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Non-Invasive Equivalent Circuit Method for Three-Phase Induction Motor Efficiency Estimation using Particle Swarm Optimization

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Abstract *– In this paper, the on-service non-invasive efficiency estimation using equivalent circuit (EC) for three-phase induction motor replacement program is presented and investigated. The motor equivalent circuit parameters (ECPs) are estimated by particle swarm optimization (PSO) using measurement data during on-service condition. Then, the non-invasive equivalent circuit method (NIECM) for motor efficiency estimation can be performed using the PSO based motor ECPs estimation. In the proposed NIECM, the induction motor ECPs are estimated by using the measured motor voltage, current, real and reactive powers, power factor, and speed. Therefore, the motor efficiency can be non-invasively analyzed. The developed NIECM software has been tested with nine motors in the laboratory and investigated with five motor replacement programs. The experimentation results of the proposed NIECM, comparing to conventional slip method (SM) and current method (CM), are illustrated and discussed. Among NIECM, CM, and SM, the proposed NIECM provide the minimum error in efficiency estimation comparing to the shaft-torque method. Therefore, the proposed NIECM can, potentially and conveniently, be applied for the on-service non-invasive three-phase induction motor efficiency estimations, with the reasonable mismatch to the laboratory shaft-torque method.*

Keywords – *equivalent circuit method, current method, non-invasive induction motor efficiency estimation, particle swarm optimization, slip method.*

1. INTRODUCTION

Induction motors are the most common industrial driving device and sharing the large power consumption in both industrial and commercial sectors. Therefore, the manufacturers are interested in increasing the efficiencies of induction motor for their product attractiveness to the user and the energy service company (ESCO). In motor efficiency determination, the standard laboratory input-output method in IEEE-112 [1] and shaft-torque method in IEC60034-2-1 [2] are available. These standard tests are the putative acceptable accurate induction motor efficiency determination. However, for the on-service motor, the shaft-torque method testing procedure requires the motor interruption and transportation to the laboratory. The efficiency test for large motor are, therefore, leading to high outlay and time consuming. As a result, the trustable high efficiency motor replacement program is difficult to evaluate. To obtain the agreeable economic evaluation for high efficiency induction motor replacement program, the non-invasive motor's efficiency determination during on-service condition is a key important tool for assessment.

When the motor is under operation, the non-invasive evaluation methods are preferred. The commonly used non-invasive motor's efficiency estimation methods are nameplate method (NM), slip method (SM), and current method (CM) [3]. NM, SM, and CM are the most convenience conventional non-invasive methods. However, those methods provide low accuracy in motor efficiency estimations [4]-[8]. The others methods are the air gap torque method (AGTM) and equivalent circuit method (ECM) [5]-[12]. The AGTM and ECM are more accurate than NM, SM and CM [6], [7]. The ECM requires the motor equivalent circuit parameters (ECPs), which can be obtained in prior from the manufacturer or laboratory testing [7]. Meanwhile, the AGTM [8]-[9] requires the stator resistance value in the analysis with the voltage and current waveforms measurements, which require recordable instrument. Without the motor ECPs, both ECM and AGTM require motor interruption for data collections. However, when the motor ECPs are known, the ECM has advantage over AGTM due to it requires only simple electrical data measurements, which are voltage, current, real and reactive powers, power factor, and speed. It is practically difficult to get the motor ECPs without laboratory test. Moreover, the motor ECPs may differ from the factory test condition after long operating time and rewinding. Obtaining the on-service motor ECPs without motor interruption is, therefore, benefit to investigate and evaluate the motor operation. The induction motor ECPs can be obtained from the manufacturer catalog data [13]. However, the ECPs of the long ageing motor may differ from the manufacturer catalog. Accordingly, many researches focused on the methods for non-invasive ECPs estimation using

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artificial intelligent (AI) techniques had been proposed [14]-[23]. For example, the genetic algorithm (GA) based induction motor parameters identification was proposed in [14]-[16]. Meanwhile, in [17]-[20], the particle swarm optimization (PSO) based induction motor ECPs identification and its improvement were introduced. The earlier techniques for induction motor ECPs estimation still lay on using AI optimization techniques, for examples, hybrid GA-PSO [21], meta-heuristic methods [22], gravitational search algorithm [23]-[24]. Therefore, the intelligent optimization techniques are founded to be effective methods for induction motor ECPs identification. As a result, the induction motor efficiency can be further investigated by the non-invasive AI estimation for motor ECPs. With the AI based induction motor ECPs estimations, the ECM can be applied to non-invasive ECM (NIECM) for motor efficiency estimation and beneficially for experimentation. However, there are several practical conditions effecting the motor efficiency that obstruct most researches to only ECPs estimation, without motor efficiency investigation. This paper, therefore, further investigates the proposed algorithm with several motors in different conditions. The PSO based induction motor ECPs estimation and its application to motor efficiency estimation have been successfully developed and tested. The new, old (more than five years of operation), and re-winding motors, with different size were used for testing and verifying the accuracy level of the proposed NIECM, comparing to the laboratory test results in compliance to IEC-112 standards. Afterward, five on-site motor replacement programs were used to verify the practical accuracy and limitation of the method. The experimentation results of the proposed ECM are compared to the conventional slip method (SM) and current method (CM). It is very well-known that the current method usually provides the very high error for motor efficiency estimation, especially when the motor is operated in light load condition. However, it is one of the non-invasive method commonly used and discussed for motor efficiency estimation. In addition, the study found that the current method provides reasonable result when motors are operated at full load and near full load. Therefore, the results of current method are addressed and discussed.

The organization of the paper is as follows. The methods for on-service three-phase induction motor efficiency estimation are discussed in Section 2. Then, Section 3 illustrates the development of motor efficiency estimation software using the proposed NIECM. The experimentation results are addressed and discussed in Section 4. Lastly, in Section 5, the conclusion is given.

2. NON-INVASIVE THREE-PHASE INDUCTION MOTOR EFFICIENCY ESTIMATION

The accurate efficiency test for three phases induction motors are based on the input-output method recommended in IEEE-112 standard and the shaft-torque method recommended in IEC60034 [1-2] standard. In the shaft-torque method, the input and output power output of the motor can be obtained as shown in Figure 1.

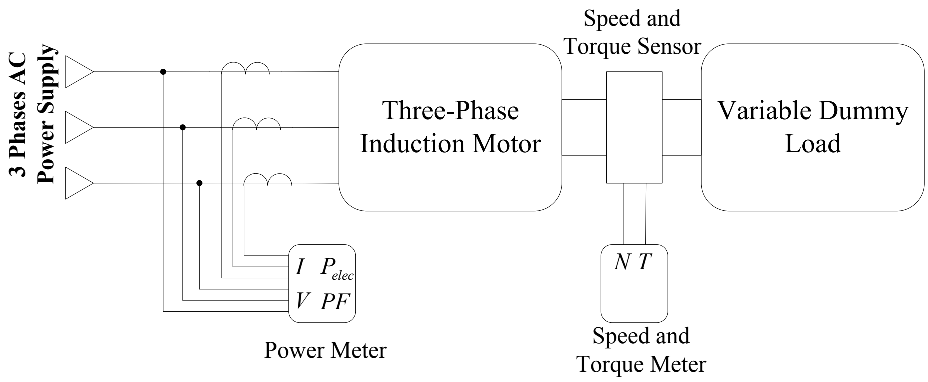

Fig. 1. Diagram for laboratory shaft-torque method for induction motor efficiency testing.

In Figure 1, the motor efficiency can be accurately obtained by,

$$Eff = \frac{P_{out}}{P_{elec}} \cdot 100\% \tag{1}$$

$$P_{out} = \frac{2\pi N}{60} T / 1000 \tag{2}$$

where,
Eff is the motor efficiency (%),
P_{out} is the motor output power (kW),
P_{elec} is the motor input power (kW),
N is the motor rotor speed (rpm), and
T is the motor output torque (Nm).

However, the torque sensors are rarely installed due to its high investment cost. The motors' efficiencies under operation are, therefore, difficult to determine accurately. The commonly used conventional non-intrusion on-service three-phase induction motor efficiency estimations methods [3]-[6] are;
- Nameplate method (NM); the method is based on the assumption that the motor efficiency is constant and is the value indicated in the motor specification.
- Slip method (SM); the method is based on the assumption that the motor efficiency is changed

proportionately to the slip in linear form. The motor efficiency determination is computed by;

$$Eff = \frac{S_{meas}}{S_{rated}} \cdot \frac{P_{rated}}{P_{elec}} \cdot \left(\frac{V_{meas}}{V_{rated}}\right)^2 \times 100\% \quad (3)$$

where,

S_{meas} is the motor measured slip,

S_{rated} is the motor rated slip,

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

V_{meas} is the motor measured voltage (V), and

V_{rated} is the motor rated voltage (V).

Current method (CM); the method is based on the assumption that the motor efficiency is changed proportionately to the current in linear form. The motor efficiency determination is computed by;

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

where

I_{meas} is the motor measured current (A) and

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

- Equivalent circuit method (ECM); this more accurate method is based on the induction motor equivalent circuit theory when the motor ECPs, as indicated in Figure 2, are known. The six ECPs, shown in Figure 2, are as follows;

X_1 is the motor stator leakage reactance (Ohm),

R_1 is the motor stator resistance (Ohm),

X_m is the motor magnetizing reactance (Ohm),

R_c is the motor core loss resistance (Ohm),

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

R_2 is the motor rotor resistance (Ohm).

As a results, the motor electromagnetic power (P_{mech}), which is defined as air-gap power subtracted by the rotor winding loss, in kW, can be computed by,

$$P_{mech} = 3I_2^2 R_2 \left(\frac{1-S}{S}\right) / 1000 \quad (5)$$

where, S is the rotor slip.

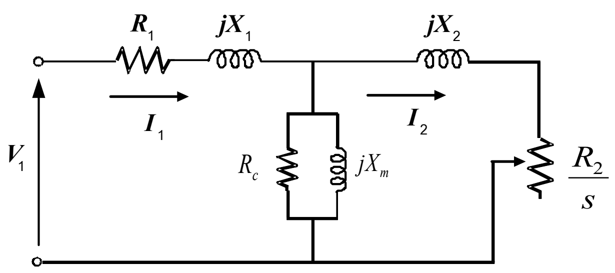

Fig. 2. The induction motor EC.

The non-invasive speed measurements for motors can be measured during in-service using light reflecting sticker for stroboscope. In this research, the speed measurement is used as input, to investigate the motors ECPs for research study propose. Then, the motor's efficiency during operating condition can be determined by.

$$Eff = \frac{P_{mech} - P_{msloss}}{P_{elec}} \times 100\% \quad (6)$$

Where P_{msloss} is the motor mechanical loss (fiction and windage loss) plus stray loss (kW). The motor mechanical and stray losses are varying size-by-size of the motor. In this paper, the motor mechanical and stray losses value recommended by [1] are used as reference.

3. DEVELOPMENT OF MOTOR EFFICIENCY ESTIMATION USING NIECM

3.1 Development of Motor Efficiency Estimation Software Using NIECM

In the developed software for NIECM, the six parameters are estimated using PSO [23]. The motor ECPs are searched from values corresponding to the measurable variables, which are, current (*I*), voltage (*V*), real power (P_{elec}), power factor (*PF*), and speed (*N*), without disturbing the motor operation. More specifically, the measured $\{I, V, P_{elec}, PF, N\}$ are the input of the software, and $\{X_1, R_1, X_m, R_c, X_2, R_r\}$ are the output of the computational procedure and then the motor efficiency can be determined by Equation 6. In practice, the stator and rotor resistances are depending on the temperature and then consequence to the motor's efficiency. Therefore, obtaining those actual on-site parameters is the advantage of the proposed NIECM. The change in stator and rotor resistances due to the temperature are handled by the proposed NIECM. From the input data, $\{I, V, P_{elec}, PF, N\}$, the initial particle can be defined as [11],

$$\mathbf{P^{(m)}} = [\rho_1^{i(m)} \rho_2^{i(m)} \rho_3^{i(m)} \rho_4^{i(m)} \rho_5^{i(m)} \rho_6^{i(m)}] \quad (7)$$

where $\rho_1^{i(m)}, \rho_2^{i(m)}, \rho_3^{i(m)}, \rho_4^{i(m)}, \rho_5^{i(m)}, \rho_6^{i(m)}$ represent the parameters $X_1, R_1, X_m, R_c, X_2, R_r$, respectively, for particle *i* of iteration *m*. Then the current (I^{cal}), real power (P_{elec}^{cal}), and power factor (PF^{cal}), of each particle, can be computed from each particle *i* and the measured voltage (V^{meas}) and speed (N^{meas}). Therefore, the evaluation function (EV) of each particle can be computed as,

$$EV = \left(\frac{I^{cal}}{I^{meas}} - 1\right)^2 + \left(\frac{P^{cal}}{P^{meas}} - 1\right)^2 + \left(\frac{PF^{cal}}{PF^{meas}} - 1\right)^2 \quad (8)$$

Where I^{meas}, P^{meas}, and PF^{meas} are the measured values of motor current, real power, and power factor, respectively. Accordingly, the particle providing best EV represents the particle that most likely to be the actual motor ECPs. Then the velocity for updating each particle is computed by,

$$\mathbf{v^{i(m)}} = [v_1^{i(m)} v_2^{i(m)} v_3^{i(m)} v_4^{i(m)} v_5^{i(m)} v_6^{i(m)}] \quad (9)$$

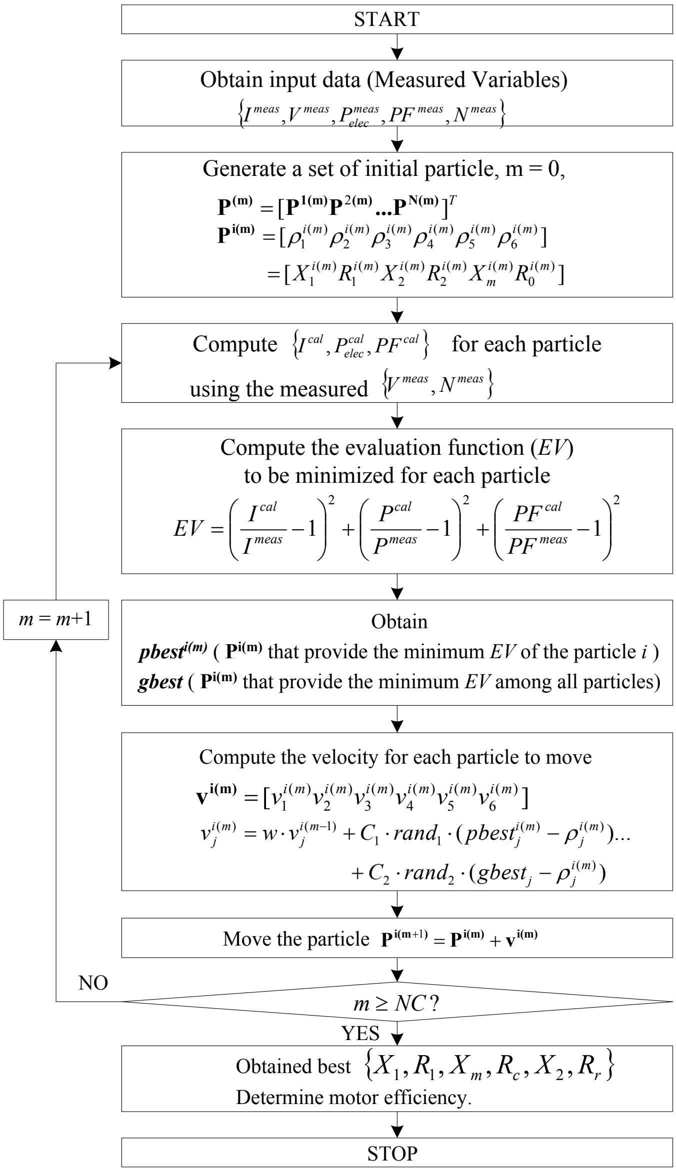

Fig. 3. PSO based induction motor ECPs estimation.

$$v_j^{i(m)} = w \cdot v_j^{i(m-1)} + C_1 \cdot rand_1 \cdot (pbest_j^{i(m)} - \rho_j^{i(m)}) + C_2 \cdot rand_2 \cdot (gbest_j^{i(m)} - \rho_j^{i(m)}) \quad (10)$$

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, [25]. $pbest_j^{i(m)}$ is the particle that provide minimum EV of the particle i. Whereas, $gbest_j^{i(m)}$ is the particle that provide minimum EV among all particle. Afterwards, the particles are updated by,

$$\mathbf{P}^{\mathbf{i(m+1)}} = \mathbf{P}^{\mathbf{i(m)}} + \mathbf{v}^{\mathbf{i(m)}} \quad (11)$$

The motor ECPs estimation process is shown in Figure 3. In this paper C_1, C_2 and w are set as 1, and the number of iterations, NC, is 1000. Finally, the motor ECPs obtained by the procedure in Figure 3 are used to estimate the motor power output and efficiency, by Equations 5 and 6. The user interface window of the software is shown in Figure 4. Note that the proposed NIECM deal with the steady state parameter of the motor's EC. Therefore, the physical phenomenon is not included in the analysis. The overall motor's EC is obtained by using the practical measured electrical value at the motor's terminal. In some practical situation, the harmonic current waveform effect the motor efficiency. However, the proposed method is based on the motor normal operating condition the and therefore, the power quality issues is not in the scope of the paper.

3.2 Development of Portable Motor Efficiency Estimation Instrument Using NIECM

The algorithm in Section 3.1 can be used for motor efficiency estimation with standard power meter. However, to provide more user friendly on-site estimation, the non-invasive on-service portable instrument for motor efficiency estimation using the proposed NIECM. The measuring device is shown in Figure 4. The user interface screen for the proposed NIECM is shown in Figure 5.

Fig. 4. The non-invasive on-service portable instrument for motor efficiency estimation using the proposed NIECM.

Fig. 5. User interface window of the non-invasive on-service portable instrument for motor efficiency estimation using the proposed NIECM.

In the non-invasive on-service portable instrument for motor efficiency estimation using the proposed NIECM, the currents are measured by current transformer and the voltage can be connected to the motor terminal using RS323. Meanwhile, the non-contact speed sensor can be measured at the motor shaft using RS433. Therefore, the motors' voltage, current, power, power factor, and speed can be non-intrusion obtained and the motor efficiency can be estimated using the proposed NIECM.

4. EXPERIMENTATION RESULTS AND PRACTICAL INVESTIGATIONS

The experimentation results with nine motors tested in laboratory were used in the development and test of NIECM. Furthermore, the field test results with five motors replacement program were investigated. The PSO parameters and the motor ECPs upper and lower limits are shown in Table 1. Meanwhile, the initial values for the motor ECPs, in the proposed method, are obtained by the standard and most common values of practical motors. In this research, the lower and upper limit of the motor ECPs are not specified in the optimization process, since there are several and wide variety of motor models and sizes for investigations.

Table 1. PSO parameters.

Parameter	Value
Population size	1000
Local best influence	1
Global best influence	1
Inertia weight	1
Maximum iterations	100

4.1 Experimentation Results with Motor Tested in Laboratory

In this research, nine motors, with different condition and size, had been tested in the laboratory by shaft-torque method in compliance to IEC60034-2-1 standard. The tested motors are shown in Table 2. In Table 2, the motors' rated data are obtained from motors' nameplates. The tested motors were arbitrarily sampled for testing the proposed method. The motor are from different manufacturers, different past condition, and different specifications. Therefore, the specification in Table 2, given by the manufacturers, are different. However, the investigation is not based on comparing motors to each other's. In fact, different motors provide diversity cases study among CM, SM, and the proposed NIECM. The motors were tested for efficiencies at the load factor of 10, 20, 30, …, 100%. The motors' voltage, current, electrical power, speed and torque are recorded and used as reference. The laboratory test for shaft-torque method is shown in Figure 6, with the testing procedure in accordance to IEC6034-2-1.

There are several laboratory procedures for motor efficiency testing in IEC60034-2-1. However, the main aim of the research is on non-invasive on-service motor efficiency estimation. Meanwhile, the laboratory test for Method 2-1-1H-Determination of Efficiency by Use of Equivalent Circuit Parameters is comparatively lower accuracy than Method 2-1-1A-Direct Measurement of Input and Output, since it cannot represent mechanical loss such as, fiction and windage loss of the motor. In addition, it cannot represent the accurate equivalent circuit parameters for the on-service motor with winding high temperature condition. In addition, Method 2-1-1B-Summation of Losses, additional load losses according to the Method of Residual Loss provides the lower accuracy than Method 2-1-1A, due to it requires several indirect process of losses estimations. Therefore, Method 2-1-1A is used as reference in the research. The shaft-torque testing procedure had been done under the same condition for all tested motors in the laboratory certified by the Ministry of Energy of Thailand. Therefore, the uncertainty of the shaft-torque method in this research is considerable minimal.

Figure 7 shows the results of the proposed NIECM comparing to the conventional SM and CM. The experimentation results of the proposed method with 100 PSO runs of 80 and 100% loading are shown in Appendix A. In summary, the root mean square errors of the efficiency estimations for CM, SM, and the proposed NIECM, when using shaft-torque as reference, are shown in Table 3. Note that the CM resulted in the unreasonable estimated efficiencies, higher than 100%, for the motors in light-load condition, due to the calculation method in Equation 4 cannot represent no-load loss of motor, realistically. It is observed that for small size (1.5 kW) motor under light load condition, the proposed NIECM give the high error in efficiency estimation. Meanwhile, the SM resulted in the closest efficiency estimation for small size motor during light load.

In the experimentation results, CM can gives the more accurate motor efficiency estimation than those of SM at the loading condition higher than 50% of motor rated power. Inversely, the SM results in the better motor efficiency estimation than CM when the motors are operating in light load condition. Among all investigated methods, the proposed NIECM provides the best accuracy on induction motor efficiency estimation with overall root mean square error of 1.10 % mismatch to the reference shaft-torque method.

From the experimentation results, the CM provides the unacceptable high error when the motors are operated in light load condition, below 50% of rated power, with the overall root mean square error of 17.43% comparing to the shaft-torque method. This manner is in corresponding to the experimentation results in [5] and [10]. However, the experimentation during light load condition provides the valuable information of all investigated methods. The CM results in the low error of induction motor efficiency estimation of 1.73% mismatch to shaft-torque method at the 50% of rated power loading condition and above. Meanwhile, the root mean square error on the induction motors efficiency estimated by SM is 1.68% mismatch to shaft-torque method for the loadings between 10 to 100% of rated power. Nevertheless, the root mean square error of the induction motor efficiency estimated by the SM is 2.14% mismatch to shaft-torque method for the induction motor operated at near rated condition (50% of rated power and above). The SM is less accurate than CM under the near rated conditions for efficiency estimation

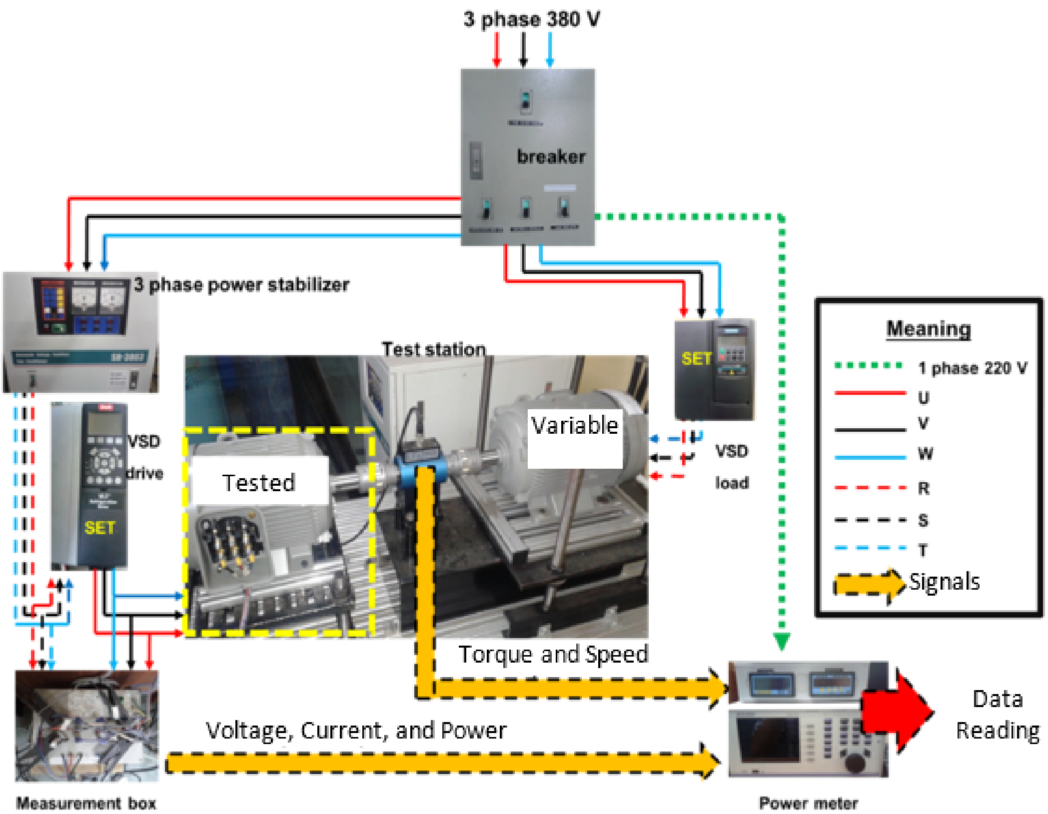

Fig. 6. The laboratory test for shaft-torque method.

Table 2. List of laboratory tested motors.

Number	Rated Voltage (V)	Rated Current (A)	Rated Power Factor (%)	Rated Power (kW)	Rated Speed (rpm)	Condition
1	380	3.4	82	1.5	1430	New
2	380	3.7	no data	1.5	1400	More than 10 years of operation
3	380	3.6	no data	1.5	1420	Re-winding
4	380	21.73	80.4	11	1460	New
5	380	22.3	84	11	1460	More than 10 years of operation
6	380	no data	no data	11	1450	Re-winding
7	400	56	85	30	1470	New
8	380	56.8	no data	30	1470	More than 10 years of operation
9	380	57	no data	30	1470	Re-winding

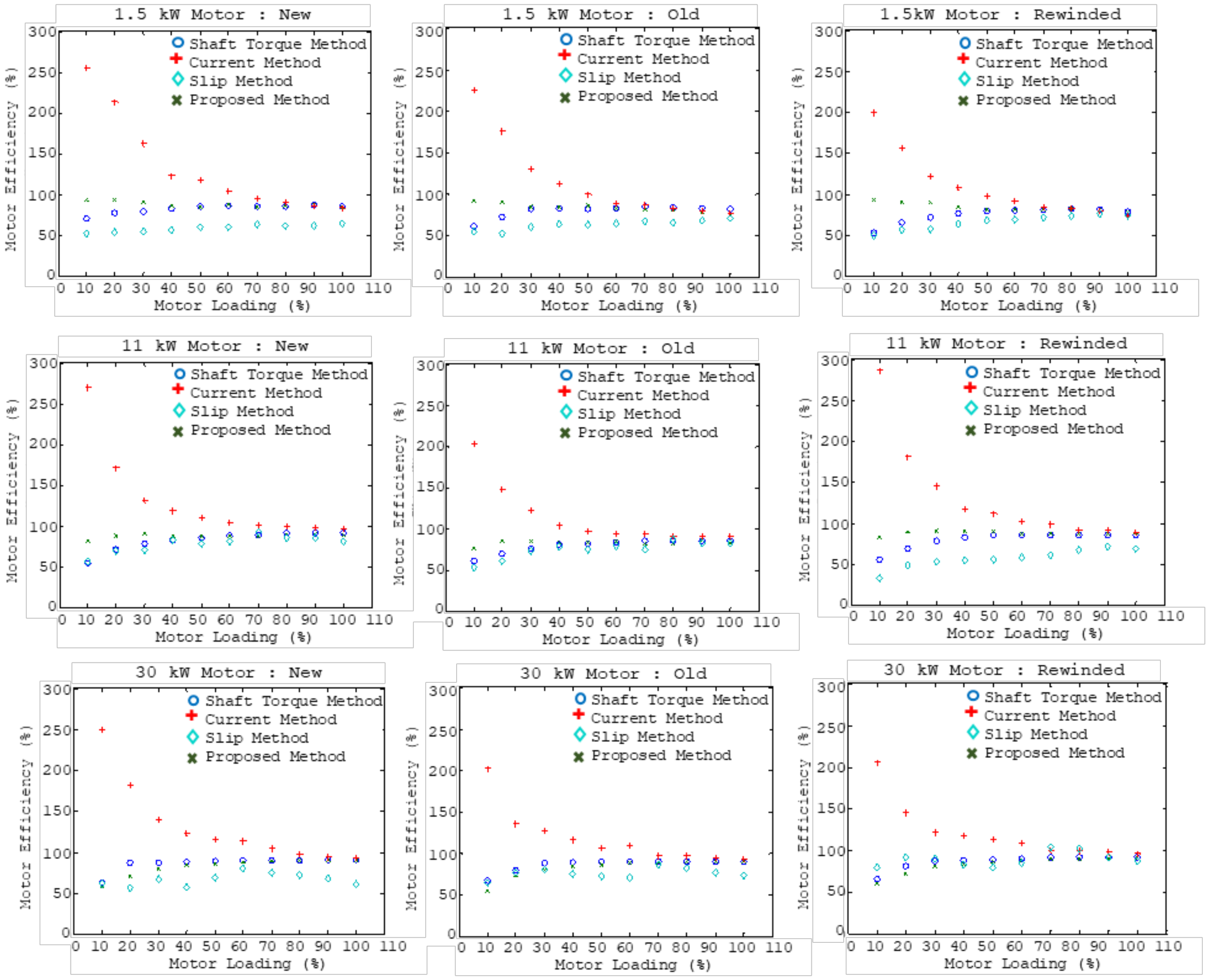

Fig. 7. Motors' efficiencies determined by shaft-torque, the proposed NIECM, CM, and SM.

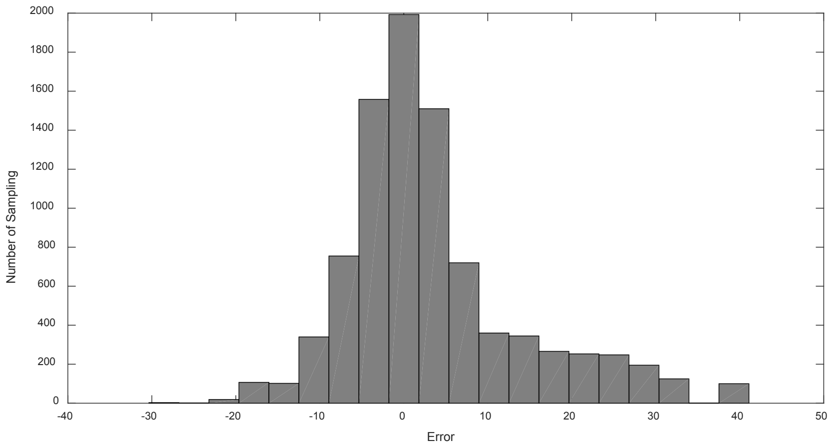

Fig. 8. Histogram of the efficiencies mismatched from shaft torque method of the proposed ECM for the nine tested motors at 10, 20, …, 100% of rated power loading.

As expected, for induction motor efficiency estimation, the proposed NIECM results in the minimum root mean square error of 0.32 % mismatch to shaft-torque method, for the estimation of induction motor operated at 50% of rated power and above. Moreover, the proposed NIECM provides the lowest root mean square error for the induction motor operated at below 50% of rated power comparing to those of estimated by CM and SM. The overall root mean square error of the proposed NIECM is 1.10% mismatch to shaft-torque method, which is the lowermost to CM and SM, for the operating range of induction motor from 10% to 100% of rated power loading.

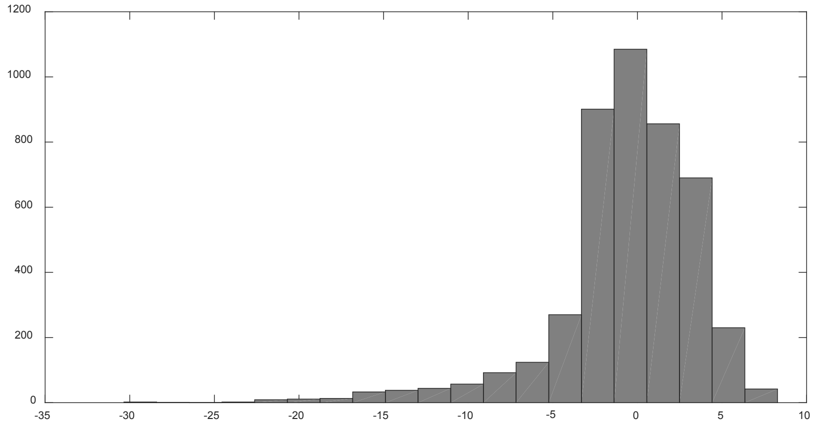

Fig. 9. Histogram of the efficiencies mismatched from shaft torque method of the proposed ECM for the nine tested motors at 50, 60, …, 100% of rated power loading.

The error analysis was carried out in two sectors, which are: (1) the efficiencies mismatched for the tested motors at 10-100% of rated power loading, as shown by histogram in Figure 8 and; (2) the efficiencies mismatched for the tested motors at 50-100% of rated power loading, as shown by histogram in Figure 8. The histogram of the efficiencies mismatched from shaft torque method (error) of the 100 computational trials for nine tested motors at ten loading points are illustrated in Figure 9. Therefore, the total sampling number is 9,000 and the results show that the errors at the 95% of confidence level are in the range of 3.28-3.72% mismatch to shaft-torque method. Figure 8 shows the histogram of the errors obtained from nine motors at the loading of 50% of rated power above. In this case, the results show that the errors at the 95% of confidence level are in between -0.783 to -0.536 % mismatch to shaft-torque method. The investigation results indicate that the proposed method can be efficiently and effectively estimate the induction motor efficiency, especially at the 50% of rated power loading and above.

4.2 Experimentation Results with Manufacturers' Data for Large Motors

The proposed NIECM was also tested with several large size motors including 55, 75, 110, 132, and 200 kW. The results of large motors investigation had been done with information provided by manufacturer, with has been done under IEC60034-2-1 Method A. Tables 4 shows the result of the efficiency estimation under the proposed NIECM comparing to the laboratory testing data.

The experimentation results shown that the proposed NIECM can successfully estimate the motor efficiency with the minimal error of 0.00698% for 200 kW motor. Meanwhile, the maximum error in this experimentation is 0.43535% for 55 kW motor, with is under acceptable error value.

4.3 Practical Investigation of Using the NIECM Software for Induction Motor Replacement Program

The proposed NIECM is mainly aimed at estimation of motor efficiency with non-invasive and under on-site condition. Therefore, the investigations of applying the proposed NIECM under practical information comparing to other conventional methods were carried out to confirm the potential of the proposed NIECM relevance to real practice. Under practical motor replacements study, the NIECM was examined under actual condition with several unknown and uncontrollable conditions.

For practical investigation on three-phase induction motor replacement program with the proposed NIECM, five practical in-service motors were examined and replaced by new motors. The selected five field experimented motors are listed in Table 5. The new motors for replacement are shown in Table 6.

The motors' voltages, currents, powers, power factors, and speeds had been measured, without interrupting motors operation. Then, the motor efficiencies were estimated by CM, SM, and the proposed method. Afterward, the existing motors were replaced by new motors. The power consumption of new motors were, then, measured for determine the power reduction by motor replacements. The experimentation procedure can be illustrated as Figure 10.

The experimentation results are shown in Tables 7 to 9. The motor power reduction estimated by CM, SM, and the proposed NIECM are shown and compared to measured values. CM provide misleading estimation in most case study. Meanwhile, SM resulted in overestimated power reduction in most cases, whereas the proposed NIECM provides the minimum error in power reduction among all methods, for motor replacement case studies.

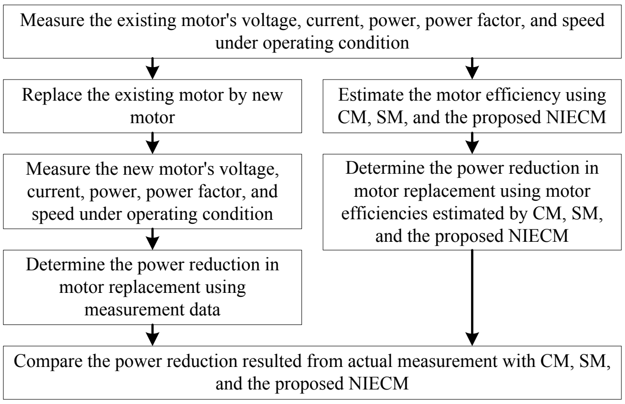

Fig. 10. The practical investigation of the motor power reduction estimated by CM, SM, and the proposed NIECM for induction motor replacement program.

In the case study shown in Table 7, the 7.5 kW motor was replaced by new motor with the same rated power. The SM resulted in the error in power reduction estimation of 1.20 kW (15.93%). Whereas, the proposed NIECM resulted in the lowest error in power reduction estimation of 0.18 kW (2.35%). Similarly to the previous case, the power reduction estimated by CM gave the wrong impression that the replacement program was not provide the power saving.

In Table 8, the existing 11 kW motor was replaced by the new 11 kW motor and had been examined. The SM resulted in over estimation of the power reduction by 5.22 kW (47.43%). Meanwhile, CM provided the lower error in power reduction estimation than those of estimated by SM, with the error of 1.11 kW (10.10%). Nevertheless, the proposed NIECM gave the power reduction estimation closest to actual measurement with the error of 0.42 kW (3.80%).

The experimentations for 22 kW motor replacement case study are shown in Table 9. The experimentation results are similar to most previous cases. The SM resulted in the high error and CM resulted in the misrepresented motor replacement program evaluation. Meanwhile the proposed NIECM provided the lowermost power reduction estimation error in this cases of 0.33%.

Table 4. Efficiency estimation result of 55, 75, 110, 132, and 200 kW motors.

Motor Rated	Voltage (V)	Power Factor (lagging)	Current (A)	Power (kW)	Speed (rpm)	Testing Efficiency (%)	NIECM Estimated Efficiency (%)	Absolute Error (%)
55	415	0.9	90	58.20	1480	94.50	94.94	0.43535
75	415	0.91	122	79.03	2985	94.90	95.17	0.26995
110	415	0.92	175	115.67	2976	95.10	95.19	0.09179
132	415	0.87	220	138.08	1486	95.60	95.81	0.20573
200	415	0.88	335	211.86	2975	94.40	94.39	0.00698

Table 5. List of field experimented motors.

Number	Rated					Condition
	Voltage (V)	Current (A)	Power Factor (%)	Power (kW)	Speed (rpm)	
A1	380	15.5	90	7.5	2900	34 years in operation
B1	400	21.5	85	11	2900	15 years in operation and re-winding
C1	380	41.5	86	22	2930	25 years in operation

Table 6. List of replacement motors.

Number	Rated					Condition
	Voltage (V)	Current (A)	Power Factor (%)	Power (kW)	Speed (rpm)	
A2	380	15.5	90	7.5	2900	New
B2	400	21.5	85	11	2900	New
C2	380	42.5	90	22	2930	New

Table 7. Experimentation result from replacement of A1 by A2 case study.

Replacement of A1 by A2	SM	CM	NIECM
Existing motor rated power (kW)	7.5	7.5	7.5
Existing motor measured power (kW)	6.02	6.02	6.02
Existing motor efficiency estimation (%)	54.35	84.19	72.95
Existing motor output power estimation (kW)	3.27	5.07	4.40
New motor efficiency from nameplate (%)	81.69	81.69	81.69
New motor input power estimation (kW)	4.01	6.20	5.38
Power reduction estimation (kW)	2.02	-0.18	0.64
Measured new motor input power (kW)	5.20	5.20	5.20
Measured power reduction (kW)	0.82	0.82	0.82
Error of power reduction estimation comparing to measured power reduction (kW)	1.20	1.00	0.18
Error of power reduction estimation comparing to measured power reduction (% to motor rated)	15.93	13.39	2.35

Table 8. Experimentation result from replacement of B1 by B2 case study.

Replacement of B1 by B2	SM	CM	NIECM
Existing motor rated power (kw)	11	11	11
Existing motor measured power (kw)	13.45	13.45	13.45
Existing motor efficiency estimation (%)	45.10	85.99	81.51
Existing motor output power estimation (kw)	6.06	11.56	10.96
New motor efficiency from nameplate (%)	86.88	86.88	86.88
New motor input power estimation (kw)	6.98	13.31	12.61
Power reduction estimation (kw)	6.47	0.14	0.83
Measured new motor input power (kw)	12.20	12.20	12.20
Measured power reduction (kw)	1.25	1.25	1.25
Error of power reduction estimation comparing to measured power reduction (kw)	5.22	1.11	0.42
Error of power reduction estimation comparing to measured power reduction (% to motor rated)	47.43	10.10	3.79

Table 9. Experimentation result from replacement of C1 by C2 case study.

Replacement of C1 by C2	SM	CM	NIECM
Existing motor rated power (kw)	22	22	22
Existing motor measured power (kw)	22.29	22.29	22.29
Existing motor efficiency estimation (%)	60.51	91.91	85.42
Existing motor output power estimation (kw)	13.49	20.49	19.04
New motor efficiency from nameplate (%)	87.39	87.39	87.39
New motor input power estimation (kw)	15.43	23.44	21.79
Power reduction estimation (kw)	6.86	-1.15	0.50
Measured new motor input power (kw)	21.86	21.86	21.86
Measured power reduction (kw)	0.43	0.43	0.43
Error of power reduction estimation comparing to measured power reduction (kw)	6.43	1.58	0.07
Error of power reduction estimation comparing to measured power reduction (% to motor rated)	29.21	7.20	0.33

5. CONCLUSION

This paper presents the investigation of NIECM with laboratory tested motors and field experimentation results. The proposed NIECM was investigated by comparing to conventional CM and SM methods on several motors, with different sizes and conditions, using the standard laboratory shaft-torque method as reference for motor efficiencies. The experimentations shown that the proposed NIECM can provide the best accuracy for non-invasive efficiency estimation of three-phase induction motor. In addition, the field experimentation with several practical motor replacement case studies shown that the proposed NIECM provides the minimum error in power reduction estimation comparing to SM and CM. Therefore, the proposed NIECM can be the potential method for handily non-invasive on-service three-phase induction motor efficiency estimation, using basic instrumentation and NIECM algorithm in personal computer.

ACKNOWLEDGEMENT

This research was fully granted by the joint program funding from Thailand Research Fund (TRF) and Electricity Generating Authority of Thailand (EGAT), under contract number RDG61D0012.

NOMENCLATURE

AGTM	Air Gap Torque Method
AI	Artificial Intelligent
CM	Current Method
ECM	Equivalent Circuit Method
ECPs	Equivalent Circuit Parameters
ESCO	Energy Service Company
GA	Genetic Algorithm
NM	Nameplate Method
PSO	Particle Swarm Optimization
SM	Slip Method

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APPENDIX

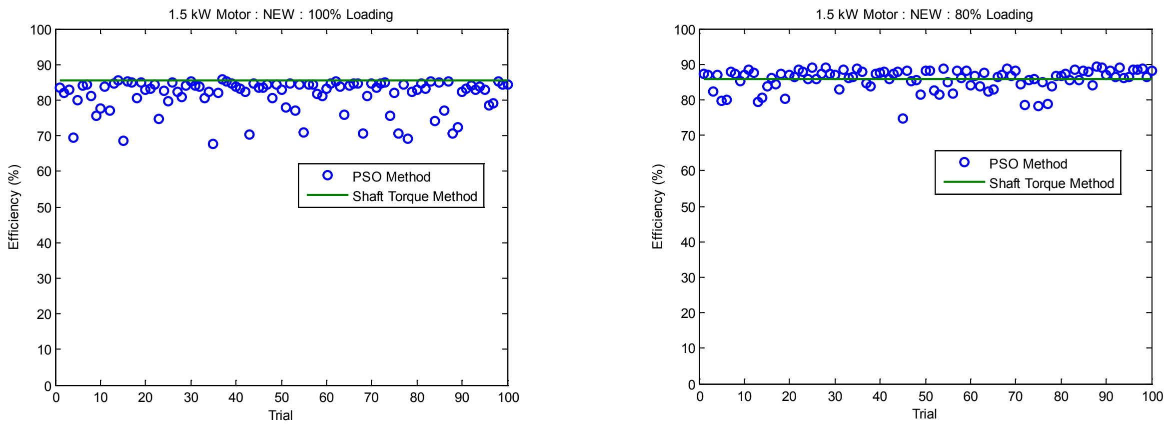

Fig. A1. Efficiencies estimated by the proposed NIECM (PSO Method) for the new 1.5 kW three-phase induction motor with 100 trials in computation.

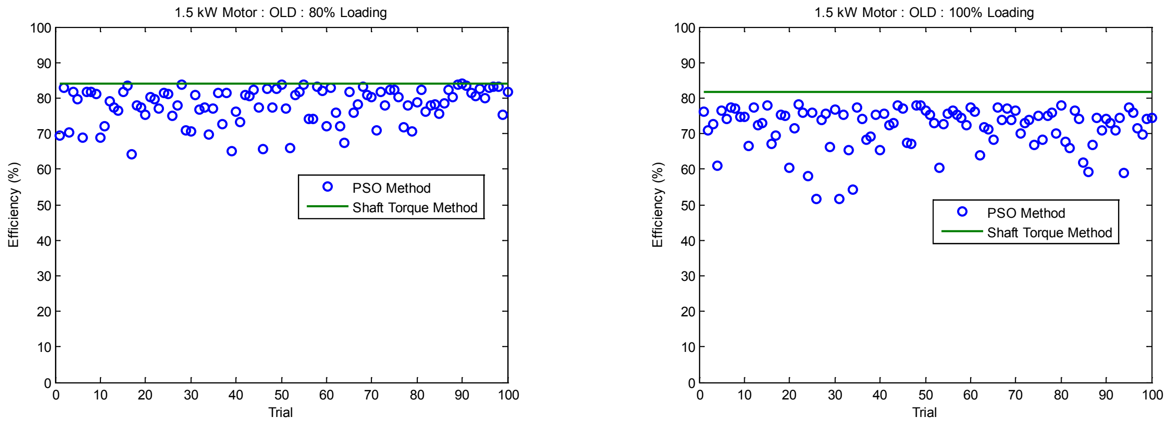

Fig. A2. Efficiencies estimated by the proposed NIECM (PSO Method) for the old 1.5 kW three-phase induction motor with 100 trials in computation.

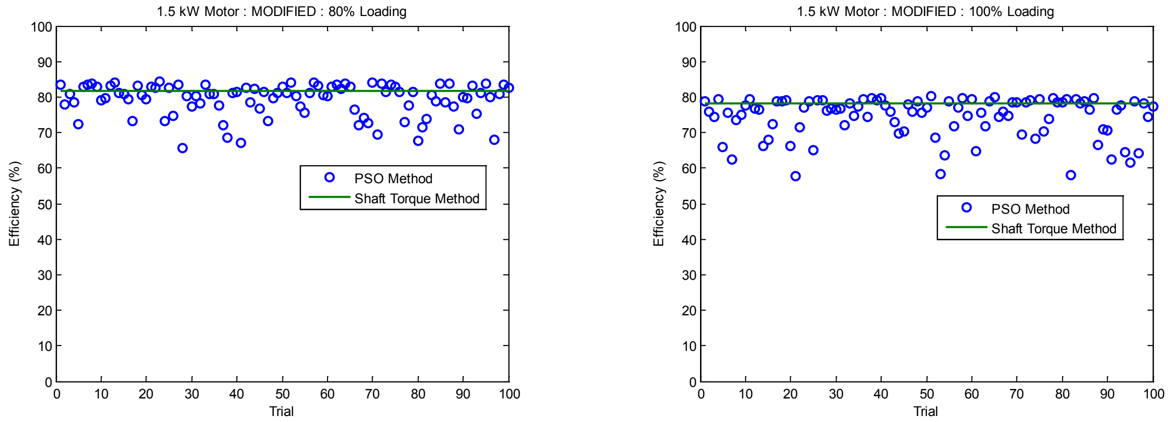

Fig. A3. Efficiencies estimated by the proposed NIECM (PSO Method) for the re-winding 1.5 kW three-phase induction motor with 100 trials in computation.

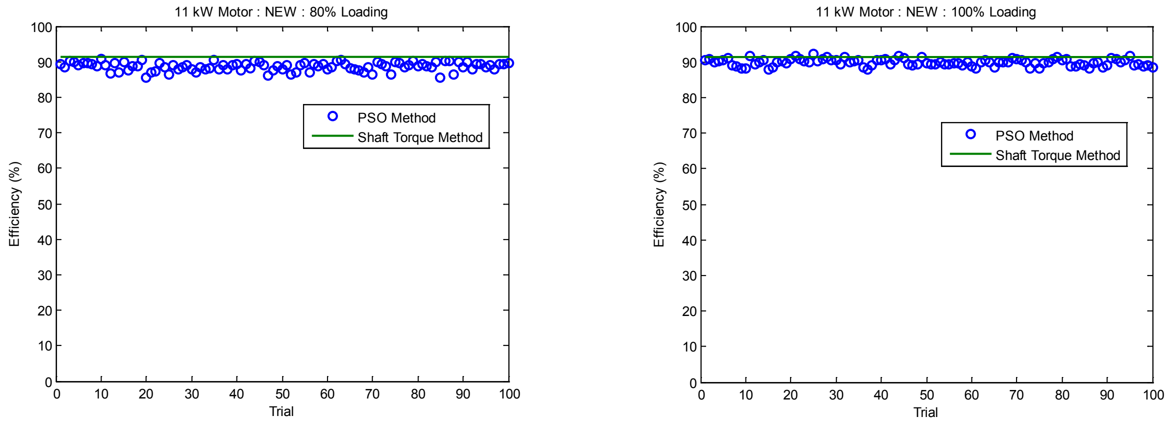

Fig. A4. Efficiencies estimated by the proposed NIECM (PSO Method) for the new 11 kW three-phase induction motor with 100 trials in computation.

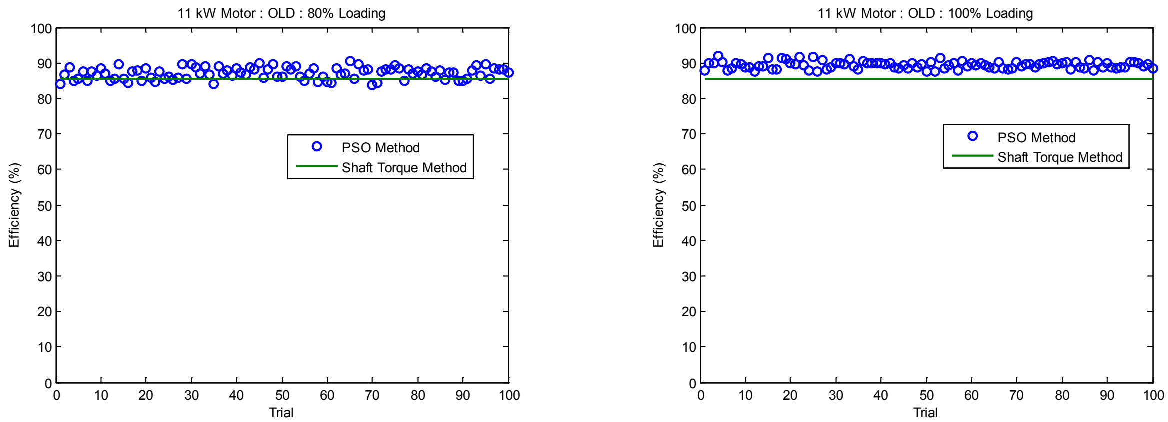

Fig. A5. Efficiencies estimated by the proposed NIECM (PSO Method) for the old 11 kW three-phase induction motor with 100 trials in computation.

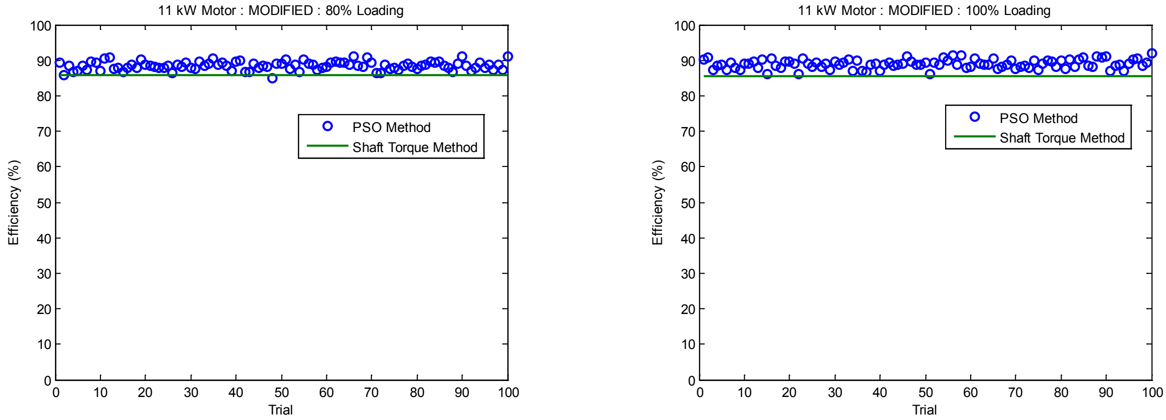

Fig. A6. Efficiencies estimated by the proposed NIECM (PSO Method) for the re-winding 11 kW three-phase induction motor with 100 trials in computation.

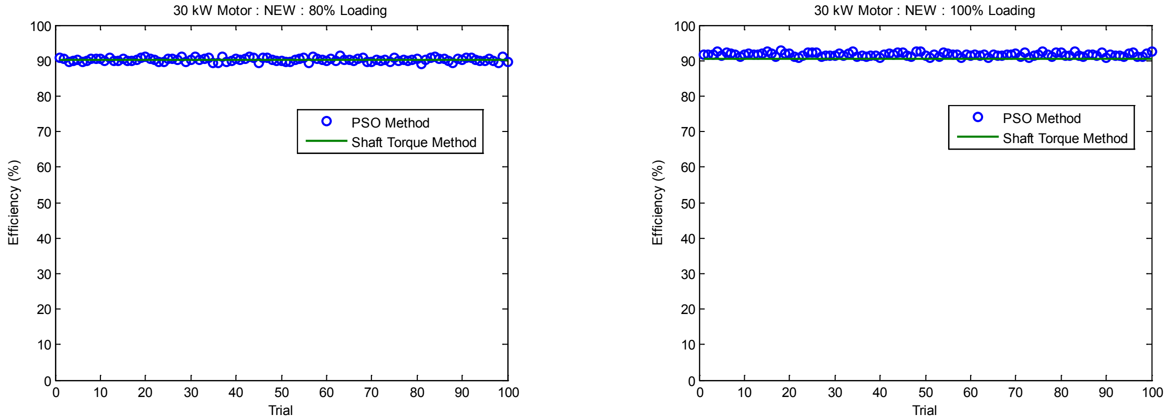

Fig. A7. Efficiencies estimated by the proposed NIECM (PSO Method) for the new 30 kW three-phase induction motor with 100 trials in computation.

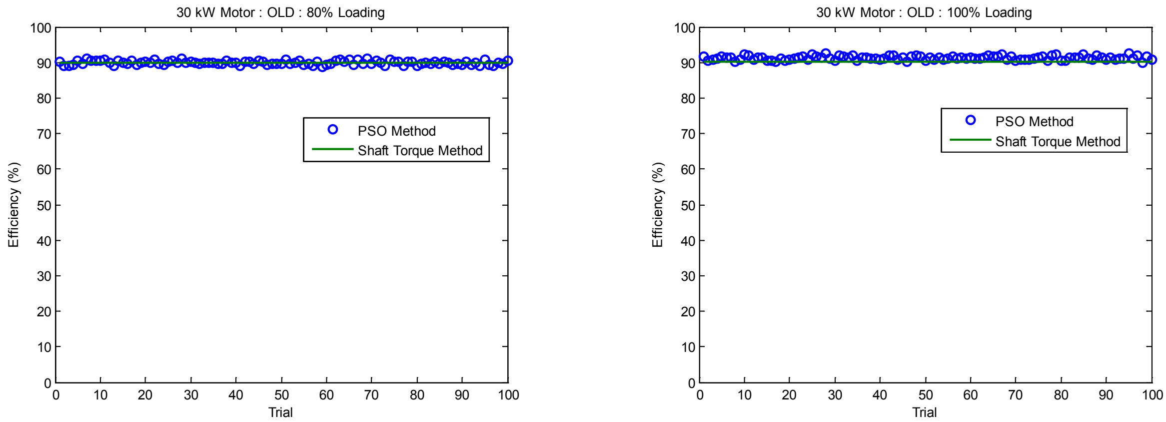

Fig. A8. One hundred trials of efficiencies estimated by the proposed NIECM (PSO Method) for the old 30 kW three-phase induction motor.

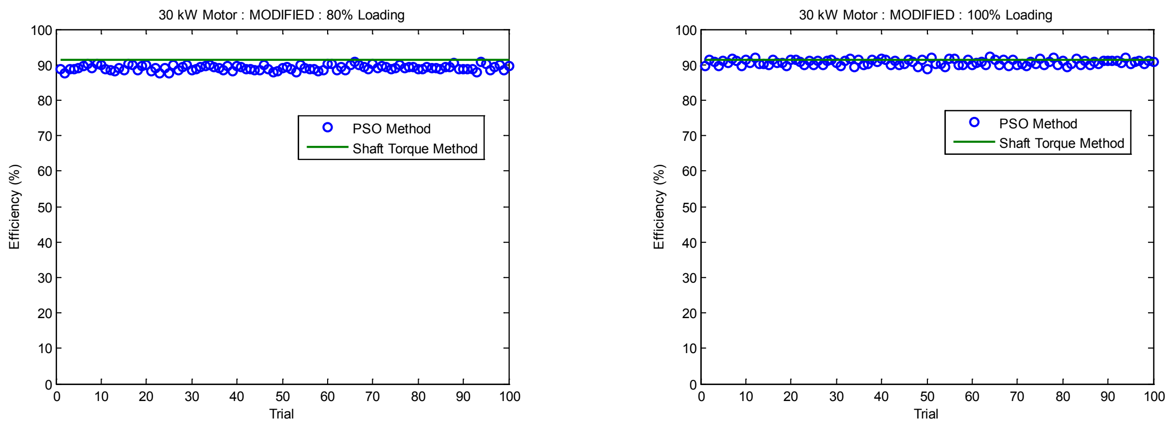

Fig. A9. Efficiencies estimated by the proposed NIECM (PSO Method) for the re-winding 30 kW three-phase induction motor with 100 trials in computation.