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Optimal design of the Brushed DC motor implemented for car window lifting system using Taguchi method

Optymalizacja magnetoelektrycznego silnika prądu stałego do podnoszenia szyb samochodowych z zastosowaniem metody Taguchi

***Abstract**. The paper presents the results of the multi-objective optimization of the brushed permanent magnet motor for a car window lifting system. The issue was executed by the use of orthogonal Taguchi tables. Application of the Taguchi method leads to simplified optimization. This is because, during the optimization process, the analysis tasks were computed for pre-defined numbers of the experiments. The number of experiments depends on a number and an assigned variability of a design variables. The motor was described by three variables, describing its structure of the magnetic circuit. The optimality criteria were formed by different combinations of functional parameters of the device. The selected functional parameters are taken into account in the multi-objective function. The mathematical model of the brushed DC motor includes (a) the electromagnetic field equations with non-linearity of the ferromagnetic material, (b) equations of the external supply circuit, and (c) equations of mechanical motion. The selected results of optimization were presented and discussed.*

***Streszczenie.** W artykule przedstawiono wyniki wielokryterialnej optymalizacji magnetoelektrycznego silnika prądu stałego do napędu szyb w samochodach. Zadanie wykonano przy wykorzystaniu metody tablic Taguchi. Wspomniany algorytm pozwala na skrócenie czasu trwania obliczeń, bowiem przetwarzanie danych dotyczących rozkładu pola elektromagnetycznego oraz parametrów funkcjonalnych, uwzględnianych w wielokryterialnej funkcji celu, wykonywane są dla zadanej liczby eksperymentów. Obiekt został opisany przy wykorzystaniu trzech zmiennych decyzyjnych. W procesie optymalizacji uwzględniono wybrane parametry funkcjonalne urządzenia. Model matematyczny silnika magnetoelektrycznego zawierał równania pola elektromagnetycznego z uwzględnieniem nieliniowości obwodu magnetycznego, zależności matematyczne zewnętrznego obwodu zasilającego oraz równanie równowagi mechanicznej. W artykule przedstawiono i omówiono wybrane wyniki testów numerycznych.*

Keywords: Taguchi method, brushed permanent magnet motor, multi-objective optimization, finite element method
Słowa kluczowe: metoda Taguchi, magnetoelektryczny silnik prądu stałego, optymalizacja wielokryterialna, metoda elementów skończonych

Introduction

The DC motors with permanent magnets (PM) have better functional parameters in relation to conventional DC motors. The brushed DC motors are equipped with a mechanical commutator and can be directly supplied by a car accumulator. The disadvantage of brushed motors is the low durability of the sliding contact, but in comparison to brushless DC motors. Brush DC motors do not require an electronic commutator, which increases reliability and reduces the cost of the whole drive system.

At present, the brush motor excited by permanent magnets can be employed in various applications, such as: combustion and electric vehicles, mechanical tools, toys and household [1]. The most number of PM brushed motors used in automotive industry is found in the range of 12-14V [2].

New electrical machines applied in automotive applications must meet the requirements concerning the energy efficiency and minimization of materials used to construction. The multi-objective optimization of the electrical machines taking into account the energy consumption and reduction of manufacturer and operation costs is commonly employed in the production of electromagnetic devices [3].

Nowadays, designed electric motors are often described by finite element methods (FEM) models or field-circuit coupled mathematical models [4, 5]. In case description of the designed devices by the FEM model to optimization can be successfully applied the nature-inspired optimization algorithms [6]. The nature-inspired optimization algorithms take into consideration interactions in groups of individuals forming an organized society [7]-[9]. The constraints can be taken into account in an easy way in such types of optimization algorithms [10].

The optimization process is iterative; it usually concerns iteratively repeating the process of simulating phenomena for various variants (structures) of an object – using a mathematical model of these phenomena and determining the functional parameters of the designed device. During the optimization process in subsequent iterations, the positions of all individuals creating the searching group are determined. The total calculation time of the optimization process for the electromagnetic devices described by FEM modes depends on the accuracy of the calculation of the electromagnetic field, and the number of individuals. Very often the special modifications are made to shortened total time of optimization process [11].

The disadvantages of the application of a nature-inspired algorithm are the long optimization time and the necessity to adaptation the selected optimization algorithm to considered electromagnetic devices. Adaptation procedure should be performed for characteristic coefficients of the optimization algorithm. Moreover, the heuristic algorithms include random coefficients, thus the optimization process should be repeated several times to find the global extreme point. Algorithm adaptation and repeat optimization processes additionally extend the time of optimization calculations.

As opposed to the nature-inspired algorithms methods, the Taguchi method is much easier and requires much less computational effort. After extracting the set of design variables and determining the levels of variability for all design variables, the orthogonal Taguchi table is determined. For each variant of the designed device, the values of design variables are taken according to the Taguchi table, next calculations of functional parameters are executed [12]. The quality of the optimal Taguchi method solution is limited by the assumed number of levels of variability of design variables. The optimal structure is searched within the calculated number of computation experiments.

The main aim of the research was the optimization of brushed DC motor for lifting car windows. The optimal solution was determined using Taguchi method. Such an approach allows to reduce calculation time by calculating the parameters for an assigned number of experiments.

The organization of the manuscript is following, it contains six main parts. The first section presents the issue (e.g. the review of design solutions for electric machines, the main optimization techniques, and the features related to the analyzed methods, etc.). Then, a brushed DC motor is presented. Next section is related to the optimization method – Taguchi algorithm – applied for the car window lifting system. Final part of the article is focused on the results and short conclusions.

Structure of the brushed DC motor

The optimized brushed DC motor is destined for a car lifting system. The brushed DC motor is a part of the drive system including (a) DC motor, (b) worm gear, and (c) mechanism with a rotating drum.

The stator of the motor is equipped with two pieces of permanent magnet. The rotor winding is distributed in eight rotor slots. Selected structural parameters and material properties are presented in Table 1.

Table 1. Structural parameters of the brushed DC motor

Parameter	Data	
	Unit	Value
Number of stator poles	[-]	2
Number of rotor slots	[-]	8
Inner stator diameter	[mm]	40.8
Stator stack length	[mm]	60
Stator and rotor material	[mm]	M19_24G
Rotor outer diameter	[mm]	40
Shaft diameter	[mm]	6
Supply voltage (DC)	[V]	12

The analyzed brushed DC motor is defined by three design variables describing the structure of the magnetic circuit. The set of design variables include: h – permanent magnet thickness, τ - permanent magnet span, B_{S0} - rotor slot opening width. The variables form vector $\boldsymbol{s}$. The structure of the optimized motor is presented in Figure 1.

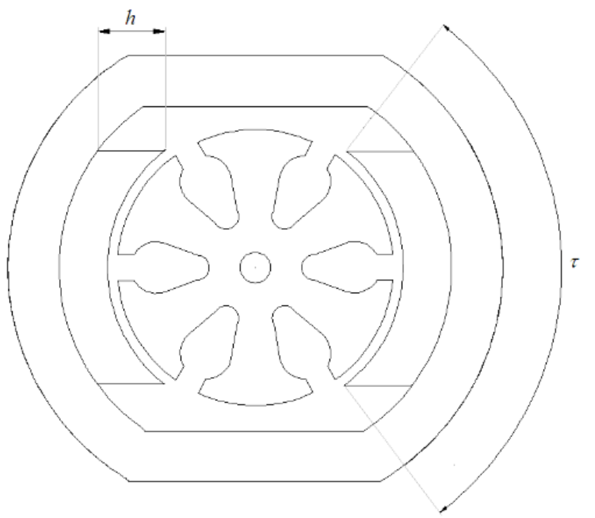

Fig.1. Structure of the brushed DC motor

Mathematical model of brushed DC motor

In PM motors, the magnetic field is generated simultaneously by permanent magnets and the armature winding [13]. The set of equations describing the distribution of the magnetic field has a form:

$$\text{rot}\left(\frac{1}{\mu}\text{rot}\boldsymbol{A}\right) = \boldsymbol{J_W} + \boldsymbol{J_{PM}} \quad (1)$$

where: μ is the magnetic permeability, $\boldsymbol{A}$ is magnetic vector potential, $\boldsymbol{J_w}$ is the vector of the current density in armature winding, $\boldsymbol{J_{PM}}$ is the polarization current density vector in areas with permanent magnets, J_{PM}=rot$\boldsymbol{M}$, $\boldsymbol{M}$ is magnetization vector.

The electromagnetic field in electromagnetic devices is excited by supply voltage. Due to the rotary elements and the non-linearity of the ferromagnetic circuit, the value of the current in the armature winding is unknown [14]. The instantaneous value of current in the armature winding is necessary to determine the magnetic field distribution [15], [16], therefore the equation describing the magnetic field must be solved simultaneously with the equation of the external supply circuit:

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} + Ri = u \quad (2)$$

where: ψ is the flux linkage of the armature winding, R is the armature resistance, i is the armature current, u is the supply voltage.

In dynamic states (start-up and load change), the velocity is not known in advance. Therefore, the mathematical model must be supplemented by mechanical motion equation [17]:

$$J\frac{\mathrm{d}\omega}{\mathrm{d}t} = T_e - T_L \quad (3)$$

in which: J is the rotor inertia, ω is angular velocity, T_e is the electromagnetic torque, T_L is the load torque.

Definition of the multi-objective function

The multi-objective compromise function can be formed by many functional parameters designed electromagnetic devices [18]. Some parameters forming the multi-objective function can be maximized or minimized. During optimization of electromagnetic devices the constrained optimization or multi-objective optimization are applied. In addition the compromise objective function include two, three and even more functional parameters of the optimized electromagnetic devices [19].

In electric machines applied in the automotive industry, there should be designed the device with high-efficiency and low total weight. Machines designed above requirements allow to obtain compromise between manufacture cost and operating cost [20].

During the optimal design of the brushed DC motor for car window lifting two multi-objective compromise functions are considered. The following motor parameters are taken into consideration: $\eta(\boldsymbol{s})$ is the car window motor efficiency, $I(\boldsymbol{s})$ is the is armature current, $m_{PM}(\boldsymbol{s})$ is the total mass of permanent magnet material and $T_c(\boldsymbol{s})$ is the cogging torque, which generate the torque ripple in the designed motor, where $\boldsymbol{s}=[h, \tau, B_{s0}]^T$ is the vector of design variables.

In the first case, the multi-objective has form [21]:

$$f(s) = \frac{\eta(\boldsymbol{s})}{\eta_0} + \frac{I_0}{I(\boldsymbol{s})} + \frac{m_{0\text{PM}}}{m(\boldsymbol{s})} \quad (4)$$

where: η_0, $m_{0\text{PM}}$ and I_0 are the average values of efficiency, permanent magnet mass and current for all experiments included in the Taguchi table.
The second variant of the objective function was adopted:

$$f(s) = \frac{\eta(\boldsymbol{s})}{\eta_0} + \frac{I_0}{I(\boldsymbol{s})} + \frac{T_{c0}}{T_c(\boldsymbol{s})} + \frac{m_{0\text{PM}}}{m(\boldsymbol{s})} \quad (5)$$

where: T_{c0} is average value of cogging torque from all experiments.

The upper and lower values of the design variables are presented in Table 2.

Table 2. The upper and lower values of the design variables

Design variable	Lower	Upper
h	4.8	5.8
τ	0.7	0.775
B_{s0}	2.6	3.4

Optimization results

The Taguchi optimization method relies on performing computational experiments according to a strictly defined orthogonal table. The number of experiments is determined on the basis of the number of design variables and the adopted number of variability of decision variables [22].

The design variables describing the structure of the designed motor are divided into four levels. The values of the design variables' individual levels are presented in Table 3.

In order to determine the optimal solution (a variant of the designed brushed DC motor) the Taguchi method was applied. In the case of three design variables and four discrete variability of design variables, the 16 variants must be calculated.

Table 3. Table including design variables and variability levels

Design variable	Level 1	Level 2	Level 3	Level 4
h	4.8	5.1	5.3	5.8
τ	0.700	0.725	0.75	0.775
B_{s0}	2.6	2.8	3.0	3.4

The calculations are made for Samarium magnets ($SmCo_{20}$) with residual magnetic flux density (B_r=0.85 T). After calculation all experiments, the average values of functional parameters used to determination the multi-objective compromise functions can be calculated. The average functional parameters for all experiments are the following: η_0=75.42%, m_{0PM}=0.281kg and I_0 =14.217A.

The results of calculations from the objective function described by equation 4 are presented in Table 4.

Table 4. The Taguchi table for $SmCo_{20}$ material

h	τ	B_{s0}	η(s)	m_{PM}(s)	I(s)	$f_1(s)$
[mm]	[°]	[mm]	[%]	[kg]	[A]	[-]
4.8	0.7	2.6	80.89	0.246	5.86	4.6327
4.8	0.725	2.8	79.02	0.265	3.06	6.7456
4.8	0.75	3.0	79.15	0.264	3.05	**6.7620**
4.8	0.775	3.4	79.23	0.273	3.045	6.7386
5.8	0.7	2.8	79.37	0.256	11.44	3.3832
5.8	0.725	2.6	80.48	0.265	8.65	3.7617
5.8	0.75	3.4	80.96	0.274	5.84	4.5244
5.8	0.775	3.0	79.13	0.283	3.05	6.6885
5.1	0.7	3.0	74.99	0.270	19.79	2.7429
5.1	0.725	3.4	76.56	0.280	16.98	2.8455
5.1	0.75	2.6	78.06	0.291	14.23	2.9893
5.1	0.775	2.8	79.41	0.299	11.43	3.2261
5.3	0.7	3.4	66.74	0.295	33.71	2.2488
5.3	0.725	3.0	68.43	0.305	30.96	2.2773
5.3	0.75	2.8	70.11	0.316	28.18	2.3126
5.3	0.775	2.6	70.12	0.327	28.19	2.2825

Taking into account the f_1 objective function the hight value was obtained for variants 2, 3 and 4. The optimal variant has the following design variables: h=4.8 mm, τ=0.75 and B_{S0}=3.0 mm. The functional parameters for optimal brushed DC motor are: η=80.15 %, m_{PM}=0.264 kg and I=3.05 A.

If the objective function composed from four parameters (efficiency, mass of the permanent magnet material, armature current and cogging torque) is taken into consideration, the three best solutions are 8, 2 and 3 variants from Taguchi Table. The optimal variant has following design variables: h=5.8 mm, τ=0.775 and B_{S0}=3.0 mm. In this case the parameters of the optimal brushed DC motor are: η=80.13 %, m_{PM}=0.283 kg, I=3.05 A and T_c=41.61 mNm.

Next, the efficiency characteristic of an optimal variant of the brushed DC motor equipped with SmC_{20} magnets for different motor velocities has been analyzed. Figure 2 presents the η=f(n) waveform for optimal variant solution with SmC_{20}.

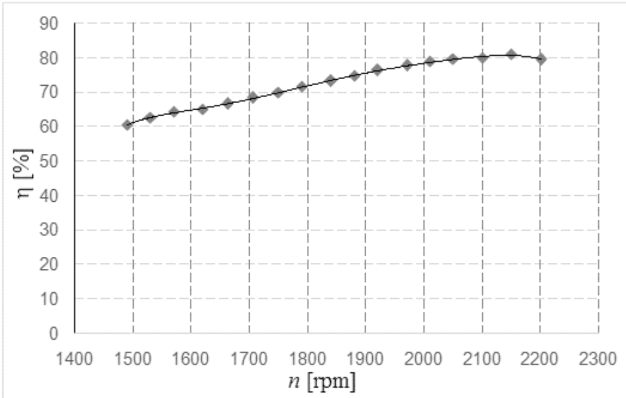

Fig.2. The efficiency characteristic for SmC_{20} magnet material

Next, the optimization process was performed for a motor with magnets made from $NdFe_{35}$ material with residual flux density B_r=1.21 T. The results of the simulation calculations are presented in Table 5. The average values of functional parameters for all experiments from the Taguchi table are determined: η_0=74.99 %, m_{0PM}=0.247 kg and I_0 =16.955 A and T_{c0}=71.79 mNm. In the case of both multi-objective function, the best value of the objective function for the fourth variant from the Taguchi table is obtained. The optimal brushed DC motor is characterized by the following parameters: η=78.43 %, m_{PM}=0.243 kg, I=3.15 A and T_c=56.42 mNm.

Table 5. The Taguchi table for $NdFe_{35}$ material

h	τ	B_{s0}	η(s)	m_{PM}(s)	I(s)	T_c	f_1(s)	f_2(s)
[mm]	[°]	[mm]	[%]	[kg]	[A]	[mNm]	[-]	[-]
4.8	0.7	2.6	78.47	0.219	10.85	55.32	3.740	5.038
4.8	0.725	2.8	79.61	0.227	7.94	50.23	4.288	5.718
4.8	0.75	3.0	80.16	0.235	6.05	136.4	4.926	5.452
4.8	0.775	3.4	78.43	0.243	3.15	56.42	**6.151**	**7.424**
5.8	0.7	2.8	78.48	0.236	10.84	46.52	3.661	5.204
5.8	0.725	2.6	77.10	0.228	13.75	51.36	3.348	4.746
5.8	0.75	3.4	79.61	0.244	7.93	164.2	4.215	4.652
5.8	0.775	3.0	79.65	0.252	10.83	47.93	3.610	5.109
5.1	0.7	3.0	72.45	0.241	22.41	52.77	2.750	4.111
5.1	0.725	3.4	74.07	0.250	19.49	47.01	2.848	4.376
5.1	0.75	2.6	75.64	0.258	16.64	124.5	2.988	3.565
5.1	0.775	2.8	75.66	0.267	17.63	39.05	2.898	4.737
5.3	0.7	3.4	64.08	0.263	37.83	45.63	2.244	3.818
5.3	0.725	3.0	65.78	0.272	34.98	32.25	2.272	4.499
5.3	0.75	2.8	65.79	0.282	33.01	127.4	2.269	2.833
5.3	0.775	2.6	65.81	0.291	33.02	26.16	3.740	5.038

The carried out computation for two types of permanent magnet materials, $SmCo_{20}$ and $NdFe_{35}$. The application of stronger magnets – $NdFe_{35}$ does not increase the efficiency of the designed motor and also increases the maximum value of the cogging torque. The $NdFe_{35}$ magnet requires modification of the variability intervals (reduction) compared to the weaker $SmCo_{20}$ magnets.

Conclusions

The manuscript concerns the optimization of the brushed DC motor for the car lifting window system. A 2D FEM mathematical model of the optimized motor was developed. The Ansys environment was applied to determine the magnetic field distribution and functional parameters taking into account in multi-objective compromise function. The optimization was executed using the Taguchi method.

Most of the articles published in world literature present the application of non-deterministic methods, most often from the group of nature-inspired algorithms, for the optimization of electromagnetic devices. Methods from the nature-inspired optimization algorithms group exploit interaction in groups of cooperating individuals to solve an optimization task. The optimization process requires determining the positions of the individuals constituting the group in subsequent iterations of the optimization algorithm. Therefore, the value of the objective function, i. e. the magnetic field distribution and functional parameters, must be determined many times. In the case of determining the parameters of an electromagnetic device using the FEM model, the optimization process may be very time-consuming.

The main advantage of the Taguchi method is the small number of experiments in comparison to the nature-inspired optimization algorithm. Additionally, the application of the Taguchi method is very simple. The user has to specify the number of decision variables and determine the levels of variability.

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