Comparative Study of Methods to Evaluate Three Phase Induction Motors Loading

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***Abstract*— There are several methods for evaluating the loading condition of three phase induction motors (TPIMs). This evaluation allows inferring about the technical feasibility of replacing the motor in use by another one of less power, contributing to the efficient use of electric energy. The work presented in this document consisted of a comparative evaluation of the Linearization (LM) and Characteristic Curves (CCM) methods; as well as those used by the software BD Motor and MarkIV Plus. The results obtained with the application of the methods were compared with reference values, which were acquired through laboratory tests of the TPIM. In the laboratory tests, a computerized bench consisting of a TPIM and a dynamometer was used. Finally, the methods were compared to each other, leading to the conclusion that the method with the best precision is the CCM, followed by the current method used in MarkIV Plus software. However, the latter uses more accessible information than the required by the CCM.**

***Keywords*— Three phase induction motors; motor load evaluation; comparative analysis; oversized motors.**

I. INTRODUCTION

Electric motors and drive systems are responsible for approximately 46% of all global electricity consumption [1]. They are essential for the operation of an industrial plant, accounting for about 70% of the consumption of electric energy consumed by the Brazilian industrial sector [2].

TPIMs are the most used motors in the industry due to their cost advantages and low maintenance requirements, which are very influential in the costs of setting up and operating a company [3]. Therefore, it can be stated that TPIMs are responsible for consuming a significant portion of the energy produced in Brazil.

Among the various types of existing motors, TPIMs are the ones that best meet the need for energy efficiency and can yield up to 95% [3]. However, there is often oversizing of these motors, which, in terms of energy efficiency, leads to energy waste. The main causes of this oversizing are (i) the expectation of a future load increase, or (ii) the replacement of a damaged motor with a larger power one, due to the lack of a suitable motor at the time of the change. The latter usually performed with urgency, as the company cannot stop its production [4]. The significant use by the industry, added to the fact that they are often oversized, result in a strong contribution of these motors to the waste of electric energy [5].

The global economy has faced a crisis and markets have become more competitive. This situation affects the industry, inducing companies to seek to minimize their operating costs, which electricity consumption generally contributes significantly [6]. Such scenario leads companies to invest in actions to optimize the energy efficiency, which consist of reducing the waste of energy used to perform a certain activity, without impairing its quality [7].

The analysis of the loading condition of a TPIM is essential to determine if there is any technical and economic possibility of action to reduce the costs with electric energy. For this, several techniques are widely used. The objective of the present work is to make a comparative evaluation of these techniques, specifically for motors with a squirrel cage rotor, in order to establish the margin of error that exists between them. Thus, to conclude with a procedure that is more suitable for a more reliable evaluation.

II. TPIM BEHAVIOR IN LOADING CONDITION

In order to perform this work, it is important to understand how slip, power factor, efficiency and electric current behave as the mechanical load on the machine shaft changes. The behavior of those parameters is discussed below.

A. Efficiency x loading

The efficiency curve x loading of a TPIM can be seen in Fig. 1, corresponding to curve A. It is observed that the curve initially presents linear characteristic and accentuated growth, reaching an efficiency of approximately 80% for a condition of the load of 30%. When the rated load is between 60% and 100%, the efficiency has stable values with small variations and subsequently decreases to a load conditions above nominal.

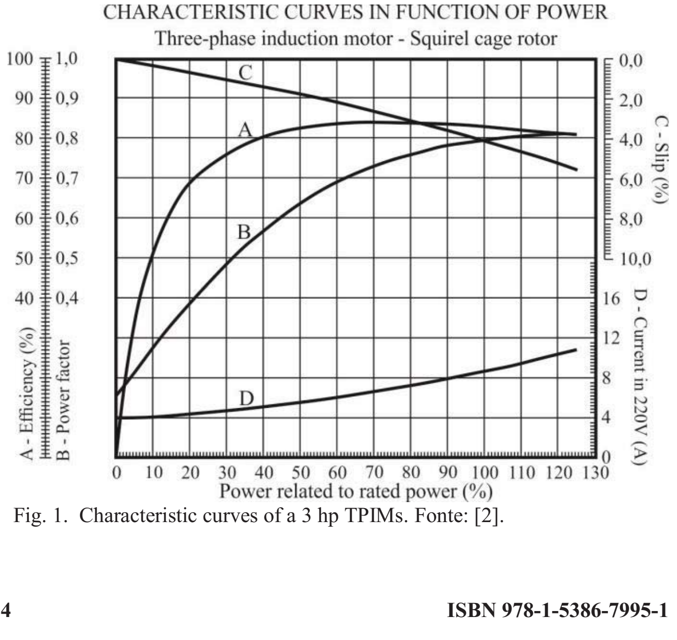

Fig. 1. Characteristic curves of a 3 hp TPIMs. Fonte: [2].

B. Power factor x loading

According to ABNT NBR 5383-1, the power factor x charge curve is obtained by measuring the current, voltage and power for the different charging situations, using Equation 1:

$$cos\varphi = \frac{P}{\sqrt{3}.V.I} \tag{1}$$

Where V is the value of the measured input voltage (V), I is the measured phase current value (A) and P is the measured input power (W).

The curve can be seen in Fig. 1, corresponding to curve B. It is observed that the power factor tends to rise when the load increases, but with a less accentuated growth than the efficiency x load curve. The range in which the power factor is in the best-operating conditions is between 75% and 100% of the nominal load. In this range, the efficiency is also in its most acceptable values, being this the optimal range of operation of a TPIM.

C. Slip x loading

The slip x loading curve can be obtained from the procedures described in ABNT NBR 5383-1, using stroboscopes or digital tachometers. The curve obtained from these procedures can be seen in Fig. 1, corresponding to curve C. It is observed that the slip increases almost linearly as the loading on the machine shaft increases.

D. Current x loading

The current x loading curve is obtained from the current measurement for different loading situations and can be seen in Fig. 1, corresponding to curve D. This curve alone is not a good parameter for loading analysis, because it does not translate the actual loading conditions due to lack of linearity. According to the current curve in Fig. 1, a current equal to 50% of the nominal current does not correspond to a 50% charge but to a charge of approximately 25%.

III. ACTIONS OF ENERGY EFFICIENCY IN TPIMS

According to Chiovatto [8], the four main causes of the inefficient use of an electric motor are oversizing, inadequate repair, use of low-efficiency motors and low-efficiency motor-load coupling.

Oversizing can be considered the main cause of inefficient use of TPIMs. From a sample of 2119 motors in the Brazilian industry, it was estimated that 36% operated with a load less than 50% of nominal [9].

In some cases, it is necessary to oversize the motor in order to meet loads with high inertia or for possible overload situations, but in most cases, a lower power motor can be used [7].

An oversized motor consumes energy higher than the energy consumed by a properly sized motor because it operates with low efficiency and low power factor. In addition, they have a higher initial cost and a shorter service life [7].

The most frequent causes of oversizing are: (i) lack of knowledge of load characteristics, (ii) safety coefficients in the design stage, (iii) anticipation of future load increases, (iv) replacement of a damaged motor with a higher power output when there is a lack of a power spare in the inventory and (v) reduction of production by consumer market retraction [10].

The energy efficiency actions in TPIMs are summarized in the replacement of standard motors by high-performance motors and in the replacement of oversized motors with correct power motors (lower than previous motor power) [4].

In order to propose such actions, it is first necessary to identify whether the motor is in oversizing condition. For this purpose, there are computer methodologies and tools available, among them the BD MOTOR software, the MarkIV Plus software, the Characteristic Curves Method and the Linearization Method.

When an oversized motor is found, a study regarding its replacement is performed. For this, a careful economic analysis is necessary, where its costs and benefits must be analyzed. The first cost to consider is the acquisition cost, which refers to the purchase price of the motor. The second is the operational cost, which is the costs of the motor during its operating time, encompassing both maintenance and the amount of electricity consumed [7].

IV. METHODS AND COMPUTATIONAL TOOLS FOR VIABILITY ANALYSIS OF ELECTRIC MOTORS REPLACEMENT

The most commonly used methods and software for the punctual analysis of three-phase induction motors in Brazil are the following: Characteristic Curves Method, Linearization Method, BD Motor software and MarkIV Plus software. These are presented below.

A. Characteristic Curves Method (CCM)

According to Barros et al. [11], for the application of the characteristic curves method, it is necessary to measure the motor working current and to have its characteristic curves. The procedure is as follows:

1) Measurement of the current (I) of the motor to be analyzed under its normal working conditions.

2) Refer to the motor operating characteristic curve, collecting the power factor (cos φ) and efficiency (η) values for measured current. One can use the motor characteristic curve supplied by the manufacturer.

3) Calculate the active power (P_a) of the motor, using the following expression (2):

$$P_a = U.I.cos\varphi.\sqrt{3} \tag{2}$$

P_a is the active power of the motor [W], U is the operating voltage [V] and I is the current measured in the motor [A].

4) Calculate the useful power of the motor (P_u), in cv, by multiplying the active power and the motor efficiency (η) and dividing the result by the respective conversion factor.

5) Check the motor loading by observing the ratio between the useful power (P_u) and the nominal power (P_n) of the motor.

B. Linearization Method (LM)

The linearization method presented by Santos et al. [12], was developed to determine the monthly losses of a given motor. For its implementation, the following script is adopted:

1) Calculation of the working rotation (n_T)

$$n_T = \frac{(n_S - n_N)}{(I_N - I_o)}(I_N - I_T) + n_N \tag{3}$$

Where n_T is the working rotation [rpm], n_S is the synchronous rotation [rpm], n_N is the nominal rotation [rpm], I_N is the nominal current [A], I_o is the empty current [A] and I_T is the working current [A].

2) Working conjugate calculation (C_T)

$$C_N = \frac{P_N}{n_N} \therefore C_T = \frac{(n_S - n_T)}{(n_S - n_N)} C_n \quad (4)$$

Where C_N is the nominal conjugate [N.m] and C_T is the working conjugate [N.m].

3) Working power calculation (P_T)

$$P_T = C_T . n_T \quad (5)$$

Where P_T is the working power [W].

4) Electrical power calculation (P_{EL})

$$P_{EL} = \frac{P_T}{\eta_T} \quad (6)$$

Where P_{EL} is the electrical power.

5) Motor working efficiency calculation (η_T)

$$\eta T = \frac{-B \pm \sqrt{B^2 - 4AP}}{2A} \quad (7)$$

The parameters A, B and P can be calculated by Equations 8, 9 and 10, respectively:

$$A = \frac{0.50\eta(75) - 0.72\eta(50)}{\eta(50)\eta(75)[\eta(50) - \eta(75)]} \quad (8)$$

$$B = \frac{0.75 - A[\eta(75)]^2}{\eta(75)} \quad (9)$$

$$P = \frac{P_T}{P_N} \quad (10)$$

Where $\eta(75)$ is the efficiency at 75% of load and $\eta(50)$ is the efficiency at 50% of the load.

6) The calculation of the apparent and reactive electrical powers should be done by using the following expressions.

a) Apparent power (S)

$$S = E_T I_T \sqrt{3} \quad (11)$$

b) Working power factor ($cos\phi t$)

$$cos\phi t = \frac{P_{EL}}{S} \quad (12)$$

c) Reactive power (Q)

$$Q = Ssen\phi t \quad (13)$$

7) Loss calculation (P_d)

$$P_d = P_{DEL} - P_T \quad (14)$$

Where P_{DEL} are the electrical losses.

8) Losses per month (P_M)

$$P_M = P.hour.day \quad (15)$$

Where P_M are the losses per month [Wh] and P is the P parameter calculated previously.

C. BD MOTOR software

The BD Motor simulation program was developed by CEPEL - Eletrobras Electrical Energy Research Center for PROCEL – National Energy Conservation Program (Programa Nacional de Conservação de Energia) and assists the users to evaluate the feasibility of acquiring, replacing or repairing three-phase induction motors.

The software has a database with information of 2,640 registered motors of the manufacturers Kohlbach, WEG, EBERLE, and Metalcorte which power waves from 0.25 to 250 hp. For each motor, the database stores various parameters, such as rotation, efficiency, power factor, rated current, among others. The software also makes it possible to register new motors.

D. MarkIV Plus software method

MarkIV Plus software was developed by researchers from the Federal University of Itajubá (UNIFEI), PROCEL and Eletrobrás. It is a tool for the diagnosis and energy management of electrical installations and has several analysis modules, such as the Switchbox module, Cooling module, Transformers module, and even a module for Motors only, which will be the focus of this work.

The motor module of the program is divided into the following steps: Plate Data, Efficiency Curve x Load, Power Factor Curve x Load, Location and Conservation and Transmission, Operation, Load Characteristics, and Measurements.

Mark IV does not have a database of motors like BD Motor, so the user needs to provide data for the program.

V. COMPARATIVE STUDY OF METHODS FOR TPIM LOADING ANALYSIS

A. Preliminary conditions

The experiments were performed at the Electric Machines Drives Laboratory of the Amazonian Energy Development Center - CDEAM of the Federal University of Amazonas. The bench used in the experiments can be seen in Fig. 2. This is equipped with a dynamometer, consisting of a TPIM of 5 cv, responsible for imposing load to the TPIM on test, this one with nominal power of 3 cv.

Fig. 2. Bench used in the experiments.

The 3 cv motor and dynamometer specifications can be seen in Table I, respectively. All benches of this laboratory are powered and monitored through an automation system installed on a computer. Using the automation system, it is possible to adjust the rotation values of both dynamometer motor and the motor on test and adjust the torque limit that the dynamometer will make on the motor on test. The measurements of the time the bench is being tested and the temperature values in each of the motor phases are also performed.

TABLE I. RATED VALUES OF STANDARD 3 CV MOTOR AND DYNAMOMETER MOTOR.

Motor		**Dynamometer**	
Power (CV)	3	**Power (CV)**	5
Voltage (V)	220/380	**Voltage (V)**	220/380
Current (A)	8.7/5.04	**Current (A)**	14.0/8.11
Efficiency (%)	83	**Efficiency (%)**	85.5
Frequency (Hz)	7,13	**Frequency (Hz)**	60
Power factor	0.80	**Power factor**	0.81
Rotation (rpm)	1725	**Rotation**	1715

B. Methodological procedure

Experiments were performed aiming to obtain the necessary data for the application of the methods. These experiments consisted in imposing different loading conditions on the motor, which is possible by adjusting the torque limiting the dynamometer motor exerts on the test motor shaft and doing the measurements of the desired parameters for each loading condition.

The parameters requested by the computational tools, and therefore measured in these experiments, are line current, line voltage, active input power and rotation in the motor shaft.

The first stage of the experiment consisted in starting the motor under test without load, that is, in the 0% loading condition. After a wait of approximately 2 minutes for the rotation to enter equilibrium condition, the required parameters were measured.

The second step consisted in starting the motor of the dynamometer so that it imposes the pre-defined load on the shaft of the motor under test. After approximately 2 minutes, the parameters were measured. Then the above procedure was repeated until TPIM reached the loading condition of approximately 100%.

To measure the values of current, voltage and input power, a Minipa ET-4080 wattmeter was used. The machine shaft rotation measurement was performed using the Testo 470 tachometer.

C. Results

1) Methods application

The procedure of applying the methods consisted of performing the evaluation of the steps proposed by each method, using as input parameters the data obtained by experiments. The applications of the methods were performed for loads equal to 30%, 50%, 60%, 70% and 80%, in order to cover the conditions of oversizing and good sizing. The parameters corresponding to these loads were obtained by means of interpolation of the characteristic curves obtained by experiments.

For the different loads, the values of the parameters obtained by means of interpolation of the collected data are shown in Table II. These parameters were used as a reference to evaluate the accuracy of the load analysis methods.

TABLE II. PARAMETER VALUES USED AS REFERENCCE.

Loading (%)	***Current (A)***	***PF***	***Power (kW)***	***Rotation (rpm)***	***Voltage (V)***
30,00	6,07	0,67	1,57	1.763,45	222,3
50,00	6,67	0,73	1,90	1.755,98	221,6
60,00	6,90	0,75	2,03	1.752,51	221,8
70,00	7,13	0,77	2,15	1.749,43	221,3
80,00	7,41	0,79	2,26	1.747,88	221,3

2) Methods analysis

a) Characteristic Curves Method (CCM)

The results of the CCM loading are shown in Table III. The CCM presents low error for all loading conditions, as can be seen in Fig. 3. The largest errors occur for smaller loads, reaching approximately 2% and then decreases. The explanation for this behavior is the fact that the CCM equations have been developed for situations in which the motor is near to the nominal condition, where the characteristic curves are considered linear. Therefore, in the operating condition where the curves are not linear, the method tends to have larger errors.

It should be noted that, even in the worst error condition, this is low enough so that no misunderstanding is made at the conclusion of the motor loading condition (oversized or good sized), which could happen if the method in question yields results very different from the real ones.

TABLE III. CCM, LM, BD MOTOR AND MARKIV PLUS LOADING RESULTS.

Real loading (%)	**CCM (%)**	**LM (%)**	**BD MOTOR (%)**			**MarkIV Plus (%)**	
			Current	Power	Rotation	Current	Rotation
30	30,68	49,82	56,8	56,99	49,82	33	49,67
50	50,22	59,75	67,7	70,13	59,75	48,67	59,67
60	59,86	64,32	71,71	75,29	64,33	54,67	64,33
70	69,53	63,38	75,62	80,05	68,38	60,67	68,33
80	80,03	70,41	80,26	84,4	70,42	67,67	70,33

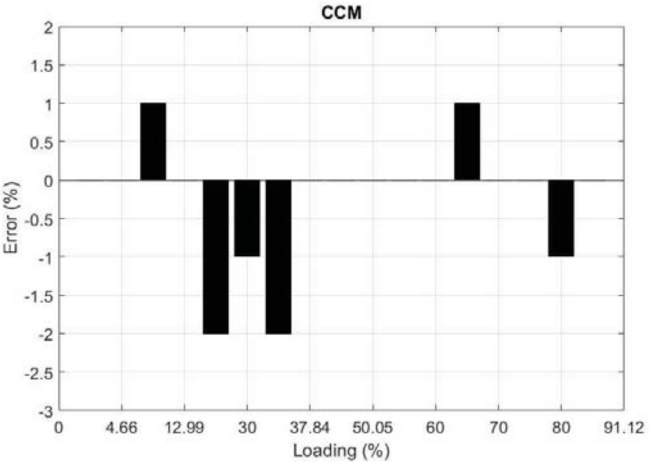

Fig. 3. CCM errors x loadings.

a) Linearization method (LM)

The results of the LM loading and error are shown in Table III. The LM at first presents a high error. Later this error tends to fall, and then rise again. As in the CCM method, this behavior is due to the fact that the equations have been deduced for conditions close to the nominal ones, where the curves are approximately linear. The further away from the condition where the curves are linear, greater error are expected by the method. Such behavior can be seen in Fig. 4.

Despite the high error for some loads, the method does not lead to a mistaken conclusion of the motor loading condition, at least in this case. In cases of oversizing, even if the method has resulted in a loading greater than the actual load, it still fits in oversizing condition.

The advantage presented by this method is that it requires only current or rotation measurement and motor datasheet data, i.e. it only requires the measurement of a single parameter, requiring only one measuring instrument. It is worth mentioning that, for very old motors, sometimes the datasheet is not available.

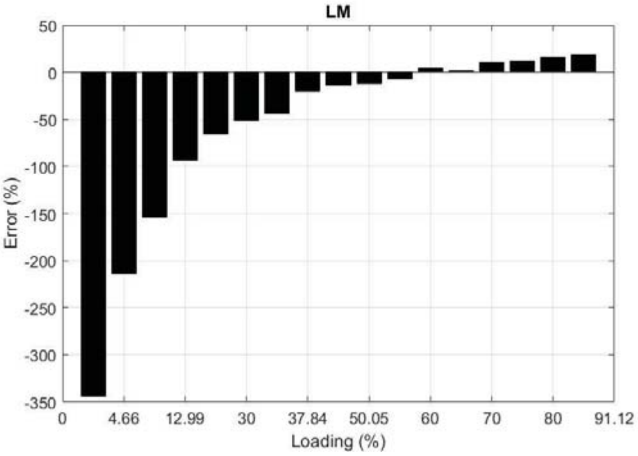

Fig. 4. LM errors x loading.

b) BD Motor

The results of the BD Motor software for the current measurement, input power, and rotation measurement options are shown in Table III.

As in previous methods, the BD Motor presents minor errors for conditions close to the range where the characteristic curves are linear. The behavior of the errors for the current, power and rotation evaluation option are shown in Fig. 5.

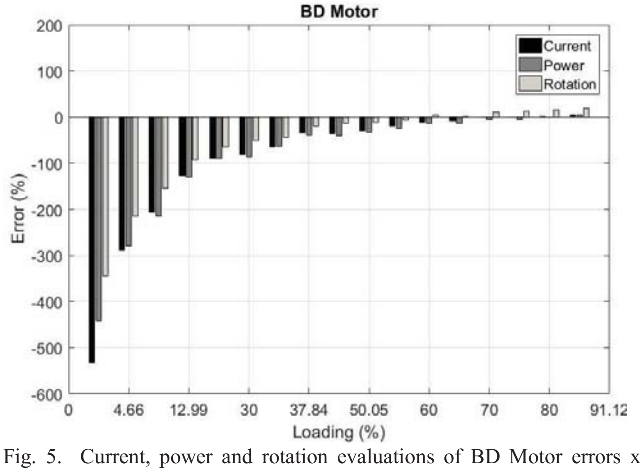

Fig. 5. Current, power and rotation evaluations of BD Motor errors x loading.

In some cases, the current rating may lead to a misunderstanding in the conclusion of the motor loading condition. For a real load of 60%, considered oversized, after a careful economic analysis, it could be concluded that the best alternative would be to make the replacement of the motor by a lower power motor. If the current evaluation were used, it would result in a loading equal to 71.71%, as can be seen in Table II, and it is considered well dimensioned. The same occurs in the most severe power evaluation. For a true load equal to 50%, the power rating results in a load equal to 70.13%.

The advantage of this software it needs only one input parameter, requiring only one measurement and thus requiring a single measuring instrument. In addition, the software has a database with 2640 motors, and in many cases, there is no need to have the datasheet or catalog data. Once the motor is found in the database, it simply includes the chosen measurement parameter. It happens that, sometimes, the motor that is intended to evaluate does not exist in the database. In this case, it is necessary to use motor data closer to what will be evaluated which increases the error.

c) MarkIV Plus

The load and error results from the MarkIV Plus software for the current and rotation measurement options are shown in the Table III. As in the methods presented earlier, the MarkIV Plus presents minor errors for conditions close to the range where the characteristic curves are linear. The behavior of the errors for the current and rotation evaluation are shown in Fig. 6.

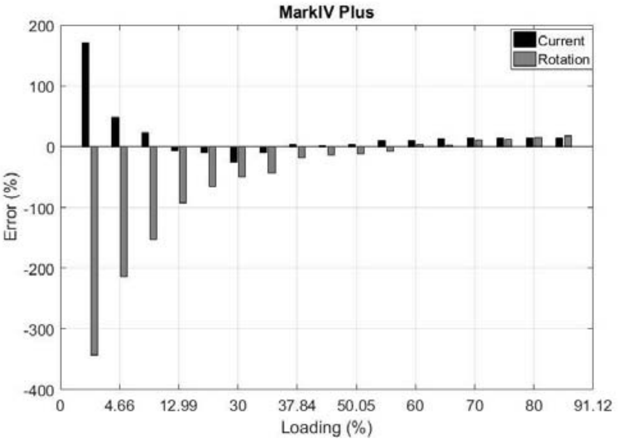

Fig. 6. Current and rotation evaluations of MarkIV Plus errors x loading.

Although in some cases it presents relatively high errors, in none of the evaluation options the MarkIV Plus leads to misunderstandings in the conclusion of the motor sizing condition. The advantage of this software is the need for a single measurement parameter. However, it requires the provision of all datasheet data and some catalog data.

D. Comparative study of applied methods

First, a comparative study was performed between the evaluation options of the methods that have more than one possibility to evaluate the loading. Then, a comparative study was performed between all methods, where those with more than one evaluation parameter will be represented by the option with the best performance in the first study.

1) BD Motor

The errors for the evaluation options of the BD Motor are shown in Fig. 5, where it can be observed how the power evaluation has errors very close to those observed in the current evaluation. However, close to the nominal load, the current evaluation has a smaller error. In turn, the rotation evaluation presents the smallest error for smaller loads. However, when close to the nominal load, the error becomes greater. For some cases studied, the current and power ratings lead to a mistaken conclusion of the motor loading condition, as previously mentioned.

From this analysis, it is concluded that the rotation evaluation is the most adequate. Although in some cases it presents a greater error than the other methods, it does not lead to a mistake in the conclusion of the loading motors condition.

2) *MarkIV Plus*

The errors for the MarkIV Plus evaluation options are shown in Fig. 6, where it can be seen how the current evaluation has initially positive errors and the rotation evaluation has initially negative errors. For smaller real loads, the current evaluation presents errors closer to 0%, but, close to the nominal conditions, the rotation evaluation presents errors closer to 0%.

Considering that near the nominal loading conditions the motors are well sized and there is no energy efficiency action to be taken in this sense, added to the fact that none of the evaluation options lead to a mistaken conclusion of the motor sizing condition, it is estimated that the current rating has the best performance. Since it presents minor errors for low loads and the energy efficiency actions aim to replace motors that are running under low loads.

3) *All the methods*

The errors of the CCM, LM, BD Motor by rotation and the MarkIV Plus by current are shown in the Fig. 7.

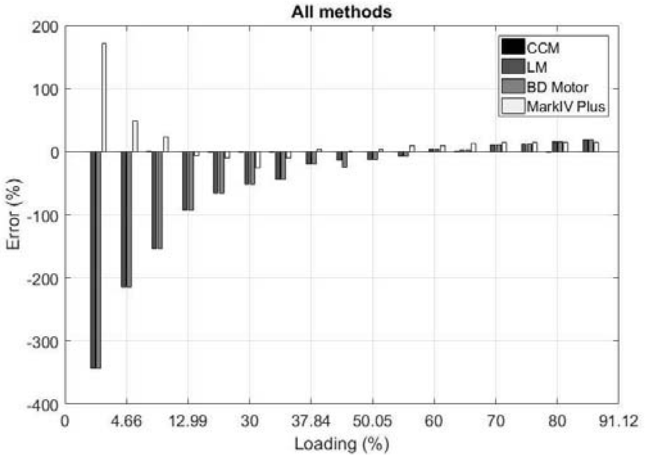

Fig. 7. CCM, LM, BD Motor by rotation and MarkIV Plus by current errors x loading.

At the beginning of the analysis, it is verified that the LM error curve is equal to the MarkIV Plus curve. This occurs because the rotation evaluation of BD MOTOR uses the same equations of the LM. The method which presented an error closest to 0% is the CCM, although this method needs the measurement of two parameters, while the others only need the measurement of one parameter. In addition, this method needs two characteristic curves, which are the efficiency and the power factor curves. Those curves are not always available, and to obtain them from the manufacturers is sometimes difficult.

After the CCM, the next method which error was closest to 0% is the MarkIV Plus by current. This method requires only one parameter of measurement, although it needs the plate data and some catalogue data, therefore the process of obtaining those data from the manufacturer might present some difficulties.

Subsequently, the next methods are LM and BD MOTOR. LM need only a few plate data and one parameter of measurement. Similar to the LM, the BD MOTOR needs only one parameter of measurement, and additionally it has a database with 2640 motors, which would only be necessary to identify the desired motor in the database.

From this analysis, it is necessary to study the development of a method that maintains a balance between error and input parameters. A method that requires the measurement of many parameters is not feasible due to the difficulty to perform field measurements, either because of the lack of adequate instrumentation or due the difficult access of certain parts of the motors. As mentioned previously, there are difficulties in obtaining the characteristic curves of the motor, therefore, the methods that require this information are also impracticable in many cases.

In this work, the application of CCM was only possible after obtaining the characteristic curves of the motor. Such action is inadmissible in the field, since it requires the motor to be turned off and, in a company, it generates great losses in the production.

VI. CONCLUSÃO

For the purpose of this work, the TPIM test was performed, in order to raise the necessary characteristic curves, which in theory should be provided by the manufacturers. However, even for the study case, these curves were not informed by the manufacturers because they are no longer being produced.

The method that showed to be more precise was the CCM, although it is one of the least practical as it requires the measurement of more than one parameter, also, it needs the information of the characteristic curves of the motor, which is difficult to obtain. The method used in the MarkIV Plus software by current presented the second lowest error. The latter being simpler as it requires only the measured current and a few plate and catalogue information.

An advantage of the methods is the fact that the percentage of the load on the motor shaft was made available without the use of the characteristic curves, except for the CCM.

After analyzing the methods, it was verified the need to develop a new method capable of maintaining the balance between accuracy and simplicity of application, since the most accurate methods available need information that are sometimes inaccessible.

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