Estimating Induction Motor Efficiency under No-controlled Conditions in the Presences of Unbalanced and Harmonics Voltages

Vladimir Sousa, *Member IEEE*, Percy R. Viego, Julio R. Gómez, Enrique C. Quispe, *Senior Member, IEEE* and Milén Balbis, *Member IEEE*

Abstract-- This paper presents the application of a method to determine the output power, losses, and efficiency of induction motors, working in no-controlled conditions, in the presences of unbalanced and harmonics voltages. The method uses the steady state equivalent circuits, with some considerations for the analysis of motor performance, fed with unbalanced and harmonic voltages. The parameters of circuits are determined with low invasiveness, by applying a Bacterial Foraging Algorithm as technique of evolutionary search. With this, the efficiency and other operational parameters can be estimated at any operating point. The method was tested in a 12.6 kW motor working in an industrial network, with harmonics and voltage unbalanced.

Index Terms-- Equivalent circuits, energy management, harmonic analysis, induction motors, industrial power systems, power quality, parameter estimation, unbalanced voltage.

I. INTRODUCTION

IN INDUSTRIAL power supplies is common to find problems of power quality. Among these, the flow of harmonics and unbalanced voltages are frequent. The existence of harmonics is due to the presence of nonlinear devices such as rectifiers, arc furnaces, adjustable-speed drives, etc. The presence of unbalanced is due mainly to the existence of significant amount of single-phase loads. These problems significantly affect the efficiency and other operational characteristics of the induction motors.

Three-phase induction motors are widely used in industrial and commercial systems, because of their ruggedness, simplicity and relatively low cost. Approximately 68% of the electricity consumed worldwide in the industrial sector and 46% of global electricity consumption is used to drive electrical motors. Therefore, efficiency and reliability of induction motors operation are important goals to improve the industry energy efficiency and to reduce both the energy consumption as well as the production costs [1].

In the presence of harmonics with unbalanced, is particularly important to quantify the effect of these phenomena on the motor performance. This allows calculation of the derating power required and justify the need of load balancing and attenuating harmonics with filters.

The IEEE Std-112-2004 [2] and IEC Std-60034-2-1-2014 [3] standards are not applicable for in-situ efficiency measurement, due to their highly intrusive nature or special requirements such as rated voltages and frequencies or specific devices, for instances, variable power supply. For these reasons, there are different methods for the in-situ efficiency estimation of induction motors. The most commonly used of methods under field conditions are slip and current methods, but are not suitable for any precise efficiency assessment [4].

There are several computerized methods and techniques such as: ORMEL 96, MotorMaster, Ontario Hydro, testers MAS-1000, Motor-Check, the Vectron Motor Monitor, and Motor Efficiency Wizard. These have been used on a large scale; however, neither considers the effect of unbalanced with harmonic distortion on motor efficiency [4].

The air gap torque method [5] considers harmonic distortion and unbalanced voltage because it uses the instantaneous values of currents and voltages to calculate the air gap torque. However, the accuracy of this method is significantly degraded mainly, due to the assumption of a fixed value for the core, windage, and friction losses [4].

The solution of equivalent circuit model of an induction motor for in situ estimation of efficiency, has been widely used [4], [6-14]. For these cases, the parameters of the equivalent circuit are estimated with the help of a search algorithm applying optimization-based techniques. With the equivalent circuit parameters, the losses, the efficiency and output power can be calculated for each operating point.

Among the most commonly used heuristic techniques, the genetic algorithm (GA) has been successfully employed to estimate parameters and, consequently, the efficiency of an induction machine in-situ [4], [6]-[7]. However, they do not consider appropriately the operation of the motor working in the presence of unbalanced and harmonics voltages simultaneously.

Vladimir Sousa and Milén Balbis, are with GIOPEN of the Electrical Engineering program in Faculty of Engineering of Universidad de la Costa, Calle 58 No.55-66, Barranquilla, Colombia (e-mail: vsousa1@cuc.edu.co, mbalbis1@cuc.edu.co).

Percy R. Viego and Julio R. Gómez are with the Center of Energy and Environmental Studies of the Faculty of Engineering of Universidad de Cienfuegos, Cuatro Caminos, Cienfuegos, Cuba (e-mail: pviego@ucf.edu.cu, jgomez@ucf.edu.cu).

Enrique C. Quispe is with the Energy Research Group GIEN, Energy and Mechanical Department of Universidad Autónoma de Occidente, Calle 25 No.115-85, Cali, Colombia (e-mail: ecquispe@uao.edu.co).

978-1-4673-8756-9/15/$31.00 ©2015 IEEE

In [6] a GA for balanced voltage conditions is used, while in [4], motor efficiency under unbalanced conditions, without harmonics, is analyzed. In [7] motor efficiency is analyzed in presence of harmonics, without considering voltage unbalanced.

Other studies use the particle swarm optimization technique [8], and artificial neural networks for determining motor parameters [9]. These papers do not consider the motor model working in the presence of harmonics and unbalanced voltages.

Bacterial foraging algorithm (BFA), proposed in [10], is another evolutionary algorithm, used for the solution of equivalent circuits of induction motors [11]-[13].

In [11] only the positive sequence circuit is considered, limiting its use to those cases in which the voltage is balanced; while in [12], the negative and positive sequence circuits of the fundamental component are considered, allowing analyzing unbalanced motors, but without harmonics.

In [13] a BFA is used for the parameters identification of harmonics equivalent circuits, and to determine efficiency of induction motors working under non-sinusoidal voltage conditions, but without considering unbalanced. In [14], equivalent circuit model that allows analysis of motor operation in the presence of harmonics and unbalanced is used. However, the study was conducted in laboratory conditions, without analyzing behaviors of industrial supply networks, such as, non-nominal voltages, harmonic variation, among others.

The contribution of this work, is the application of BFA, for the parameters and efficiency estimation of induction motors, working under non-controlled conditions, with non-nominal voltages, unbalanced voltages and harmonic variables in time.

The application of the method requires the nameplate data, as well as measurements of voltages and line currents, input power, stator resistance and rotor speed. The method was evaluated on a 12.6 kW motor.

This work is organized as follows. In Section II, the problem statement is discussed. In Section III and IV, the method is described in detail. In Section V, the proposed method is applied in a 12.6 kW induction motor in non-controlled conditions, and the results are discussed based on comparison between estimation and measurements of efficiency.

II. PROBLEM STATEMENT

Voltage unbalanced is defined as the difference in magnitude, phase, or both, of line voltages. Unbalanced power supply creates significant unbalanced currents in a machine and produce positive and negative sequence flux components. These fluxes act against each other, and reduce the net torque [4].

Moreover, harmonics are sinusoidal voltages or currents with frequencies that are integer multiples of the fundamental electrical system frequency [15]. These are classified as positive sequence harmonics: $kp = (3n+1)$; negative sequence harmonics: $kn = (3n+2)$ and zero sequence harmonics: $kz = 3n$, being $n = 0, 1, 2,\ldots,$. In induction motors, positive sequence harmonics contribute to torque in the positive (forward) direction, and negative sequence harmonics provide torque in the negative (backward) direction [15]. The circulation of zero-sequence currents harmonics is null because the induction motor is usually Delta or isolated Wye connected [16].

The interaction of the voltages and currents unbalanced and distorted produce in the motor shaft, torque pulsation at frequency multiples of the fundamental frequency [17].

The harmonic studies on unbalanced three-phase systems can be developed using sequence or phase components. In sequence components, the positive and negative sequence equivalent circuits of the induction motor are required for each harmonic [16]. In this context, positive sequence is the natural sequence of each harmonic, and negative sequence, is the inverse sequence of natural flow direction of each harmonic.

Based on this, the proposed method for assessing energy performance of induction motors working in-situ, in the presence of unbalanced voltage and harmonic distortions, consists in determining the parameters of the equivalent circuits shown in Fig. 1. With the equivalent circuits of each sequence of harmonics, can be analyzed the effects caused by harmonics and unbalanced on the motor losses.

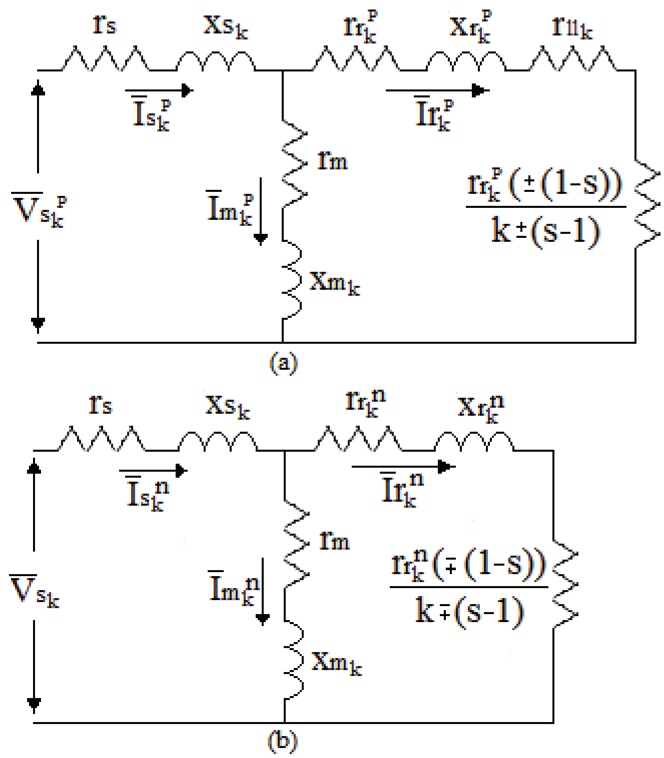

Fig.1. Equivalent circuits of an induction motor fed with harmonics and unbalanced voltage. (a) Positive sequence of each harmonic. (b) Negative sequence of each harmonic.

In Fig 1:

k: harmonic order (p.u), r_s: stator resistance (Ω), x_s: stator leakage reactance (Ω), r_{ll} : stray load loss resistance (Ω), r_m : core loss resistance (Ω), x_m: magnetizing reactance (Ω), r_r: rotor resistance (Ω), x_r: rotor leakage reactance (Ω), s: slip (p.u), I_m: magnetizing current (A), V_s: stator phase voltage (V), I_s: stator phase current (A), I_r: rotor phase current (A).

Subscript k in variables indicates that the equivalent circuit considers the fundamental component and harmonics. Superscript p indicates positive sequence of each harmonic, and n indicates negative sequence of each harmonic.

The upper circuit corresponds with positive sequence of each harmonic, including the fundamental component. In the variable resistance with slip, the upper sign (+) is used for positive sequence harmonics (3n+1), including the fundamental component; and the lower sign (-), is used for negative sequence harmonics (3n+2).

The lower equivalent circuit corresponds to the negative sequence of each harmonic, including the fundamental component. Therefore the signs of the variable resistor with slip, are contrary to upper circuit.

This model is general, and can be used to study the motor performance fed with non-nominal voltages, balanced voltages, unbalanced voltages, in the presence of harmonics, or with a combination of these.

The motor efficiency can be determined as follows:

$$\eta = \frac{P_{out}}{P_{in}} \cdot 100 = \left(\frac{P_{dev} - P_{fw}}{P_{in}} \right) \cdot 100 \quad (\%) \qquad (1)$$

where:

η: motor efficiency (%), P_{out}: output power (W), P_{in}: input active power (W), P_{fw}: friction and windage losses (W), P_{dev} : developed power (W).

The value of P_{in} can be measured with a low intrusive level using an adequate electrical instrument, such as a power analyzer. In the presence of unbalanced and harmonics voltage supplies, developed power is the sum of positive and negative sequences of each harmonic. This value can be calculated at each operating point from the equivalent circuit as:

$$P_{dev} = P_{dev,kp}{}^{p} + P_{dev,kn}{}^{p} + P_{dev,kp}{}^{n} + P_{dev,kn}{}^{n} \quad (W) \qquad (2)$$

$$P_{dev} = 3 \cdot \left(\begin{array}{l} \left[I^2_{r,kp}{}^{p} \right] \cdot \left[r_{r,kp}{}^{p} \cdot \left(\dfrac{(1\text{-}s)}{kp+(s\text{-}1)} \right) \right] + \\ + \left[I^2_{r,kn}{}^{p} \right] \cdot \left[r_{r,kn}{}^{p} \cdot \left(\dfrac{(s\text{-}1)}{kn\text{-}(s\text{-}1)} \right) \right] + \\ \left[I^2_{r,kp}{}^{n} \right] \cdot \left[r_{r,kp}{}^{n} \cdot \left(\dfrac{(s\text{-}1)}{kp\text{-}(s\text{-}1)} \right) \right] + \\ \left[I^2_{r,kn}{}^{n} \right] \cdot \left[r_{r,kn}{}^{n} \cdot \left(\dfrac{(1\text{-}s)}{kn+(s\text{-}1)} \right) \right] \end{array} \right) \quad (W) \qquad (3)$$

III. METHOD DESCRIPTION

The method use two consecutively BFA programmed in Matlab. With the first BFA, the parameters (x_s, x_m, r_m and r_r) of the positive sequence of the fundamental component are determined. With the second BFA, the parameters (r_r and x_r) of the negative sequence of the fundamental component and of the positive and negative sequence for each harmonic are determined. After obtaining the circuit parameters, losses, output power and efficiency are calculated.

The objective function of BFA 1 is (4).

$$MinJ = \left| \frac{Pin_{fund,est}}{Pin_{fund,cal}} - 1 \right|^2 + \left| \frac{\bar{I}s_{fund,est}}{\bar{I}s_{fund,cal}} - 1 \right|^2 \qquad (4)$$

where MinJ is the objective function of BFA 1, subscript est: estimated values obtained from the equivalent circuit parameters, cal: calculated values from the measurements, fund: fundamental component.

The objective function of BFA 2 is (5), where, MinK is the objective function of BFA 2, Z: motor impedance (Ω).

$$MinK = \left| \frac{\bar{Z}_{fund,est}{}^{n}}{\bar{Z}_{fund,cal}{}^{n}} - 1 \right|^2 + \left| \frac{\left[\bar{Z}_{k_p,est}{}^{p} \right]}{\left[\bar{Z}_{k_p,cal}{}^{p} \right]} - 1 \right|^2 + \qquad (5)$$

$$\left| \frac{\left[\bar{Z}_{k_p,est}{}^{n} \right]}{\left[\bar{Z}_{k_p,cal}{}^{n} \right]} - 1 \right|^2 + \left| \frac{\left[\bar{Z}_{k_n,est}{}^{p} \right]}{\left[\bar{Z}_{k_n,cal}{}^{p} \right]} - 1 \right|^2 + \left| \frac{\left[\bar{Z}_{k_n,est}{}^{n} \right]}{\left[\bar{Z}_{k_n,cal}{}^{n} \right]} - 1 \right|^2$$

The parameters are determined by using collected considerations of classical literature and scientific articles. It allow that during stochastic search for obtaining the global minimum of (4) and (5), the parameters are within reasonable values, and facilitate the search for the best solution in the output power and efficiency.

These considerations are:

- The parameters of the stator and magnetization branches, are considered constant for positive and negative sequences for each harmonic, including the fundamental component [18].
- Stator resistance (r_s) is measured directly and corrected to operating temperature, according to temperature class using the IEEE Std-112-2004 [2] standard.
- Stator leakage reactance (x_s) for the fundamental component (x_{sfund}) is considered between (7-15) percent of the motor base impedance [19]:

  The motor base impedance is calculated as:

  $$Z_b = \frac{V_n}{\sqrt{3} \cdot I_n} \quad (\Omega) \qquad (6)$$

  where:

  V_n: nominal motor voltage (V), I_n: nominal motor current (A).
- For each harmonic, the stator reactance (x_{sk}) is directly proportional to frequency [18]:

  $$x_{sk} = k \cdot x_{sfund} \quad (\Omega) \qquad (7)$$
- Rotor leakage reactance of the fundamental component (x_{rfund}) relates to the stator reactance of the fundamental component (x_{sfund}) through the factor k_{re}, according to NEMA design class machine (using the IEEE Std-112-2004 [2] standard):

  $$x_{rfund} = k_{re} \cdot x_{sfund} \quad (\Omega) \qquad (8)$$

  where: k_{re}= 1 for design A and D, k_{re}= 0.67 for design B, and k_{re} = 0.43 for design C.
- Representative resistance of core losses (r_m) is considered

between (10-20) percent of the motor base impedance [19].

- Harmonics magnetizing reactance (x_{mk}) is directly proportional to the frequency [18]:

$$x_{mk} = k \cdot x_{mfund} \quad (\Omega) \qquad (9)$$

- Stray load losses representative resistance of the fundamental component (r_{llfund}) is determined using equation (10) [4]. The value of k_{ll} is obtained from IEEE Std-112-2004 [2] and depends of the size of the machine.

$$r_{llfund} = k_{ll} \cdot \left(\frac{1-s_{nom}}{s_{nom}} \right) \cdot r_{rfund} \quad (\Omega) \qquad (10)$$

- Stray load losses representative resistance of the harmonic components (r_{llk}) is assumed as [18]:

$$r_{llk} = k^{0.8} \cdot r_{llfund} \quad (\Omega) \qquad (11)$$

- Mechanical losses or friction and windage losses are considered as 1.2% of the rated input power [4], [13].

IV. Characterization of Harmonics

Most existing standards on harmonics limits are fixed values. In addition, many works that analyze the effect of harmonics on the motors, consider harmonics with constant values [7], [13]. However, field measurements clearly indicate that voltage and currents harmonics are time-variant due to continual changes in system configuration and operating point [20]. This behavior calls for statistical techniques to quantify harmonic level [21].

In this work, the statistical tools are primarily used to ensure that data of currents and voltages harmonics used to determine the motor efficiency, are within the range of greater frequency.

V. Method Evaluation in Industrial Conditions

The method was applied in a laboratory of testing motors ubicated within an oil refinery industry, in one of the production areas. It does not have an exclusive power supply. The laboratory is composed by a motors testing bank of WEKA MOTORENPRÜFSTÄNDE manufacturer, MT-50 model [22]. This bench allows the output power measurement for various load conditions. The electrical measurements were performed using a power analyzer FLUKE 435. These instruments have an accuracy according to the standards [2], [3]. In Table I the nameplate data of the tested motor are presented.

The motor is fed directly from the grid. This network is characterized by presenting harmonic due to the widespread use of inverter in the refinery. Line voltages are balanced; therefore, the unbalanced was induced by placing a fixed resistor in one of the phases.

Fig. 2 present the scheme of the test setup used for the experiment.

TABLE I
NAMEPLATE DATA OF 12.6 KW INDUCTION MACHINE

Specifications	
Power (kW)	12.6
Efficiency (%)	92
Voltage (V)	460
Current (A)	19.8
Frequency (Hz)	60
Power factor (p.u)	0.87
Poles	2
Speed (rpm)	3540
Connection	Δ
Insulation class	F
NEMA Design	B
Ra at 32.5 °C (Ω)	1.163

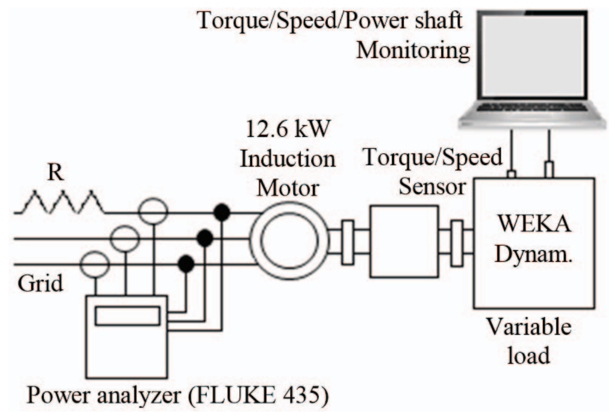

Fig.2. Scheme of the test setup.

Tables II shows measured data for the four operating point analyzed.

TABLE II
MEASURED DATA

OP	1	2	3	4
$Vs_{,fund}^{p}$	454.40	447.00	449.20	434.40
$Is_{,fund}^{p}$	5.92	8.73	9.21	11.25
$Vs_{,fund}^{n}$	11.40	18.80	37.50	30.20
$Is_{,fund}^{n}$	4.90	5.60	5.43	4.40
$Vs_{,5th}^{p}$	17.60	16.14	17.3	16.00
$Is_{,5th}^{p}$	0.24	0.30	0.31	0.39
$Vs_{,5th}^{n}$	5.08	7.88	4.03	6.60
$Is_{,5th}^{n}$	0.059	0.097	0.10	0.19
$Vs_{,7th}^{p}$	5.50	8.37	6.78	6.01
$Is_{,7th}^{p}$	0.12	0.13	0.15	0.20
$Vs_{,7th}^{n}$	0.15	0.55	0.81	1.89
$Is_{,7th}^{n}$	0.056	0.029	0.019	0.038
n	3576.00	3558.00	3555.00	3540.00
f	59.95	60.20	59.61	60.25
P_{in}	6265.00	9855.50	10438.00	12829.00
P_{out}	5600.00	8600.0	9300.00	11100.00
VUF	2,51	4,21	8,35	6,95

In table II, Voltage Unbalance Factor (VUF) is defined by

IEC Std-60034-26-2006 [23], as the ratio of the negative sequence component to the positive sequence component of the fundamental, expressed in percent. As shown, the power supply conditions are different for each operating point due to the changing conditions in the industrial electrical grid. In addition, VUF is higher than 1%. From this value, IEC Std-60034-26-2006 [23] recommends to apply a derating factor to mitigate the heating effects of unbalance.

Fig. 3 shows a sample of measurement of individual voltage distortion corresponding to harmonics of fifth and seventh order, in one of the phases. The rest of the harmonics are negligible. The time interval between readings is 1 second. As seen, the behavior of the harmonics varies greatly.

Individual voltage distortion (IVD) is defined by IEEE Std-519-1993 [24] as:

$$IVD = \frac{V_k}{V_{fund}} \cdot 100 \qquad (\%) \qquad (12)$$

Similarly, individual current distortion (ICD) can be calculated.

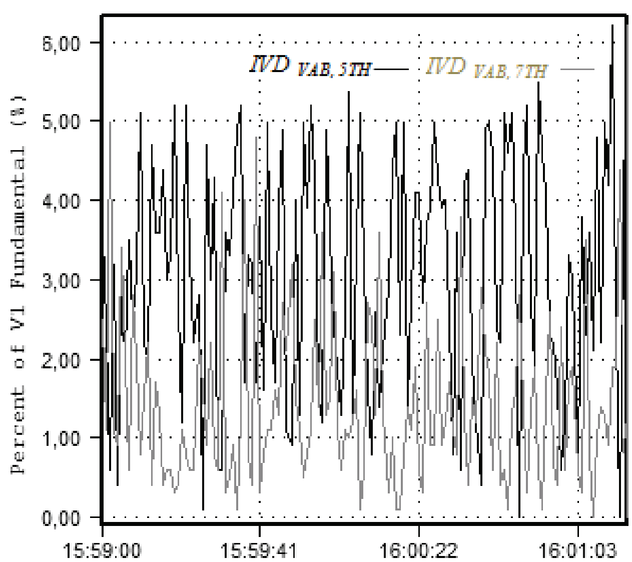

Fig.3. Measurement sample of the individual voltage distortion of 5th and 7th harmonic.

Table III presents the IVD corresponding to the four operating points.

TABLE III
INDIVIDUAL VOLTAGE DISTORTION FOR THE FOUR OPERATING POINTS

OP	1	2	3	4
IVD $_{VAB,5TH}$	4.20	4.30	4.68	4.92
IVD $_{VBC,5TH}$	4.69	4.91	4.01	4.24
IVD $_{VCA,5TH}$	2.90	2.14	3.00	2.24
IVD $_{VAB,7TH}$	1.23	1.96	1.48	1.81
IVD $_{VBC,7TH}$	1.21	1.68	1.36	1.42
IVD $_{VCA,7TH}$	1.22	1.99	1.71	1.02

In Fig. 3 and Table III, is shown that individual voltage distortion values of the fifth harmonic are higher than 3%. This is the established limit by the IEEE Std-519-1993 [24] for individual voltage distortion.

In order to determine the motor efficiency under harmonics and voltage unbalanced in real conditions with varying magnitudes, measurement data that are repeated with more frequency are used. This requires a statistical analysis.

Table IV presents statistical parameters results. Table V summarizes the results from the histograms. The application of the probability distribution function allowed identifying that there is a 72% of probability that IVD$_{5TH}$ is above 3%. Moreover, there is only a 6% of probability that IVD $_{7TH}$ is above 3%.

TABLE IV
STATISTICAL PARAMETERS FOR IVD

X	Xmin	Xmax	Xmean	Xσ_x
IVD $_{VAB,5TH}$	2.00	6.10	3.86	1.08
IVD $_{VBC,5TH}$	0.40	6.40	4.00	1.17
IVD $_{VCA,5TH}$	0.60	6.60	3.54	1.25
IVD $_{VAB,7TH}$	0.10	4.80	1.42	0.90
IVD $_{VBC,7TH}$	0.30	4.40	1.29	0.77
IVD $_{VCA,7TH}$	0.10	5.20	1.20	0.96

TABLE V
HISTOGRAM SUMARIZED RESULTS OF IVD

X	Range	Frequency
IVD $_{VAB.5TH}$	(4-5)	33.2
IVD $_{VBC.5TH}$	(4-5)	31.3
IVD $_{VCA.5TH}$	(2-3)	35.4
IVD $_{VAB.7TH}$	(1-2)	41.8
IVD $_{VBC.7TH}$	(1-2)	46.6
IVD $_{VCA.7TH}$	(1-2)	41.8

Table V shows that measurements data used to determine the efficiency of the motor, presented in Table IV, are within the range of values of highest frequency of occurrence. The same analysis is made for currents.

Once performed the statistical analysis, the software is executed. In this case, the equivalent circuit of the positive and negative sequence of the fundamental component, and both, the fifth and the seventh harmonic, are obtaining. In Table VI, the results of the output power, efficiency and comparison between the estimated and measured results are shown.

TABLE VI
COMPARISON OF MEASURED AND ESTIMATED EFFICIENCIES

OP	1	2	3	4
Output power (measured) (W)	5600	8600	9300	11100
Output power (estimated) (W)	5531	8723	9415	11182
Efficiency (measured) (%)	89.50	87.40	89.20	86.60
Efficiency (estimated) (%)	88.30	88.50	90.20	87.20
Error (%)	-1.35	1.26	1.13	0.65

Errors in determining the efficiency show values below than 1.35% in all operating points, and less than 1% in the operating point 4. This demonstrates the good accuracy of the proposed method.

In Table VII the parameters values of the solved equivalent circuits are presented.

TABLE VII
ESTIMATED PARAMETERS

OP	1	2	3	4
$r_{s,\text{fund, 5th, 7th}}$	1.52	1.52	1.52	1.52
$x_{s,\text{fund}}$	1.29	1.68	0.97	1.86
$r_{m,\text{fund, 5th, 7th}}$	1.38	2.21	2.68	1.57
$x_{m,\text{fund}}$	116.32	94.81	88.00	81.68
$x_{r,\text{fund}}^{p}$	1.94	2.52	1.45	2.79
$r_{r,\text{fund}}^{p}$	0.88	0.88	0.84	0.86
$x_{r,\text{fund}}^{n}$	0.03	1.28	1.29	2.71
$r_{r,\text{fund}}^{n}$	1.29	1.88	1.64	7.49
$r_{ll,\text{fund}}$	0.65	0.78	0.60	0.73
$x_{s,5th}$	6.45	8.4	4.85	9.3
$x_{m,5th}$	581.6	474.05	440.00	408.40
$x_{r,5th}^{p}$	1.43	1.85	1.07	2.05
$r_{r,5th}^{p}$	1.22	1.85	0.72	1.81
$x_{r,5th}^{n}$	1.39	1.40	0.91	1.94
$r_{r,5th}^{n}$	9.39	42.68	28.92	8.31
$r_{ll,5th}$	2.45	2.86	2.27	2.55
$x_{s,7th}$	9.03	11.76	6.79	13.02
$x_{m,7th}$	814.24	663.67	616.00	571.76
$x_{r,7th}^{p}$	1.38	1.79	1.03	1.98
$r_{r,7th}^{p}$	1.27	1.92	0.75	1.88
$x_{r,7th}^{n}$	1.32	1.01	0.99	1.67
$r_{r,7th}^{n}$	2.00	5.42	8.61	37.46
$r_{ll,7th}$	3.27	3.58	2.74	3.57

VI. CONCLUSION

The developed method based on the solution of the equivalent circuits of the induction motor fed with harmonics and unbalanced voltage simultaneously, using a BFA procedure as a search algorithm, allows determining the parameters of those circuits and estimating the efficiency of the machine at any point of operation and in non-controlled conditions.

The method was applied in industrial environment, where unlike laboratory conditions, harmonics, unbalanced and other electrical parameters, vary according to the characteristics of the specific electrical system. In this case, the results presented good accuracy, with errors less than 1.35%. This demonstrates the applicability of the method in situ.

The variation in harmonics behavior in the studied conditions, demonstrated the need for statistical analysis, to identify the values of voltage and current magnitudes that most affect motor performance.

REFERENCES

[1]. E.C. Quispe, X.M. Lopez-Fernandez, A.M.S. Mendes, A.J.M. Cardoso, J.A. Palacios, “Influence of the positive sequence voltage on the derating of three-phase induction motors under voltage unbalance”, in Proc. IEEE Int. Electr. Mach. and Driv. Conf. (IEMDC), 2013, pp. 100-105.

[2]. IEEE Standard test procedure for polyphase induction motors and generators, IEEE Standard 112, 2004.

[3]. IEC Standard methods for determining losses and efficiency from tests, IEC Standard 60034-2-1, 2014.

[4]. A. Gharakhani and P. Pillay, “An in-situ efficiency estimation technique for induction machines working with unbalanced supplies”, IEEE Trans. Energy Convers., vol. 27, no. 1, pp, 85-95, 2012.

[5]. B. Lu, T. G. Habetler and R. G. Harley, “A nonintrusive and in-service motor-efficiency estimation method using air-gap torque with considerations of condition monitoring”, IEEE Trans. Ind. Appl., vol. 44, no. 6, pp. 1666–1674, 2008.

[6]. M. Çunkaş and T. Sağ, “Efficiency determination of induction motors using multi-objective evolutionary algorithms”, Adv. Eng. Softw., vol. 41, no. 2, pp. 255-261, 2010.

[7]. P. Phumiphak and C. Chat-Uthai, “Nonintrusive method for estimating field efficiency of inverter-fed induction motor using measured values”, in Proc. IEEE Int. Conf. Sustainable Energy Technol, 2008, pp. 580–583.

[8]. C. P. Salomon, W. C. Santana, L. E. Borges, E.L. Bonaldi, L. E. L. de Oliveira, J. G. Borges, G. Lambert-Torres and A. R. Donadon, “A stator flux synthesis approach for torque estimation of induction motors using a modified stator resistance considering the losses effect”, in Proc. IEEE Int. Electr. Mach. and Driv. Conf. (IEMDC), 2013, pp. 1452-1458.

[9]. D. Bae, D. Kim, H.-K. Jung, S.-Y. Hahn and C. Koh, “Determination of induction motor parameters by using neural network based on FEM results”, IEEE Trans. Magn., vol. 33, no. 2, pp. 1924-1927, 1997.

[10]. Y. Liu and K. M. Passino, “Biomimicry of social foraging bacteria for distributed optimization: models, principles, and emergent behaviors”, J. Optim. Theory Appl., vol. 115, no. 3, pp. 603-628, 2002.

[11]. V. P. Sakthivel, R. Bhuvaneswari and S. Subramanian, “An accurate and economical approach for induction motor field efficiency estimation using bacterial foraging algorithm”, Measurement, vol. 44, no. 4. pp. 674-684, 2011.

[12]. V. Sousa, P. R. Viego and J. Gómez, “Bacterial foraging algorithm application for induction motor field efficiency estimation under unbalanced voltages”, Measurement. vol. 46, pp. 2232-2237, 2013.

[13]. V. Sousa, P. R. Viego, J. Gómez, N. Lemozy, A. Jurado and E. C. Quispe, “Procedure for determining induction motor efficiency working under distorted grid voltages”, IEEE Trans. Energy Convers., vol. PP, no. 99, pp. 1-9. 2014.

[14]. V. Sousa, E. C. Quispe, J. Gómez, P. R. Viego, N. Lemozy, A. Jurado and M. Brugnoni, “Bacterial foraging algorithm application for induction motor field efficiency estimation under harmonics and unbalanced voltages”, in Proc. IEEE Int. Electr. Mach. and Driv. Conf. (IEMDC), 2013, pp. 1174-1178.

[15]. IEEE Recommended practices and requirements for harmonic control in electrical power systems, IEEE Standard 519, 1993.

[16]. J. Pedra, L. Sainz and F. Córcoles, “Harmonic modeling of induction motors”, Electr. Power Syst. Res., vol. 76, no 11, pp. 936-944, 2006.

[17]. J. C. A. Escobar and F. de la Rosa “Shaft torsional vibration due to non-linear loads in low capacity turbine units”, in Proc. IEEE Power Engineering Society, 2001, pp. 1403–1408.

[18]. P. G. Cummings, “Estimating effect of system harmonics on losses and temperature rise of squirrel-cage motors”, IEEE Trans. Ind. Appl., vol. IA-22, no. 6, pp. 1121-1126, 1986.

[19]. V. Ivanov-Smolenski, Electrical Machines, vol. 2, Moscú: Mir, 1984.

[20]. A. Enmanuel, J. Orr, D. Cyganski, E. Gulachenski, “Survey of harmonic voltages and currents at distribution substation,” IEEE Trans. Pow. Deliv., vol.6. no.4. pp. 2204-2212. 1991.

[21]. Y. Baghzouz, R.F. Burch, A. Capasso, A. Cavallini, A.E. Emanuel, M. Halpin, A. Imece, A. Ludbrook, G. Montanari, K.J. Olejniczak, P. Ribeiro, S. Rios-Marcuello, L. Tang, R. Thaliam and P. Verde, “Time-varying harmonics. I. Characterizing measured data”, IEEE Trans. Pow. Deliv., vol. 13, no. 3, pp. 938-944, 1998.

[22]. WEKA MOTORENPRÜFSTÄNDE manufacturer. [Online]. Available: http://www.weka-motorenpruefstaende.de/.

[23]. IEC Standard rotating electrical machines-Part26: Effects of unbalanced voltages on the performance of three-phase cage induction motors, IEC Standard 60034-26, 2006.

[24]. IEEE Recommended practices and requirements for harmonic control in electrical power systems, IEEE Standard 519. 1993.