Parameter estimation of induction motors using Wild Horse Optimizer

Jovan Vukašinović, Miloš Milovanović, Nebojša Arsić, Jordan Radosavljević, Saša Štatkić, Bojan Perović and Andrijana Jovanović

Abstract—**In this paper, a new metaheuristic algorithm called the Wild Horse Optimizer (WHO) is for the first time proposed for estimation of the equivalent circuit parameters of the single-cage induction motors. The parameters of the motors are found as a result of the error minimization function between the calculated and manufacturer data. Simulation results obtained using the WHO algorithm are compared to the results obtained using other optimization methods applied in solving the induction motor parameter estimation problem. The performances of the methods are evaluated using the motors of different powers (i.e. 5 HP and 40 HP), based on the statistical analysis of the results obtained in several independent runs of the methods. It is shown that the proposed WHO algorithm has better performance, i.e. it is able to provide quality solutions with faster convergence speed and better statistical indicators.**

Index Terms—**Induction motors, Parameter estimation, Optimization, Metaheuristic, Wild Horse Optimizer (WHO)**

I. Introduction

Induction motors are the most widespread electric motors in the world, and as such they represent one of the largest consumers of the electricity. Today, induction motors consume between 35% and 40% of the world's total electricity production. Knowing the parameters of the equivalent circuit of an induction motor is of great importance for drive control processes, as well as for fault diagnosis of the induction motor.

Classical methods for determining the parameters of the equivalent circuits of induction motors are based on no-load and short-circuit experiments. Because these tests are very difficult to perform in cases where the motor is already connected to a mechanical load, these methods are not always easily applicable in industry. For these reasons, in the recent years, many analytical and optimization methods have been proposed to estimate the parameters of induction motors. Some of the commonly used methods for estimation the parameters of induction motors that can be found in the literature are: Particle Swarm Optimization (PSO) [1], Genetic Algorithm (GA) [2], Charged System Search (CSS) [3], hybrid GA and PSO (HGAPSO) [4], Gravitational Search Algorithm (GSA) [5], hybrid Phasor Particle Swarm Optimization and Gravitational Search Algorithm (PPSOGSA) [6], and Shuffled Frog Leaping Algorithm (SFLA) [7].

In this paper, the Wild Horse Optimizer (WHO) [8] is for the first time proposed for estimating the single-cage induction motors parameters. It could be regarded as the main contribution of the paper. In the scientific literature, there is no research that deals with the direct application of the WHO algorithm for solving any problem of induction motor parameter estimation. The WHO algorithm has shown very good results in solving different complex benchmark functions, as pointed out in [8], and practical engineering problems, such as the problems of the parameter estimation of diode PV models [9], static/dynamic PV models [10], and damage identification in steel plates [11]. For this reason, the authors of this paper have decided to use the WHO algorithm.

II. Problem formulation

In order to optimize the values of the electrical parameters, the formulation of the objective function is required. In this case the objective function has the following form [7]:

$$OF = F_1^2 + F_2^2 + F_3^2 + F_4^2 , \qquad (1)$$

where

$$F_1 = \frac{T_{fl.cal} - T_{fl.mf}}{T_{fl.mf}} , \qquad (2)$$

$$F_2 = \frac{T_{st.cal} - T_{st.mf}}{T_{st.mf}} , \qquad (3)$$

$$F_3 = \frac{T_{\max.cal} - T_{\max.mf}}{T_{\max.mf}} , \qquad (4)$$

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$$F_4 = \frac{pf_{fl.cal} - pf_{fl.mf}}{pf_{fl.mf}}. \quad (5)$$

In (1) – (5) variables have the following meaning: *OF* is the objective function, F_i (i = 1,2,…,4) is the i-th component of the objective function (i.e., it is an error between the calculated and manufacturer value), T is a torque, I is a current, pf is a power factor, subscripts *st*, *fl* and max correspond to the start load, full load, and maximum load, respectively. Also, subscripts *cal* and *mf* are used for the calculated and manufacturer data.

According to Fig. 1, the stator ($\underline{I}_s$) and rotor ($\underline{I}_r$) currents in terms of slip (s) can be calculated using the following equations:

$$\underline{I}_s(s) = \frac{\underline{V}_{ph}}{R_s + jX_s + \underline{Z}_p(s)}, \quad (6)$$

$$\underline{I}_r(s) = \frac{\underline{Z}_p(s)\cdot \underline{I}_s(s)}{\frac{R_r}{s} + jX_r}, \quad (7)$$

where $\underline{V}_{ph}$ is the stator phase voltage, R_s is the stator resistance, R_r is the rotor resistance, X_s is the stator leakage reactance, X_r is the rotor leakage reactance, and X_m is the magnetizing leakage reactance.

The equivalent impedance ($\underline{Z}_p$) and Thevenin's equivalent impedance ($\underline{Z}_{Th}$) are:

$$\underline{Z}_p(s) = \frac{1}{\frac{1}{jX_m} + \frac{1}{\frac{R_r}{s} + jX_r}}, \quad (8)$$

$$\underline{Z}_{Th} = R_{Th} + jX_{Th} = \frac{1}{\frac{1}{R_s + jX_s} + \frac{1}{jX_m}}. \quad (9)$$

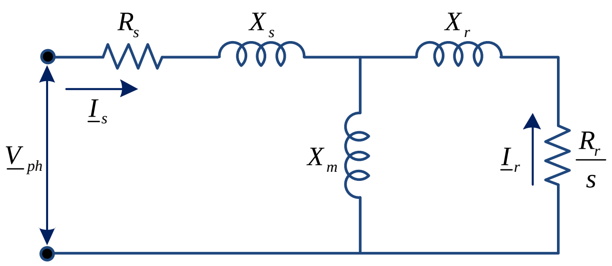

Fig. 1. One phase steady-state equivalent circuit of a single-cage three-phase induction motor.

The torque in terms of slip can be obtained by using the following equation:

$$T(s) = \frac{3p}{\omega_s}\left[I_r(s)\right]^2 \frac{R_r}{s}. \quad (10)$$

Thus, $T_{fl} = T(s_{fl})$, $T_{st} = T(1)$, and $T_{\max} = T(s_{\max})$, where the maximum torque slip ($s_{\max}$) is given by (11).

$$s_{\max} = \frac{R_r}{\sqrt{R_{Th}^2 + \left(X_{Th} + X_r\right)^2}}. \quad (11)$$

The apparent, active and reactive powers are:

$$\underline{S}(s_{fl}) = 3\cdot \underline{V}_{ph}\cdot\left[\underline{I}_s(s_{fl})\right]^*, \quad (12)$$

$$P_{fl} = \mathrm{Re}\left\{\underline{S}(s_{fl})\right\}, \quad Q_{fl} = \mathrm{Im}\left\{\underline{S}(s_{fl})\right\}. \quad (13)$$

Finally, the power factor can be calculated:

$$pf_{fl} = \arctan\left(\frac{Q_{fl}}{P_{fl}}\right). \quad (14)$$

According to [6, 7], the following constraints are taken into account:

$$R_s, R_r, X_s, X_r, X_m > 0, \quad (15)$$

$$X_s = X_r. \quad (16)$$

III. Solution Method

The WHO algorithm [8] is a recently proposed metaheuristic algorithm developed by Naruei and Keynia. This algorithm is inspired by the social life behavior of wild horses in the nature. Wild horses exhibit different group behaviors, such as grazing, chasing, mating, dominance and leadership.

The WHO algorithm consists of the following steps [8]:

A. Creating an Initial Population and Forming Horse Groups, and Selecting Leaders

The WHO begins with an initial population of N agents, $\mathbf{POP}(1) = \left[\mathbf{X}_1(1), \mathbf{X}_2(1), ..., \mathbf{X}_N(1)\right]^T \subseteq \mathbf{U}$. In the initial iteration, the i^{th} agent $\mathbf{X}_i(1)$ can be expressed as: $\mathbf{X}_i(1) = \left[X_i^1(1), ..., X_i^d(1), ..., X_i^n(1)\right]$, where X_i^d is the position of the i^{th} agent in the d^{th} dimension, n is the dimension of the problem, while $\mathbf{U}$ is the space of possible solutions. The initial population is divided into several groups. Each group has only one leader (stallion) and one or more mares and foals.

B. Grazing of Horses

The following equation is used to simulate the grazing:

$$\mathbf{X}_{i,G}^j(t+1) = 2\cdot \mathbf{Z}(t)\cdot\cos\left(2\cdot\pi\cdot R\cdot \mathbf{Z}(t)\right)\times \times\left(\mathbf{Stallion}^j(t) - \mathbf{X}_{i,G}^j(t)\right) + \mathbf{Stallion}^j(t) \quad (17)$$

where $\mathbf{X}_{i,G}^j(t)$ and $\mathbf{X}_{i,G}^j(t+1)$ are the current position and new position of the foal or mare, respectively; t is the current iteration; t + 1 is the next iteration; $\mathbf{Stallion}^j(t)$ is the current position of the stallion; R is a uniform random number between [-2,2], and $\mathbf{Z}(t)$ is an adaptive mechanism described in [8].

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C. Horse Mating Behavior

To simulate the departure and mating of horses, the following formula can be used:

$$\mathbf{X}_{G,k}^{p} = \text{crossover}\left(\mathbf{X}_{G,i}^{q}, \mathbf{X}_{G,j}^{z}\right); \quad i \neq j \neq k; \\ p = q = \text{end}; \quad \text{crossover} = \text{mean} \tag{18}$$

where $\mathbf{X}_{G,k}^{p}$, $\mathbf{X}_{G,i}^{q}$ and $\mathbf{X}_{G,j}^{z}$ are the positions of horses *p*, *q* and *z* from groups *k*, *i* and *j*, respectively.

D. Leadership and Leading the Group by the Leader

The mathematical model of leading the group by the stallion can be described by (19).

E. Exchange and Selection of Leaders

In this step, the leaders of the groups – stallions are selected. Firstly, to preserve the stochastic nature of the algorithm, the leaders are selected randomly. In the later stages of the iteration process, the leaders are selected based on their fitness values using (20).

$$\mathbf{Stallion}_{G,i}(t+1) = \begin{cases} 2\cdot\mathbf{Z}(t)\cdot\cos\left(2\cdot\pi\cdot R\cdot\mathbf{Z}(t)\right)\times\left(\mathbf{WH}(t)-\mathbf{Stallion}_{G,i}(t)\right)+\mathbf{WH}(t) & \text{if } R_2 > 0.5 \\ 2\cdot\mathbf{Z}(t)\cdot\cos\left(2\cdot\pi\cdot R\cdot\mathbf{Z}(t)\right)\times\left(\mathbf{WH}(t)-\mathbf{Stallion}_{G,i}(t)\right)-\mathbf{WH}(t) & \text{if } R_2 \le 0.5 \end{cases}, \tag{19}$$

$$\mathbf{Stallion}_{G,i}(t+1) = \begin{cases} \mathbf{X}_{G,i}(t+1) & \text{if } \text{cost}\left(\mathbf{X}_{G,i}(t+1)\right) < \text{cost}\left(\mathbf{Stallion}_{G,i}(t)\right) \\ \mathbf{Stallion}_{G,i}(t) & \text{if } \text{cost}\left(\mathbf{X}_{G,i}(t+1)\right) \ge \text{cost}\left(\mathbf{Stallion}_{G,i}(t)\right) \end{cases}. \tag{20}$$

In (19) and (20), **WH**(*t*) presents the position of the water hole (i.e. the global best position). More details about the WHO algorithm can be found in the paper [8].

As for any other optimization problem, a potential solution can be presented by a vector consisting of a combination of control variables, i.e., in this case, corresponding induction motor parameters. The electrical parameters of the single-cage motors are the following: R_s, R_r, X_s, X_r, and X_m. Generally, it is supposed that the stator and rotor leakage reactances are equal: $X_s = X_r$. Therefore, the position of the agent *i* can be defined as follows:

$$\mathbf{X}_i = \left[R_{s,i}, R_{r,i}, X_{s,i}, X_{m,i}\right]. \tag{21}$$

The flowchart of the WHO algorithm is given in Fig. 2.

IV. Simulation Results and Discussion

The proposed WHO method is tested on two three-phase single-cage induction motors. The manufacturer data of the test motors are shown in Table I.

TABLE I
MANUFACTURER DATA OF THE TEST MOTORS [6,7]

Parameters	Values	
Rated power P_n (HP)	5	40
Rated voltage U_n (V)	400	400
Rated frequency f_n (Hz)	50	50
Starting current I_{st} (A)	22	180
Full-load current I_{fl} (A)	8	45
Number of pole pairs *p*	2	2
Starting torque T_{st} (N·m)	15	260
Full-load torque T_{fl} (N·m)	25	190
Maximum torque $T_{\max}$ (N·m)	42	370
Full-load power factor pf_{fl}	0.8	0.8
Slip at full load s_{fl}	0.07	0.09

The following parameter ranges are considered:

- For the motor of 5 HP:

$$0.1 \le R_s \le 5,\ 1 \le X_s \le 15,\ 50 \le X_m \le 150, \\ 0.5 \le R_r \le 10,\ 1 \le X_r \le 15$$

- For the motor of 40 HP:

$$0.01 \le R_s \le 0.5,\ 0.1 \le X_s \le 2,\ 5 \le X_m \le 15, \\ 0.05 \le R_r \le 1,\ 0.1 \le X_r \le 2$$

The algorithm was developed in the MATLAB computing environment. To examine the effectiveness of the proposed WHO algorithm, the same problem was solved using the PPSOGSA algorithm [6] (which proved to be effective in solving problems in this area). The obtained results are compared with those obtained using the other methods reported in the literature.

The algorithms are implemented with the following control parameters: for the PPSOGSA [6], c_1 and c_2 are set to 2, α is set to 25, and G_0 is set to 1; for the WHO [8], the crossover process is carried out using the mean value of corresponding group members (mean crossover type), crossover percentage is set to 0.1, and the percentage of stallions in the total population (*PS*) is set to 0.2. For both algorithms, the population size (*N*) and the maximum number of iterations ($t_{\max}$) are set to 300 and 100, respectively.

The results of WHO and PPSOGSA are obtained after fifty consecutive test runs. The best results achieved over these runs are presented in Tables II and III. Also, the tables show the results obtained by other optimization methods. The corresponding steady-state equivalent circuit electrical parameters of the test motors are presented in Table IV.

By comparing the results from Tables II and III, it can be seen that the values of the objective function (*OF*) obtained with the WHO are lower than those obtained by other methods, except the MSFLA [7] for the motor of 5 HP. In [7], a larger range of control variables was taken into consideration, i.e. the optimal value of the stator resistance was 0.0037 Ω, which is far less than the value of 0.3 Ω obtained by the WHO, as presented in Table IV; that may be a possible reason why the *OF* value obtained using the MSFLA is less than the value obtained by the WHO.

The convergence profiles of the WHO and PPSOGSA for the motors of 5 HP and 40 HP are shown in Figs. 3 and 4, respectively. The figures indicate that the proposed WHO algorithm converges to the optimal solution in lower iterations in comparison to the PPSOGSA algorithm.

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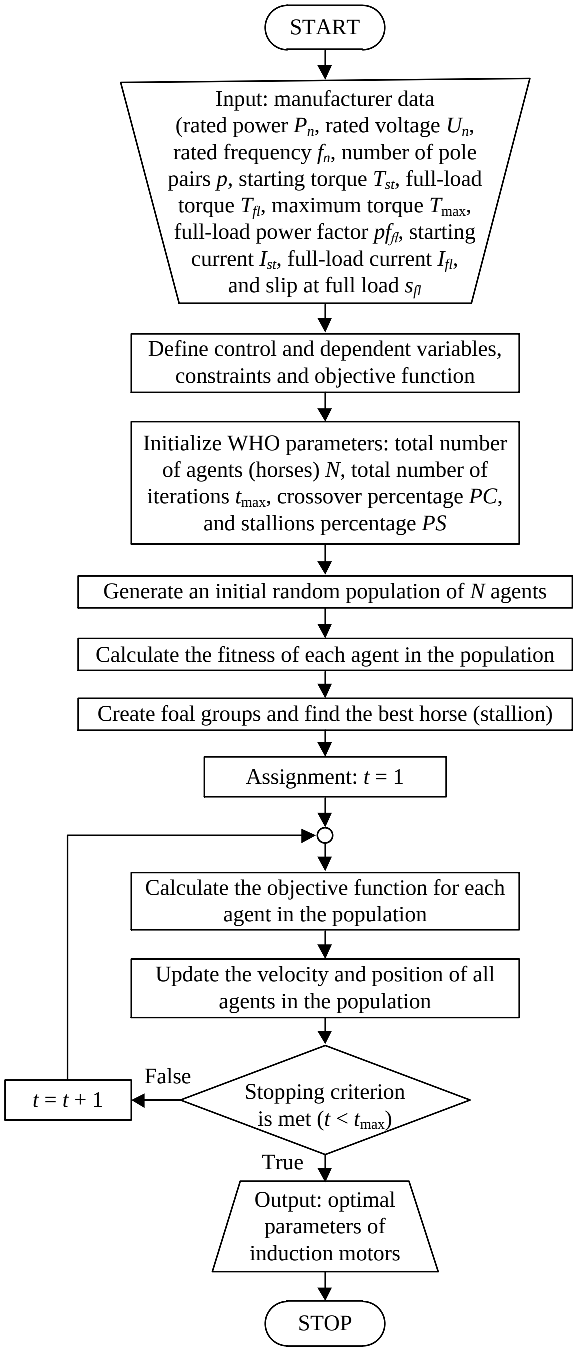

Fig. 2. The flowchart of the WHO algorithm in solving the induction motor parameter estimation problem.

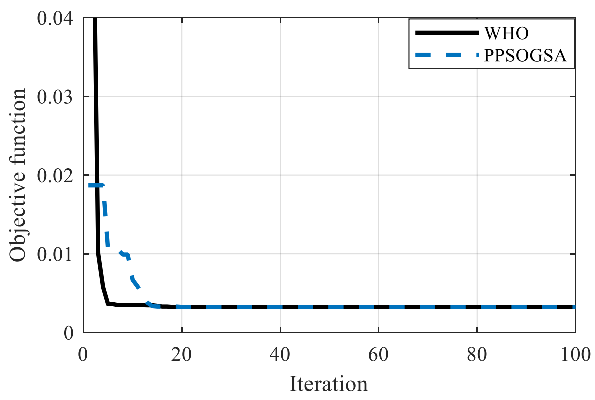

Fig. 3. Convergence profiles obtained for the motor of 5 HP.

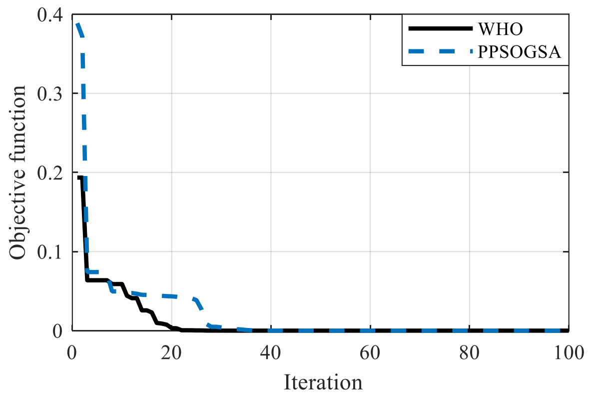

Fig. 4. Convergence profiles obtained for the motor of 40 HP.

Torque-slip characteristics of the motors of 5 HP and 40 HP obtained using the WHO algorithm are presented in Figs. 5 and 6, respectively. From these figures, it is evident that the results obtained by the WHO are in very good agreement with the manufacturer values.

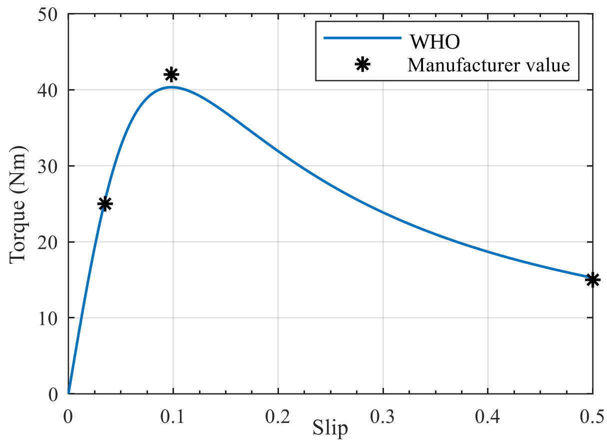

Fig. 5. Torque versus slip curve for the motor of 5 HP.

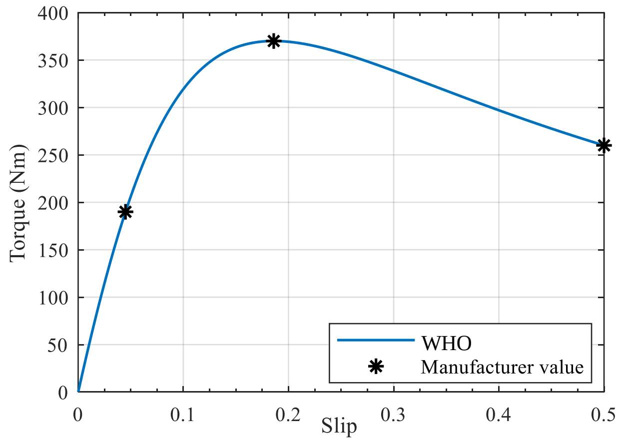

Fig. 6. Torque versus slip curve for the motor of 40 HP.

The statistical parameters of the results (i.e. minimum, maximum and mean values of the objective function, as well as the standard deviations) obtained by the WHO and PPSOGSA over fifty runs for the both test motors are presented in Table V. The results from Table V show that the proposed WHO algorithm is more robust compared to the PPSOGSA. From the aspect of running, the running time of the WHO is a little shorter than the time of the PPSOGSA.

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TABLE II
A COMPARISON OF THE RESULTS OBTAINED BY THE PROPOSED METHOD AND OTHER METHODS FOR THE MOTOR OF 5 HP

Parameter	Manufacturer data	PSO [7]		SFLA [7]		MSFLA [7]		PPSOGSA		WHO	
		Reported result	Error (%)	Reported result	Error (%)	Reported result	Error (%)	Obtained result	Error (%)	Obtained result	Error (%)
T_{st} (Nm)	15	15.3465	2.31	15.4939	3.29	15.2725	1.82	15.3029	2.02	15.2987	1.99
T_{fl} (Nm)	25	25.5692	2.28	25.6484	2.59	25.5541	2.22	25.6067	2.43	25.5979	2.39
T_{max} (Nm)	42	39.0047	–7.13	40.7390	–3.00	40.3870	–3.84	39.9683	–4.84	40.0016	–4.76
pf_{fl}	0.8	0.7888	–1.40	0.7710	–3.63	0.7991	–0.11	0.8000	0.00	0.8000	0.00
OF	/	0.006334059*		0.003972333*		0.002297462*		0.003336732		0.003232706	

*Recalculated value

TABLE III
A COMPARISON OF THE RESULTS OBTAINED BY THE PROPOSED METHOD AND OTHER METHODS FOR THE MOTOR OF 40 HP

Parameter	Manufacturer data	PSO[7]		SFLA [7]		MSFLA [7]		PPSOGSA		WHO	
		Reported result	Error (%)	Reported result	Error (%)	Reported result	Error (%)	Obtained result	Error (%)	Obtained result	Error (%)
T_{st} (Nm)	260	261.1978	0.46	260.3347	0.13	259.5611	−0.17	259.9991	−0.00	260.00	0.00
T_{fl} (Nm)	190	188.9053	−0.58	193.5212	1.85	190.6352	0.33	189.9865	−0.01	190.00	0.00
T_{max} (Nm)	370	360.8307	−2.48	365.0454	−1.34	370.8140	0.22	370.0364	0.01	370.00	0.00
pf_{fl}	0.8	0.7883	−1.46	0.7860	−1.75	0.7995	−0.06	0.7999	−0.00	0.80	0.00
OF	/	0.000882452*		0.000830679*		1.92569×10^{-5}*		3.03638×10^{-8}		0	

*Recalculated value

TABLE IV
ELECTRICAL PARAMETERS OF INDUCTION MOTORS OBTAINED BY THE PROPOSED METHOD AND OTHER METHODS

Parameter	Motor of 5 HP					Motor of 40 HP				
	PSO [7]	SFLA [7]	MSFLA [7]	PPSOGSA	WHO	PSO [7]	SFLA [7]	MSFLA [7]	PPSOGSA	WHO
R_s (Ω)	0.9872	0.0008	0.0037	0.3300	0.3000	0.3555	0.3437	0.2707	0.2694	0.2778
X_s (Ω)	5.3785	5.5847	5.7202	5.6667	5.6771	0.4353	0.4345	0.4773	0.4842	0.4797
X_m (Ω)	77.042	77.9101	94.1401	91.5892	91.9613	6.4223	6.2629	7.5432	7.7277	7.6037
R_r (Ω)	2.0322	2.1330	2.1818	2.1526	2.1574	0.3455	0.3360	0.3573	0.3631	0.3611
X_r (Ω)	5.3785	5.5847	5.7202	5.6667	5.6771	0.4353	0.4345	0.4773	0.4842	0.4797

TABLE V
STATISTICAL PARAMETERS AND EXECUTION TIMES OF WHO AND PPSOGSA METHODS

Power (HP)	Method	Minimum	Maximum	Mean	Standard deviation	Execution time [s]
5	PPSOGSA	0.00334	0.00348	0.00338	0.00024	1.89
	WHO	0.00323	0.00323	0.00323	0	1.73
40	PPSOGSA	3.0364×10^{-8}	0.04491	0.00389	0.01151	1.46
	WHO	0	0.00592	0.00041	0.00154	1.35

V. CONCLUSION

The main conclusions that can be drawn from the presented results and discussion of them are the follows:

- By comparing the results obtained using the WHO algorithm with those obtained using other algorithms (i.e. using the PSO, SFLA, MSFLA, and PPSOGSA algorithms), it is found that the WHO provides effective, robust and high-quality solutions.
- It is shown that the results obtained by the WHO algorithm are in very good agreement with the manufacturer data. The maximum relative deviations are less than 5%.
- The average running time of the WHO algorithm for both test motors was less than 2 s. This means that the calculation speed of the WHO algorithm is high.
- It is found that the WHO algorithm has better performance than the PPSOGSA algorithm in terms of the solution quality and convergence speed.

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