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Estimation efficiency of rewound induction motors in situ using a numerical model

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ABSTRACT

This paper presents an effective technique for determining the impact of rewinding practices on the motor efficiency and characterizing the efficiency reduction when electrical motors are rewound several times. This technique focuses on a new approach and a statistical study to find a numerical model for the estimation efficiency of rewound induction motors in the field. The experimental results from 101 induction motor tests are analyzed. A numerical model is determined and compared with different methods: separate losses method, modified current method and simple current method. An error analysis is conducted to examine the level of uncertainty by testing three asynchronous motors at 110 kW, 160 kW, and 300 kW. The results show that this approach can predict and estimate the efficiency reduction in rewound motors without expensive tests and can help the energy manager make effective cost decisions in replacing the rewound motors with more efficient ones by using an assessment of overconsumption and maintenance costs. Another advantage of this model is that it can be used to improve the software tools and can also be a very strong indicator to audit the repair quality.

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1. INTRODUCTION

Increased energy demand, fluctuations in oil prices, energy supply uncertainties and concerns regarding global warming have reinforced the priority given by several countries around the world to energy efficiency policies. Electrical motors and more specifically, induction motors are the main loads in electrical power systems of industrialized countries [1]. The enormous number of these machines represents a significant potential for the application of demand side energy management techniques [2, 3]. The efficient operation of the motors can bring direct and important savings in consumed energy levels and indirectly reduce greenhouse gas emissions. Improving energy efficiency in industry involves first an accurate assessment of electricity consumption, and therefore an accurate assessment of the efficiency of electric motors, as they are the most energy-intensive equipment in industry.

Generally, the measurement of efficiency is based on the measurement of the input power (P_{in}) and the output power (P_{out}). These types of methods require decoupling and moving the motor from the industrial process to the laboratory. However, the evaluation can also be performed indirectly by evaluating the various losses of the motor by using a minimum of measurements accessible on-site or by estimating the machine parameters [4, 5]. On-site measurements make it possible to minimize the evaluation efficiency period since no movement of the motor to the laboratories is necessary [6, 7].

Several papers have also been published regarding efficiency evaluations of induction motors on-site. However, very little has been done on estimating the efficiency after a rewinding process, which in fact can affect many induction motors in the industrial sector. The real efficiency of a motor is usually different from the value mentioned on its nameplate, because the efficiency may decrease significantly due to ageing or rewinding [8], which creates an overconsumption of electrical energy. In this paper, a new approach referred to as the local statistical method (LSM) is proposed for this purpose, which requires only the results of in-situ no-load testing during the rebuilding phase and one measurement point on load. The proposed technique is validated by field and experimental results with three induction motors.

2. FORMULATION OF THE PROBLEM

In industry, park machines are generally equipped with thousands of motors that have been rewound several time, and traditional methods of rewinding and refurbishment can decrease the efficiency. When the refurbishment does not respect the requirements of Electrical Apparatus Service Association (EASA) standard, the motors can easily lose 10% of the initial value shown on the nameplate [9]. Generally, electrical machine rebuilding and refurbishment centers do not have the funds to test their machines with the well-accepted efficiency test of the IEEE standard 112 or the new IEC Standard 60034-2-1 [10]. In fact, these facilities can only start up the motors and run them under a no-load condition with their autotransformers. Thus, they generally do not present any information regarding the efficiency degradation of an induction motors after its repair [11].

The authors in [12] proposed measures to improve the energy efficiency and the availability of electric motors in industry because to have high-efficiency motors in factories is just a step but not an end in itself, and the efficiency of motors is decreased when the motor is rewound. Therefore, for an electric motor to remain efficient in time with lasting durability, proper maintenance and protection is necessary. There are several computer tools and software packages to calculate the gain of replacing old motors with a new high-efficiency motor [13]. However, these tools cannot provide information regarding the reduction in efficiency after the refurbishment of a machine. Refurbishment workshops with best practices on rewinding procedures can often repair and rewind motors with no important efficiency reduction; hence, there is a need to develop an indicator of the repair quality.

The rest of this manuscript is organized as follows: in section 3, the proposed methodology is presented in detail. The experimental results and analysis are detailed in section 4. Section 5 presents the numerical model and the developed algorithm. In section 6 describe a validation of the proposed numerical model by comparison to real measurements. Section 7 offers a discussion and then the conclusions are presented in section 8.

3. METHODOLOGY

Over the years, the problem of efficiency reduction ($\Delta\eta$) has been observed by an increase in electrical consumption of rewound motors. Subramanian and Bhuvaneswari [14] presented a new method for the determination of induction motor efficiency using an evolutionary programming technique. This method is very accurate and does not require no-load measurements. However, when an electric motor is damaged it will automatically rewind, and in this evident situation lays the importance of this technique. Therefore, in this paper we will use the results of no-load tests that we normally and easily perform after each rewinding operation, adding a one-measurement point on load in situ. The idea of the method is to characterize the reduction in efficiency according to the number of rewinds and the rated power. The available data for this method are as follows: one point on load condition from the site, the current under no-load test conditions, the line voltage, the value of the stator resistance and the nameplate data.

The estimation of the efficiency can be based on one or more methods combined. These methods differ in their precision, implementation and convenience compared to the operating conditions [15-18]. In our case, decoupling the motor from its load will not be required, and the exploitation of the obtained results during the repair of hundreds of motors will enable us to evaluate the efficiency reduction based on the rated power (P_u) and the number of rewinding (N_R). Our searched system is as follows $\Delta\eta=f(N_R, P_u)$.

For this analysis, we will consider hundreds of electric motors from a workshop for rebuilding and refurbishment. Then, the results are listed in a table, in which the stray load losses (P_{sll}), stator copper losses, windage and friction losses were calculated. The rotor copper losses were ignored. A statistical study to predict the efficiency reduction was conducted. Then, multiple linear regressions were utilized to solve the equations by using MATLAB software.

3.1. Definition of motor losses and efficiency

The analysis of the motors by measuring the losses is particularly useful to understand how the conditions in which repairs are carried out affect the efficiency. For the purposes of an efficiency evaluation, motor losses are classified into five categories: stator copper losses (P_{sc}), rotor copper losses (P_{rc}), stray load losses (P_{sll}) [19], windage and friction losses (P_{wf}) and core losses (P_{cl}). The first three losses vary according to the load, while the other two losses are independent of the load. Even though, the windage and friction loss are almost constant, we are talking about an asynchronous motor and speed varies about 3% from no-load to rated load. The windage varies with the speed raised to the third power. Therefore, the windage and friction loss varies with the load.

The electric motor absorbs a power (P_{in}) from the electrical network and transmits only a transmitted power (P_{tr}) to the rotor after dissipating part of the power in the form of copper losses (P_{sc}) and iron losses (P_{is}) at the stator. There are also copper losses (P_{rc}), iron losses (P_{ir}) at the rotor, mechanical losses at the bearings and the stray load losses. Koprivica in [19] presents an application of one simple and accurate method for the measurement of stray load losses (additional load losses) in induction machines. The accurate prediction of losses [20] and speed [21, 22] of induction machines is an up-to-date topic of high interest in both industrial environments and the academic and research world.

3.2. Induction motor power flow

Stator copper losses (P_{sc}) are losses in the stator windings. Rotor copper losses (P_{rc}) are the losses in the rotor windings including the brush contact losses for wound-rotor motors. These losses are determined from the per-unit slip using (1), [15].

$$\mathrm{P_{rc}} = (\mathrm{P_{in}} - \mathrm{P_{sc}} - \mathrm{P_{cl}}) \times \mathrm{S} \quad (1)$$

where S is the slip and P_{cl} (core loss) is a result of an alternating magnetic field in a core material.

A no-load test supplies the motor without a load and measures the power absorbed (Pin0). This test will determine the collective losses (Pc), which remain constant regardless of the load. The absorbed power in the general case is:

$$\mathrm{P_{in}} = \sqrt{3}.\mathrm{U}.\mathrm{I}.\cos\phi \quad (2)$$

where P_{in} is the input power of the motor. The index '$_0$' will be added to denote the formulas of the no-load test, such as in (2) below for the stator copper losses under no-load test conditions.

$$\mathrm{P_{sc0}} = \frac{3}{2}.\mathrm{R_s}.\mathrm{I_0^2} \quad (3)$$

The core losses (P_{cl}) are due to the magnetizing hysteresis and eddy currents in the iron [23]. This parameter varies approximately with the square of the input voltage. However, for a fixed voltage, it remains approximately constant from the no-load case to the full-load case. The core loss is usually measured from the no-load test. Friction and windage losses (P_{wf}) are the mechanical rotational losses due to the friction and windage. This value is also practically constant from the no-load case to the full-load case and is generally measured from the no-load test [15].

$$\mathrm{P_c} = (\mathrm{P_{cl}} + \mathrm{P_{wf}}) \quad (4)$$

$$\mathrm{P_c} = \sqrt{3}.\mathrm{U_0}.\mathrm{I_0}.\cos\phi_0 - \frac{3}{2}.\mathrm{R_s}.\mathrm{I_0^2} \quad (5)$$

The power flow is:

$$\mathrm{P_{in}} = \mathrm{P_{out}} + \mathrm{P_{sc}} + \mathrm{P_{rc}} + \mathrm{P_c} + \mathrm{P_{sll}} \quad (6)$$

where P_{out} is the output power of the motor. Therefore, the power flow under no-load test conditions is given by:

$$\mathrm{P_c} = \mathrm{P_{in0}} - \mathrm{P_{sc0}} \quad (7)$$

Below are the formulas for calculating the efficiency reduction of the rewound motor. The losses due to the load are:

$$\mathrm{P_{losses}} = \left(\sqrt{3}.\mathrm{U_0}.\mathrm{I_0}.\cos\phi_0 - \frac{3}{2}.\mathrm{R_s}.\mathrm{I_0^2}\right) + \frac{3}{2}.\mathrm{R_s}.\mathrm{I^2} + \mathrm{P_{sll}} \quad (8)$$

The actual efficiency (η_a) of motor is then defined as:

$$\eta_a = \frac{P_{in} - P_{losses}}{P_{in}} \quad (9)$$

The efficiency reduction $\Delta\eta$ is:

$$\Delta\eta = \eta_n - \eta_a \quad (10)$$

where η_n is the efficiency mentioned in the nameplate.

3.3. Regression linear multiple analysis

Multiple linear regressions are the most common figures in a linear regression analysis. As a predictive analysis, multiple linear regressions are used to explicate the relationship between the dependent variable from two or more independent variables. Our system is composed of three characters:

- P_u=X^1 : The rated power of the rewound motor
- N_R=X^2: Number of rewinding operations
- $\Delta\eta$=Y : Reduction in the efficiency after each rewinding

For reasons of simplicity, the chosen model is a linear regression; thus, the numerical model takes the following form:

$$Y = \alpha_0 + \alpha_1.\alpha X^1 + \alpha_2.X^2 \quad (11)$$

These equations are stacked together and written in vector form as follows:

$$Y = \begin{bmatrix} y_1 \\ \cdots \\ y_n \end{bmatrix};\ \alpha = \begin{bmatrix} \alpha_1 \\ \cdots \\ \alpha_n \end{bmatrix};\ e = \begin{bmatrix} e_1 \\ \cdots \\ e_n \end{bmatrix} \quad (12)$$

$$Y = \begin{bmatrix} \Delta y_1 \\ \cdots \\ \Delta y_n \end{bmatrix} = X \begin{bmatrix} 1 & P_{u1} & N_{R1} \\ \cdots & \cdots & \cdots \\ 1 & P_{un} & N_{Rn} \end{bmatrix}.\alpha \begin{bmatrix} \alpha_1 \\ \cdots \\ \alpha_n \end{bmatrix} + e \begin{bmatrix} e_1 \\ \cdots \\ e_n \end{bmatrix} \quad (13)$$

We must determine α_1, α_2 and α_3 such that $\sum_i^n e_i^2$ is minimized i.e., $\|e\|^2$ is minimized (least square criterion); therefore, we will project orthogonally Y in $X^T.\alpha$. The ordinary least squares (OLS) method is the simplest and thus the most familiar estimator. The resolution of the system by MATLAB software is given by (14):

$$\alpha = (X^T.X)^{-1}.X^T.Y \quad (14)$$

To check if the numerical model chosen is good or not, the ratio of the standard deviation of the error to the norm must be calculated. Therefore, if the error is less than 3%, then the chosen model is considered to be good. After finding such a model, if additional values of N_R and Pu are given without the associated value of $\Delta\eta$, then the fitted model can be used to create a prediction of the value of the reduction efficiency $\Delta\eta$.

4. EXPERIMENTAL TEST FOR THE CHARACTERIZATION OF THE EFFICIENCY REDUCTION

4.1. Efficiency reduction as a function of the number of rewindings

Table 1 show the characteristics of an induction motor, which the variation of the efficiency illustrated in Figure 1. After evaluating the losses of this motor, which is rewound 6 times, there is an excess reduction in efficiency that is related to the number of rewinds, the lower load and the oversizing.

Table 1. Specifications of the rewound motor

Rated voltage(V)	Rated current(A)	Power factor	Input power (kW)	Nominal efficiency (A)	Current at no-load test (A)	Power factor at no-load test	Resistance of stator (Ω)
660	445	0.89	452.74	0.91	100	0.17	0.5

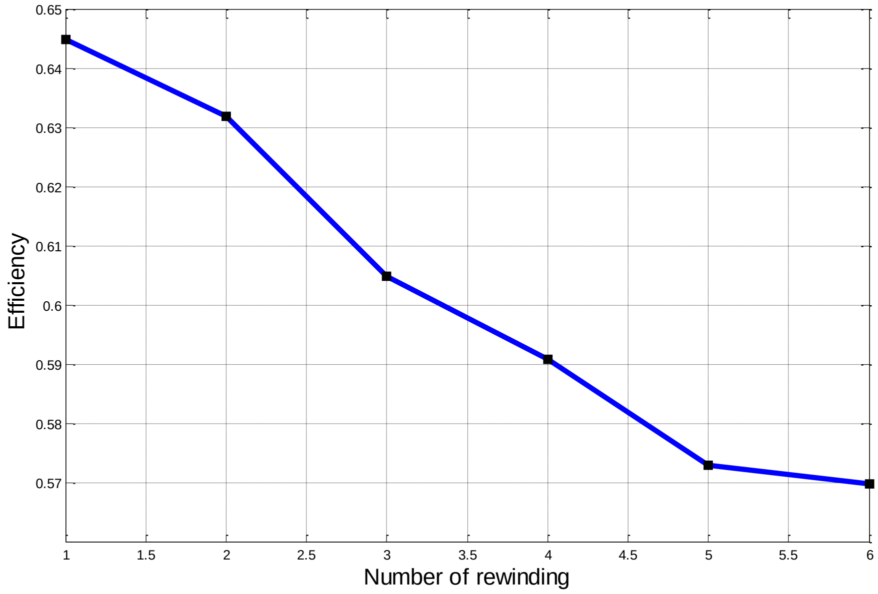

Figure 1. Efficiency dependence on the number of rewinds

4.2. Efficiency reduction as a function of the rated power

The second step of the efficiency estimation as a function of the rated power after rewinding consists of selecting motors with different powers, rewinding all the motors at one time and plotting the evolution of the efficiency as a function of the power. From Figure 2, we observe that the performance drop is approximately linear. While the power (P_u) increases, the efficiency reduction becomes important.

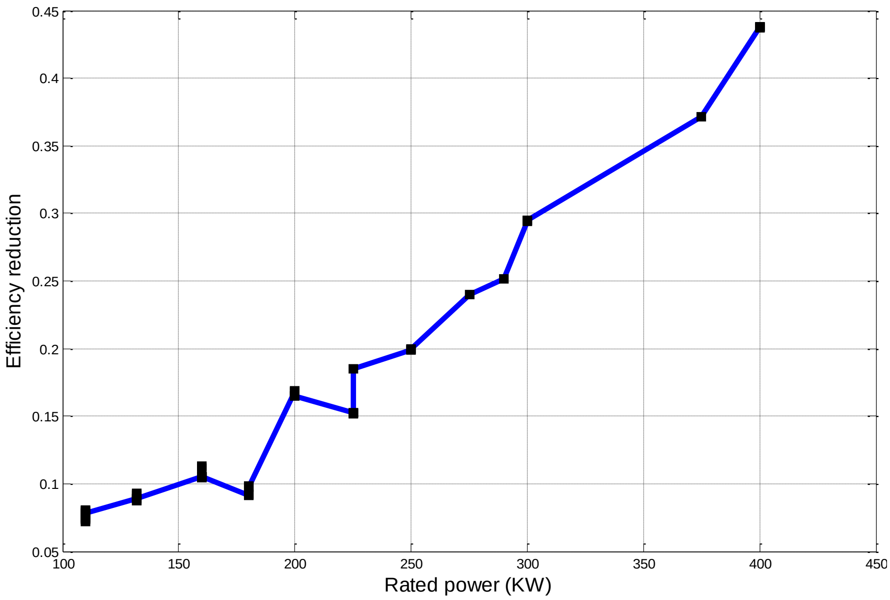

Figure 2. Decrease in the efficiency dependence on the power

5. EFFICIENCY ESTIMATION OF THE REWOUND MOTORS

To determine the evolution in the efficiency as a function of the number of rewinds (N_R) and the rated power (P_u) by a multiple linear regression analysis, the motors whose different data and characteristics are known are used. Table 2 shows an extract of the necessary data.

Table 2. Sample of available data

No.	P_u	N_R	I_n	I_{rew1}	I_{rew2}	I_{rew3}	$\cos\Phi_0$	R_s (25°C)
1	375	4	386	90	94	96	0.17	0.7
2	290	3	305	61	65	66	0.17	0.6
5	110	3	118	36	42	46	0.17	0.5
6	132	2	140	46	52		0.17	0.5

I_{rewi} is the current under no-load test conditions for the rewinding operation number i. The selected sample comprises 101 motors of different powers. This sample may have power redundancies provided that the number of rewindings of the motor is different. What interests us the most in this study is the reduction in the efficiency after each rewinding operation.

5.1. Calculation of the motor efficiency reduction

It was possible to plot the evolution of the efficiency based on the number of rewinds on the one hand and on the rated power on the other hand. Only the no-load tests were carried out on all the rewound motors by measuring the no-load current I_0 and the stator resistance R_s. These measurements were used to calculate the constant losses (mechanical, iron). It is possible to measure another operating point on load in situ. Table 3 contains all the parameters necessary to calculate the reduction in efficiency.

Table 3. Sample of the actual efficiency calculation

P_u (kW)	N_R	P_{in} (kW)	P_c (kW)	P_{sc} (kW)	P_{Sll} (kW)	Efficiency (η_a)
160	2	165.98	8.530	20.418	2.4	0.826
290	1	306.82	9.836	83.722	4.35	0.695
375	4	392.71	8.989	156.44	5.62	0.579

5.2. Determination of the numerical model

For the resolution of the problem, MATLAB software was used. Table 4 contains the values of the column matrix Y and matrix X^T.

Table 4. Sample of values used for linear multiple regression analysis

Matrix Y=$\Delta\eta$	Matrix X^T	
0.1169	3	110
0.1029	2	132
0.1547	1	180

After executing the calculation code using MATLAB software, the following results were obtained:

$$\alpha_2 = 0.0019\ ; \quad \alpha_1 = 0.00102\ ; \alpha_0 = -0.0403$$

Therefore, the evolution in the efficiency reduction as a function of rated power (P_u) and the number of rewinding (N_R) is as follows:

$$\Delta\eta = 0.0019 * N_R + 0.00102 * P_u - 0.0403 \tag{15}$$

The model is well chosen because the error is very small, and the criterion of validation is well checked:

$$C_r = \frac{\|e\|^2}{\|y\|^2} = 2.9\%$$

Even if the error was higher than 3%, our method remains relevant and applicable as long as the error is less than 5% because it is easier. Moreover, the model is more accurate with a large number of motors. These calculations will be performed one time, and the user has the ability to update the numerical model if other samples need to be inserted into the calculation.

5.3. Determination of the critical efficiency

The objective of this section is to define an optimization criterion that will help the energy manager of an industrial plant make the right decision to rewind or acquire a new motor based on the critical efficiency. We will determine the critical efficiency that the motor must have so that the motor cost and the rewinding cost do not exceed 70% of the cost of a new motor.

− The energetic overconsumption (ΔC) in kW is:

$$\Delta C = P_u \times \left(\frac{1}{\eta_a} - \frac{1}{\eta_n}\right) \tag{16}$$

− The overconsumption cost (Ce) is:

$$C_e = \Delta C \times K \times € \tag{17}$$

where € is the cost per KWh and K is the coefficient of the use of the motor.

− Cost of rewinding an electric motor:

The cost of rewinding (C_{rew}) electric motors consists of two main elements: the cost of the raw material (C_{rm}) that varies from one motor to another according to the technology and the motor power. There is also the cost of worker (C_{mp}), which is calculated as follows:

$$C_{mp} = T_b \times N_e \times T_h \tag{18}$$

where T_b is the time for rewinding the motor, N_e is the number of operators and T_h is the hourly rate cost. The cost of rewinding (C_{rew}) is given by:

$$C_{rew} = C_{mp} + C_{rm} \tag{19}$$

− Motors rewound several times:

The critical efficiency is the efficiency, which will generate an energy over-cost plus the rewinding cost carried out during T_m, which is equal to the 70% of the cost of acquiring (C_{acq}) a new motor, hence the following equations:

$$F \times C_{rew} + C_e = 0.7 \times C_{acq} \tag{20}$$

where F represents the rewind frequency performed during T_m.

$$0.7 \times C_{acq} - F \times C_{rew} = P_u \times \left(\frac{1}{\eta_c} - \frac{1}{\eta_n}\right) \times T_m \times K \times € \tag{21}$$

Thus, the critical efficiency is:

$$\eta_c = \frac{1}{\frac{0.7 \times C_{acq} - F \times C_{rew}}{P_u \times T_m \times K \times €} + \frac{1}{\eta_n}} \tag{22}$$

6. EXPERIMENTAL RESULTS

Three induction motors where use in this experimental, shown in Table 5, are not part of the group of motors for which the numerical model is obtained. To validate, the proposed method, shown in Figure 3, will be applied to test these three induction motors with different ratings: 110 kW, 160 kW, and 300 kW. The efficiency reductions obtained by the application of the proposed algorithm are compared to those obtained from the separate losses method used as a reference, the modified current method and the simple current method [24, 25]. The results are presented in Figure 4.

Table 5. Nameplate information of the motors

No.	U(V)	F(Hz)	P_u(kW)	N_R	cosϕ	I(A)	RPM(r/min)	η_n(%)
1	380/660	50	110	1	0.85	117.5	1480	93
2	380/660	50	160	1	0.88	168	1485	94
3	380/660	50	300	2	0.89	307	1400	95

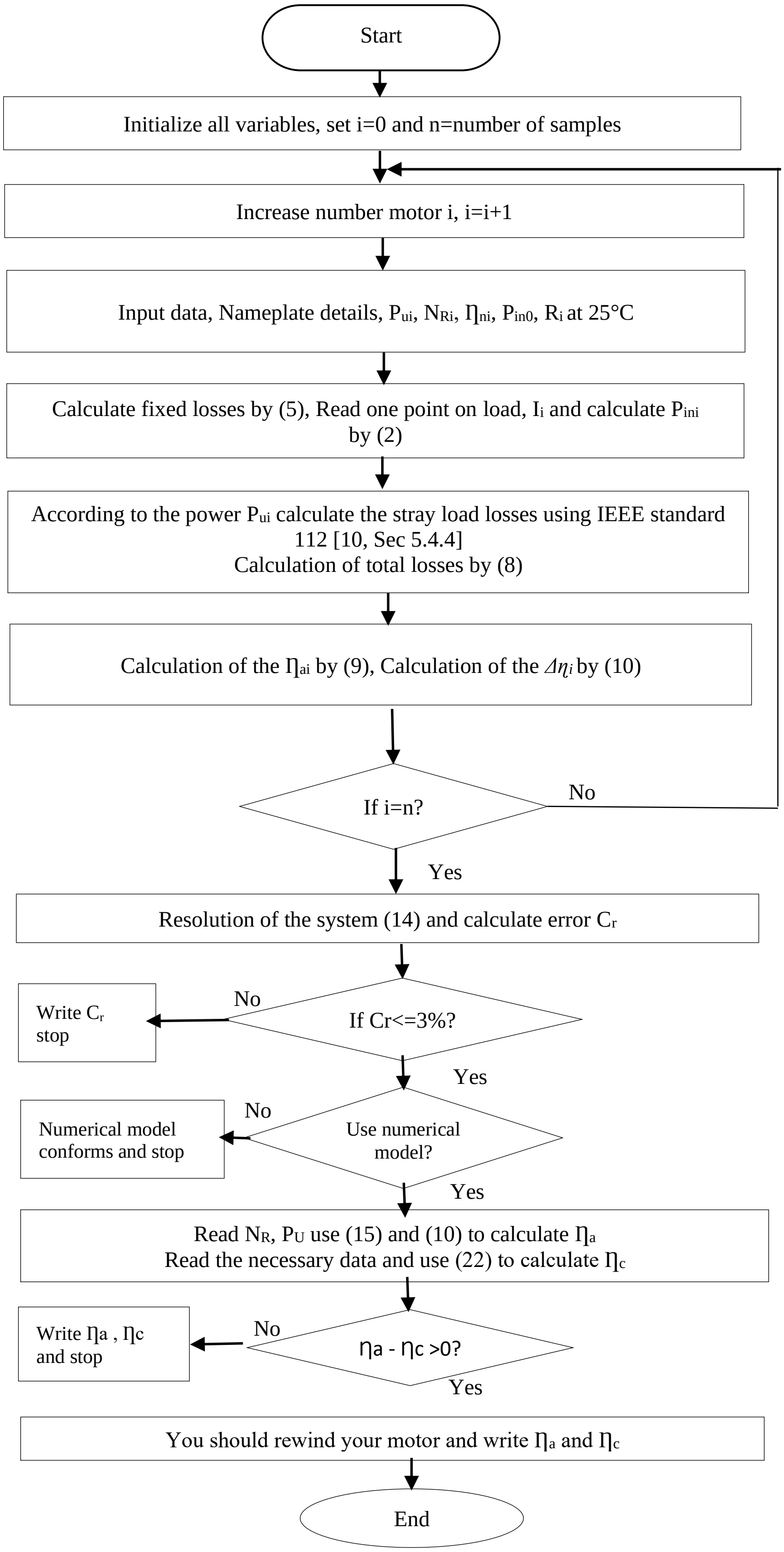

Figure 3. Flowchart of the proposed technique

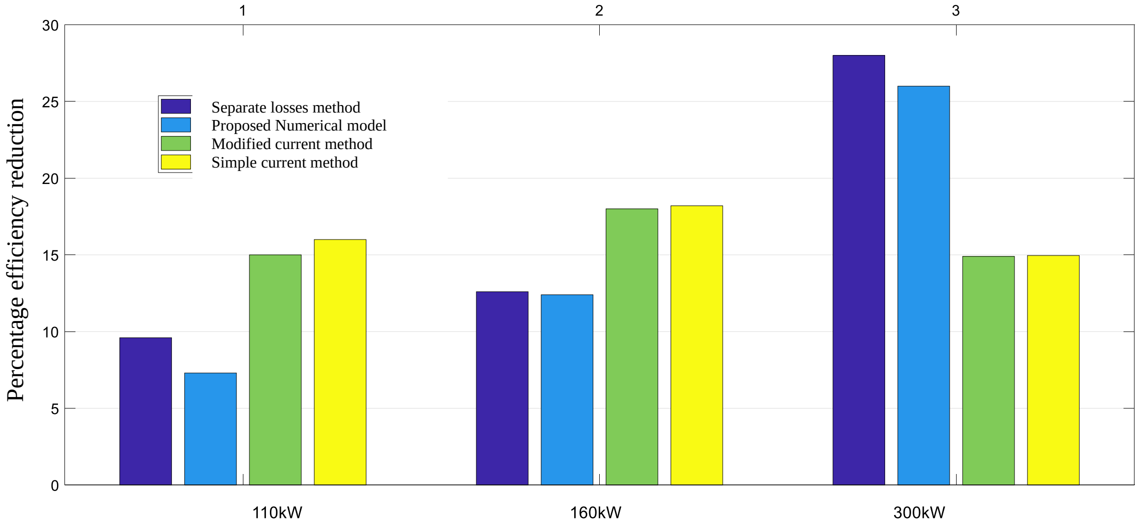

Figure 4. Comparison of experimental results of each motor with the numerical results

7. DISCUSSION

The results provided by separate losses method and numerical model are similar. Predicting the efficiency of the rewound motor by this approach is more accurate than that of the modified current and simple current methods. This numerical model allows us to assess the overconsumption to decide between rewinding or buying a new electrical motor. By analyzing Figure 2, the reduction in efficiency is approximately linear and is aggravated with the power of the motors. Therefore, for powerful motors, a very high efficiency reduction is demonstrated compared to the motors with small powers. Normally, the rewinding of large horsepower motors is economically viable [26]. However, in some countries, repairing electrical motors causes a serious decrease in the efficiency compared to what occurs in other countries. This shows the advantage and the relevance of our approach to estimate efficiency. Hence, there is a need to develop an easy and valid technique that considers the specificity of each country and the level of expertise in terms of rewinding practices and procedures.

The reduction in efficiency varies remarkably according to the power of the motor and the number of rewindings. Therefore, we can use the previous equation to predict the performance of a motor from the same site before rewinding it. This model can also be used to evaluate the losses in the rewound motors for a site that demonstrates the same rewinding practices or the same repairs. Then, application of this model is not restricted to the group of motors for which numerical model was derived. This information will be very useful for evaluating the extra energy cost that will be generated by the reduction in efficiency after each rewinding operation. Sometimes the extra energy cost exceeds the purchase price of a new motor.

Note that the coefficients of this numerical model will change if the refurbishment conditions are changed or the rewinding process is improved, which can be used to audit the repair quality of electrical machines. This is a strong indicator to audit repairers according to their expertise, knowing that the change in rewinding procedures is very long and depends to some extent on the skills of the staff involved. This method is applicable in other industrial sites, and it is only necessary to apply the algorithm mentioned in section 5 with the corresponding numerical model. The relevance of the method depends on the steps chosen, the precision of the numerical calculation, and the inaccuracies related to the operating conditions, namely, the measurement of the resistance's stator at 25°C, the power factor under no-load conditions, the measurement instrument used and whether the copper losses in the rotor are ignored or not. The results reveal that the proposed method can evaluate the efficiency of induction motor with less than 3% error under normal load conditions.

8. CONCLUSION

This paper has presented a new approach for the estimation efficiency of rewound induction motors in situ. For this purpose, the measurements of the no-load test after refurbishment of more than 101 induction motors were used. The relationship between the efficiency reduction and number of rewindings on the one hand and between efficiency reduction and rated power on the other hand are combined to obtain a numerical model. The proposed method was tested by three categories of motors (110 kW, 160 kW, 300 kW) in situ;

the results are compared with the separate losses method, modified current method and simple current method. The experimental results show that the proposed method is more accurate than the modified current method and simple current method.

The advantages of the proposed method are described as follows: the method is a simple procedure that does not require decoupling the motor from its process, is inexpensive, efficient and accurate and uses only the results of no-load tests of the refurbished motors. Note that by using this model, the overconsumption of plants that contain several rewound motors will be estimated accurately. The critical efficiency provides reliable information for the decisions to directly replace induction motors with more efficient motors. Another major contribution of this paper is that this method can be used to satisfy the lack of information recorded in the software tools for the optimization of energy to predict reduction in the efficiency after refurbishment and can be considered as the first indicator of repair quality. The algorithm is designed to be without difficulty and can be applied to any motor rewinding workshop or industrial plant.

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