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APPLICATION OF MIXED ALGORITHMS OF OPTIMIZATION IN DESIGNING OF BIG POWER LOW VOLTAGE INDUCTION MOTORS[1]

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The thesis deals with a problem of designing low voltage high power induction motors. Hybrid optimization algorithms are used. Selected global and deterministic optimization algorithms with modifications are applied. These modifications are the author's original scientific contribution to their basic form.

1. INTRODUCTION

To optimize high power induction motors, discrete and continuous variables should be used, where discontinuous variables can be of an integer and fractional type. Such an approach is rare in the contemporary literature. The most common practice so far has been to calculate using only continuous variables. Only the number of series turns of stator winding or the diameter of wire have been declared as discrete.

For the optimization of induction motors such an approach is not sufficient. Therefore, it seems necessary to widen the spectrum of discontinuous variables. For a motor as a real object it is necessary to take into account several design and functional constraints. An additional problem is a relatively flat objective function. This function cannot be conditioned directly by decision variables of

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optimization. The value of the objective function can be calculated only after conducting complete design calculations.

2. THE THESES

1. Algorithms of optimization of low-voltage high-power induction motors require using not only continuous decision variables, but also discrete variables. Increasing the number of discrete variables creates an opportunity to develop a motor construction that is optimal from the perspective of material and operational costs.
2. For issues of optimization with limitations, when the objective function cannot be defined in an explicit form, it is necessary to use hybrid optimization algorithms constituting a combination of the global optimization algorithms and the deterministic methods.

3. OPTIMIZATION ALGORITHMS

The results obtained by the application of three new hybrid algorithms: GA-R, ES$\mu+\lambda$-R, PSO-R were compared. These hybrid algorithms were created by connecting three algorithms of global optimization, i.e. genetic algorithm GA, evolutionary strategy ES$\mu+\lambda$ and particle swarm optimization PSO with a suitable modified Rosenbrock method [6,7,8,12].

At first, in this optimization three algorithms of global optimization, i.e. genetic algorithm GA, evolutionary strategy ES and particle swarm optimization PSO were used. In these algorithms the continuous, discontinuous integer and fractional variables were taken into account. This enables one to achieve a close proximity of the global optimum. Then, the values of the discontinuous variables were assumed stable. The best solution obtained by the algorithm of global optimization became the starting point of the modified deterministic Rosenbrock algorithm. In the Rosenbrock algorithm only 8 continuous variables were used. By using Rosenbrock's algorithm we try to get closer to the global optimum.

All three global optimization algorithms process the whole population of potential solutions at the same time. The genetic algorithm, as well as the evolutionary strategy, uses the mechanism of an evolution process, whereas the PSO algorithm is based on the model of behaviour of a group of animals (birds, fish, or insects).

Rosenbrock's method, belonging to the group of deterministic methods, processes only one solution at a given moment.

All algorithms of the optimization were implemented in the computer program OPTYM v.2 [11] in Matlab v. 7.0 in which for the calculation of the successive version of the motor, the computer program SPOS1 [10] was used.

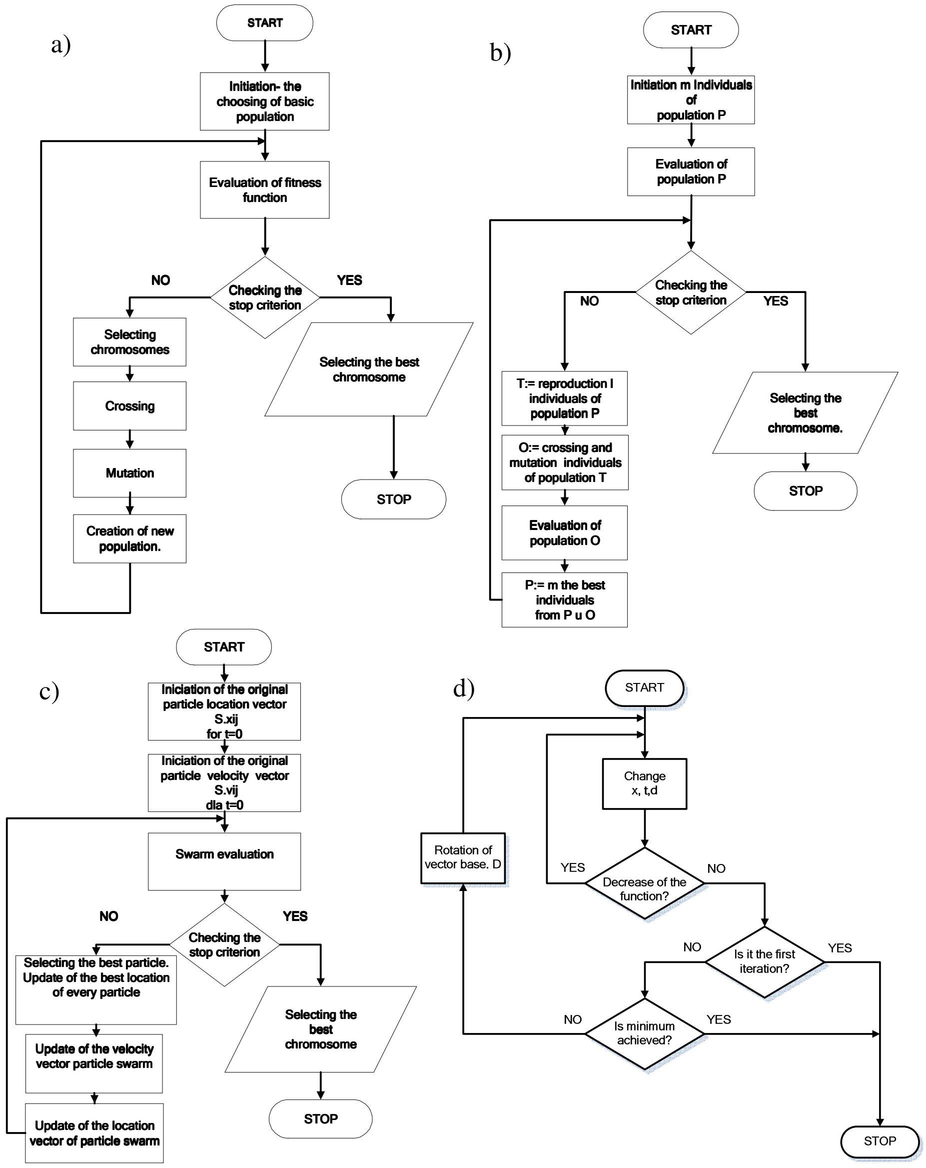

Fig. 1. Scheme of operation: a) genetic algorithm GA b) evolutionary strategy ES(μ+λ) c) particle swarm optimisation PSO d) Rosenbrock's algorithm

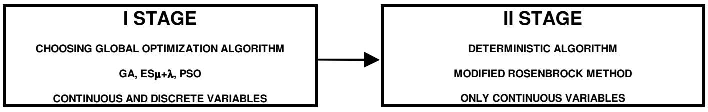

Fig. 2. Block scheme of hybrid optimization algorithm

The use of the algorithms presented here for induction motor optimization required introducing many modifications, i.e.:

- adaptation of algorithms so that they work with continuous variables, discrete variables and continuous and discrete variables at the same time by implementing proper/special functions decoding a single solution for deterministic algorithms or the whole population of solutions for global optimization algorithms;
- adjusting Rosenbrock's deterministic algorithm for operation in the space of cubic limitations imposed on decision variables;
- for ESλ+μ algorithm, modifying the vector of standard deviations in case of infringing cubic limitations, and introducing the procedure of shuffling the population of solutions a given number of times before the next reproduction to the temporary population, thanks to which a greater diversity of population is provided;
- for ESλ+μ and PSO algorithms, introducing the repair procedure, in case a given individual infringes cubic limitations, by putting it on the infringed limitation, or by returning to the inside of the area of cubic limitations, by a random generation of a new individual.

4. DEFINING THE PROBLEM OF MOTOR OPTIMIZATION

Objective function F_c in the form [9]:

$$F_c = K_m + (K_p + K_q)* n_0 \tag{1}$$

was minimized, where: $n_0 = 1$ or 0, K_m, $K_e = K_p + K_q$ - the materials and operating unit costs ratio to the price of 1 kWh [5].

The limitations were taken into account by introducing the external penalty function. The minimization resulted in the function of the form:

$$F_p(x) = F_c + P(x) \tag{2}$$

where external penalty function $F_p(x)$ is in the form:

$$P(x) = \sum_{i=1}^{n} w_i * (p_i(x)) \tag{3}$$

w_i – the penalty coefficient

$$p_i(x) = \begin{cases} 0 & gdy \quad g_i(x) \le 0 \\ \dfrac{|g_i(x) - g_i|}{g_i} & gdy \quad g_i(x) > 0 \end{cases} \tag{4}$$

g_i – the set value of i – function of the limitation, $g_i(x)$ - the value of i – function of the limitation for the variable in the x individual, $p_i(x)$ - the value of i – function of the limitation ratio to the value of the limitation.

In the set of optimization variables, 8 are continuous. They are: the basic dimensions of the stator core, the dimensions of the stator and rotor slots. They are expressed as relative, proportional. In addition, there are 3 discrete variables [8,12], ie:

1. **Qs** – the number of stator slots
2. **Qr** – the number of rotor slots
3. **asq** – the number of parallel paths of the stator winding.

In many papers there is the discrete change of the number of series coils with the imposed number of stator and rotor slots. The author used a discrete change of the number of stator slots **Qs** determining the discrete change of the number of rotor slots **Qr**. Such an approach has an innovative character. It significantly increases the probability of finding an optimal solution. (and, at the same time, is an extension of solutions encountered in the literature). It was also assumed that the number of parallel branches of the stator winding can take values of **asq** = 1, **p**, 2**p**. (where p – the number of motor pole pairs). Acceptance of the set above causes a discreet change of the following variables:

- The number of series turns of the stator winding **Ns,**
- The stator winding pitch **ys,**
- The number of parallel wires of the stator winding **asd.**

The basic limitations are as follows:

- **dtets** – the steady temperature increase (dtets = 115^{0}C),
- **Mb1m**, **Mk1m** – the minimal values of the pill-out and starting torque (Mb1m = 1.7 , Mk1m = 1.2),
- **Sk1m** – the maximal value of the starting complex power (Sk1m = 8),
- **etam** – the minimal value of the motor efficiency (etam = 0.92).

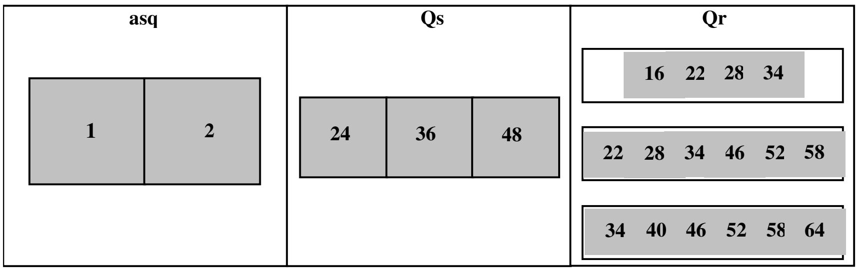

Fig. 3. The structure of the cell array storing discontinuous variables for the case p = 1

Additional constraints are: the maximal values of the flux density in the core of the motor, the minimal values of the dimensions of the stator and rotor slots, and the maximal value of the filling factor of the stator slot.

The solutions where the external diameter of the stator core was smaller than the admissible value of the motor frame size were taken into account.

5. THE RESULTS OF OPTIMIZATION OF INDUCTION MOTOR

The object of the investigation was a three-phase, two-pole, low voltage induction squirrel-cage motor of 380 V (triangle connected) rated voltage and rated output power of 250 kW. For the frame size of this motor equal to 355 mm, the maximal external diameter of the stator core is Dse = 600 mm.

The values of the objective function Fc calculated using all the algorithms of the global optimization, for 100 populations of 100 individuals, are shown in Figure 4.

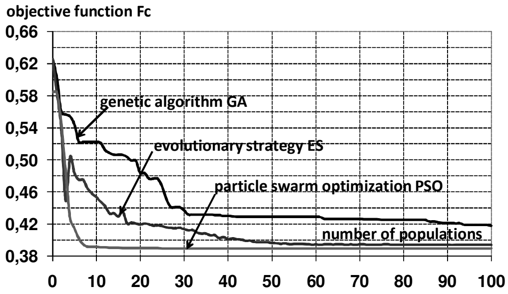

Fig. 4. The values of the objective function Fc vs. the number of populations for different algorithms of the global optimization

Figure 5 shows the results of these calculations for 20 iterations for the modified Rosenbrock's method, used for the further optimization of the motor.

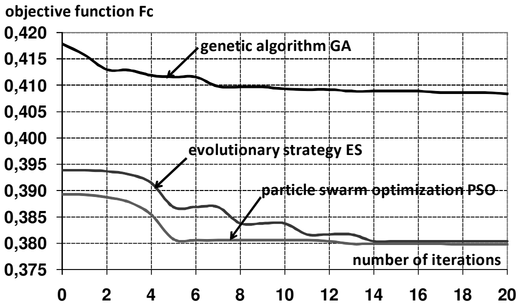

Fig. 5. The values of the objective function Fc vs. the number of the iterations for modified Rosenbrock's method

The values of the optimization variables and the objective function calculated using all hybrid algorithms are shown in Table 1.

Comparing the values of the objective function, we can state that the lowest value of the objective function is obtained by the hybrid optimization algorithm PSO-R. This algorithm also gives good results very fast - after about 10 populations for the first time, and 5 iterations for the second time of the optimization process.

Table 1. The values of the optimization variables and objective function

	Km	**Ke**	**Fp**
GA	0.0702	0.3476	**0.4178**
ESμ+l	0.0661	0.3276	**0.3938**
PSO	0.0627	0.3266	**0.3893**
GA-R	0.0669	0.3415	**0.4083**
ESμ+l-R	0.0601	0.3202	**0.3803**
PSO-R	0.0623	0.3174	**0.3797**
Existing motor	0.0654	0.4160	**0.4813**

Figure 6, column I represents continuous variables; column II represents continuous and discrete – the genetic algorithm in both cases; column III presents Rosenbrock's method. This metod is mariginally better. On the contrary, increasing the number of discrete variables is significantly better in comparison to using only continuous variables. This constitutes proof of the first thesis made in this dissertation.

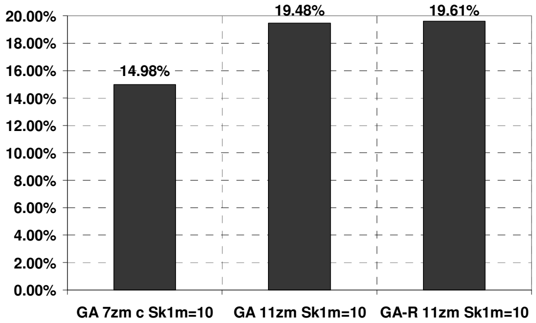

Fig. 6. Percentage change of the total costs of the optimized motor for algorithms: GA for 7 continuous variables, GA for 11 variables and GA-R for 11 variables

Figure 7a presents a percentage decrease in the total costs of the optimized motor for an individual hybrid algorithm in relation to the total costs of the existing motor, respectively. Figure 7b presents a percentage decrease in the total costs of the optimized motor for an individual hybrid algorithm in comparison with the first stage of their operation. A bigger decrease in the total unit costs of the optimized motor ratio to the total costs of the existing motor in this case is obtained by using hybrid optimization algorithms PSO-R.

Fig. 8 and 9 present: slot shapes of the stator and rotor, respectively. The shapes for the existing and designed motors by using the hybrid algorithms.

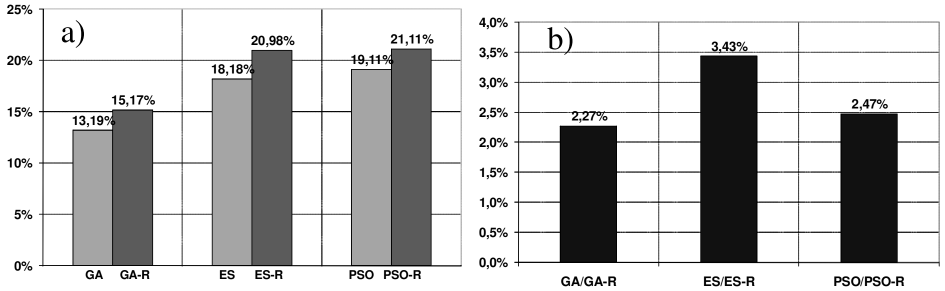

Fig. 7. Decrease in the total costs a) of the optimized motor ratio to the total cost of the existing motor, b) of the optimized motor calculated using hybrid algorithms ratio to the total costs calculated using only global optimization algorithms

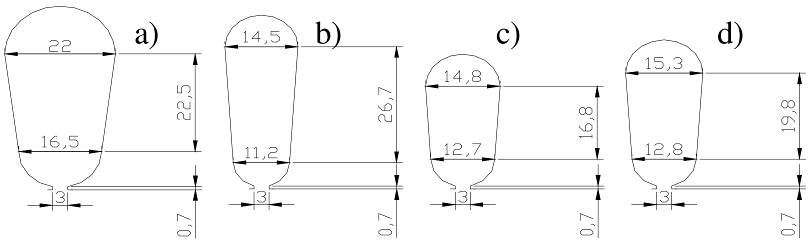

Fig. 8. Shapes and dimension of the stator slots for: a) existing and designed motors using hybrid algorithms: b) GA-R algorithm, c) ESμ+λ-R algorithm, d) PSO-R algorithm

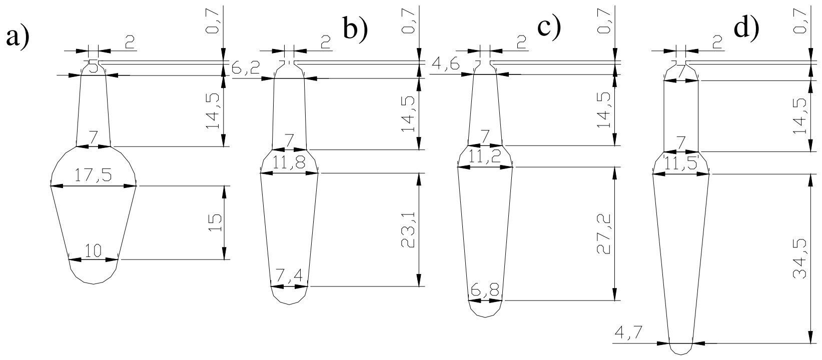

Fig. 9. Shapes and dimensions of the rotor slots for: a) existing and designed motors using hybrid algorithms: b) GA-R algorithm, c) ESμ+λ-R algorithm, d) PSO-R algorithm

6. CONCLUSION

The research confirms the truth of the thesis:

1. Using continuous and discrete decision variables in the optimization of the low voltage big power induction motor allows achieving approximately 20 % lower total costs (material and operational costs) than in the case of using only continuous variables.
2. Using global optimization algorithms for cases with limitations can be effective although the objective function cannot be defined in an explicit form. This approach enabled the author to achieve the global optimum, or its very close proximity. The results were improved by using the deterministic methods.

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ZASTOSOWANIE MIESZANYCH ALGORYTMÓW OPTYMALIZACJI W PROJEKTOWANIU NISKONAPIĘCIOWYCH SILNIKÓW INDUKCYJNYCH DUŻEJ MOCY

Streszczenie

Rozprawa dotyczy wykorzystania hybrydowych algorytmów optymalizacji do projektowania niskonapięciowych silników indukcyjnych dużych mocy. W pracy przedstawiono opracowane hybrydowe algorytmy optymalizacji: GA-R, ES-R, PSO-R, będące połączeniem trzech algorytmów optymalizacji globalnej, tj.: algorytmu genetycznego GA, strategii ewolucyjnej ES i algorytmu optymalizacji rojem cząstek PSO z odpowiednio zmodyfikowaną metodą Rosenbrocka. Ponadto dokonano porównania wyników obliczeń optymalizacyjnych silnika dla algorytmów optymalizacji globalnej jak i algorytmów hybrydowych. Zaimplementowane algorytmy wymagały wprowadzenia wielu zmian, tj. adaptacja do pracy tylko ze zmiennymi ciągłymi, tylko dyskretnymi oraz ciągłymi i dyskretnymi, przez zastosowanie odpowiednich funkcji dekodujących pojedyncze rozwiązanie dla metody deterministycznej oraz całe populacje rozwiązań dla algorytmów optymalizacji globalnej; dla algorytmu ES zmodyfikowanie wektora odchyleń standardowych w przypadku naruszenia ograniczeń kostkowych, oraz wprowadzenie procedury tasowania populacji rozwiązań zadaną ilość razy przed kolejną reprodukcją; dla algorytmów ES i PSO wprowadzenie procedur naprawy w przypadku naruszenia ograniczeń kostkowych przez danego osobnika. Zastosowanie hybrydowych algorytmów optymalizacji do optymalizacji silnika zmniejszyło koszty materiałowe i eksploatacyjne o około 20% w stosunku do silnika istniejącego, a uzyskane rozwiązania mają lepsze parametry eksploatacyjne.

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