MULTI-OBJECTIVE OPTIMIZATION OF A PERMANENT MAGNET BRUSHLESS DC MOTOR USING WHALE OPTIMIZATION ALGORITHM

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Abstract

In this paper, the algorithm and computer script for the multi-objective optimization of permanent magnet brushless DC motors for propulsion of electric vehicles have been developed. The optimization procedure was based on the whale optimization algorithm. The optimization procedure was tested using the selected benchmark function. The mathematical model of the outer-rotor BLDC motor was developed. The designed motor is described by four design variables. The multi-objective compromise function contains two functional parameters of the designed motor: efficiency and total mass of materials used in the construction of the motor. Selected optimization results are presented and discussed.

1 Introduction

Optimization algorithms are more and more commonly used in electrical machines optimal design [1], just like in other fields requiring devices and systems with strictly and precisely defined properties [2]. If optimization algorithms do not allow to fulfill these requirements, then they certainly indicate what affects the parameters of the designed device or system significantly.

Optimization algorithms have a very long history, which probably began with Euclid. He proved, that among all rectangles with equal length sum of edges, square is the one with the greatest area [3].

Nowadays, many papers are devoted to the application of various optimization algorithms in the optimal design of electromagnetic devices [4]. Those papers are divided into two main groups: (a) application to optimization algorithms to improve various parameters of designed devices [5], and (b) development of new more efficient optimization algorithms [6]. The previous decade has brought enormous development of optimization algorithms that can successfully and effectively support the design process [7].

The aim of the paper is application whale optimization algorithm to structure optimization of the outer-rotor permanent magnet brushless DC (BLDC) motor to electromobility applications.

2 Whale optimization algorithm

Whale optimization algorithm (WOA) was proposed by S. Mirjalili and A. Lewis in 2016 [8]. The algorithm is based on the hunting behavior of some whale species.

Whale optimization algorithm involves determining positions of all individuals in pod utilizing position of best-adapted or random whale. At the beginning of optimization calculation, positions of all whales are chosen randomly. In the next stage, the hunting method (siege mechanism or spiral mechanism) is determined. The probability of choosing both methods is equal.

In the case of choosing a siege mechanism, C and A coefficients for *i*-th whale are calculated:

$$\mathrm{A}_i^k = 2 \cdot a \cdot r_1 - \mathrm{a}, \; C_i^k = 2 \cdot r_2 \tag{1}$$

where: k is the iteration number, r_1, r_2 are the randomly generated from range $[0; 1]$, a decrease from 2 to 0 with the increasing number of iteration. In the next stage position of whales are calculated:

$$X_{i+1}^k = X_i^* - A_i^k \cdot \left| C_i^k \cdot X_i^* - X_i^k \right| \tag{2}$$

where X_i^* is the possible position of prey and it depends on the value of $|A|$. If $|A| < 1$ then $\mathrm{X}_i^* = X_i^{best}$, where X_i^{best} is the position of best-adapted whale. Otherwise ($|A| \geq 1$) $\mathrm{X}_i^* = X_i^{rand}$.

In the case of choosing the spiral mechanism D' is determined:

$$D_i'^k = \left| X_i^{best} - X_i^k \right| \tag{3}$$

Finally, position of all whales is calculated using formula:

$$X_{i+1}^k = D_i'^k \cdot e^{bl} \cdot cos(2\pi l) + X_i^{best} \tag{4}$$

where: b is the constant number, l is the generated randomly from range $[-1, 1]$.

3 Test of the optimization procedure

Optimization algorithm was elaborated in a Python programming environment. Then the algorithm and software correctness were checked using drop-wave benchmark function. The drop wave function is described by formula (5):

$$f(x_1, x_2) = -\frac{1 + \cos\left(12\sqrt{x_1^2 + x_2^2}\right)}{0{,}5(x_1^2 + x_2^2) + 2} \tag{5}$$

The drop-wave function has only one global minimum for $x_1 = 0$ and $x_2 = 0$ and it is equal to $f(0,0) = -1$ [9]. Figure 1 presents a 3D plot of drop – wave function when $x_1, x_2 \in [-1,1]$.

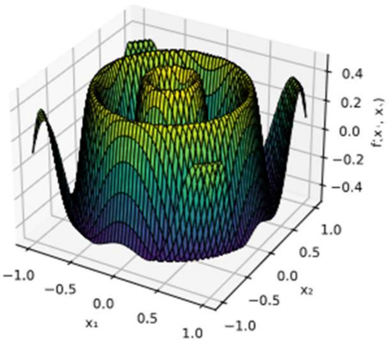

Fig. 1: 3D visualisation of drop - wave function

For testing purposes, a population of 40 whales and a maximal number of iterations equal to 50 were adapted. Then optimization software was run 20 times for random initial populations.

Among all the analyzed runs, the developed procedure stuck at the local minimum only twice. Figure 2 illustrates the convergence curve for the run completed with the best final value of the objective function.

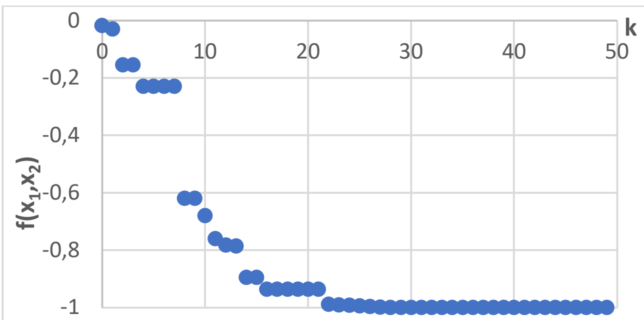

Fig. 2: Convergence curve for the best final objective function.

4 Results of multi-objective optimization

The considered motor is an outer-rotor BLDC motor for electric bike. The following parameters of the designed motor have been assumed: rated value of torque T_N=10 Nm, rated supply voltage U_N=36 V, rated velocity n_N=280 rpm, and no-load velocity n_{max}=420 rpm.

The aim of the optimization procedure is determining the vector of design parameters of the designed motor ensuring maximum value of multi-objective function. The outer-rotor BLDC motor is described by four design variables: d_o – is the outer rotor diameter, B_δ – is the maximum value of magnetic flux density in air gap; J_w – is the current density in motor stator winding, B_s – is the average magnetic flux density in stator teeth.

The developed model of the outer-rotor BLDC motor allows to calculate following functional parameters of the designed motor: (a) motor efficiency (η), (b) total mass of constructional elements (m_t), and (c) temperature of motor winding in steady-state operation (ϑ_w).

The compromise multi-objective additive function has adopted:

$$f(d_o, B_\delta, J_{w,} B_s) = \left(\frac{\eta}{\eta_0}\right) + \left(\frac{m0}{m_t}\right) \tag{6}$$

in which: η_0, m_0 and ϑ_0 are average functional parameters after initiation, respectively.

The optimization calculation was performed for a population of whales equal to 50. The optimal values of design variables are: d_o=109.79 mm, B_δ=0.728 T, J_w=2.78 A/mm^2, and B_s=1.61 T. The optimal functional parameters are: η=88.6 %, m_t=5.28 kg and ϑ_w=76,42°C.

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