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An Improved Big Bang-Big Crunch Algorithm for Estimating Three-Phase Induction Motors Efficiency

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ABSTRACT

Nowadays, the most generated electrical energy is consumed by three-phase induction motors. Thus, in order to carry out preventive measurements and maintenances and eventually employing high-efficiency motors, the efficiency evaluation of induction motors is vital. In this paper, a novel and efficient method based on improved big bang-big crunch (I-BB-BC) algorithm is presented for efficiency estimation in the induction motors. In order to estimate the induction motor's efficiency, the measured current, the power factor and the input power are applied to the proposed method and an appropriate objective function is presented. The main advantage of the proposed method is efficiency evaluation of induction motor without any intrusive test. Moreover, a new effective and improved version of BB-BC algorithm is introduced. The presented modifications can improve the accuracy and speed of the classic version of algorithm. In order to demonstrate the capabilities of the proposed method, a comparison with other traditional methods and intelligent optimization algorithms is performed.

KEYWORDS: Efficiency estimation, Improved big bang-big crunch algorithm, Induction motor, Measurement.

1. INTRODUCTION

The electrical system as one of the main parts of the energy system is very important in any country such as industrial countries. This system shares the largest amount of energy comparing to other energy systems including oil, gas, coal, etc. Electrical motors use 70 to 75 percent of the total electricity which is consumed in industry. Thus, evaluation of induction motor's efficiency is an important issue for energy saving managements. Using the estimated efficiency of the induction motor, its performance can be judged and replacing the existing low efficiency motor by a high efficiency motor could be decided. In the recent years, several studies have been performed in this area which have some problems. The simplest and cheapest evaluation of efficiency is reading the motor's nameplate. This method assumes the efficiency to be constant and equal to the inscribed value on the plaque. This works well when the efficiency-load curve is smooth [1]. In Ref. [2], several intrusive methods have been explored to estimate the efficiency of the induction motor. Intrusive testing can be considered as a kind of interrupted testing. This procedure is done when the motor is removed from its normal operation mode. It usually requires no-load or blocked rotor tests. However, non-intrusive methods rely only on terminal voltage and current measurements while the motor is running. In these methods, to efficiency determination only requires values of the inputs to the motor, not the outputs. In simple terms, the non-intrusive method is performed for in-service motors. In the recent years, non-intrusive methods have been widely attended for these continuous applications [3-4].

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IEEE standard has introduced a proper measuring technique based on parameters identification of the equivalent circuit [5]. However, it requires rather intrusive measurements including no-load test, locked rotor test, DC test and the stray-load losses measurement, which are not possible in many cases. Another way for efficiency estimation is torque-based method. Torque-based methods are of two types: shaft torque measurement [1-2] and air-gap torque method [6]. In the shaft torque method, the shaft torque and the rotor speed are directly measured using sensors without the need to calculate the losses. The shaft torque measurement requires expensive equipments that may not be available in all areas and also, it is highly intrusive in efficiency estimation. In contrast to this, the air-gap torque method is a nonintrusive method for in-service motor-efficiency estimation using only motor terminal quantities and nameplate information. However, the no load test is avoided by the use of some empirical data. This causes lower estimation accuracy in comparison to the other well-known methods. In addition, the stator resistance shall be measured accurately at an operating temperature with a specific device. This causes extra cost, and installation concerns. The proposed method in Ref. [7] is the segregated losses method, which requires five types of losses measurements including: stator copper losses, rotor copper losses, core losses, stray-load losses and friction losses. The main disadvantage of this method is its intrusive measurements and the separation of different losses in machine. This technique involves separating rotor and reverse rotation tests for direct stray-load losses measurements. However, due to the need of performing two separate tests, it is not an appropriate method for efficiency determination of the induction motor. Some researchers used no-load tests to determine the motor efficiency in rated load [8-9]. The disadvantage of this approach is to separate the motor for no-load test. In Ref. [10], based on slip testing methods, motor efficiency is determined with a significant error (more than 10%). Ref. [11] has defined an instrument that could be used to measure the input power to determine the efficiency of an installed operating induction motor without removing power from the motor. The applied instrument is power analyzer which is very costly. So, it is not economical to use this method for small motors. In the recent years, the artificial intelligence-based methods are developed rapidly in the engineering fields [12-13] and several techniques have been proposed for efficiency evaluation of the induction motors [14-26]. Heuristics techniques employ the measured data such as current, voltage, input power, speed, and power factor. Using these measurements, parameters of the induction motor can be estimated and the efficiency of induction motor can be evaluated under different conditions. Genetic algorithm (GA) was one of the first employed heuristic methods in this field [14-20]; the main problem of GA is its premature convergence and low speed. Particle swarm optimization (PSO) was another employed algorithm that has higher speed rather than GA; but unfortunately it can conduct the estimation process to outside of the search space. Therefore, to obtain the final results, PSO must be implemented for several times [21-22]. In Refs. [23-26], the bacterial foraging algorithm (BFA) has been used to determine the motor efficiency. The main disadvantage of this method is its numerous parameters and lacking a reliable method for adjusting them.

Although the mentioned studies gave important results, such results are not efficient to estimate accurately the efficiency in induction motors without performing additional investigations. To address these shortcomings, here a new version of big bang-big crunch algorithm is proposed to overcome the above mentioned problems. This algorithm not only eliminates the mentioned problems of the previous methods but rather is very fast and there are a few numbers of parameters which are needed to be adjusted across the algorithm implementation.

Some important contributions of this work against past well-known works can be listed as follows:

- A new version of BB-BC algorithm is proposed for efficiency estimation.
- Every six equivalent circuit parameters of the induction motor are taken into the account.
- The efficiency is estimated and validated using the experimental data.
- The results of the proposed method are verified

against the results of past well-known works. According to the validation, the introduced method is more reliable than the methods that were presented in the previous researches.

- Three different fitness functions are applied to the proposed algorithm. The results related to these functions are discussed and compared with each other.

2. INDUCTION MOTOR'S EFFICIENCY ESTIMATION

2.1. Problem description

To estimate the efficiency of induction motor, multiple samples of input signals (current, speed, power factor and input power) should be available. So, at first the necessary tests have been carried out on a typical induction motor. Consequently, using the equivalent circuit model of induction motor in the steady-state condition, the objective function is created. In order to determine the efficiency of induction motor, three different objective functions are developed using the estimated and the measured data (current, power factor and input power). Afterwards, using various algorithms, equivalent circuit parameters are estimated in a way to minimize the difference between the measured and predicted values. Finally, using the estimated parameters and the input/output powers, the efficiency of an induction motor is calculated.

2.2. Machine equations

As previously mentioned, the equivalent circuit parameters are used for estimation the motor efficiency. Induction motor equivalent circuit is presented in Fig. 1.

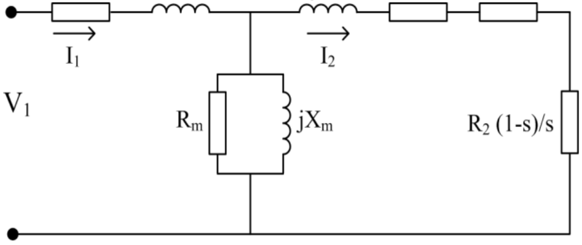

Fig. 1. Steady-state equivalent circuit of induction motor

where:

V_1: stator voltage (V)
I_1: stator current (A)
I_2: rotor current (A)
I_m: magnetizing current (A)
R_1: stator resistance (Ω)
R_2: rotor resistance referred to stator (Ω)
R_m: core loss resistance (Ω)
R_{st}: stray-load resistance (Ω)
X_1: stator leakage reactance (Ω)
X_2: rotor leakage reactance referred to stator (Ω)
X_m: magnetizing reactance (Ω)
S: slip
P_{in}: input power
P_{out}: output power

The stray-load losses could be modeled by adding an equivalent resistor to the equivalent circuit suggested by IEEE standard [5]. This resistance (R_{st}) can be calculated using the following equation:

$$R_{st} = \frac{0.018(1 - S_{fl})}{S_{fl}} \tag{1}$$

Using the equivalent circuit of Fig. 1, the admittances of stator and rotor can be expressed as follow:

$$Y_1 = \frac{1}{R_1 + jX_1} \tag{2}$$

$$Y_2 = \frac{1}{(R_2 / s) + jX_2 + R_{st}} \tag{3}$$

Similarly, the admittance of parallel branch in the equivalent circuit can be obtained from Eq. (4):

$$Y_m = \frac{1}{R_m} - \frac{j}{X_m} \tag{4}$$

At last, the total impedance of the equivalent circuit can be stated by the series-parallel combination of the above mentioned admittances as follows:

$$Z_1 = R_1 + jX_1 + \frac{1}{Y_2 + Y_m} \tag{5}$$

After calculating the admittances, efficiency of the motor can be calculated using the Kirchhoff's law as the following:

$$I_{1e} = \left| \frac{\overline{V_1 Y_1 (Y_2 + Y_m)}}{\overline{Y_1 + Y_2 + Y_m}} \right| \tag{6}$$

$$I_{2e} = \left| \frac{\overline{V_1 Y_1 Y_2}}{\overline{Y_1 + Y_2 + Y_m}} \right| \tag{7}$$

$$\cos\varphi_e = \frac{\mathrm{Re}(\overline{I_{1e}})}{\overline{I_{1e}}} \tag{8}$$

$$P_{in\,e} = 3(I_1^2 R_1 + I_2^2 (R_2 / s + R_{st}) + I_m^2 R_m) \tag{9}$$

$$P_{out\,e} = 3 I_2^2 R_2 (\frac{1-s}{s}) - P_{fw} \tag{10}$$

$$\eta = \frac{P_{out\,e}}{p_{in\,e}} \tag{11}$$

It should be noted that mechanical losses (or friction and windage losses), P_{fw}, are nearly constant from no-load to full-load. So, here it is taken as a constant percentage of the rated input power where P_{fw}=1.2%P_{in} as suggested by many motor efficiency estimation methods [1-6], [21-26].

2.3. Objective functions

To estimate the efficiency, in the first step the equivalent circuit parameters should be identified. To estimate the equivalent circuit parameters, different objective functions are introduced. The conventional way for this purpose is to estimate the unknown parameters to minimize the sum of squared errors between the calculated and measured results. Additionally, it must also be provided the constraints to be met. To achieve a comprehensive conclusion, different objective functions are defined. In past researches [23-26], current, power and torque have been used for this purpose. As a new work, in the current research a combination of these parameters is recommended to be used to construct the objective functions as follows:

$$F_1(x) = \sum_{j=1}^{n}\left(\frac{I_{1ej}}{I_{mj}} - 1\right)^2 + \sum_{j=1}^{n}\left(\frac{Pf_{ej}}{Pf_{mj}} - 1\right)^2 \tag{12}$$

$$\begin{aligned} F_2(x) = {} & \sum_{j=1}^{n}\left(\frac{P_{inej}}{P_{inmj}} - 1\right)^2 + \sum_{j=1}^{n}\left(\frac{I_{1ej}}{I_{mj}} - 1\right)^2 + \\ & \sum_{j=1}^{n}\left(\frac{Pf_{ej}}{Pf_{mj}} - 1\right)^2 \end{aligned} \tag{13}$$

$$F_3(x) = \sum_{j=1}^{n}\left(\frac{P_{inej}}{P_{inmj}} - 1\right)^2 + \sum_{j=1}^{n}\left(\frac{I_{1ej}}{I_{mj}} - 1\right)^2 \tag{14}$$

In the above equations, indices *e* and *m* are related to the estimated and measured values, respectively, and *n* is the sampling number.

2.4. Improved big bang-big crunch (i-bb-bc) algorithm

BB-BC algorithm is a recently developed method that relies on theory of the universe evolution [27]. BB-BC algorithm has been used in some problems such as optimal power flow [28-29]. BB-BC is developed from the Big Bang and the Big Crunch phases [27].

In the Big Bang phase, the first population is spread uniformly into search space. The second phase (Big Crunch) that computes a center of mass for population is a convergence operator. The center of mass could be calculated as follows [27]:

$$\vec{x}^c = \frac{\sum \vec{x}_i f_i^{-1}}{\sum f_i^{-1}} \tag{15}$$

where:
x_i: a member of population, and
f_i : fitness function's value.

Following the Big Crunch phase, new population must be generated for as the next Big Bang phase. The new generations must be spread around the center of mass by adding a normal random number as the following [28]:

$$\vec{x}_{new} = \vec{x}_c + \frac{rand \times (x_{\max} - x_{\min})}{k} \tag{16}$$

Where:
rand: a random number with normal distribution,
k: iteration number,
x_{min}: lower limit of the parameters, and
x_{max}: upper limit of the parameters.

In order to modify the performance of BB-BC method, here a modification is proposed for Eq. (16). This modification that is shown in Eq. (17) will be called as Improved Big Bang-Big Crunch (I-BB-BC) algorithm.

$$\vec{x}_{new} = \vec{x}_c + \frac{rand \times (x_{\max} - x_{\min})}{(f_{best})^p} \tag{17}$$

In this improved form the best fitness of individuals (f_{best}) is employed instead of iteration number (*k*); while the best fitness is increased, new populations will be spread nearer to center of mass. Note that the fitness function is declared as $f = 1/F$, where, *F* is the objective function that was introduced in Eqs. (12)-(14). Also, standard deviation of the normal random number must be adjusted for better results.

Following the new bang, center of mass should be recomputed and steps should be repeat till the ending condition is met. Fig. 2 shows the operation flowchart of the I-BB-BC algorithm.

3. EXPERIMENTAL MEASUREMENTS

As was mentioned before, for non-intrusive determination of the induction motor's efficiency, the losses should be determined. To estimate the parameters of the induction motor, experimental samples should be taken from the actual motor. As it is known, by the load torque changing, motor speed, current and power factor change. Sampling the measurements (current, power factor and speed) is performed from 25% to 100% of the full load. The reason for this kind of sampling is to increase the accuracy of optimization algorithms. Because a large number of samples help the algorithm to has a good performance in searching the problem domain. Fig. 3 shows the measurement circuit that was used in the laboratory. Tables 1 and 2 show the nameplate data and the measured values for a typical 2 hp induction motor, respectively.

4. PARAMETERS ESTIMATION AND EFFICIENCY EVALUATION RESULTS

To implement the algorithm, a program using the GUI/MATLAB is developed. Features of this program are applicable for any number of variables that are bounded by imposing constraints. To demonstrate the effectiveness of the proposed algorithm and compared it with other well-known algorithms, the problem is solved using various algorithms (GA, PSO and BB-BC) with different objective functions and the efficiency of induction motor have been identified. The results are given in the following.

4.1. Estimations using Eq. (12) as the objective function

Using Eq. (12), the motor parameters are estimated and the results are presented in Table 3. After estimating the parameters, motor efficiency was computed from Eq. (11) and the results are shown in Table 4. This Table also shows the output estimated errors (differences between the results of the heuristic algorithms and the actual values).

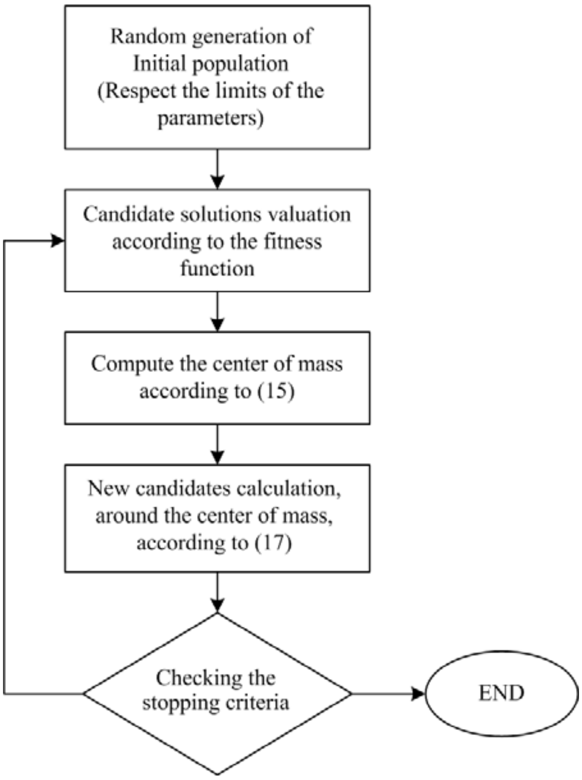

Fig. 2. I-BB-BC steps

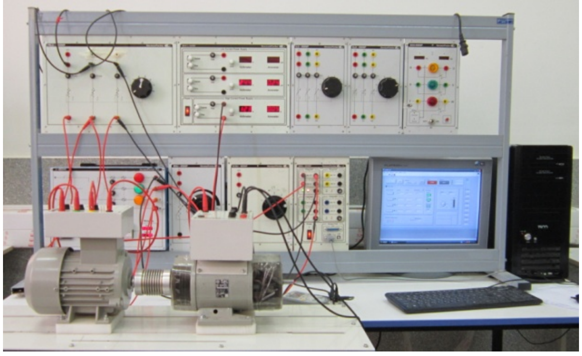

Fig. 3. Measurement setup in laboratory

Table 4 indicates that the I-BB-BC algorithm is close to the real values in three points (25%, 50% and 100% of full load) and only in 75% of the full load, the PSO algorithm has reached to a better result. To study the speed of the algorithms about achieving the optimal response, Fig. 4 shows the cost function reduction due to the number of iterations.

Table 1. Nameplate data for a typical 2hp induction motor

Brand	Siemens	Design class	B
Insulation Class	B	IP	55
I	4 A	Power Factor	0.76
Poles	4	Speed	1440 rpm
f	50 Hz	$V_{L\text{-}L}$	230/400 V
Connection	Y-d	Type	STC-3

Table 2. Measured values for a typical 2hp induction motor

Motor load (%)	I_1 (A)	PF	P_{in} (W)	P_{out} (W)	Efficiency (%)
25	2.71	0.412	738.9	382.01	51.70
50	3.01	0.573	1141.7	753.52	66.00
75	3.44	0.682	1555.6	1110.1	71.36
100	3.99	0.751	1999.5	1463.1	73.18

Table 3. The results of motor parameters estimation by various algorithms for objective function of Eq. (12)

Parameter (ohm)	GA	PSO	BB-BC	I-BB-BC
R_1	3.68	5.12	4.47	4.81
X_1	6.91	8.076	5.58	5.90
R_2	3.51	3.37	3.12	3.70
X_2	3.36	2.52	3.91	3.34
R_m	502.63	530.66	475.63	489.24
X_m	82.58	77.99	79.27	79.85

Table 4. The results of efficiency estimation by various algorithms for objective function of Eq. (12)

Motor load (%)	Efficiency (%)				Error (%)			
	GA	PSO	BB-BC	I-BB-BC	GA	PSO	BB-BC	I-BB-BC
25	55.74	53.92	53.45	52.18	7.82	4.29	3.38	0.93
50	69.53	67.44	66.69	66.54	5.35	2.18	1.04	0.81
75	74.52	72.47	72.95	73.06	4.43	1.56	2.22	2.38
100	76.17	74.01	74.13	73.49	4.09	1.11	1.29	0.42
Average					5.42	2.28	1.98	1.13

The obtained results show that the accuracy of the I-BB-BC is better than other algorithms.

4.2. Estimations using Eq. (13) as the objective function

In this objective function the input power, input power factor and input current are applied. In Tables 5 and 6, the results of the estimated parameters and the efficiency of the motor determined by different algorithms are given. Table 6 also shows the errors of efficiency estimation by different optimization algorithms.

As shown in Table 6, the mean error of BB-BC and I-BB-BC algorithms has increased with respect to the first objective function. However, when using this objective function for GA and PSO algorithms, the error is reduced.

Fig. 5 is a graph of cost function based on the number of iterations. It is clear that the convergence of BB-BC and PSO is almost identical. However, BB-BC convergence is faster than PSO and to achieve the optimal solution, the number of iterations is less than PSO needs.

Fig. 5 also shows that the convergence of I-BB-BC is rapid and the convergence of the GA is slow. In the low number of iterations, GA is not a good algorithm and for better performance, it needs to be increased the number of iterations. However, for better comparison, all the conditions are assumed to be equal in all cases.

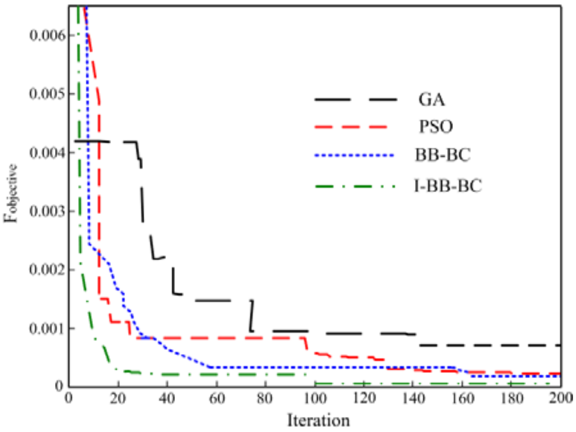

Fig. 4. Convergence characteristics of various algorithms for first objective function of Eq. (12)

Table 5. The results of motor parameters estimation by various algorithms for objective function of Eq. (13)

Parameter (ohm)	GA	PSO	BB-BC	I-BB-BC
R_1	3.79	3.58	3.48	3.55
X_1	7.15	4.85	4.77	5.02
R_2	3.49	3.82	3.97	3.88
X_2	3.92	4.61	4.46	4.51
R_m	512.78	471.14	466.95	475.04
X_m	82.66	82.69	82.23	82.76

4.3. Estimations using Eq. (14) as the objective function

To use the objective function of Eq. (14), only the input power and current are applied. Table 7 shows the results of different algorithms in estimating parameters of the induction motor.

Table 6. The results of efficiency estimation by various algorithms for objective function of Eq. (13)

Motor load (%)	Efficiency (%)				Error (%)			
	GA	PSO	BB-BC	I-BB-BC	GA	PSO	BB-BC	I-BB-BC
25	52.07	52.68	52.34	52.19	0.71	1.89	1.23	0.94
50	69.72	67.21	67.45	67.03	5.63	1.83	2.19	1.56
75	74.59	72.67	73.76	72.85	4.52	1.83	3.36	2.08
100	76.12	74.79	75.38	74.49	4.01	2.20	3.00	1.79
Average					3.71	1.93	2.44	1.59

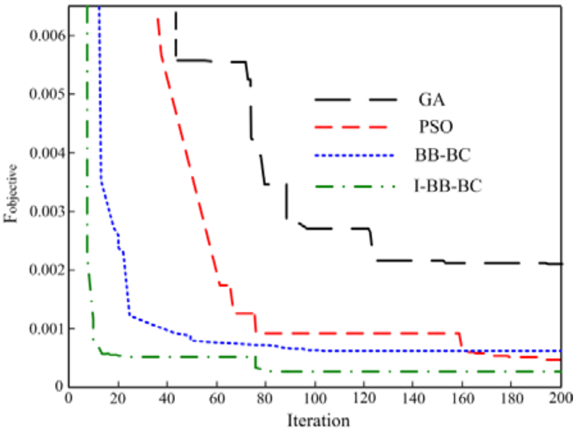

Fig. 5. Convergence characteristics of various algorithms for objective function of Eq. (13)

After estimating the parameters of the motor, it is also possible to calculate the efficiency as shown in Table 8. This Table also shows the estimated errors of the calculated efficiency with implementation of the third objective function. As seen, the resultant error by using this function is much less than other functions in the implementation of all four algorithms.

Figure 6 shows a graph of cost function reduction based on the number of iterations. It is clear that I-BB-BC algorithm has the lowest cost function and its convergence is very fast.

4.4. Validation against traditional methods and discussion

It is clear that despite the satisfactory results of the introduced algorithm in comparison with other heuristic algorithms, results of the proposed method should be compared with traditional methods. For this purpose, the results of efficiency evaluation using the introduced algorithm are compared to the classical methods (such as slip [10], current [6] and the equivalent circuit methods [11]). The obtained results are presented in Table 9.

Table 7. The results of motor parameters estimation by various algorithms for objective function of Eq. (14)

Parameter (ohm)	GA	PSO	BB-BC	I-BB-BC
R_1	4.12	4.15	4.55	4.19
X_1	4.33	4.54	4.67	4.58
R_2	3.80	3.81	3.75	3.78
X_2	3.08	4.19	5.08	4.92
R_m	514.48	495.60	487.36	497.43
X_m	81.37	81.99	81.42	81.59

Table 8. The results of efficiency estimation by various algorithms for objective function of Eq. (14)

Motor load (%)	Efficiency (%)				Error (%)			
	GA	PSO	BB-BC	I-BB-BC	GA	PSO	BB-BC	I-BB-BC
25	53.44	52.78	52.61	52.01	3.36	2.09	1.76	0.60
50	67.69	67.12	67.15	66.49	2.56	1.69	1.74	0.74
75	73.07	72.56	71.87	71.67	2.39	1.68	0.71	0.43
100	74.97	74.47	74.31	73.86	2.44	1.76	1.54	0.93
Average					2.68	1.80	1.43	0.68

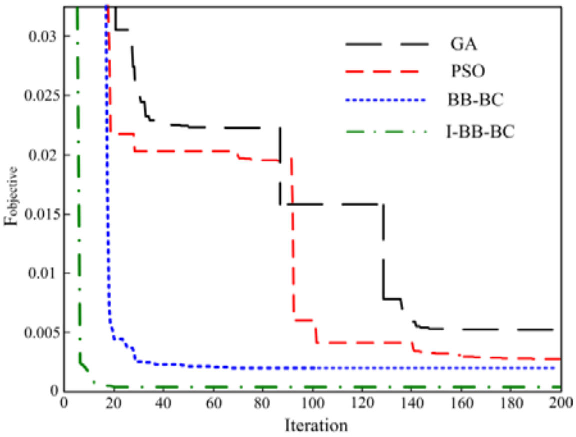

Fig. 6. Convergence characteristics of various algorithms for objective function of Eq. (14)

Table 9 shows that employing traditional methods for efficiency estimation during different loads (especially when the motor works with a load less than the rated load), causes many errors. The error of the equivalent circuit method is lower than the slip and the current methods. But as this method requires intrusive tests, it is not an appropriate method. The results of implementing various algorithms against different objective functions show that the objective function of Eq. (14) leads to the optimal solution with more accuracy and higher speed. As seen in Table 8, estimated efficiency by all algorithms is very close to the measured values and the estimated error in all algorithms is very lower than that for other objective functions.

Table 9. The results of efficiency estimation by traditional methods

Motor load (%)	Efficiency (%)			Error (%)		
	Slip method [10]	Equivalent circuit method [11]	Current method [6]	Slip method [10]	Equivalent circuit method [11]	Current method [6]
25	42.17	48.61	65.75	18.43	5.97	27.17
50	58.07	63.54	72.16	12.01	3.72	9.33
75	66.99	70.02	72.85	6.12	1.87	2.08
100	72.01	72.23	72.64	1.59	1.29	0.74

Among the mentioned traditional methods and the heuristic algorithms, I-BB-BC has smaller errors in efficiency estimation rather than other methods. Additionally, the comparison between efficiency computations for various heuristic algorithms is given in Table 10. From Table 10, it is clear that the average computation time of the I-BB-BC method is less than other methods. Meanwhile, the results (Figs. 4-6) show that the proposed algorithm can reach the lowest cost function in comparison with other algorithms. Therefore, the objective function of Eq. (14) employed with I-BB-BC algorithm is proposed as a suitable method for estimating the efficiency of induction motors.

Table 10. Comparison of computation time (second) for various algorithms

Algorithm	Objective function		
	Equation (12)	Equation (13)	Equation (14)
GA	4.98	5.28	5.12
PSO	4.27	4.48	4.39
BB-BC	4.18	4.23	4.13
I-BB-BC	3.33	3.42	3.28

In addition to very good results obtained in the estimation of efficiency, DC test which is usually performed in the stator resistance estimation was removed and the stator resistance was taken into account as a parameter that was estimated using the introduced method. In the past researches [11], [14-16], efficiency estimation is performed for motors with the same reactances of rotor and stator (class A); however, in this study, two reactances were not selected equal. So, the efficiency estimation could be applied to each motor with each insulation class.

5. CONCLUSION

In this paper, using an improved version of the I-BB-BC algorithm and employing different objective functions, the induction motor parameters were estimated. Then using the determined parameters, the motor's efficiency was calculated. Finally, to prove the capability of the introduced method, a comparison with other traditional and intelligent methods such as GA, PSO and BB-BC was performed. The comparison shows that the efficiency estimation by I-BB-BC algorithm has much less error than other methods and results are very close to the actual values. In addition, it quickly converges to optimal solution. So, according to the speed and accuracy of the proposed algorithm, it can be used as a reliable method for accurate determination of the efficiency in induction motors. In addition, the proposed method can be used to monitor the status of induction motors in the industrial areas.

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