of the magnetic circuit. The fundamental role of a type of an optimization criterion function is comparatively analysed and a new effective criterion function is introduced.*

Keywords: *magnetic circuit optimization, criterion function, transverse flux motor*

1. INTRODUCTION

Nowadays, a design of electromechanical convertors is often reduced to the problem of optimization, e.g. in terms of maximization of the average torque and/or reduction of torque pulsations. To this end, various optimization methods

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and criterion functions have been used [2, 11, 12]. In this paper, the problem of evolutionary optimization of the magnetic circuit for a modular reluctance TFM (Fig. 1) is tackled from the viewpoint of comparison of various optimization criterion functions.

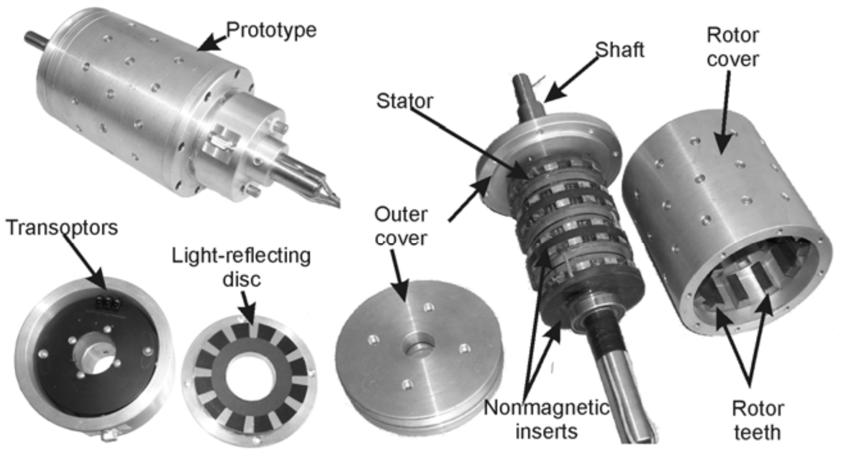

Fig. 1. Prototype TFM and its units

The motor is characterized by a high ratio of the electromagnetic torque to its volume [4, 5, 7]. The motor under study consists of three equal modules, with the rotor segments shifted between each other by ten mechanical degrees. Three stator modules are centered along the motor shaft. Each segment 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 given in Table 1.

TABLE 1
Specifications for TFM

Supply voltage	U_n = 24 V
Rated current	I_n = 12 A
Rotational speed	0÷300 obr/min
Winding	Three-phase
Number of turns	130
External diameter of rotor	158 mm
External diameter of stator	103,5 mm
Air gap	δ = 0,5 mm

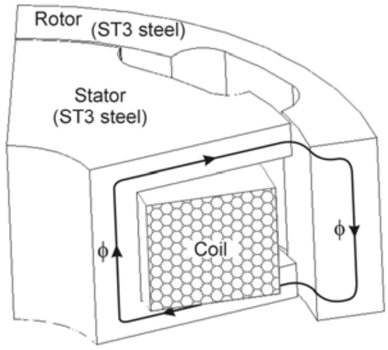

Fig. 2. Simplified topology of magnetic flux circulation

A simplified topology of circulation of the main flux is shown in Fig. 2, which illustrates the operation principle of the machine. Control of the motor reduces to supplying the phases according to the sequence A, B, C, A. Connection of any phase results in adequate positioning of the rotor with respect to the stator (the teeth are aligned). Since the rotor modules are shifted between each other, the successive connection of the phases causes the rotor to rotate.

2. NUMERICAL MODEL

3-D FEM is a necessary numerical tool for an analysis of special-construction motors like TFM [6, 7]. A numerical model of the motor is based on the Flux3D program [1]. 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. A structure of the motor module and a discretization mesh for the* numerical model is depicted in Fig. 3.

a) b)

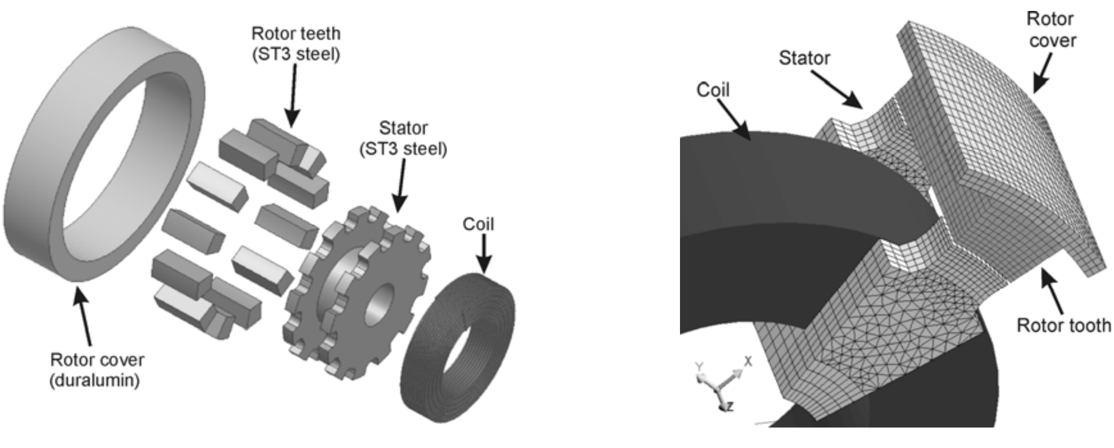

Fig. 3. TFM module:
a) structure; b) discretization mesh

The electromagnetic torque is calculated by the virtual work method as a derivative of the magnetic coenergy with respect to the rotation angle between the rotor and stator. The rotation of the rotor vs. stator is modeled by the sliding surface method [1, 3, 6]. The magnetic histeresis and eddy currents are omitted in the calculations as well as a constant current density is assumed in the whole cross-section of the coils.

A detailed description of the numerical model for the motor can be found in Refs. [6, 7]. In the comparative analysis, a useful torque pulsation factor is employed

$$\varepsilon = \frac{T_{\max} - T_{\min}}{T_{av}} \cdot 100\% \tag{1}$$

where T_{max}, T_{min}, T_{av} denote the maximum, minimum and average values of the electromagnetic torque, respectively.

3. TFM OPTIMIZATION BY MEANS OF AN EVOLUTIONARY ALGORITHM

In this paper, minimization of certain criterion functions is numerically done making use of an evolutionary algorithm (EA), being a generalization of a genetic algorithm [9, 11]. EA is known to have a (very) low probability to be stuck in a local minimum.

Construction optimization of TFM is performed under assumptions of constant volume and constant external diameter of the motor module. The optimization tool, that is EA available in the Matlab environment, is coupled with the Flux3D program used to design the magnetic circuit. A general block diagram of the optimization process is presented in Fig. 4.

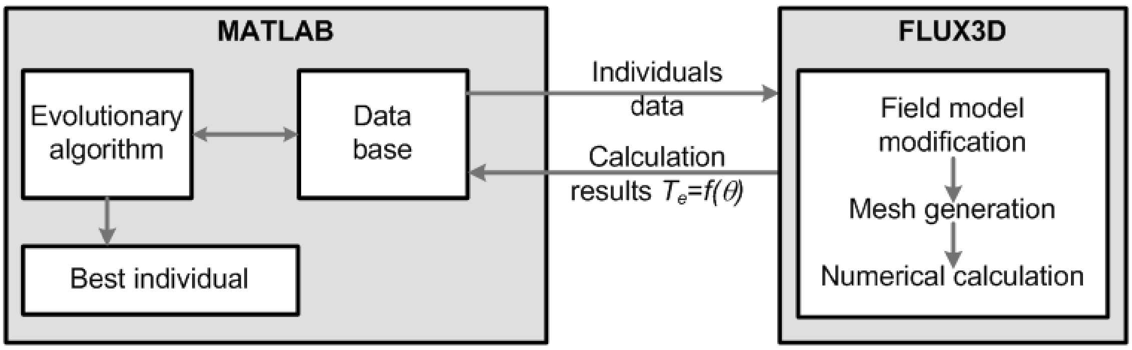

Fig. 4. General diagram of optimization process

Since field models are characteristic of a high computational burden, in particular for 3D FEM, the optimization algorithm is extended to include a database. The database is used to store data of individuals and the calculated electromagnetic torque. Prior to each field calculation cycle, the data base is searched to check up whether field calculations have already been made for the generated individual. In case such an individual has been found in the database, the magnetic field calculations are omitted. This enables to essentially save computation times as the execution times both for the save operation and searching the database are negligible when compared to the torque calculation times.

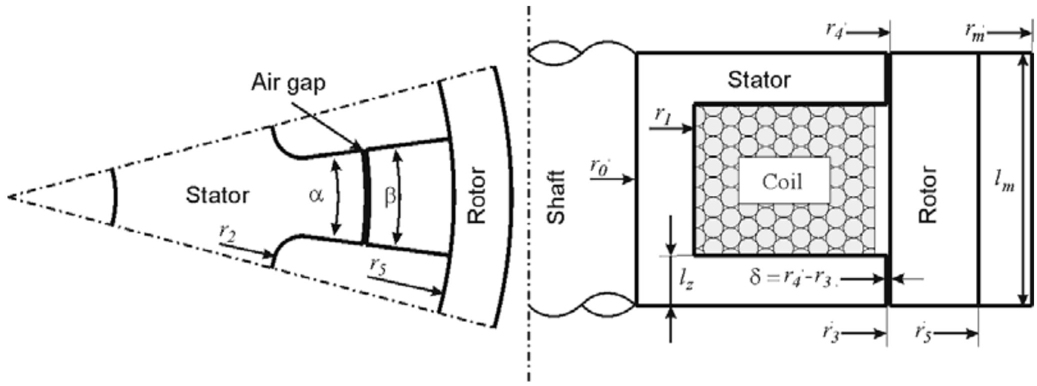

Fig. 5. Cross-section of module of TFM

A cross-section of the module of the TFM is illustrated in Fig. 5. With a constant air gap δ = 0.5 mm, the following construction parameters are assumed to be the decision variables in the optimization task: r_1, r_2, r_3, l_z, α, β, which are arranged in the vector $\underline{x}$. The limitation to only 6 variables results from the earlier analysis of influence of specific construction parameters on electromechanical properties [9]. In fact, the remaining construction parameters of the motor have been found to affect the average electromagnetic torque only slightly.

4. CALCULATION RESULTS FOR VARIOUS CRITERION FUNCTIONS

Using the evolutionary optimization algorithm a number of computer simulation runs have been performed. EA is set to operate on 20 individuals per population and a number of generations equal to 100 is assumed as a stop condition for the algorithm. The first optimization task is pursuing the maximum average value of the electromagnetic torque, the task often encountered in high-torque applications. For such an optimization task, the criterion or objective function can be proposed as

$$\min_{\underline{x}} \quad \xi_1(\underline{x}) = \left(\frac{T_{av}}{T_b} \right)^{-2} \tag{2}$$

where T_b is the average electromagnetic torque for the basic (unoptimized) prototype of the TFM.

The EA procedure was run five times for various initial conditions and same parameter values for the genetic operators. The lowest obtained value of the criterion function was $\xi_{1\min}$ = 0.277. In this case, the obtained construction parameters and the calculated integral parameters of the TFM are listed in Table 2.

TABLE 2
Construction parameters and integral parameters for TFM before and after optimization (2)

	r_1 [mm]	r_2 [mm]	r_3 [mm]	l_z [mm]	α [°]	β [°]	T_{max} [N·m]	T_{min} [N·m]	T_{av} [N·m]	ε [%]
Before optimization	23	42,5	49,75	6	15	15	3,45	2,17	2,99	42,84
After optimization	26	42,5	52,75	8,5	12,5	12,5	6,66	4,01	5,61	47,37
Change [%]	+13	0	+6	+42	-17	-17	+93	+85	+87	+10,6

As a result of optimization of the construction parameters of the TFM the average electromagnetic torque is increased by as high as 87%, with the external construction parameters (r_m, l_m) and the supply conditions retained. However, the side effect is that pulsations of the electromagnetic torque are increased by some 10%.

In another optimization task considered, the intersest is to find a construction solution for which pulsations of the electromagnetic torque would be minimized, the task encountered in another group of applications (opposite to the one related with criterion (2)). In this case, the criterion function can be assumed as

$$\min_{\underline{x}} \quad \xi_2(\underline{x}) = \left(1 - \frac{\varepsilon}{100} \right)^{-2} \tag{3}$$

Several runs of the EA procedure have been performed for the criterion (3). For the best obtained solution, the construction parameters and integral parameters are listed in Table 3. The obtained solution enables to reduce pulsations of the electromagnetic torque down to 19%. However, the average electromagnetic torque is lower than that obtained for the criterion (2).

TABLE 3
Construction parameters and integral parameters for TFM before and after optimization (3)

	r_1 [mm]	r_2 [mm]	r_3 [mm]	l_z [mm]	α [°]	β [°]	T_{max} [N·m]	T_{min} [N·m]	T_{av} [N·m]	ε [%]
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	12,5	12,5	4,63	3,78	4,34	19,68
Change [%]	+17	+5	+4	+25	-17	-17	+34,2	+74,2	+45,2	-54,1

The criterion (2) has led to high average electromagnetic torque (compared to the basic TFM model) at the cost of the increased pulsations. On the other hand, the criterion (3) has provided the reduction of pulsations of the electromagnetic torque by more than 50%, with lower average torque. Therefore, in the next stage of our study, we seek for a sort of a compromise between the high electromagnetic torque and its low pulsations, the requirement represented by an appropriate weighting of the criteria (2) and (3). Now a new, „compromise” objective function can be proposed as

$$\min_{\underline{x}} \ \xi_3(\underline{x}) = \left(k\left(\frac{T_{av}}{T_{pocz}}\right)^2 + (1-k)\left(1-\frac{\varepsilon}{100}\right)^2 \right)^{-1} \tag{4}$$

where $k \in [0, 1]$ is the weighting coefficient.

The criterion (4) covers a plethora of optimization tasks, ranging from the high-torque ones as in (2) to the low-pulsation ones as in (3). Selection of a specific weighting coefficient depends on on a specific TFM application. In our optimization run, we put k = 0.5, which translates to the requirement of *both* high torque and low pulsations. The results for the best obtained solution are listed in Table 4.

TABLE 4
Construction parameters and integral parameters for TFM before and after optimization (4)

	r_1 [mm]	r_2 [mm]	r_3 [mm]	l_z [mm]	α [°]	β [°]	T_{max} [N·m]	T_{min} [N·m]	T_{av} [N·m]	ε [%]
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

A prototype TFM of Fig. 1 was constructed according to the solution presented above. The average electromagnetic torque is increased by 73% as compared to the basic TFM model, with torque pulsations reduced by 27% at the same time. This illustrates the power of our new criterion (4) in the construction optimization of the TFM.

There are some other criterion functions encountered in the literature. In Ref. [10], the following objective function is introduced, which aims at increasing the electromagnetic torque under a simultaneous reduction of its pulsations

$$\min_{\underline{x}} \quad \xi_4(\underline{x}) = \left(\frac{T_{av}}{s \cdot \varepsilon} \right)^{-1} \tag{5}$$

where *s* is the standard deviation of the electromagnetic torque

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \left(T_{av} - T_{ei} \right)^2} \tag{6}$$

with T_{ei} being the value of the electromagnetic torque for the i-th angle of rotation of rotor vs. stator.

Our optimization procedure was also run according to the criterion function (5). Table 5 lists the interesting parameters for the best solution obtained along the criterion (5). The average electromagnetic torque is seen to be increased by 35.7% and pulsations are reduced by more than 50% as compared to the basic TFM model.

TABLE 5
Construction parameters and integral parameters for TFM before and after optimization (5)

	r_1 [mm]	r_2 [mm]	r_3 [mm]	l_z [mm]	α [°]	β [°]	T_{max} [N·m]	T_{min} [N·m]	T_{av} [N·m]	ε [%]
Before optimization	23	42,5	49,75	6	15	15	3,45	2,17	2,99	42,84
After optimization	30	43,5	49,75	5,5	15	12,5	4,33	3,56	4,06	18,93
Change [%]	+30	+2	0	-8	0	-17	+25,5	+64	+35,7	-55,8

All the best solutions, that is according to (2), (3), (4) and (5), are now additionally compared in terms of plots of Fig. 6 of the electromagnetic torque vs. rotor rotation angle. Optimization according to the criterion (5) seems inferior to all the other optimization cases. The flexibility of the criterion function (4) is an additional advantage here.

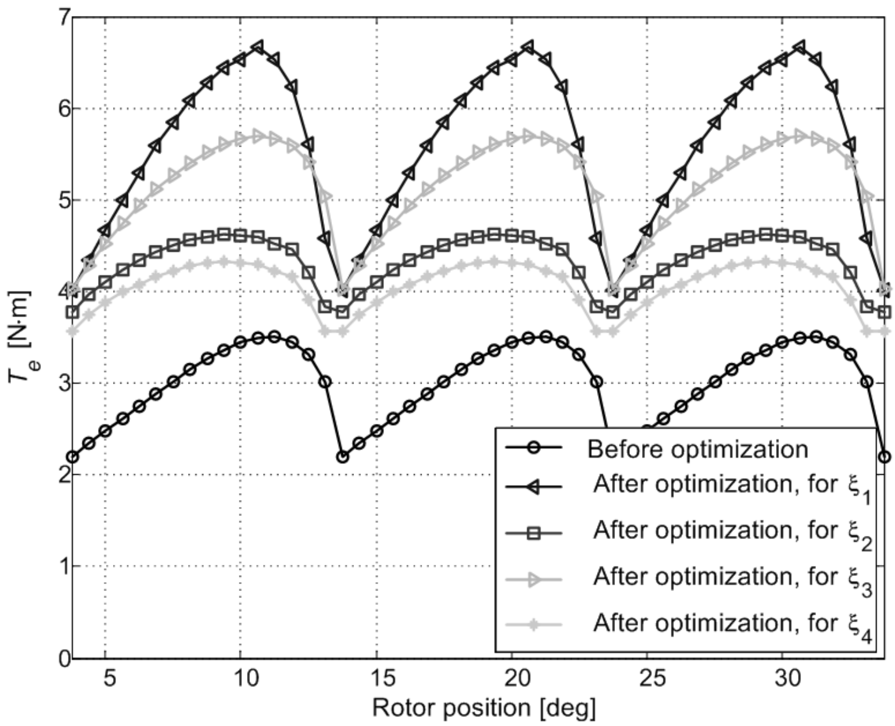

Fig. 6. Electromagnetic torque vs. rotor rotation angle

5. CONCLUSIONS

This paper has presented various possible solutions to the problem of optimization of construction parameters of TFM making use of a combination of an evolutionary algorithm and 3D FEM. An optimum design enables to determine optimal construction parameters aiming at improved electromechanical parameters of the motor. In addition to advantageous effects of the evolutionary algorithm, the performance of the optimization process depends largely on a type of a criterion function used. The criterion function can be formulated in a different way for the same construction optimization task, e.g. the criteria ξ_3 and ξ_4. The former one is a new flexible and effective criterion function proposed for the purpose, with a range of values of the weighting coefficient covering various optimal torque vs. pulsation tasks, depending on specific applications of the motor. Future works will attempt at construction of a bank of motor prototypes for various values of the weighting coefficient in order to easily pick up a due prototype for a specific application.

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LITERATURE

1. Flux3d, *User's guide*, vol. 1-4, 2004..
2. Goldberg D.E.: *Algorytmy genetyczne i ich zastosowanie*, WNT, Warszawa, 1998.
3. Goryca Z., Łukaniszyn M., Jagieła M., Wróbel R.: *Analiza momentu elektromagnetycznego w silniku reluktancyjnym*, XXXIX SME, Cedzyna/Kielce 2002, pp. 333-339.
4. Isastia V., Bellulcci M.: *A New Configuration of a TFPM Machine for a Wheel Motor*, ICEM, 5-8 September, Cracow, 2004, Vol. 1, pp. 139-140.
5. Kastinger G.: *Design of a novel transverse flux machine*, ICEM 2002, Brugge, August 2002.
6. Kowol M.: *Obliczanie momentu elektromagnetycznego modułowego silnika reluktancyj-nego z wirnikiem zewnętrznym, VII Międzynarodowe Warsztaty Doktoranckie*, OWD'2005, Wisła, vol. 2, pp. 291-296.
7. Łukaniszyn M., Kowol M.: *Analiza pracy modułowego silnika reluktancyjnego z wirnikiem zewnętrznym*, Śląskie Wiadomości Elektryczne, 4'2005, pp. 4-7.
8. Łukaniszyn M., Kowol M.: *Wpływ zmian konstrukcyjnych na parametry elektromechaniczne silnika reluktancyjnego z wirnikiem zewnętrznym*, Przegląd Elektrotechniczny, 11'2006, pp. 43-45.
9. 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, pp. 157-166
10. Łukaniszyn M., Tomczewski K., Witkowski A., Wróbel K.: *Optymalizacja kształtu obwodu magnetycznego przełączalnego silnika reluktancyjnego na podstawie przebiegów momentu*, XLIII Międzynarodowe Sympozjum Maszyn Elektrycznych, SME'2007, Poznań, 2007, pp. 195-196.
11. Michalewicz Z.: *Algorytmy genetyczne + Struktury danych = Programy ewolucyjne*, WNT, Warszawa, 1996.
12. Wincenciak S.: *Metody i algorytmy optymalizacji kształtu obiektów w polu elektromag-netycznym*, Oficyna Wydawnicza PW, Warszawa 1998.

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ANALIZA FUNKCJI CELU
W OPTYMALIZACJI OBWODU MAGNETYCZNEGO
SILNIKA RELUKTANCYJNEGO TFM

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STRESZCZENIE *W artykule przedstawiono optymalizację obwodu magnetycznego silnika reluktancyjnego o budowie modułowej z wirnikiem zewnętrznym (rys. 1), przy zastosowaniu różnych wariantów funkcji celu. 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, ze modele polowe charakteryzują się dużym kosztem obliczeń, w szczególności przy zastosowaniu trójwymiarowej metody elementów skończonych, algorytm optymalizacyjny został rozbudowany dodatkowo o bazę danych. W bazie tej zapisywano dane osobników oraz obliczony dla nich moment elektromagnetyczny. Przed wykonaniem obliczeń polowych, zostaje wykonana procedura przeszukiwania bazy, w celu sprawdzenia, czy dla wygenerowanego osobnika nie zostały juz wcześniej wykonane obliczenia polowe.

Pierwszym zadaniem optymalizacyjnym było poszukiwanie największej wartości średniej momentu elektromagnetycznego. Funkcję celu opisano zależnością (2). W dalszej części pracy przeprowadzono obliczenia poszukiwania takiego rozwiązania, dla którego pulsacje momentu elektromagnetycznego (ε) byłyby jak najmniejsze. W tym przypadku funkcja celu została opisana zależnością (3).

Pierwsze rozwiązanie charakteryzowało się uzyskaniem dużej wartości średniej momentu elektromagnetycznego w stosunku do modelu podstawowego, jednakże pulsacje momentu również wzrosły (tab. 2). Natomiast dla drugiego rozwiązania uzyskano zmniejszenie pulsacji momentu elektromagnetycznego o ponad 50% w stosunku do modelu bazowego, przy czym uzyskana wartość średnia momentu elektromagnetycznego jest mniejsza niż dla pierwszego rozwiązania (tabela 3). Stąd też w kolejnym etapie obliczeń optymalizacyjnych problem optymalizacji zdefiniowano jako poszukiwanie wysokiej wartości średniej momentu elektromagnetycznego przy jednoczesnej minimalizacji jego pulsacji. Dla tak zdefiniowanego zadania funkcję celu opisano zależnościami (4) i (5). Wyniki obliczeń zamieszczono w tabelach 4 i 5.

Przeprowadzona analiza pozwala na określenie optymalnych wymiarów obwodu magnetycznego, które w efekcie dają najlepsze rozwiązanie pod kątem poprawy wartości parametrów elektromecha-

nicznych silnika już na etapie projektowania. Prezentowana metoda optymalizacyjna jest względnie prostym i skutecznym narzędziem do poszukiwania optymalnych parametrów konstrukcyjnych modeli numerycznych.