Title: Assessment of the energy efficiency estimation methods on induction motors considering real-time monitoring

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Abstract:

Different methods have been developed to estimate the energy efficiency of induction motors. The accuracy of these methods vary with the load factor, the unbalanced voltage (UV) and harmonics. The feasibility of these methods for efficiency estimation in real-time were theoretically and experimentally assessed during the operation under different operational conditions (i.e. balanced sinusoidal voltage (BSV), harmonics, UV and harmonics with UV). Results show that for load factors over 80%, the air-gap method is applicable under any condition, while the slip method is only applicable under BSV or balanced harmonic voltage. Moreover, for load factors over 40%, the nameplate method is applicable under BSV. Other methods result in errors over 8% and optimization methods are not applicable for real-time monitoring. Electric systems generally operates with some degree of UV and harmonics, while induction motors mostly operate with load factors below 60%, limiting the use of these methods for real-time measurement.

Keywords: Energy efficiency; Harmonics; Induction motors; Real-time monitoring; Voltage unbalance.

Nomenclature

f - Fundamental frequency of the electric grid (Hz).

fund - Fundamental component.

i_a, i_b - Instantaneous stator phase currents of phases a and b respectively (A)

I_a, I_b and I_c- Rms line currents (A).

I_{fe} - Core loss current (A)

I_m - Average measured current (A).

I_{ma}- Magnetizing current (A)

I_n - Nominal current (A).

I_r - Rotor current referred to stator (A)

I_s - Stator phase current (A)

k - Harmonic order (p.u).

L_f - Load factor (%).

n_m - Measured shaft speed (rpm).

n_r - Rated shaft speed (rpm).

n_s - Synchronous speed (rpm).

P - Number of poles.

P_{cur} - Rotor copper loss (W)

P_{cus} - Stator copper loss (W)

P_{fe}- Core loss (W)

P_{fw} - Friction and windage loss (W)

P_{in} - Input active or electrical active power (W).

P_{nl} - Combined no-load losses (P_{fe}+P_{fw}) (W)

P_{out} - Output or mechanical shaft power (W).

P_r - Rated output power (W).

P_{sll} - Stray-load loss (W)

R_{fe} - Core loss resistance (Ω)

r_r - Rotor resistance referred to stator (Ω)

r_s - Stator resistance (Ω)

s - Slip (p.u)

s_m - Measured slip (p.u).

s_r - Rated slip (p.u).

T_{ag} - Air-gap torque (Nm)

T_{shaft} - Shaft torque (Nm)

v_{ab}, v_{bc} - Instantaneous stator line voltages of lines ab and bc respectively (V)

V_{ab}, V_{bc} and V_{ca}- Rms line voltages (V).

V_{avg} - Average voltage of the three phases (V)

V_m - Average measured grid voltage (V).

V_r - Rated voltage (V).

V_s - Phase voltage (V)

$\left|\mathrm{V}-\mathrm{V}_{\mathrm{avg}}\right|$ - Maximum deviation of a voltage from the average voltage (V).

x_m - Magnetizing reactance (Ω)

x_r - Rotor Leakage reactance referred to stator (Ω)

x_s - Stator leakage reactance (Ω)

η - IM efficiency (%).

1. Introduction

Induction motors (IM) account for some 68% of the energy consumption of industry worldwide, thus to reduce the global consumption of electricity it is important to improve their efficiency [1, 2]. Furthermore, improving the efficiency of IM and drive mechanical systems might reduce around 20% to 30% of the energy consumption, also reducing some 10% of the overall electricity demand [3].

There are different approaches to improve the energy efficiency of IM, namely:

- The correct selection of the motor size to guarantee a high load factor (currently around 60% of IM operate below 60% of their nominal load, which reduce their efficiency [4]);
- The use of control devices like variable-frequency drives for pumps and fans [5];
- Avoid negative effects of rewinding and power quality issues like voltage unbalance, harmonics and voltage variation [6].

Some regulatory frameworks (i.e. Mandatory Energy Performance Standards (MEPS)), have been established in different countries, aiming at reducing the energy consumption of IM. The compliance with the MEPS, which is enforced by law, defines the minimum efficiency (or the maximum energy consumption) for IM. In this way, the average efficiency of the IM available in the market is improved, by forcing companies to meet the efficiency levels [7, 8].

To assess the energy efficiency of IM and to improve the overall performance of industrial systems, it is essential to identify energy losses, to properly apply the MEPS, and to monitoring in real-time the efficiency and load factor [9, 10]. However, assessing the energy efficiency and load factor of IM, requires field measurements of the shaft power, which is very intrusive and costly based on current technology, or even by applying the standards IEEE Std-112-2004 [11] and IEC Std-60034-2-1-2007 [12].

As an alternative to the field measurements of the shaft power, several methods to estimate both the efficiency and load factor of IM, have been developed, which will be referred as energy efficiency estimation methods (EEEM):

- Nameplate method [13, 14]
- Slip method [15, 16]
- Current method [13, 15]
- Equivalent circuit method [13, 15]
- Segregated loss method [13, 15]
- Torque method [4, 9, 10, 13, 15, 17 - 23]
- Computer tools [7]
- Optimization methods based on heuristic techniques and evolutionary algorithms (HTEA) [6, 24-34].

The real-time response of IM, is essential to identify their load and efficiency profiles (including peak and off-peak usage hours), and for the early detection of operating condition modifications that might affect their efficiency and lifespan [10]. In industrial electrical systems, voltage unbalance can result from unbalanced loads, unsymmetrical transformer windings, transmission impedances, three-phase motors with phase asymmetry and other non-symmetrical conditions [35]. Moreover, the presence of harmonics in the power supply is caused by non-linear loads like the caused by operating power electronics devices, arc furnaces, resonance of shunt capacitors and/or inductor series, etc. [24]. Voltage unbalance and harmonics can simultaneously occur in electrical networks when their causes coincide (e.g. an IM with phase asymmetry or in an unbalanced power grid, drive by a variable-frequency drives). In particular, energy quality issues (i.e. voltage unbalance and harmonics), which are expected to increase in the near future with the new modes of producing and consuming electricity, are very significant [36]. Therefore, since IM frequently operates at partial loads, with energy quality issues, which differ from nominal operating conditions, it is essential to consider the influence of the operating conditions on the accuracy when using EEEM [4, 6, 26]. Overall, EEEMs does not considered the influence of voltage unbalanced, harmonics or the combination of both on the energy efficiency of IMs, which affect their accuracy, as will be further discussed. Consequently, this study aims at evaluating the accuracy of the EEEMs available for the real-time estimation of the energy efficiency of IMs, when operating in the presence of voltage unbalance, harmonics, and at different load factors.

2. Literature review

Different studies have assessed EEEMs according to their level of intrusion, costs of measuring and accuracy of results. Lu et al [13], compared different EEEM, excluding the HTEA methods, considering the number of parameters to measure and the intrusion level of the measurements, the tests to the IM required (e.g. no load, full load, variable voltage/frequency, etc.), and the expected error. The influence of the operation at partial loads and the energy quality issues on the EEEM results were not discussed in this study.

Chirindo et al [14] discussed the behavior of the stray-load loss, and the variation of the equivalent circuit parameters caused by harmonics, to estimate the efficiency of IM with variable-frequency driver. This study only considered the use of HTEA methods. Hsu et al [15], compared some EEEM also excluding HTEA methods, based on their operating principle, the intrusion level of the measurements and the accuracy of the results. The study also considered the effects of voltage unbalanced for different load factors.

Salomon et al [22] also compared different EEEM, focusing on the air-gap torque, and excluding the HTEA methods. In this study, the effects of voltage unbalanced and harmonics were not included in the assessment.

Ferreira and Almeida [37] assessed the EEEM with lower complexity, regarding the measurement equipment and data processing required in each case. The air-gap torque and the HTEA methods were not included in the study. Furthermore, the influence of voltage unbalanced, harmonics were not assessed.

Verucchi et al [38] compared the EEEM standardized in the most important MEPS, assessing the differences in the approaches used to calculate the losses and their influence in the results. However, the EEEM discussed in this study are not applicable for field conditions. Additionally, the influence of partial load operation, voltage unbalanced and harmonics were not discussed in the study.

In summary, none of the studies discussed the influence of operating conditions at partial loads, in the presence of harmonics and voltage unbalance on the energy efficiency estimation error of the EEEM; neither assessed the potentialities to estimate the real-time response of IMs.

3. Energy efficiency of induction motors

2.1. Real-time monitoring of energy efficiency and load factor

The efficiency and load factor of IM is calculated as [4, 6]:

$$\eta = \frac{P_{out}}{P_{in}} \cdot 100 \ (\%) \quad (1)$$

$$L_f = \frac{P_{out}}{P_r} \cdot 100 \ (\%) \quad (2)$$

The real-time response of IM instantly changes to variations on the input conditions, generating an interrupted flow of new information [39]. Therefore, to calculate L_f and η, P_{in} and P_{out} must be measured in real-time. There are sensors available for the real-time measure of parameters like P_{in}, voltage, current, power factor, harmonics, etc. [40-42]. However, measuring P_{out} remains a challenge, which is the main reason for the use of EEEM.

2.2. Energy efficiency estimation methods (EEEM)

2.2.1. Nameplate method

The nameplate method considers that the efficiency of IMs remains constant independently of the load factor, and equal to the nameplate value [15, 16]. Since the efficiency is known in this case, the method is used to estimate the output power and the load factor of IMs. The output power is calculated using equation 1, with the input power and the nameplate efficiency. Moreover, the load factor is calculated using equation 2.

Since the input power can be measured and the information of the nameplate in general is accessible, this is a low intrusion method [6, 26]. Moreover, calculating P_{out} and L_f, which is rather easy, has low computational demand. However, since the motor efficiency is considered constant over the entire operating range, this method has low accuracy for motors operating at partial loads, because the efficiency of IMs varies with the load factor, as shown in Fig. 1 for IMs of 3 and 20 HP [43].

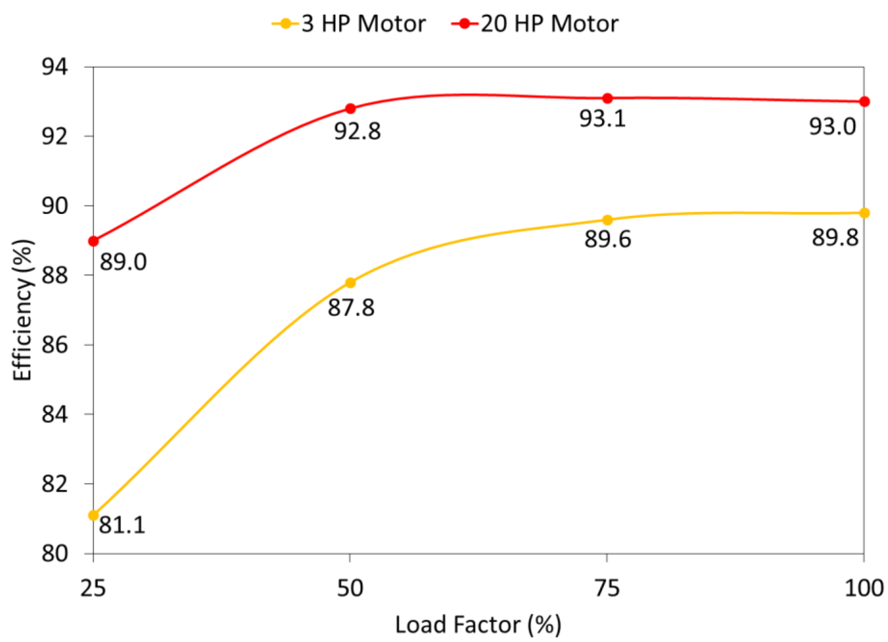

Fig. 1. Energy efficiency curve for IM of 3 HP and 20 HP. Source [43].

Other factor affecting the method accuracy, is the use of different standards to determine the nominal efficiency (e.g. mainly IEEE Std-112-2004 [11], IEC Std-60034-2-1-2007 [12]), which include different procedures and considerations, resulting in different nominal efficiencies for the same motor. Additionally, the standards do not consider the operation with voltage unbalanced and harmonics. Table 1 shows the results of using the IEEE Std-112-2004 [11] and the IEC Std-60034-2-1-2007 [12] standards in the 5.5 kW, 4 poles, and 380V motor discussed in [38].

Table 1. Nominal efficiency values for an IM of 5.5 kW, 4 poles, 380V. Source [38].

Approach	Efficiency (%)	Error (%)
Direct measurement	80.79	-
IEEE 112 F1 Standard	81.45	0.82
IEC 60034 Standard	80.00	-0.98
IEEE 112 B Standard	79.53	-1.56

An alternative to the nameplate data is the IM catalog with the nominal efficiency versus the load factor measured for several points, from which a mathematical model of the mechanical power as a function of the electrical power can be obtained by correlating both variables. Catalogue data is available for several IM manufacturers. Some catalogues, includes the efficiency for three L_f points (50%, 75% and 100%) and in some cases it is also included the efficiency for a L_f of 25% (e.g. Fig. 1.). However, as this approach do not considers the influence of unbalance voltage and harmonics in the efficiency, using the catalog data has the same limitations that using the nameplate efficiency. This procedure has been applied in some energy studies of IMs operation in the industrial sector [2], [44], [45].

2.2.2. Slip method

This method considers that the variation of the ratio between the measured motor slip and the rated motor slip is linear. The equations for estimating P_{out} and L_f are [15]:

$$P_{out} = P_r \cdot \left(\frac{S_m}{S_r}\right) = P_r \cdot \left(\frac{n_s - n_m}{n_s - n_r}\right) \quad (3)$$

$$L_f = \frac{P_{out}}{P_r} = \left(\frac{S_m}{S_r}\right) = \left(\frac{n_s - n_m}{n_s - n_r}\right) \quad (4)$$

The slip and the synchronous speed are calculated as [16]:

$$s = \frac{n_s - n_m}{n_s} \quad (5)$$

$$n_s = \frac{120 \cdot f}{P} \quad (6)$$

The intrusion level of this method is low, although it is slightly more intrusive than the nameplate method, because measuring the shaft speed might need a sensor, but there are sensorless real-time speed estimation methods [46, 47]. Since the electric power and the motor speed can be measured in real-time, this method estimates the real-time response of IMs. Moreover, it uses simple equations requiring low computational effort. However, this method is based on the rated speed depicted in the nameplate, which has a variation of up to 20% relative to the difference between the synchronous speed and the rated speed measured at the rated voltage, frequency, and load at an ambient temperature of 25°C [48]. Therefore, significant errors can result from its implementation. Some improvement was implemented in the method by considering that the variation of the slip, is proportional to the square ratio of the grid voltage to the rated voltage [13]:

$$L_f = \frac{P_{out}}{P_r} = \left(\frac{n_s - n_m}{n_s - n_r}\right) \cdot \left(\frac{V_m}{V_r}\right)^2 \quad (7)$$

However, the uncertainty in the nameplate rated velocity keep affecting the method accuracy. Additionally, voltage unbalance and harmonics voltages cause a counter-torque, which affects the shaft speed and increases the estimation error [24].

2.2.3. Current method

The current method considers that the load variation is directly proportional to the ratio of the measured current to the nominal current [13, 15]:

$$P_{out} = P_r \cdot \left(\frac{I_m}{I_n}\right) \quad (8)$$

$$L_f = \frac{P_{out}}{P_r} = \left(\frac{I_m}{I_n}\right) \quad (9)$$

Since the current and the electric power can be measured in real-time with low intrusive methods, and the calculation of the load factor and the efficiency is based on simple equations that require low computational effort, the results can be calculated in real-time. However, there is a high uncertainty in the results because:

- The ratio of the load factor and the current is nonlinear (see Fig. 2).
- The method considers that IMs working in no-load condition consume no current, which is not true. Therefore, when the load factor decreases the error of the method increases.
- In electric networks under unbalance and harmonics voltages, where the consumption of current increases as compared to the nominal conditions, the error of the method increases [26].

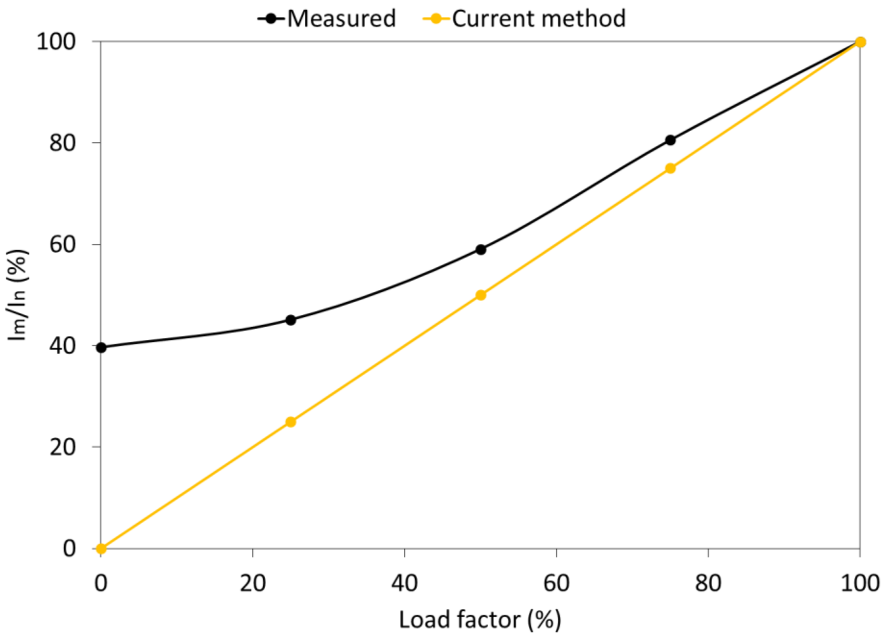

Fig. 2. Relation between the load factor and the ratio of the measured and nominal currents for measured data and the current method. Source: [43].

2.2.4. Equivalent circuit method

The energy efficiency, the shaft power and the losses of an IM can be estimated with the equivalent circuit shown in Fig. 3 and the F/F1 method of the IEEE Std-112-2004 standard [11].

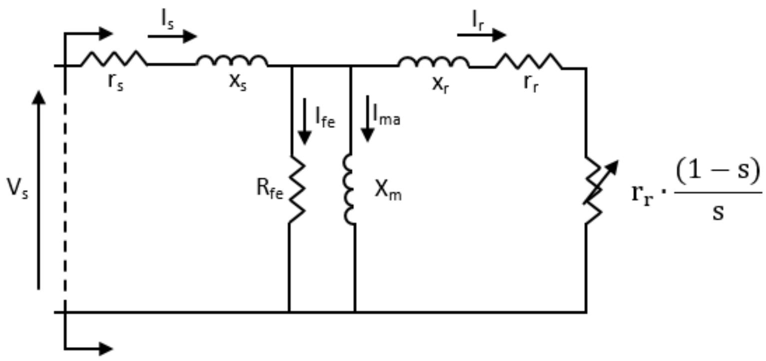

Fig 3. Equivalent circuit of an IM. Source: [11].

Once the parameters of the equivalent circuit are determined, the losses are calculated as [11]:

$$P_{cus} = 3 \cdot |I_s|^2 \cdot r_s \;\; (W) \tag{10}$$

$$P_{cur} = 3 \cdot |I_r|^2 \cdot r_r \;\; (W) \tag{11}$$

$$P_{fe} = 3 \cdot |I_{fe}|^2 \cdot R_{fe} \;\; (W) \tag{12}$$

The output power is determined as:

$$P_{out} = 3 \cdot |I_r|^2 \cdot r_r \cdot \frac{(1-s)}{s} - P_{fw} - P_{sll} \; (W) \tag{13}$$

Since this method requires measuring impedance, no-load, variable-voltage, removed-rotor, and reverse-rotation tests, it is not useful in field conditions [7]. However, this method serve as basis for other methods and off-line efficiency estimation tools, which include some modifications like:

- Ontario Hydro Modified Method F (OHMF) [49]
- Nameplate Equivalent-Circuit (ORMEL96) Method [50]
- Rockwell Motor-Efficiency Wizard (RMEW) Method [51]
- Locked Rotor Method [52]
- Standstill Frequency Response Method (SFRM) [53]
- Etc.

The intrusion level of these methods is lower than the IEEE Std-112-2004 standard, however, the OHMF, RMEW and SFRM methods require no-load, full-load and locked rotor tests which is highly intrusive [49, 52, 53]. The RMEW method requires the measured value of stator leakage reactance [51], which is not available for in-service testing. Moreover, in the ORMEL method, the parameters of the equivalent circuit are obtained from the nameplate, which is a source of significant errors since the parameters varies with the operating conditions and most IMs seldom operate in nominal conditions [4, 6].

In voltage unbalance conditions, the equivalent circuit must consider the negative sequence fluxes resulting from the currents unbalance [6], while in harmonic conditions, the equivalent circuit must consider the positive and negative sequence fluxes of higher frequency caused by harmonics currents [26]. Moreover, the combined effect of both harmonics and voltage unbalance must be considered [26]. However, the OHMF, ORMEL96, RMEW, Locked Rotor Method and SFRM does not include these considerations, thus resulting in significant errors.

2.2.5. Segregated loss method

The segregated loss method depicted in E1 of IEEE Std-112-2004 [11], determines the output power by subtracting the losses from the input power as:

$$P_{out} = P_{in} - (P_{cus} + P_{cur} + P_{fe} + P_{fw} + P_{sll})\ (W) \qquad (14)$$

Like the F/F1 method, this method, which requires the same intrusive measures, is not applicable under field conditions. However, some of its criteria are used as basis for other on-site EEEMs, such as, Ontario Hydro Modified Method E (OHME) [49]. One of the most used criteria of this method is to consider the stray-load loss as a percentage of the rated power of the motor, as shown in Table 22.

Table 2. Stray-load loss in the segregated loss method. Source: [11].

IM power (HP)	Stray-load loss (% of rated output)
1 – 125	1.8
126 – 500	1.5
501 – 2,499	1.2
> 2,500	0.9

The OHME [49], assumed the combination of losses (P_{fe} + P_{fw}) between (3.5% - 4.2%) of the rated input power [10, 50]. The stray-load loss is determined from table 2, while the other losses are determine with the input current, rotor speed and stator resistance measurements. Stator copper loss are calculated with equation 10, and the rotor copper loss as:

$$P_{cur} = (P_{in} - P_{cus} - P_{fe})\ (W) \qquad (15)$$

Some commercial devices for off-line efficiency estimation are based on this method, in which the accuracy is affected by:

- The combined losses $(P_{fe} + P_{fw})$ can vary with the motor size out of the 3.5% to 4.2% defined range [19].
- These losses vary with the voltage, which might vary in field conditions [6].
- The stray-load loss varies with the load, therefore, for partial loads differ from those of table 2 [6].

An EEEM based on segregated loss method and no-load tests is proposed in [54], which does not require the use of a dynamometer. However, it requires the no-load tests, which is highly intrusive. Additionally, was only validated for the motor working at full load, omitting the operation at partial loads, voltage unbalance and harmonic voltages.

2.2.6. Air-gap torque method

Since its first development [17], the method has been upgraded to be used as a low intrusive EEEM [4, 18, 22]. The power output is estimated as [4, 18]:

$$T_{ag} = \frac{\sqrt{3}\cdot P}{6}\{(i_a - i_b)\cdot \int[v_{ca} + r_s\cdot(2\cdot i_a + i_b)]dt + (2\cdot i_a + i_b)\cdot\int[v_{ab} - r_s\cdot(i_a - i_b)]dt\}\ (Nm) \qquad (16)$$

$$P_{out} = \frac{2\cdot\pi\cdot T_{ag}\cdot n_m}{60} - (P_{fe} + P_{fw}) - P_{sll}(W) \qquad (17)$$

The method considers the combined no-load losses (P_{fe}+P_{fw}) as 3.5% of rated output power, and P_{sll} is estimated from table 2 [18]. These considerations affect the accuracy because of the factors explained in the previous section.

The air-gap torque method has been extensively used in the development of real-time efficiency estimation tools for IM [9, 10, 20, 23]. In [9] the variation of the stator resistance with temperature is not considered, which increases the estimation errors. Furthermore, in this case, friction and windage losses are considered based on the size of the motor as shown in Table 3.

Table 3. Friction and windage loss. Source: [9]

Power (HP)	Friction and windage loss (% of rated output)
1 – 125	1.7
126 – 500	2.0
501 – 2,499	2.3
> 2,500	2.6

A novel method to determine the electromagnetic torque of IMs, based on measuring the external magnetic flux around IMs, is proposed in [55]. This approach uses an external non-invasive magnetic flux sensor that does not affect the normal operation of the motor. However, the method did not consider how to determine the mechanical torque and output power; thus, it cannot be used to assess the efficiency of IMs.

2.2.7. Optimization methods based on heuristic techniques and evolutionary algorithms

Optimization methods based on heuristic techniques and evolutionary algorithms like genetic algorithms [6, 24,25], bacterial foraging algorithm [26, 27], gravitational search algorithms [28-30, 33], cuckoo algorithm [31], particle swarm optimization [32, 34], and others, permit to estimate the parameters of a modified equivalent circuit, and operational characteristics like output power, efficiency, load factor and segregated losses.

The main advantage of the equivalent circuit solution with the HTEA approaches, is that the losses and the efficiency can be individually analyzed at every set point or load condition. Additionally, using HTEA modified equivalent circuit models were developed to assess IMs under voltage unbalance and harmonic voltage, thus considering the effects of these conditions on the efficiency, which reduces the estimation error of the results. Among the modifications made in the equivalent circuit are:

- Equivalent circuit to assess an IM under balanced and sinusoidal voltages conditions (see fig. 3), and including a parameter (in series rather than on parallel, to facilitate the evolutionary search of the solution) for the stray-load loss and the magnetization branch [25 - 33].
- A negative sequence circuit to assess IM under unbalanced voltages [6, 25, 27, 33].
- A circuit with multiple frequency parameters based on the Fourier transform to assess IM under harmonics conditions [14].
- The combination of the negative sequence circuit and the circuit with multiple frequency parameters based on the Fourier transform, to assess IM under unbalanced voltages and harmonic voltages conditions [24, 26].

The main limitation of applying HTEA methods for energy efficiency real-time estimation is that they use highly complex solution algorithms, which requires long processing times and high computational capacities (i.e. high processing performance computers for processing data and algorithms). For example, to assess IM under harmonic voltages with HTEA methods, the voltages and currents of each harmonic level needs to be measured, and the equivalent circuit of each harmonic must be analyzed in the algorithm. Additionally, the considerations used to accelerate the estimation process of the equivalent circuit parameters can lead to divergent results.

3. Materials and methods

In this section is described the experiment design, which defines how to apply the EEEM methods to a 1.1 kW De Lorenzo (DL 1021) induction motor (see table 4). Additionally, it is described how to measure the energy efficiency and the output power of the motor.

Table 4. Nameplate and catalog data of De Lorenzo motor (DL 1021)

Parameter	Value
Power (W)	1,100
Efficiency (%)	82
Voltage (V)	220
Current (A)	3.9
Frequency (Hz)	60
Power factor (p.u)	0.9
Poles	2
Speed (rpm)	3,420
Connection	Δ
Insulation class	F
NEMA design	B
r_s (at 25°C) (Ω)	4.13
Efficiency (%) at 100% L_F	82
Efficiency (%) at 75% L_F	78
Efficiency (%) at 50% L_F	70

The DE LORENZO (DL 1021) induction motor operated in a motor test bench (see fig 5). The EEEMs suitable for real-time efficiency estimations were assessed, namely:

- Nameplate method
- Slip method improved with the voltage
- Current method
- Air-gap torque method

Fig. 4 shows the adjusted mathematic model for P_{out} versus P_{in}, using the nameplate method. The input and output power (i.e. Pout and Pin) are calculated with equations 1 and 2, using the nameplate efficiency and the load factor data shown in table 4.

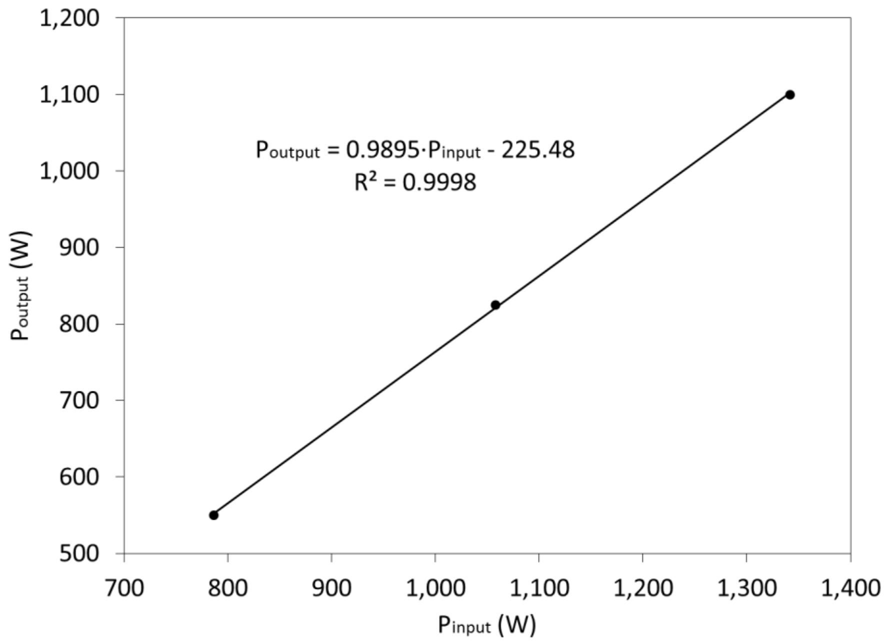

Fig. 4. Ratio of input active power to output power of the De Lorenzo (DL 1021) induction motor.

The EEEM are assessed under different load factors, operational conditions and power supply sources, which are described in table 5. In all cases, a power quality and energy analyzer (Fluke 435 series 6) was used for the electric measurements, while for the torque control and speed measurements a brake control unit (De Lorenzo DL 1054TT) and a magnetic powder brake (De Lorenzo DL 1019P) were used.

Table 5. Power supply sources for the experimental operational conditions.

Conditions	Supply source
1. Balanced sinusoidal voltage	• Voltage source: De Lorenzo (DL 1013M3)
2. Balanced harmonic voltage	• Voltage source: De Lorenzo (DL 1013M3) • Variable-frequency drives: Schneider (ATV312HU15M3) (Connected after the voltage source, operating at nominal frequency)
3. Unbalanced sinusoidal voltage	• Resistance in series with one of the supply phases.
4. Unbalanced voltage and harmonics	• Variable-frequency drives and resistance in series with one of the supply phases.

The experimental facilities, including the equipment used, are shown in fig. 5.

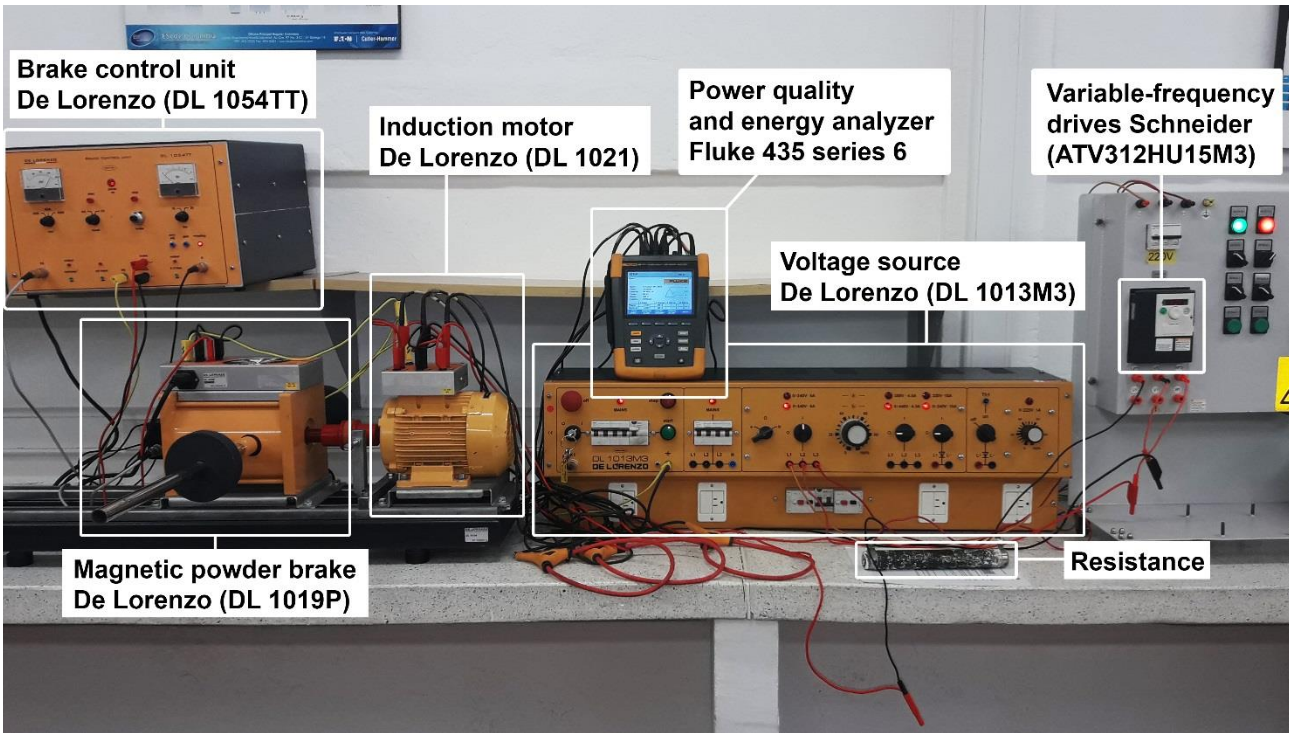

Fig.5. Experimental facility.

The laboratory includes an active multi-function filter Circutor (AFQevo) [56], to filter the harmonics, and to balance the circuit phases. Therefore, the three-phase electric power network used in the experiments, is balanced and without harmonics. The balanced sinusoidal voltage condition (condition 1), was generated by using a De Lorenzo (DL 1013M3) voltage source. Moreover, the balanced harmonic voltage (condition 2) was generated with a variable-frequency drive (Schneider ATV312HU15M3, with a six pulse converter integrated into a single control system architecture without filter), which was connected after the voltage source. In this case, the harmonic spectrum was regulated by operating the drive at a constant frequency, equal to the nominal frequency of the motor (i.e. 60 Hz). On the other hand, the unbalanced sinusoidal voltage (condition 3), was generated with an electric resistance connected in series to one phase of the IM power supply source. Finally, the unbalanced harmonic voltage (condition 4), was generated by simultaneously connecting the variable-frequency drive (operating at constant frequency) and the electric resistance connected in series to one phase of the IM power supply source.

The mechanical power was calculated as a function of the shaft torque and speed measured in the motor [4]:

$$P_{out} = \frac{T_{shaft} \cdot n_m}{9.549} \qquad (18)$$

Moreover, the percentage voltage unbalance (PVU) is calculated as [48]:

$$PVU = \frac{|V - V_{avg}|}{V_{avg}} \qquad (19)$$

Finally, the total harmonic distortion of voltage (THDV) of each phase is calculated as [57]:

$$THDV_{phase} = \frac{\sqrt{\sum_{2}^{50} V_k^2}}{V_{fund}} \cdot 100 \qquad (20)$$

Generally, when assessing the effect of harmonics on induction motors, the THDV is keep constant for all conditions using a programmable power supply control unit [24, 58, 59]. However, nonlinear loads with sinusoidal voltage sources and linear loads with non-sinusoidal voltage sources produce harmonics, which distort the sinusoidal supply waveform that affects other linear devices [60]. Thus in this study it is also considered the variations of the TDHV to get closer to field conditions.

To consider the influence of the load factor on the motor efficiency, the IM was operated at different load factors. The load factor was controlled with the brake control unit by varying the torque between 0.5 Nm and 3.0 Nm, with increments of 0.25 Nm (resulting in 11 torques). The nominal torque of the motor, calculated with equation 18 considering the nominal power, is 3.07 Nm. To prevent damage to the motor by overheating under unbalance voltage and harmonics, the maximum torque in the experiments (3.0 Nm) is slightly lower than the nominal torque of the motor. The load factor of the experiments was calculated with equation 2.

Experimental tests for each of the 11 torques defined, were developed for each condition (i.e. 44 tests). Each test was repeated 10 times to guarantee the reliability and consistency of the results.

4. Results and discussion

4.1. Results

To verify that the measured data have a normal distribution (i.e. that the experimental results are reliable), the 10 experimental datasets were statistically evaluated with the ANOVA analysis in the Statgraphics software. The results shown that the standardized kurtosis (a statistical variable) varied between -1.66 and 1.26, while the standardized bias (another statistical variable) varied between -1.60 and 1.75. Therefore, since both standardized variables varies in the range between -2 and 2, it is verified that the data have a normal distribution [61]. Moreover, the data for each load factor have an adequate coefficient of variation, varying between 0.0002% and 0.64% [61]. This proves that the experimental conditions were adequately controlled. Considering these results, the average of each dataset measurements was used (i.e. the average of the 10 repetitions per torque). Table 6 presents the data measured in the experiments for the four conditions assessed. The THDV value in the table is the average of the THDV of each phase (i.e. the average of THD V_{ab}, THD V_{bc} and THD V_{ca}).

Table 6. Experimental results.

T_{shaft} (Nm)	Condition 1 (Balanced sinusoidal voltage)						Condition 2 (Balanced harmonic voltage)					
	P_{in} (W)	P_{out} (W)	η (%)	L_F (%)	PUV (%)	THDV (%)	P_{in} (W)	P_{out} (W)	η (%)	L_F (%)	PUV (%)	THDV (%)
0.50	458	185	40.5	17	0	0	512	180	35.2	16	0	2.39
0.75	555	277	50.0	25	0	0	586	270	46.1	25	0	2.44
1.00	639	368	57.7	33	0	0	663	359	54.2	33	0	2.42
1.25	719	459	63.8	42	0	0	748	449	60.0	41	0	2.49
1.50	814	549	67.4	50	0	0	833	537	64.5	49	0	2.60
1.75	909	638	70.2	58	0	0	926	626	67.6	57	0	2.75
2.00	984	726	73.9	66	0	0	1,016	714	70.3	65	0	2.95
2.25	1,085	814	75.0	74	0	0	1,115	802	71.9	73	0	3.14
2.50	1,167	902	77.2	82	0	0	1,206	890	73.8	81	0	3.42
2.75	1,251	989	79.1	90	0	0	1,302	977	75.0	89	0	3.38
3.00	1,342	1,074	80.1	98	0	0	1,409	1,063	75.5	97	0	3.43
T_{shaft} (Nm)	**Condition 3 (Unbalanced sinusoidal voltage)**						**Condition 4 (Unbalanced voltage and harmonics)**					
	P_{in} (W)	P_{out} (W)	η (%)	L_F (%)	PUV (%)	THDV (%)	P_{in} (W)	P_{out} (W)	η (%)	L_F (%)	PUV (%)	THDV (%)
0.50	498	185	37.2	17	5.2	0	521	180	34.5	16	5.0	3.18
0.75	596	276	46.4	25	5.8	0	622	269	43.2	24	5.6	3.19
1.00	665	367	55.2	33	6.3	0	692	357	51.7	32	6.2	3.24
1.25	743	456	61.4	41	7.0	0	780	446	57.1	41	6.8	3.34
1.50	831	545	65.5	50	7.7	0	874	533	61.0	48	7.6	3.45
1.75	921	631	68.6	57	8.4	0	944	620	65.7	56	8.3	3.67
2.00	1,015	717	70.7	65	9.2	0	1,044	706	67.7	64	9.1	3.90
2.25	1,116	801	71.8	73	10.1	0	1,160	792	68.3	72	9.9	4.19
2.50	1,233	883	71.6	80	10.9	0	1,251	876	70.1	80	10.9	4.48
2.75	1,336	964	72.2	88	11.9	0	1,358	960	70.6	87	12.0	4.91
3.00	1,444	1,043	72.2	95	12.9	0	1,487	1,042	70.0	95	13.1	5.22

Table 6 shows the efficiency of the IM for all the experimental conditions considered, highlighting the influence of the THDV, PVU and the load factor on the results. As compared to condition 1, conditions 2 to 4 show that the presence of both the THDV and PVU affect the IM efficiency. Moreover, the combination of the THDV and the PVU causes the highest reductions of efficiency for the IM. The individual harmonic voltage distortion (i.e. the ratio of each individual harmonic voltage to the fundamental voltage [57]) generated with the variable-frequency drive measured in the experiments are shown in fig. 6.

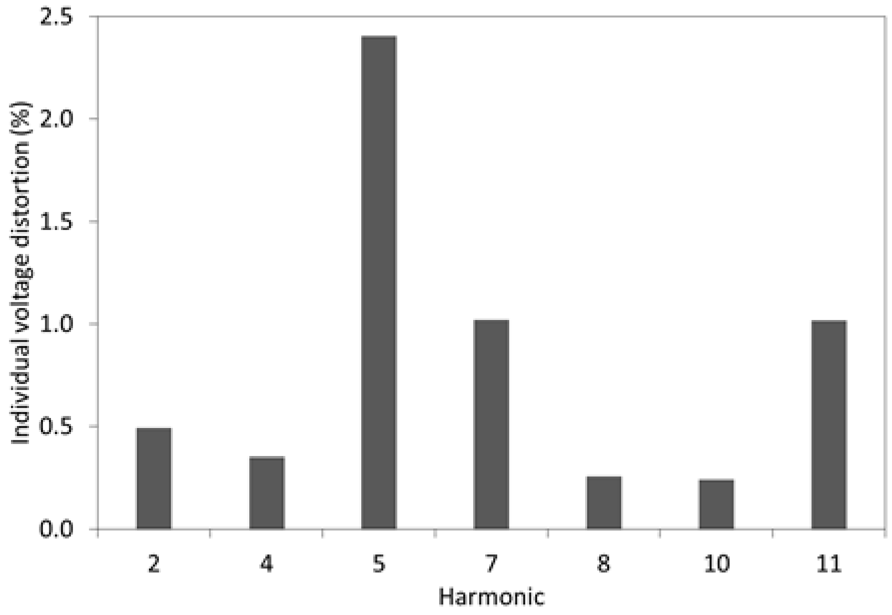

Fig. 6. Harmonic voltage distortion of the variable-frequency drive

The figure shows that the predominant harmonics are the 5th, 7th and 11th. This is the harmonic spectrum usually generated by six pulse variable-frequency drives, which have the highest negative effects on IMs [62]. Harmonics 5th and 11th are negative sequence harmonics, which generates a torque opposing the motor rotation, thus causing torque pulsations, motor vibration, etc. Moreover, harmonic 7th is a positive sequence harmonic, which generates a torque in the same direction of the motor torque. In both cases (i.e. positive and negative harmonic sequences), further harmonic currents are generated, which increase both losses and energy consumption.

The efficiency variations with the load factor in the different conditions discussed are shown in Fig. 7.

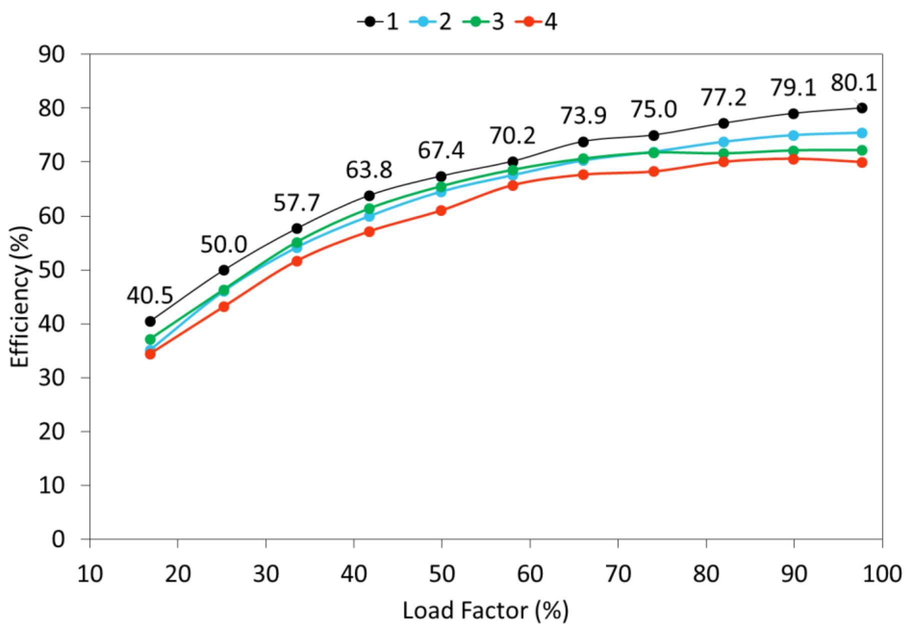

Fig. 7. Induction motor efficiency for the different conditions.

As expected, the presence of voltage unbalance and harmonics reduce the efficiency of the motor as compared to condition 1. In condition 2, the efficiency decreased an average of 3.7% because of the high

THDV generated by the variable-frequency drive. Furthermore, the efficiency reduction in this case shows that although variable-frequency drives reduce the energy consumption of systems with variable loads (in some cases over 50% [5, 7]), there are some negative effects caused by the harmonic distortion introduced by the drives that should not be overlooked. Moreover, in condition 3, the efficiency was reduced an average 3.8%, because of the high PVU resulting from the unbalanced phase. Comparing conditions 2 and 3, it is shown that for load factors over 70% (within the operational range for which IM are designed), the voltage unbalance reduces the efficiency more than harmonics. Finally, in condition 4, the efficiency reduced an average of 6.8%, as a result from the combined effects of the voltage unbalance and harmonics.

4.2. Discussion

To compare the results from EEEMs to the experimental results, an error of ± 8% defined as “useful accuracy” is considered as the limit of acceptable error [36]. Fig. 8 shows the efficiency results obtained from the experimental values and estimated with the EEEMs as a function of the load factor. Moreover, fig. 9 shows the variation of the efficiency estimation errors from the EEEMs as compared to the experimental results, as a function of the load factor and comparing with the acceptable error of ± 8%.

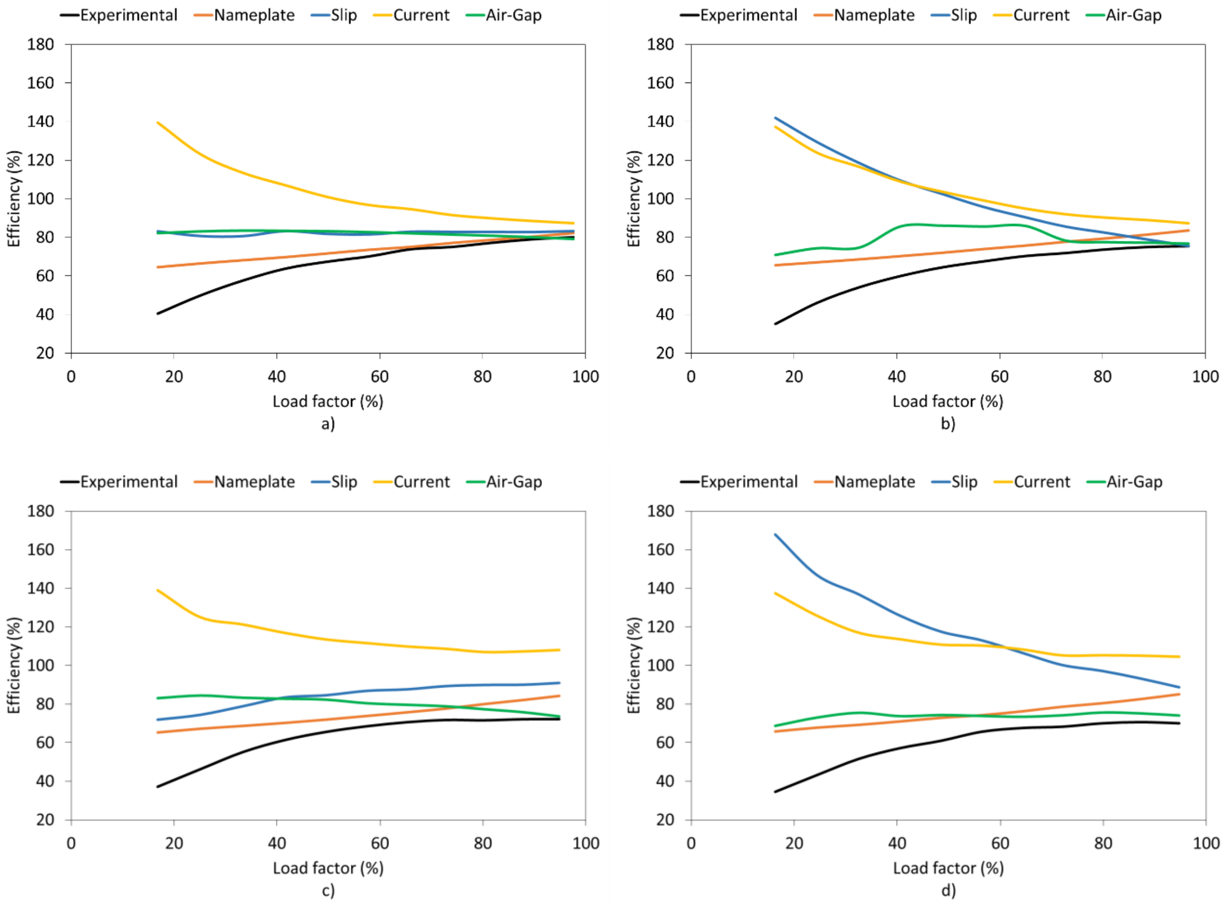

Fig. 8. Efficiency from experimental results and from EEEMs as a function of the load factor for: a) condition 1, b) condition 2, c) condition 3 and d) condition 4.

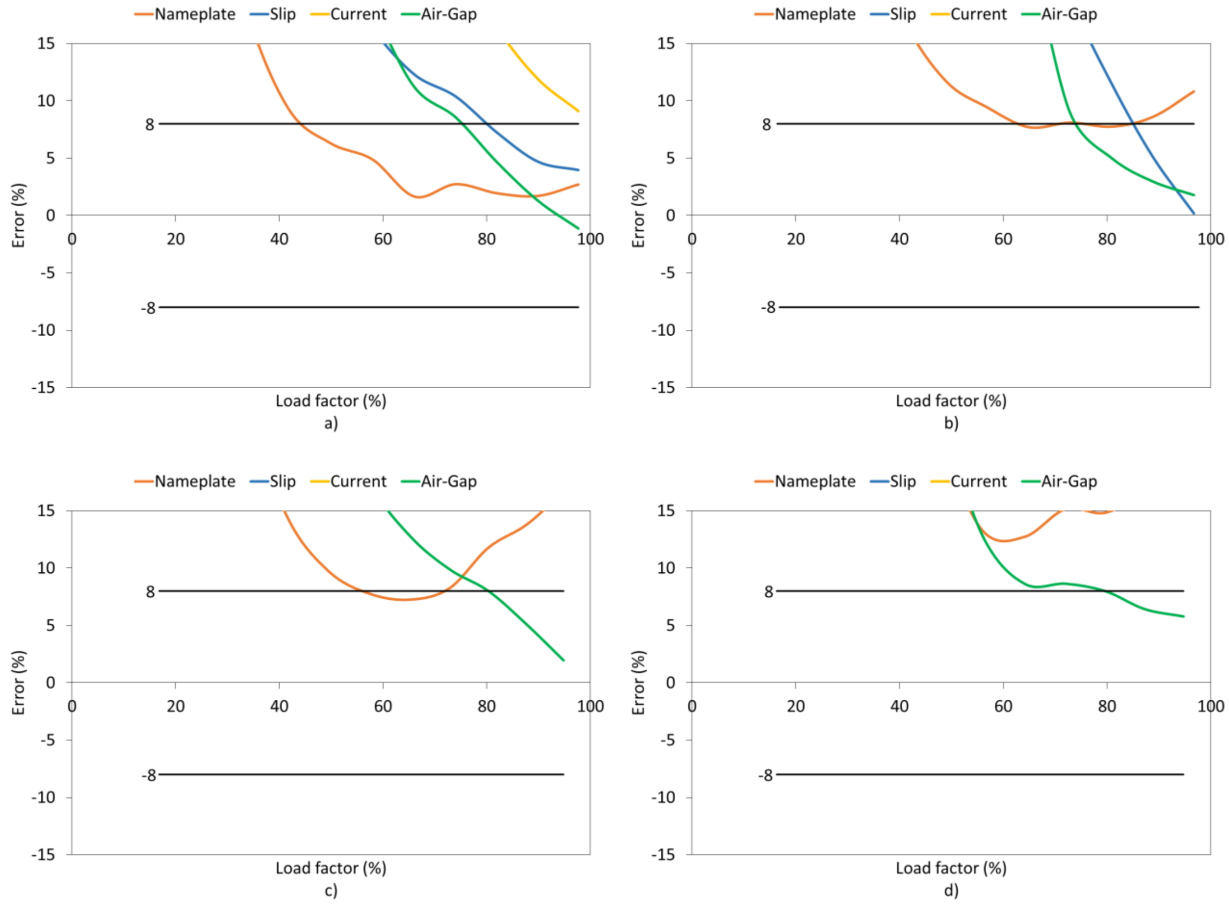

Fig. 9. Error of efficiency estimations with the EEEMs for: a) condition 1, b) condition 2, c) condition 3 and d) condition 4.

Results show that, as compared to the experimental results, the methods discussed overestimate the motor efficiency, in some cases with errors above the scale considered in figure. Under balanced sinusoidal voltage (condition 1, see fig. 9 a), the nameplate method estimated the motor efficiency with errors below the 8% for load factors over 40%, while for the slip and the air-gap methods is for load factors over 80%. The current method shows errors over 8% for all cases. Under balanced harmonic voltage (condition 2, see fig. 9 b), only the slip method (for load factors over 85%) and the air-gap method (for load factors over 70 to 80%) show results with errors below 8%. The remaining methods, significantly overestimate the efficiency with errors up to some 300%. Finally, in the presence of unbalance sinusoidal voltage (condition 3, see fig. 9 c) and unbalanced harmonic voltage (condition 4, see fig. 9 d), only the air-gap method estimated the efficiency with errors below 8%, for load factors over 80%. Under the four conditions, the current method resulted in estimations with errors over 8%, with efficiencies over 100%, which contradicts the energy conservation law. Therefore, the air gap method is suitable to estimate the motor efficiency under any condition, but for load factors over 80%. Additionally, the slip method can be used for conditions 1 and 2 (for load factors over 80%), while the nameplate method is only suitable for condition 1 (for load factors over 40%). Therefore, the accuracy of the EEEMs is significantly affected by the voltage unbalance and the harmonics. Additionally, the accuracy is considerably reduced for load factors below 80%. These results show the limitations of EEEMs for real-time estimations, mainly for electric motor under 500 HP (accounting for most of the motors in industry), which on the average operate below 60% of their load factor [4]. Overall, these results limit the use of EEEMs to estimate the energy efficiency of IM. Table 7 summarizes the applicability of EEEMs to estimate the energy efficiency of IM, as a function of the operational conditions and the load factor.

Table 7. Application results of EEEMs for efficiency estimation in different conditions.

Method	**Load factor (%)**											**Condition**
	0	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	
Nameplate					X	X	X	X	X	X	X	1
												2
												3
												4
Slip									X	X	X	1
									X	X	X	2
												3
												4
Current												1
												2
												3
												4
Air-gap									X	X	X	1
									X	X	X	2
									X	X	X	3
									X	X	X	4

The table shows that EEEMs are mostly applicable to accurately estimating the energy efficiency of IM, for load factors over 80%. Thus, considering that on the average IM operates below 60% of their load factor [4], EEEMs are seldom applicable to estimate their efficiency.

5. Conclusions

The methods developed to estimate energy efficiency of induction motors, can accurately estimate the efficiency for a limited range of load factors (mostly for load factors over 80%). The methods accuracy is significantly reduced with the reduction of the load factor. Furthermore, the presence of voltage unbalance, harmonics or the combination of both further reduce the methods accuracy.

Particularly, it is rather difficult to estimate the efficiency of induction motors accurately with the methods currently available. Moreover, the nameplate method is only applicable for load factors over 40%, under balanced sinusoidal voltage without harmonics, which is seldom the case in industrial facilities. The slip method can be also applied under this condition, and under balanced harmonic voltage, although for load factors over 80%. Finally, the air-gap method is applicable to all conditions for load factors over 80%. Therefore, in a scenario where most induction motors operate below 60% of the load factor; these methods are rather useless to estimate their energy efficiency. A source of error in this methods are mainly the considerations of mechanical and stray load losses, leading to a high level of uncertainty, mostly at partial loads and in the presence voltage unbalance and harmonics.

Overall, the methods currently available have a limited application for the real-time estimation of the energy efficiency in induction motors, especially in the presence of voltage unbalance and harmonic distortions.

Consequently, further research is required to develop new approaches to this end.

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