

*Article*

## Particle Swarm Optimization Based Equivalent Circuit Estimation for On-Service Three-Phase Induction Motor Efficiency Assessment

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**Abstract.** This paper presents the particle swarm optimization based equivalent circuit estimation (PSOBECE) method for three-phase induction motor efficiency analysis, during on-service condition. The prominent point of the paper is to accurately estimate the three-phase induction motor efficiency without disturbing motor operation, using basic electrical instruments, which are clamp-on power meter and non-contact tachometer. The proposed method estimates the parameters of induction motor equivalent circuit (EC) using motor current, real power, voltage, and speed, which can be measured without interrupting the motors operations. Afterward, the motor's efficiency can be non-intrusively determined from the EC. In this paper, the 1.5, 11 and 30 kW motors are used for test and verify the accuracy of the proposed method. The motor efficiency test results, by shaft torque method, compliance to IEC60034 standards, are used as references to verify the accuracy of the proposed method compared to the conventional slip and current methods. The proposed method resulted in the reasonable mismatch in efficiency estimation for three-phase induction motor. The root-mean square mismatch of the proposed method, comparing to those of obtained by CM and SM, is shown to be minimum. Therefore, the proposed method could effectively and conveniently be applied for the on-service three-phase induction motor efficiency estimations.

**Keywords:** Three-phase induction motor efficiency estimation, three-phase induction equivalent circuit, particle swarm optimization, slip method, and current method.

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## 1. Introduction

Nowadays, induction motors are widely used in industrial systems and machines, due to its simplicity and convenience. Induction motors share the high electricity used in both industrial and commercial sectors. Therefore, the efficiencies of induction motor are continuously increased to response to the energy conservation manner. It is not attractive to interrupt the motors operation and transport them to the laboratory for efficiencies determination. Therefore, in the high efficiency motor replacement program, the main difficulty of is to measure the efficiency of the existing motor without intrusion, in order to obtain the acceptable economic analysis. The reasonable method for induction motor efficiency determination during on-service condition is, then, beneficially for the economic analysis of high efficiency motor replacement program.

The accurate induction motor efficiency can be determined by standard testing in the laboratory [1, 2]. Meanwhile, in the on-service three-phase induction motor efficiency estimation, the non-intrusion methods are commonly preferred, depending on the instrument available and degree of motor interruptible. The distinguished methods are slip method (SM), and current method (CM). The SM and CM are convenience and simple but give the low accuracy efficiency estimations [3-5]. The later methods are equivalent circuit (EC) and air gap torque (AGT) [3-9] methods. However, the AGT [6] method requires the voltage and current waveforms measurements, which require special instrument, and the stator resistance value in the analysis which may require motor interruption for data collections. As a result, many researches proposed the methods for EC parameters estimation using artificial intelligent techniques. For example, the genetic algorithm (GA) based induction motor parameters identification was proposed by Jangjit and Laohachai in [7]. The stator current, input power and power factor were investigated by the relation with the slip. However, the method was tested with only single test case without motor efficiency investigation. Meanwhile, the particle swarm optimization (PSO) based induction motor parameter identification was proposed by Picardi and Rogano in [8]. The method aimed at determination of motor parameter including stator's impedance, rotor's impedance and motor inertia. Emara, et al., proposed the modified PSO algorithm for induction motor parameter identification in [9]. In [10], Rashag, et al., used the PSO-based RBF neural network to identify the induction motor parameters. Sakthivel, et al., in [11], presented the improved PSO algorithm for induction motor parameter determination. The results on motor parameters estimation, including stator's impedance and rotor's impedance, were investigated. The mentioned previous works [7-11] indicated that the intelligent optimization techniques can be effectively used for induction motor parameter identification and the PSO algorithm was most effective for estimating the parameters over a wide operating range of the motor. In [11], the improved PSO was used to estimate the parameters of induction motor equivalent circuit. The simplified five parameters model was used to test the proposed method with two motors. Meanwhile, the efficiency determined by the obtained parameters was not investigated. Therefore, the information on induction motor parameters can be further investigated for induction motor efficiency estimation [12-13].

This paper, therefore, proposes the on-service three-phase induction motor efficiency estimation using the particle swarm optimization based equivalent circuit estimation (PSOBECE). The proposed method aimed at the reasonable estimation of motor's efficiency without interrupting its operation by using non-intrusive measurements. The measured parameters used for estimation are the motor current, real power, voltage, and speed. The proposed PSOBECE for motor efficiency estimation is verified by comparing to the laboratory test results in compliance to IEC-60034 standards with 1.5, 11 and 30 kW three-phase induction motors during various loading conditions. The results of the proposed PSOBECE method are compared to the conventional SM and CM.

The organization of the paper is as follows. Section 2 discusses the methods for induction motor efficiency testing and estimation. The development and test of PSOBECE method for three-phase induction motor efficiency estimation is illustrated in Section 3. The experimentation results are addressed in Section 4. Lastly, the conclusion is given.

## 2. The Method for Three-Phase Induction Motor Efficiency Testing and Estimation

The standard laboratory test and conventional on-service efficiency estimation methods for three-phase induction motor has been explored and used as references to verify the proposed method.

## 2.1. Standards of Three-Phase Induction Motor Efficiency Testing

The admittedly efficiency test for three phases induction motors efficiency are based on IEEE-112 and IEC60034 [1-2] standards. Both standards recommend shaft-torque measurement for accurate motor efficiency determination. In the shaft-torque method, the input power can be directly measured by the power meter and the power output of the motor can be computed by

$$P_{mech} = \frac{2\pi N}{60} T \quad (1)$$

Therefore, the motor efficiency can be accurately obtained by

$$Eff = \frac{P_{mech}}{P_{elec}} \times 100\% \quad (2)$$

where

$Eff$  is the efficiency of motor (%),

$P_{elec}$  is the electrical power input to motor (W),

$P_{mech}$  is the mechanical power output of motor (W),

$N$  is the rotor speed of motor (rpm), and

$T$  is shaft torque output of motor (Nm).

## 2.2. On-Service Estimations for Three-Phase Induction Motor Efficiency

The conventional on-service three-phase induction motor efficiency estimations are usually low accuracy due to few parameters measured. In the on-service three-phase induction motor efficiency estimation, the non-intrusion methods are commonly used, depending on the instrument available and degree of motor interruptible. The conventional on-service three-phase induction motor efficiency estimations are usually low accuracy due to few parameters measured. The simple distinguished methods are slip method (SM), and current method (CM) [1-4]. The motor efficiency computed by SM and CM are shown in Eq. (3) and Eq. (4), respectively.

$$Eff = \frac{s_{meas}}{s_{rated}} \times \frac{P_{rated}}{P_{elec}} \times 100\% \quad (3)$$

$$Eff = \frac{I_{meas}}{I_{rated}} \times \frac{P_{rated}}{P_{elec}} \times 100\% \quad (4)$$

where

$s_{meas}$  is the motor slip measured during operation,

$s_{rated}$  is the motor rated slip,

$P_{rated}$  is the motor rated power (W),

$I_{meas}$  is the motor current measured during operation (A), and

$I_{rated}$  is the motor rated current (A).

### 3. Development and Test of PSOBCE Method

#### 3.1. Laboratory Testing for Three-Phase Induction Motor Efficiency Determination

In this paper, the laboratory test in compliance to the standards was conducted for verifying the accuracy of proposed method, comparing to others on-site three phases motor efficiency estimation methods. The 1.5, 11 and 30 kW three-phase induction motors are used for investigation. The motor efficiency test by shaft-torque method is illustrated in Fig. 1.

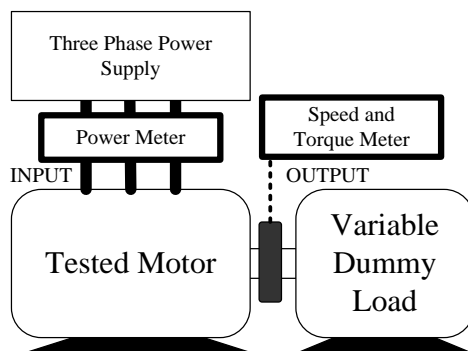


Fig. 1. Diagram of laboratory testing for three-phase induction motor efficiency determination.

The testing process based on the shaft torques method recommended by IEC60034 standards was carried out for the motors' power outputs. Then, the motors' efficiencies at the load factor of 10, 20, 30, ..., 100% are obtained by Eq. (1) and Eq. (2).

#### 3.2. PSOBCE Problem Formulation

The motor EC addressed in Fig. 2 is used for PSOBCE method. The six parameters are estimated using PSO from the measurable variables without disturbing the motor operation, including current, voltage, real power, power factor, and slip. The six EC parameters, with slip affect, indicated in Fig. 2, are as follows [3]:

$X_1$  is the stator leakage reactance (Ohm),

$R_1$  is the stator resistance (Ohm),

$X_m$  is the magnetizing reactance (Ohm),

$R_c$  is the core loss resistance (Ohm),

$X_2$  is the rotor leakage reactance (Ohm), and

$R_2$  is the rotor resistance (Ohm).

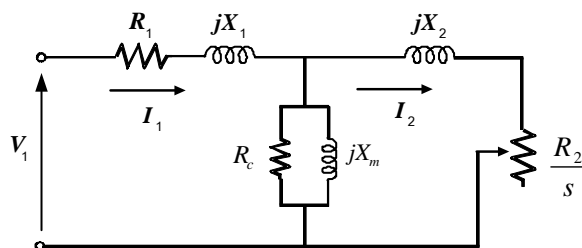


Fig. 2. The induction motor EC (where  $s$  is the rotor slip).

The set of populations in PSO [12] formulation can be expressed as,

$$\mathbf{P}^{i(m)} = [\rho_1^{i(m)} \rho_2^{i(m)} \rho_3^{i(m)} \rho_4^{i(m)} \rho_5^{i(m)} \rho_6^{i(m)}] = [X_1^{i(m)} R_1^{i(m)} X_2^{i(m)} R_2^{i(m)} X_m^{i(m)} R_c^{i(m)}] \quad (5)$$

$$\mathbf{P}^{(m)} = [\mathbf{P}^{1(m)} \mathbf{P}^{2(m)} \dots \mathbf{P}^{N(m)}]^T \quad (6)$$

where

$\mathbf{P}^{i(m)}$  is the sub-matrix of the particle  $i$  in the  $m$ -th iteration, and

$\mathbf{P}^{(m)}$  is the matrix of all particles in the  $m$ -th iteration.

The objective function is to minimize the evaluation value ( $EV$ ) as,

$$EV = \left( \frac{I_{cal}}{I_{meas}} - 1 \right)^2 + \left( \frac{P_{cal}}{P_{meas}} - 1 \right)^2 + \left( \frac{PF_{cal}}{PF_{meas}} - 1 \right)^2 \quad (7)$$

where

$I_{cal}, I_{meas}$  are the motor current obtained by analyzing the EC and by actual measurement, respectively,

$P_{cal}, P_{meas}$  are the motor real power obtained by analyzing the EC and by actual measurement, respectively, and

$PF_{cal}, PF_{meas}$  are the motor power factor obtained by analyzing the EC and by actual measurement, respectively.

Thereafter, the PSO algorithm [12] is used to solve the minimization problem. The PSOBCE computational procedure can be illustrated as follows:

- Step1: Obtain measurement value of  $I_{meas}, P_{meas}, PF_{meas}$ ,
- Step 2: Initialize  $\mathbf{P}^{(0)} = [\mathbf{P}^{1(0)} \mathbf{P}^{2(0)} \dots \mathbf{P}^{N(0)}]^T$ , randomly,
- Step 3: Set  $m=0$ ,  $\mathbf{v}^{i(0)} = [0]_{6 \times 6}$ , for all  $i$ ,
- Step 4: Compute  $I_{cal}^{i(m)}, P_{cal}^{i(m)}, PF_{cal}^{i(m)}$  of  $\mathbf{P}^{i(m)}$ , for all  $i$ ,
- Step 5: Compute  $EV^{i(m)}$ , for all  $i$ ,
- Step 6: Obtain the personal best ( $\mathbf{pbest}^{i(m)}$ ) which are  $\mathbf{P}^{i(m)}$  that provide the minimum  $EV$  of the particle  $i$  and global best ( $\mathbf{gbest}^{(m)}$ ) which is  $\mathbf{P}^{i(m)}$  that provide the minimum  $EV$  among all particle in swarm,
- Step 7: If the  $EV^{i(m)}$  computed by  $\mathbf{gbest}^{(m)}$  is less than 0.001 or  $m = 100$ , **go to Step 11**,
- Step 8: Compute the velocity as,
- $$\mathbf{v}^{i(m)} = [v_1^{i(m)} v_2^{i(m)} v_3^{i(m)} v_4^{i(m)} v_5^{i(m)} v_6^{i(m)}],$$
- $$v_j^{i(m)} = w \cdot v_j^{i(m-1)} + C_1 \cdot rand_1 \cdot (\mathbf{pbest}_j^{i(m)} - \rho_j^{i(m)}) + C_2 \cdot rand_2 \cdot (\mathbf{gbest}_j^{(m)} - \rho_j^{i(m)}),$$
- Step 9: Update the particle by  $\mathbf{P}^{i(m+1)} = \mathbf{P}^{i(m)} + \mathbf{v}^{i(m)}$ ,
- Step 10:  $m = m + 1$ , go to Step 4,
- Step 11: **Stop**.

where  $w$  is the weighting factor;  $C_1, C_2$  are the constants acceleration factors, whereas,  $rand_1$  and  $rand_2$  are uniform random numbers. In this research  $C_1, C_2$  and  $w$  used are 1, and the number of particle,  $N$  in Eq. (6), is 1000.

The EC parameters as indicated in Fig. 2 are the output of the computational procedure. As a results, the motor air-gap power ( $P_{ag}$ ) can be obtained by

$$P_{ag} = I_2^2 \left( \frac{R_2}{s} \right) \quad (8)$$

Then, the motor's efficiency at the measured condition can be determined by

$$Eff = \frac{(P_{ag} - P_{msloss})}{P_{elec}} \times 100\% \quad (9)$$

where  $P_{msloss}$  is the motor mechanical plus stray loss (kW). In this paper, the values of motor mechanical plus stray loss recommended by [1] are used.

#### 4. Experimentation Results

The 1.5, 11 and 30 kW three-phase induction motors have been tested by the method presented in Section 3.1. The motor's efficiencies at the load factor of 10, 20, 30, ..., 100%, are obtained by the shaft-torque method and used for reference. The efficiencies estimated by SM, CM, and the proposed PSOBCECE methods of all tested motor, are shown in Fig. 3 to Fig. 5 respectively. The example of the experimentation results of the proposed method with 100 PSO runs for 80% loading of the 30 kW tested motor are shown in Fig. 6.

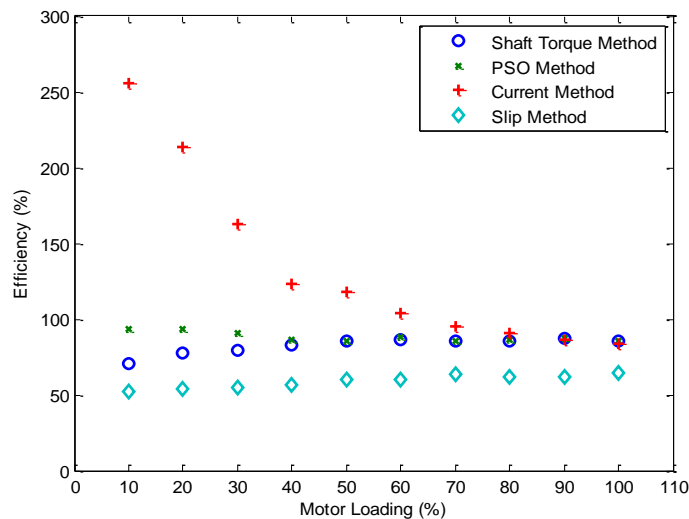


Fig. 3. The efficiencies of the investigated motors obtained by shaft torque, SM, CM, and PSOBCECE methods for the 1.5 kW tested motor.

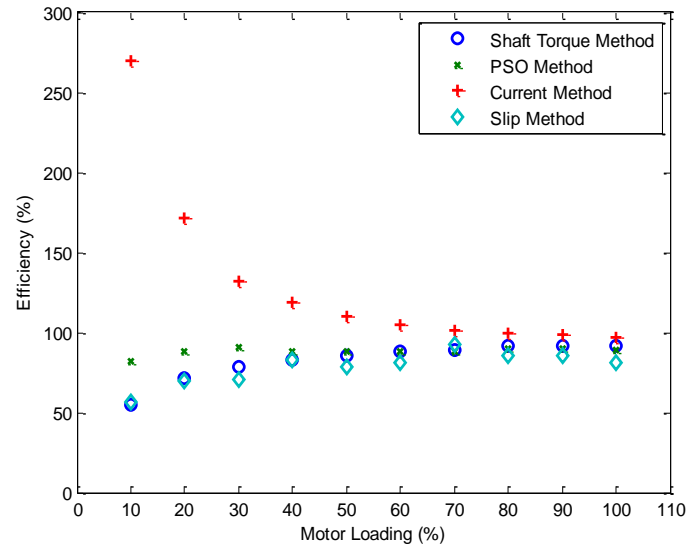


Fig. 4. The efficiencies of the investigated motors obtained by shaft torque, SM, CM, and PSOBCECE methods for the 11 kW tested motor.

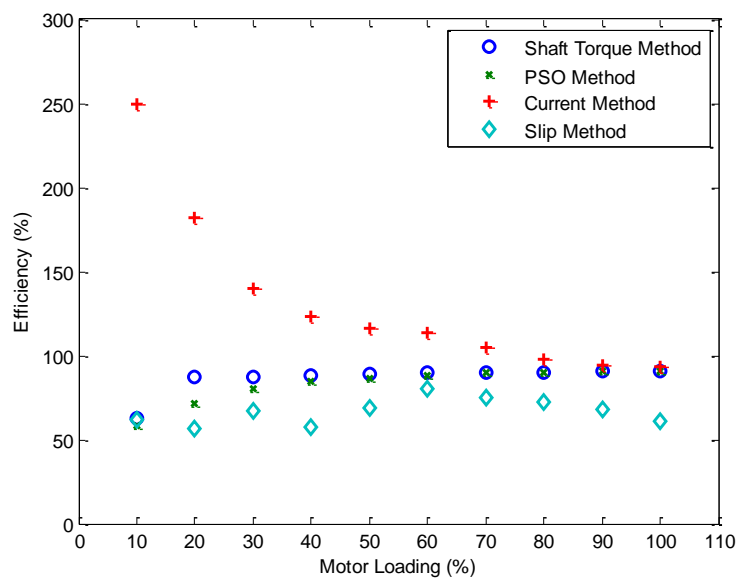


Fig. 5. The efficiencies of the investigated motors obtained by shaft torque, SM, CM, and PSOBCECE methods for the 30 kW tested motor.

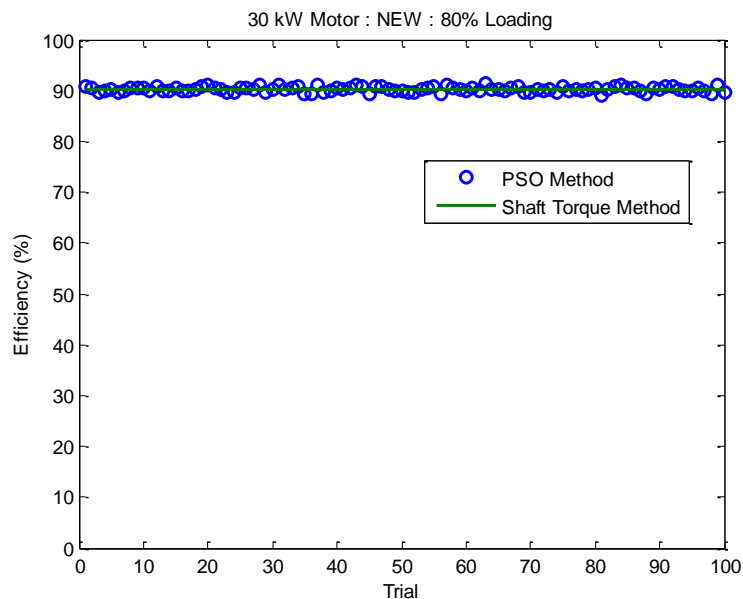


Fig. 6. One hundred trials of efficiencies estimated by the proposed PSOBCE method for the 30 kW tested motor

The results shown that the CM provides better efficiency estimation than those of SM for the loading 50% of motor rated power and higher. Contrariwise, the SM results in higher accuracies induction motor efficiencies estimations than those of CM at the motor loading lower than 50% of motor rated power. Meanwhile, The proposed PSOBCE method for induction motor efficiency estimation results in the minimum root mean square error mismatch to shaft-torque method for the estimation of induction motor operated at 50% of rated power and above as shown in Table 1 to Table 3.

Table 1. The overall root means square mismatch to shaft torque method of CM, SM, and PSOBCE for 1.5 kW tested motor.

Load (%)	Input (kW)	Output (kW)	Test Efficiency (%)	Current Method		Slip Method		PSO Method (Proposed)	
				Eff. (%)	Error (%point)	Eff. (%)	Error (%point)	Eff. (%)	Error (%point)
10.0	0.33	0.23	71.00	255.35	184.35	51.95	19.05	93.69	22.69
20.0	0.40	0.31	78.00	213.97	135.97	53.57	24.43	93.31	15.31
30.0	0.55	0.44	79.20	162.83	83.63	54.55	24.65	90.64	11.44
40.0	0.80	0.67	83.20	123.53	40.33	56.25	26.95	86.61	3.41
50.0	0.85	0.73	85.50	117.82	32.32	60.50	25.00	85.36	0.14
60.0	1.07	0.92	86.30	103.90	17.60	60.08	26.22	88.16	1.86
70.0	1.25	1.07	85.80	95.29	9.49	63.43	22.37	85.50	0.30
80.0	1.39	1.19	85.80	91.09	5.29	61.66	24.14	86.53	0.73
90.0	1.59	1.39	87.10	86.57	0.53	61.99	25.11	87.04	0.06
100.0	1.77	1.52	85.60	84.00	1.60	64.16	21.44	85.33	0.27
<b>Root Mean Square Error (Total) =</b>				<b>25.01</b>		<b>7.60</b>		<b>2.99</b>	
<b>Root Mean Square Error (&lt;50% Load) =</b>				<b>61.79</b>		<b>11.97</b>		<b>7.47</b>	
<b>Root Mean Square Error (≥50% Load) =</b>				<b>6.40</b>		<b>9.84</b>		<b>0.34</b>	



Table 2. The overall root means square mismatch to shaft torque method of CM, SM, and PSOBCE for 11 kW tested motor.

Load	Input	Output	Test Efficiency	Current Method		Slip Method		PSO Method (Proposed)	
				Eff.	Error	Eff.	Error	Eff.	Error
				(%)	(%point)	(%)	(%point)	(%)	(%point)
10.0	1.98	1.10	55.27	286.42	231.15	33.33	21.94	82.78	27.51
20.0	3.18	2.19	68.76	181.41	112.65	48.43	20.33	90.00	21.24
30.0	4.15	3.28	78.84	144.90	66.06	53.01	25.83	91.22	12.38
40.0	5.63	4.66	82.85	117.23	34.38	54.71	28.14	90.53	7.68
50.0	6.36	5.44	85.46	112.23	26.77	55.35	30.11	90.29	4.83
60.0	7.58	6.51	85.81	101.91	16.10	58.05	27.76	87.21	1.40
70.0	8.64	7.42	85.80	98.46	12.66	61.11	24.69	87.59	1.79
80.0	10.76	9.24	85.93	91.78	5.85	67.47	18.46	87.39	1.46
90.0	11.42	9.80	85.83	92.04	6.21	71.28	14.55	87.06	1.23
100.0	12.85	11.00	85.60	89.03	3.43	68.48	17.12	88.48	2.88
<b>Root Mean Square Error (Total) =</b>				<b>27.00</b>		<b>7.41</b>		<b>3.82</b>	
<b>Root Mean Square Error (&lt;50% Load) =</b>				<b>66.93</b>		<b>12.13</b>		<b>9.42</b>	
<b>Root Mean Square Error (≥50% Load) =</b>				<b>5.82</b>		<b>9.33</b>		<b>1.06</b>	

Table 3. The overall root means square mismatch to shaft torque method of CM, SM, and PSOBCE for 30 kW tested motor.

Load	Input	Output	Test Efficiency	Current Method		Slip Method		PSO Method (Proposed)	
				Eff.	Error	Eff.	Error	Eff.	Error
				(%)	(%point)	(%)	(%point)	(%)	(%point)
10.0	4.87	3.07	63.13	249.96	186.83	61.66	1.47	58.51	4.62
20.0	7.12	6.18	86.87	182.11	95.24	56.19	30.68	71.09	15.78
30.0	10.44	9.09	87.11	140.09	52.98	67.05	20.06	80.10	7.01
40.0	13.90	12.21	87.83	123.68	35.85	57.54	30.29	84.51	3.32
50.0	16.04	14.34	89.37	116.53	27.16	68.56	20.81	86.84	2.53
60.0	18.63	16.79	90.10	113.30	23.20	80.52	9.58	88.16	1.94
70.0	23.89	21.56	90.27	104.52	14.25	75.36	14.91	89.74	0.53
80.0	26.13	23.56	90.18	97.81	7.63	72.72	17.46	89.53	0.65
90.0	29.31	26.49	90.38	93.95	3.57	68.24	22.14	90.45	0.07
100.0	32.67	29.59	90.56	93.13	2.57	61.21	29.35	91.04	0.48
<b>Root Mean Square Error (Total) =</b>				<b>22.28</b>		<b>6.83</b>		<b>1.85</b>	
<b>Root Mean Square Error (&lt;50% Load) =</b>				<b>54.81</b>		<b>11.89</b>		<b>4.55</b>	
<b>Root Mean Square Error (≥50% Load) =</b>				<b>6.58</b>		<b>8.17</b>		<b>0.56</b>	

Moreover, the proposed PSOBCE method provides the lowest root mean square error for the estimation of induction motor operated at below 50% of rated power comparing to those of estimated by CM and SM. The overall root mean square error, for the estimation of induction motors operated at 10%-100% of rated power loading, of the proposed PSOBCE method are 2.99% (1.5kW), 3.82% (11kW) and 1.85% (30kW) mismatch to shaft-torque method, which are the lowermost to CM and SM.

## 5. Conclusion

This paper proposed the PSOBCE method for the on-service three-phase induction motor efficiency estimation. The proposed method was authenticated by comparing to the standard laboratory efficiency test

and conventional CM and SM methods. The experimentation shown that the proposed PSOBCECE method resulted in the fair accuracy in the three-phase induction motor efficiency estimation, without intrusion of motor operation. The root-mean square error of the proposed PSOBCECE method is shown to be the lowest comparing to CM and SM methods. Therefore, the proposed method could effectively and conveniently be applied for the on-service three-phase induction motor efficiency estimation.

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