IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received August 23, 2021, accepted August 28, 2021, date of publication September 1, 2021, date of current version September 9, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3109622

Assessing Energy Efficiency and Power Quality Impacts Due to High-Efficiency Motors Operating Under Nonideal Energy Supply

JONATHAN MUÑOZ TABORA[1], MARIA EMÍLIA DE LIMA TOSTES[1], (Member, IEEE), UBIRATAN HOLANDA BEZERRA[1], EDSON ORTIZ DE MATOS[1], (Member, IEEE), CARLINDO LINS PEREIRA FILHO[2], THIAGO MOTA SOARES[1], (Member, IEEE), AND CARLOS EDUARDO MOREIRA RODRIGUES[1]

[1]Amazon Energy Efficiency Center (CEAMAZON), Federal University of Pará, Belém 66075-110, Brazil
[2]Faculty of Electrical Engineering, Institute of Technology, Federal University of Pará, Belém 66075-110, Brazil

Corresponding author: Jonathan Muñoz Tabora (jonathan_mt24@hotmail.com)

This work was supported in part by the Pro-Rectory of Research and Post-Graduate Studies —PROPESP/Universidade Federal do Pará (UFPA), in part by the Brazilian National Council of Scientific and Technological Research (CNPq), in part by Paulo Freire Program, and in part by Honduras Presidential Program 20/20 Scholarships.

ABSTRACT The search for more competitive equipment in the global market has led to the implementation of new materials and technologies in the search for greater energy efficiency. This is certainly a guideline followed by the electric motor industry that has introduced new technologies in rotating machines, such as the permanent magnet motor, evolving into increasingly efficient motor classes. However, subjecting these efficient motors under nonideal electric grid power conditions, such as voltage unbalance, can cause these efficient machines to generate additional distortions in the voltage and current waveforms, which in turn not only affect the performance of electric motors themselves but also that of the electrical system in general. This work presents a comparison between energy efficiency gain and the corresponding power quality degradation through a detailed harmonic analysis of the effects of voltage harmonics and voltage unbalance in three 0.75-kW electric motors classes: IE2, IE3, and IE4, The results show that for increasing percentages of a specific harmonic distortion, other harmonics are also increased in the higher efficiency electric motors sample analyzed, and similar responses were also observed for large percentages of voltage unbalance, mainly in the line-start permanent magnet motor class IE4. The results achieved are interesting but rigorously reflect only the tested motor sample and cannot be generalized to all motors, in other power ranges, of the respective motor classes tested. For generalization, exhaustive tests must be accomplished to formulate general conclusions according to the electric motors' classes commercially available.

INDEX TERMS Power quality, power system harmonics, voltage unbalance, energy conversion, electric motors, permanent magnet motor, energy efficiency, public policy, economics, industry applications.

I. INTRODUCTION

Over the years, the interest in implementing energy efficiency actions has been adopted by many countries, in search of a green and sustainable future. Different national and international programs have implemented actions promoting the search for greater operational efficiencies [1]–[3]. Actions include energy performance certificates, minimum energy performance requirements, mandatory energy audits, and financing for energy efficiency investments [4]–[6], among others.

Technological advances have also allowed new loads (devices, electric motors, etc.) to be more efficient, through improvements in materials, manufacturing processes, as well as the introduction of new technologies.

From the end user's point of view, the main benefits of energy efficiency actions in equipment must be seen from the economic point of view through the reduction of the energy bill, as well as more reliability and tolerance than less efficient technologies. This justifies the fact that

The associate editor coordinating the review of this manuscript and approving it for publication was Gerard-Andre Capolino.

the new equipment are built based on the efficiency, measured through experimental tests in certified laboratories, and through which different efficiency categories are defined.

Regarding electric motors, the reference parameter is efficiency, first classified by IEC 60034-30-1 [7] in 2008. Currently, four efficiency classes are defined by the standard, i.e., IE1, IE2, IE3, and IE4, and it is expected that the next edition defines the IE5 efficiency class. From this classification, manufacturers have presented different proposals to achieve ever greater efficiencies in electric motors. Studies comparing different technologies in electric motors have been presented in [8]–[12], synchronous reluctance motors, permanent magnet motors and copper rotor motors are the main alternatives to achieve higher efficiencies [13]. These new technologies present constructive variations in relation to their predecessors, as well as new components, such as permanent magnets, which respond differently to the disturbances present in electrical systems.

Given the greater efficiencies in electric motors, as a result of the implementation of new technologies, studies comparing different efficiency classes have been presented in [14]–[18], the economical, technical and ecological benefits as well as the main operational challenges are discussed in these works.

A study presented in 1997 reveals that harmonics caused approximately 17% of the disturbances in demand-side electrical systems [19]. Currently, a greater number of nonlinear loads are present in electrical systems due to the growth of electronic devices. Harmonics impacts not only depend on their magnitudes and orders in the electrical supply waveform but also on the type of load connected. Voltage harmonic distortion in the motor supply leads to additional harmonic losses in the rotor and stator, torque reduction, noise, slippage, and mechanical vibrations, all of which contribute to the increase in the motor's internal temperature, particularly in the windings and core of the stator [15], [20]–[23].

On the other hand, the effects of high-frequency harmonics on losses have been analyzed in [24], highlighting how high-frequency harmonics result in additional increases in rotor and total losses as well as an increase in noise during operation which in turn decrease induction motors (IM's) life. In [25], it is commented as these harmonics do not depend on the percentage of motor load, other disturbance present in all electrical systems is the voltage unbalance, and whose negative impacts can result in a decrease in the useful life of electrical equipment. Electric motors are also a load sensitive to voltage unbalance, which can also be accompanied by voltage magnitude variations. Studies relating both phenomena and their negative impacts on electric motor's torque, power factor, and efficiency have been presented in [14], [16], [26]–[32].

Other works presented in [33]–[35] have also considered complex voltage unbalance, which, unlike scalar unbalance, results in additional impacts such as torque pulsation and increased losses.

The simulation and validation have also been presented in [36], [37], where it is observed how the presence of voltage unbalance results in increases in losses and consequently a reduction in the useful life of the motor. The impact of voltage unbalance and harmonics in the electrical power systems and equipment has been presented in [20], [21], [38]–[40], where equipment malfunction, temperature increases, and reduction of useful life are the most considerable impacts, while those related to the impacts on power quality have been presented in [15], [16], [38].

Although the impacts of voltage harmonics (VH) and/or voltage unbalances (VU) on IMs have already been extensively investigated, the focus is mainly on performance and temperature analysis, and few works address the impacts of these phenomena on the increase or appearance of new harmonics in the input waveform of induction motors without a rigorous analysis of its own impacts on power quality. In addition, new scenarios arise with the introduction of new technologies as future substitutes for the conventional induction motor, such as the permanent magnet motor, which changes the paradigm of the conventional induction motor and its operating characteristics.

The introduction of new technologies translates into lower consumption and greater savings, making the substitution between technologies attractive. Given this scenario, studies on the performance of new technologies such as the line-start permanent magnet motor must be carried out to evaluate the advantages and points to consider in large-scale uses.

In this sense, this work presents a comparison between energy efficiency gain and power quality degradation related to electric motors. To that end, laboratory experimental tests on three 0.75-kW induction motors belonging to classes IE2, IE3, and IE4 were analyzed under ideal operating conditions, as well as in the presence of voltage harmonics and voltage unbalance with under- and overvoltage, with special focus on the harmonics generated by each disturbance. The results revealed that, for the motors sample analyzed in this work, the more efficient motors are more sensitive to disturbances in the electrical systems, also behaving as sources of amplification of existing harmonics in the presence of these disturbances, with which the doubt arises: Are the most efficient motors less efficient in power quality terms?

II. ENERGY EFFICIENCY POLICIES

A. INDUCTION MOTORS ENERGY EFFICIENCY POLICES

Minimum Energy Performance Standards (MEPS) defines the minimum efficiency class to be manufactured and marketed based on national and energy targets. In Brazil, the minimum efficiency level for electric motors from August 2019 is the IE3 class. Despite commercially existing proposals in the world to achieve higher efficiency classes, there is a global consensus that the IE3 class is the appropriate efficiency class at this time.

The main actions used to encourage the more efficient motors in new installations as well as the replacement

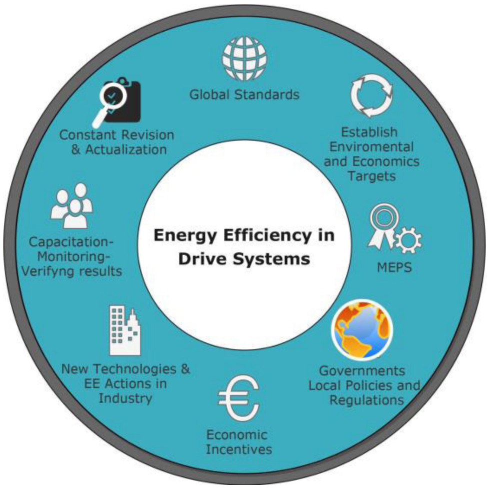


FIGURE 1. **Steps toward the implementation of energy efficiency actions on induction motor policies.**

of old/non-efficient motors are listed below and depicted in Figure 1.

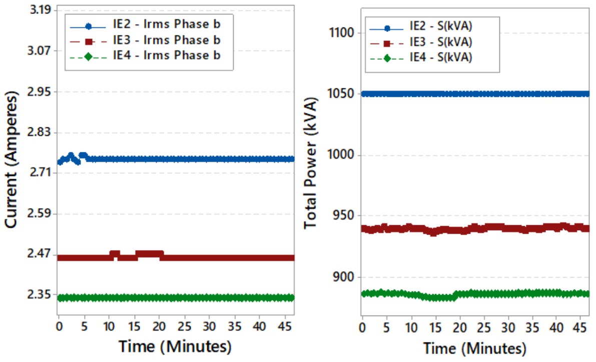
- The creation of global standards such as IEC 60034-30-1 and NEMA [29] to globally classify the efficiency classes in IMs and define the minimum efficiency levels to be within the classification [1], [7].
- The establishment of economic and environmental objectives to be met in defined periods for the correct implementation of minimum efficiency requirements for electric motors in accordance with national emission and energy reduction targets.
- The establishment of local regulations and policies by governments that define the minimum efficiency requirements as well as their classifications through departments destined for that purpose [1], [5], [41].
- The allocation of funds for the granting of incentives, through bonus to reduce the initial value of new motors, for the replacement of old/non-efficient motors or the purchase of new electric motors, as well as for research projects and development for the improvement of materials as well as the study of new technologies [6], [42], [43].
- Industry plays a key role in obtaining results. It must be the focus of regulations, motivating this sector to implement new more efficient technologies, as well as energy efficiency actions.
- The implementation of training and technical advice on the best paths to greater efficiencies as well as constant monitoring and verification.
- The constant verification and updating considering the results obtained, the definition of new routes toward greater efficiencies, considering the new technologies present in the market and updating the standards according to the indicators.

B. PROCESS TOWARD MORE EFFICIENT MOTORS

Modernization of industrial processes has also required more efficient drive systems. Different manufacturers offered higher efficiencies for the same nominal power, due to the materials and processes used in the construction of these rotative machines. However, it was not until 2008 that the IEC defined three efficiency classes, namely, IE1, IE2, and IE3.

The motors that did not reach the efficiency class IE1 were classified as IE0 and called unregulated motors, which by the year 2000 represented 80% of global electricity consumption by electric motors. With the implementation of policies and regulations that promoted the substitution between technologies, as well as the end of their useful life, this percentage went to be 30% of energy consumption in 2017. However, in this year, consumption by electric motors seems to be twice that of the year 2000 with which the IE0 class motors consumption in 2017 was two-thirds of those that existed in the year 2000, and there are still many opportunities for substitution.

In 2014 the efficiency class IE4 was defined, with which efficiencies greater than 96% can be obtained with IMs. When these classifications were defined, the manufacturers understood that they would have to go beyond conventional induction motors to get higher efficiencies, and in this way new technologies were explored and perfected, coming up with proposals such as a copper rotor motor, the synchronous reluctance motor, and the permanent magnet motor, the latter present in this study.



(a) (b)

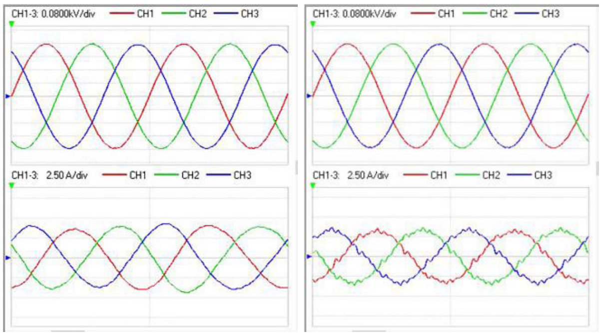
FIGURE 2. **High efficiency motors comparison: (a) Phase b total current and (b) total power in IE2, IE3 and IE4 class motors [16].**

C. COMPARISON BETWEEN TECHNOLOGIES

To compare the economy between technologies, measurements were made under the same nominal load conditions, considering the three 0.75-kW electric motors sample mentioned previously, which belongs to the efficiency classes IE2, IE3, and IE4. Figure 2 shows the total current and power of each technology. It is observed how the LSPMM presents decreases of 14% and 5% in relation to the total current and of 17% and 6% in relation to the total power comparing with IE2 and IE3 class motors, respectively.

Even though the only constructive difference between these technologies is the permanent magnets in the rotor, the IE4 class permanent magnet motor presents the lowest currents and consumption of the three technologies analyzed. Permanent magnets influence both in the reduction of the total current, by reducing the magnetization current due to the magnetic field of the magnets and consequently total consumption. Moreover, synchronous operation results in lower rotor losses and therefore lower internal and external temperatures.

However, permanent magnets result in a more distorted current waveform, as shown in Figure 3, compared with SCIM. The predominant current harmonics found in the LSPMM are those of the 3rd, 5th, 7th, 17th, and 23rd orders, while for the IE2 and IE3 class motors, the current harmonic content presents small percentages of 3rd and 7th orders resulting in a visibly lower total distortion rate, as depicted in Figure 4. It is observed how the LSPMM presents a higher current total harmonic distortion when compared to the IE2 and IE3 class motors.



(a) (b)

FIGURE 3. Voltage (up) and current (down) in phases A-B-C for (a) IE3 SCIM and (b) IE4 LSPMM [16].

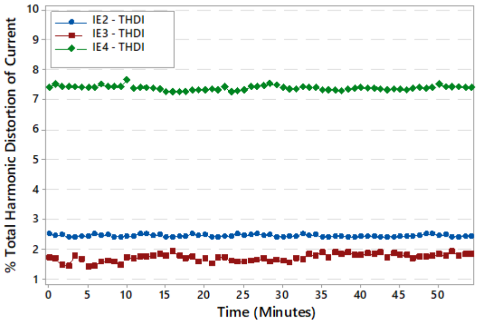
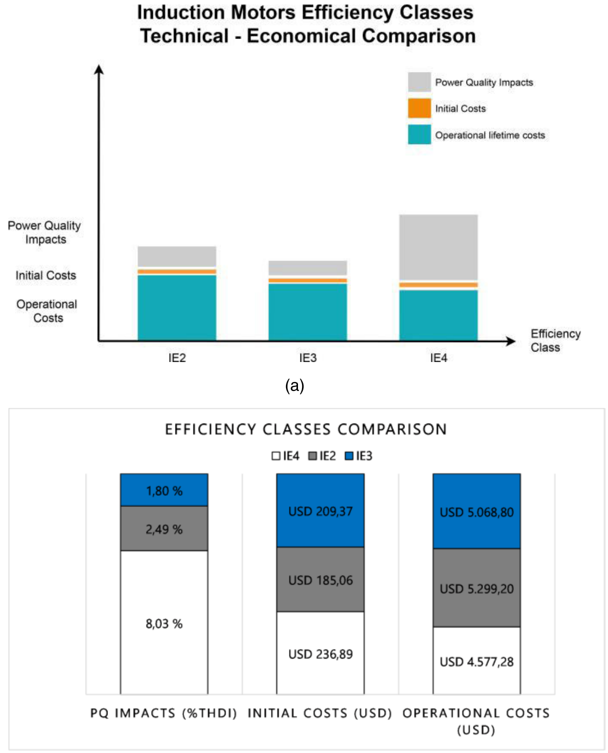


FIGURE 4. Total harmonic distortion of current for IE2, IE3, and IE4 class motors [16].

The implementation of high-quality materials translates into higher initial costs; however, the initial cost represents less than 5% of the operating cost of the electric motor during its useful life. To better analyze the efficiency of electric motors, estimates were made from the recorded measurements presented in Figure 2, as well as the initial purchase and operating costs throughout the useful life of each motor, aiming to compare them from an economic and power quality points of view, as presented in Figure 5 (a), so the economy with the purchase of electric motors with different efficiency classes must be observed considering the reduction in consumption and the estimated useful life according to the motor's nominal power.

Figure 5 (b) shows a detailed comparison between initial cost, operational costs throughout its useful life, and its impact on power quality for the three 0.75-kW, IE2, IE3, and IE4 electric motors classes, considering the consumption measured and presented in Figure 2, with 8,000 operation hours, and an electric energy cost of USD 0.08/kWh.



(a)

(b)

FIGURE 5. Cost-benefit-impacts relation for efficient motors: (a)Technical (power quality) and economical comparison for IE2, IE3, and IE4 class motors and (b) quantitative comparison in economic and technical terms [16].

It can be seen how at an economic point of view the implementation of more efficient electric motors results in greater long-term savings, regardless of their initial cost. This is undoubtedly the main motivation for replacing less efficient motors by more efficient ones. However, their impacts on a large scale, including issues related to power quality regulation, must also be analyzed to verify if the industrial installation complies with current legislation with respect to energy quality indicators, such as total harmonic distortions of current and voltage at the point of common coupling with the electrical network. To better clarify this point, the IE4 class LSPMM is cited, as presented in Figures 2, 3, 4, and 5, as being the most efficient but the most impacting with respect to harmonic distortion.

III. VOLTAGE UNBALANCE AND VOLTAGE HARMONICS

A. VOLTAGE UNBALANCE

Voltage unbalance in the motor energy supply results in large negative impacts according to the unbalance degree. The presence of voltage unbalance results in three main components: positive, negative, and zero sequences. Because most motors are connected in delta or ungrounded wye, there is no path to neutral for zero sequence components to flow. From there, both resulting components (positive and

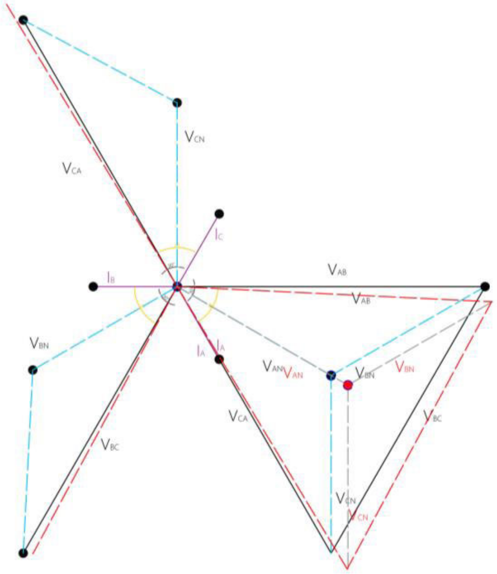


FIGURE 6. **Balanced and unbalanced voltage conditions diagram.**

negative) produce different impacts, one contributing to the resulting torque while the second creating opposite magnetic fields, resulting in greater oscillations and speed reduction as a resulting lower torque [44]. The presence of VU also results in unbalanced currents in the stator windings. Normally, the current unbalance is 6–10 times the voltage unbalance, which causes the winding to overheat [17], [39]. To better analyze this fact, see Figure 6 for an ungrounded wye connected motor. The line voltages at the electric motor's terminals are given by

$$\begin{aligned} \overline{V}_{AB} &= \overline{V}_{AN} - \overline{V}_{BN} \\ \overline{V}_{BC} &= \overline{V}_{BN} - \overline{V}_{CN} \\ \overline{V}_{CA} &= \overline{V}_{CN} - \overline{V}_{AN} \end{aligned} \tag{1}$$

The phase voltages, in blue lines, are 120° out of phase with each other. The phasor sum of the components results in the line voltages, as presented in (1). When added together, it is observed that the line voltages are $\sqrt{3}$ times the phase voltages and are also 30° ahead. Within the same diagram, the currents are observed, out of phase of the line voltages a phi (Ø) + 30° angle, which corresponds to the load power factor, and in this case an angle of 60° was assumed.

Under equilibrium conditions, the sum of both voltages and currents results in zero, as can be seen in the gray inverted triangle formed with the phase voltage phasor sum and line voltages. Voltage unbalance can occur by several factors, one of which is the unbalance of phase voltages due to unequal phase loading conditions. It can be seen how the phase magnitude unbalance results in variations in both the magnitude and the angle of the line voltages, resulting in a phase shift of the triangle, as observed in red lines.

To analyze this condition, the voltage unbalance factor (VUF) concept will be analyzed as follows:

From (2) it is stated that

$$VUF\,(\%) = k_v = \frac{V_N}{V_P} \tag{2}$$

where V_N and V_P are negative and positive sequence voltages, respectively.

Positive and negative sequence currents can be calculated using the ohm law between positive and negative sequence voltages and impedances, as shown in (3) and (4)

$$I_P = \frac{V_P}{Z_P} \tag{3}$$

$$I_N = \frac{V_N}{Z_n} \tag{4}$$

In this way, the line currents will be the sum of the positive and negative sequence components, as shown in (5):

$$\begin{aligned} \overline{I}_A &= \overline{I}_P + \overline{I}_N \\ \overline{I}_B &= a^2\overline{I}_P + a\overline{I}_N \\ \overline{I}_C &= a\overline{I}_P + a^2\overline{I}_N \end{aligned} \tag{5}$$

where $a = 1\measuredangle 120^\circ$

As noted in (5), the stator currents are the respective sum of the positive and negative sequence components. Furthermore, in (3) and (4), it is observed that these parameters depend on the positive and negative sequence voltages and impedances, respectively.

Moreover. the degree of current unbalance (current unbalance factor) can be calculated in the same way as the VUF, as presented in (6):

$$CUF\,(\%) = k_c = \frac{|I_N|}{|I_P|} = \frac{V_N/Z_N}{V_P/Z_P} = \frac{Z_P}{Z_N}k_v \tag{6}$$

In a motor with balanced voltages, only a positive sequence component exists; thus, the presence of voltage unbalance is a condition in which the negative and zero sequence components impact the positive sequence component. In motors with a delta connection, the main cause of the unbalance is the negative sequence component. It was also observed in (6) that the relationship Z_P/Z_N represents the variation in the current unbalance in relation to the voltage unbalance. Section IV presents the test bench and methodology used to analyze the impacts of VU on power quality.

B. VOLTAGE HARMONICS

The joint impact of all harmonics in a waveform is known as total harmonic distortion (THD), which is one of the most used parameters to evaluate the voltage or current quality. The mathematical expression is given by (7):

$$THD\% = \frac{\sqrt{\sum_{h=2}^{h_{max}} V_h^2}}{V_1} * 100 \tag{7}$$

where V_h is the h^{th} order harmonic voltage, V_1 is the fundamental measured voltage, and h_{max} is the order of the maximum harmonic considered.

TABLE 1. **Induction motors parameters [16].**

IM Class	IE2	IE3	IE4
Technology	SCIM,	SCIM	LSPMM
Power	0.75 kW	0.75 kW	0.75 kW
Voltage	220/380 V	220/380 V	220/380 V
Speed (rpm)	1730	1725	1800
Torque (Nm)	4.12	4.13	3.96
Current (A)	2.98/1.73	2.91/1.68	3.08/1.78
Efficiency (%)	82.6	82.6	87.4
Power Factor	0.80	0.82	0.73

Harmonic effects on induction motors vary according to the harmonic order, as well as the harmonic percentage present in the supply voltage, and they are classified as harmonics of positive, negative, and zero sequence. As most motors are connected in a delta connection, or non-grounded star, there is no way for the zero sequence harmonics to circulate and therefore do not result in any negative impact. Positive sequence harmonics on rotating machines result in positive torque and small increase in line current. The negative sequence harmonics turn out to be the most damaging for rotating machines, by producing a contrary torque to the resulting one, which results in a reduction of the total torque, vibrations, increase in the line currents, and decreases in the power factor and efficiency. Aiming to observe the impact of voltage harmonics on power quality, the following section shows the methodology used to assess the impacts of harmonics in induction motors.

IV. METHODOLOGY AND RESULTS

A. METHODOLOGY

Measurements were performed in the Amazon Energy Efficiency Center (CEAMAZON) located at the Federal University of Pará (UFPA) in Belem City, Brazil, to analyze the influence of voltage unbalance with under- and overvoltage and voltage harmonics on the power supply of the three induction motors classes, i.e., IE2, IE3, and IE4. Figure 7 shows the general test setup.

The balanced and pure sinewaves as well as the voltage unbalances and harmonics were generated using a three-phase AC source model FCATHQTM (1), capable of generating a pure sine voltage waveform as well as voltage unbalances, sags, swells, and harmonics (up to the 50th order) with different distortion magnitudes. The IM's input parameters were measured using the class "A" quality analyzer HIOKI^{TM} (2) model PW3198-90. The electric load used in this work then consists of an electromagnetic brake or Foucault brake (3). For the study, a torque of 3.8 Nm was applied to the Foucault brake, representing 92–95% of the IE2 class motor nominal torque. (4). Table 1 presents the nominal data of each motor.

At first, the induction motors were subjected to a 220-V perfect three-phase sine voltage for 1 h and 10 min so that they reached their thermal equilibrium. In a second moment, the value of each voltage harmonic (2nd, 3rd, 5th, and 7th) was increased by 2% every 10 min, until it reached 25%.

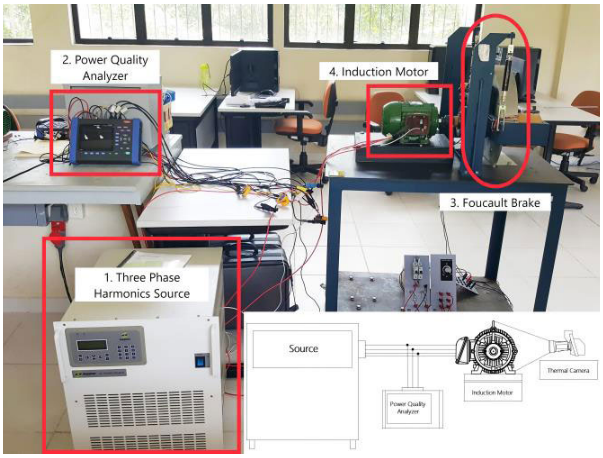


FIGURE 7. **General test setup used for the experimental tests [16].**

In relation to voltage unbalance, after reaching the thermal equilibrium, voltage unbalances with 1%, 3%, and 4% according to NEMA definition with under- and overvoltages were inserted separately in each of the motors for a period of an hour until the thermal equilibrium was reached again. It should be noted that only voltage magnitudes were varied; the phase angles remained constant. Table 2 presents voltage magnitudes for each voltage unbalance.

TABLE 2. **Voltage unbalance magnitudes [16].**

% NEMA Voltage Unbalance	Vab	Vbc	Vca
1% Undervoltage	217.34 V	219.67 V	214.03 V
3% Undervoltage	217.72 V	214.46 V	206.8 V
4% Undervoltage	197.15 V	206.69 V	214.35 V
1% Overvoltage	220.40 V	224.54 V	221.2 V
3% Overvoltage	235.85V	233.57V	224.28V
4% Overvoltage	227.91 V	219.89 V	237.57V

Regarding the methodology used for the treatment of measurement data and obtaining the results, Figure 8 presents the steps performed in the present work. At first, the tests with VH and VU were performed separately on the test bench for each of the motors analyzed, and then the measurements were made using the Power Quality analyzer equipment. The next step was to transfer the measurement data from the equipment to the analyzer (HIOKI) software. After data analysis, they were converted to CSV format files, compatible for reading in Minitab (Minitab 18) statistical software. In Minitab, the data were processed for plotting the results related to harmonic analysis.

B. VOLTAGE HARMONICS IMPACTS

The presence of voltage harmonics results in the decrease of the rotation speed for the electric motors analyzed. Figure 9 shows the speed variations in the presence of 2nd and combined 2nd, 3rd, 5th, and 7th voltage harmonics for the three IM classes.

It is observed that the second negative sequence harmonic results in greater decreases for the IE2 class SCIM, falling

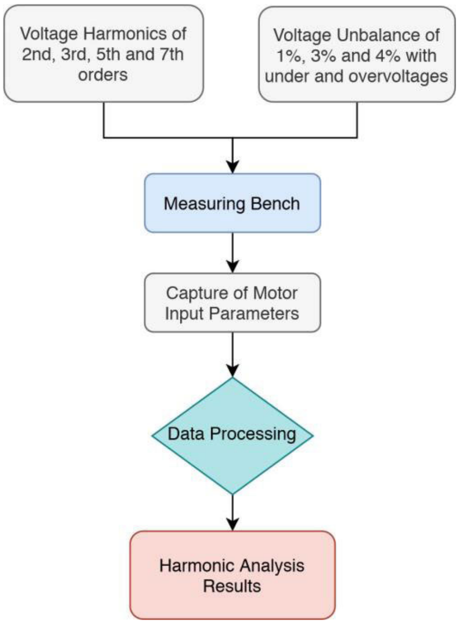


FIGURE 8. Flowchart of the methodology used in the work.

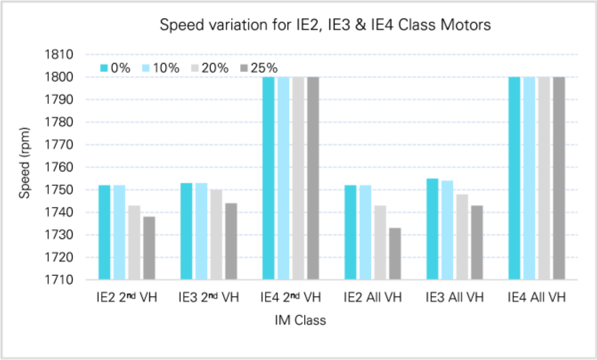


FIGURE 9. Speed variation for IE2, IE3, and IE4 class motors in presence of 2nd and combined 2nd, 3rd, 5th, and 7th voltage harmonics.

from 1752 rpm to speed values of 1738 rpm, while the IE3 class motor decreases from 1753 rpm to 1744 rpm with 25% distortion. The combination of all the harmonics then results in the greatest decreases in speed, the IE2 class SCIM again being the most affected. For the LSPMM, once the synchronism is reached, the presence of these disturbances does not result in any variation of speed both in the presence of VH and VU.

Figure 10 shows the impact of the 5th and 7th voltage harmonics of positive and negative sequence, respectively. It is observed how both harmonics result in decreases in the speed of SCIM, the 5th harmonic being the most damaging. It should be noted that despite the 7th harmonic being of positive sequence (produces a positive torque), it also results in a decrease in speed.

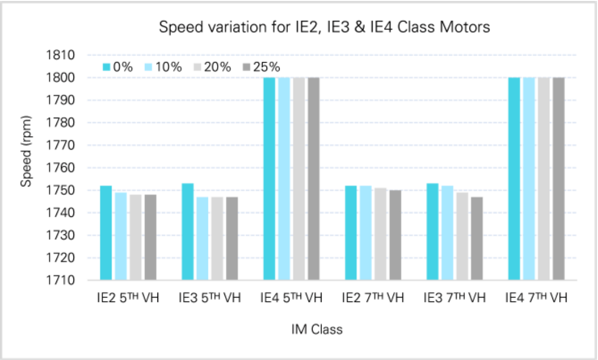
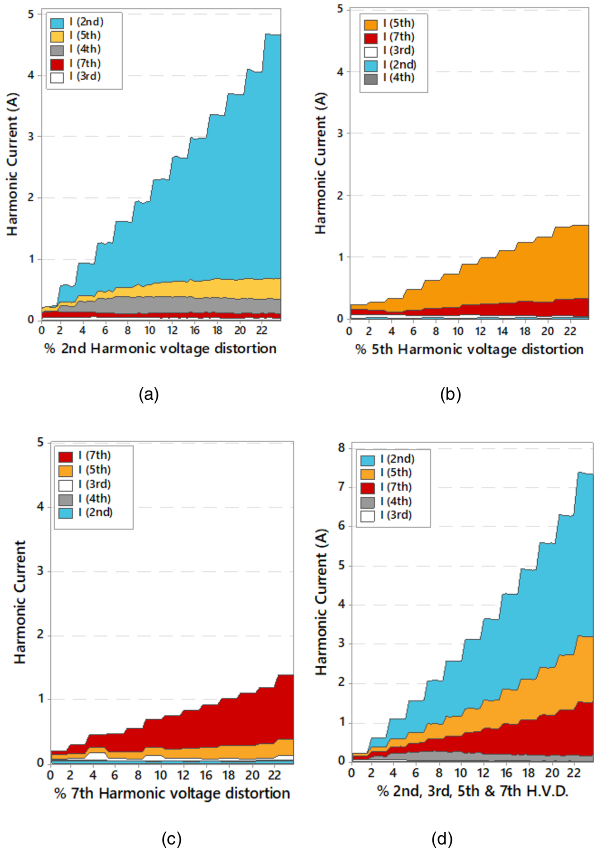


FIGURE 10. Speed variation for IE2, IE3, and IE4 class motors in the presence of 5th and 7th voltage harmonics.



(a) (b)

(c) (d)

FIGURE 11. Harmonic currents present in IMs with varying harmonic voltage distortion of (a) 2nd harmonic order; (b) 5th harmonic order; (c) 7th harmonic order; (d) 2nd, 3rd, 5th, and 7th harmonic order combined.

To explain this phenomenon, an analysis considering the harmonics present in the waveform was developed for the three IMs analyzed and is shown in Figure 11. It was observed that when the voltage distortion percentage of 7th order harmonic was increased, the 5th-order harmonic current component also increased mainly for distortions greater than 8%, as shown in Figure 11(c). As it is a negative sequence harmonic, it can result in contrary torques, which reduces the speed in the motor shaft.

This situation was also observed for the 2nd and 5th negative sequence harmonics. When the percentage of 5th harmonic of negative sequence is increased, the 7th harmonic current component also increased accordingly, as seen in Figure 11(b), while when the 2nd harmonic is increased, the 4th- and 5th-order harmonic current components become significant. The 4th order also appeared in the presence of all the harmonics analyzed. Despite the fact that these harmonics appear in the three analyzed motors, the percentages found

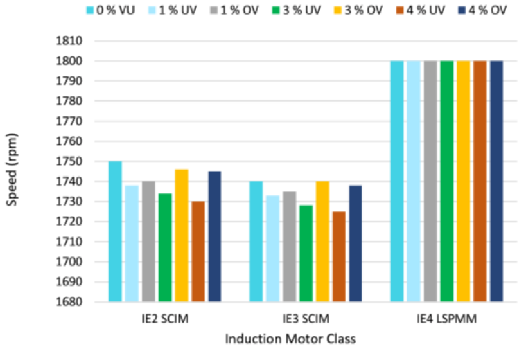
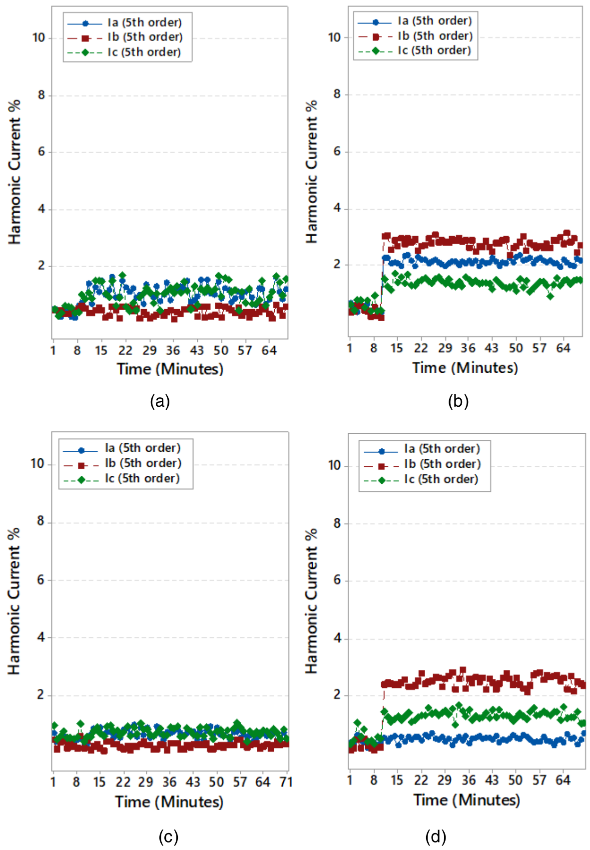


FIGURE 12. **Speed variation for IE2, IE3, and IE4 class motors in the presence of 0–4% voltage unbalance conditions with under- and overvoltages.**

were higher for the line-start permanent magnet motor class IE4, however, without impacting its speed.



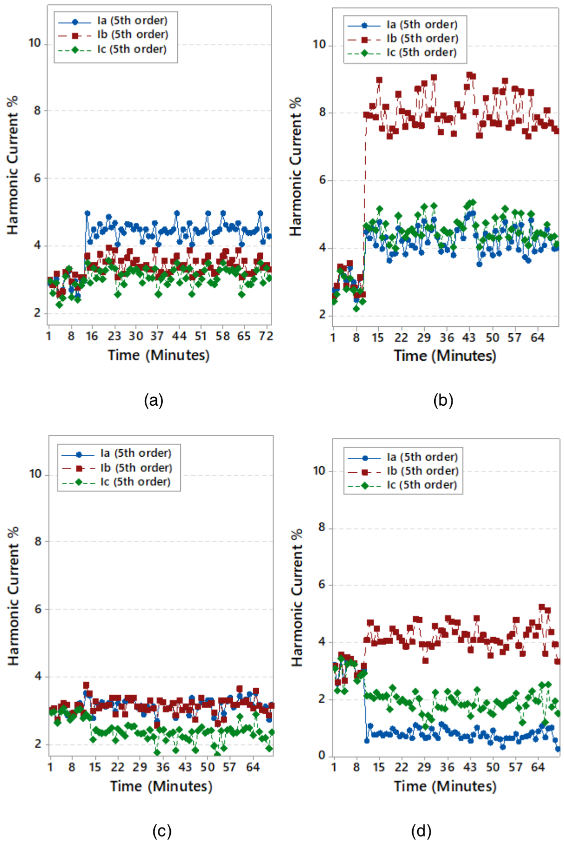
(a) (b)

(c) (d)

FIGURE 13. **Fifth harmonic current variations for phases a-b-c for the IE3 class motor for (a) 1% VU with undervoltage; (b) 4% VU with undervoltage; (c) 1% VU with overvoltage; (d) 4% VU with overvoltage.**

C. VOLTAGE UNBALANCE IMPACTS ON HARMONICS

Despite many studies that focused on the impact VU has on IM's operation, the impact that this disturbance has on voltage and current harmonics in electric motors has not been deeply analyzed. In this way and aiming to analyze the impact of this disturbance on the power quality, this section analyzes the relationship that exists between the voltage unbalance, the harmonics already existing, and those that arise with the presence of this disturbance in the electric motors presented in this study.



(a) (b)

(c) (d)

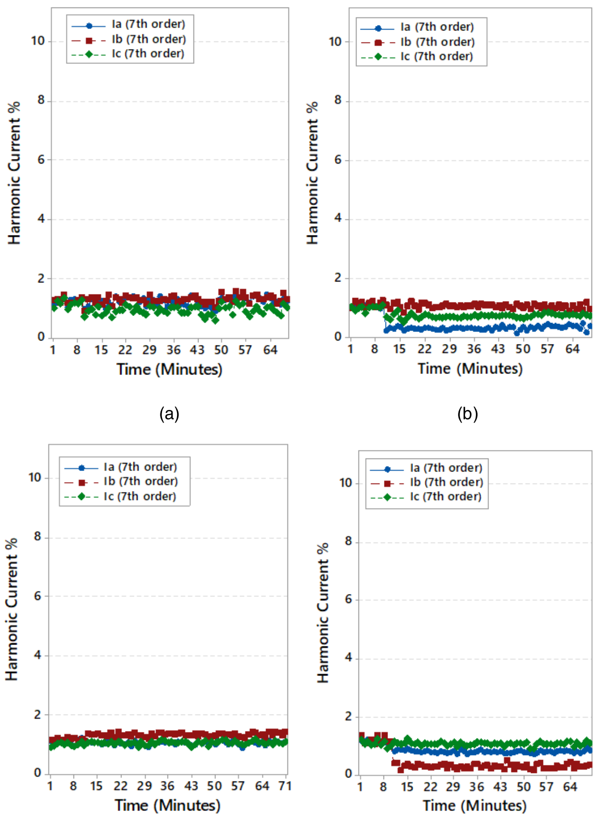
FIGURE 14. **Fifth harmonic current variations for phases a-b-c for the IE4 class motor for (a) 1% VU with undervoltage; (b) 4% VU with undervoltage; (c) 1% VU with overvoltage; (d) 4% VU with overvoltage.**

Unbalanced voltages also result in decreases in the speed of electric motors according to the type of technology, as well as the loading percentage. Figure 12 shows speed variations due to six VU conditions with under- and overvoltage. In general, it is observed that the voltage unbalance with undervoltage (UV) results in greater decreases in speed when compared to the voltage unbalance with overvoltage (OV).

In addition, voltage unbalance also results in increases in the harmonics currents according to the voltage magnitude, the VU degree as well as the IM technology. Figures 13 and 14 show the variation of the 5th-order harmonic current percentage for the IE3 and IE4 motors, respectively, for 1% and 4% VU with under- and overvoltage. The class IE2 motor presented percentages like those of the IE3 class motor.

Initially the voltage supply is perfectly balanced for phases A-B-C. An abrupt variation in the 5th harmonic current magnitude is then observed for both technologies, when inserting the VU, being more accentuated for the LSPMM, as seen in Figure 14.

It can also be observed that for IE2 and IE3 class motors, the VU with under- and overvoltage results in similar distortion degrees, while for the LSPMM the VU with undervoltage results in distortion degrees of up to twice that found in the



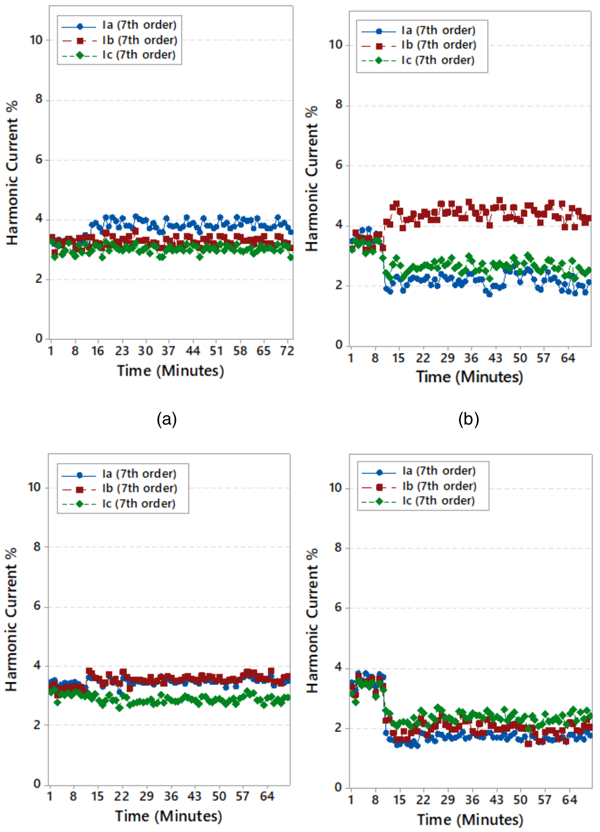
(a) (b) (c) (d)

FIGURE 15. Seventh harmonic current variations for phases a-b-c for the IE3 class motor for (a) 1% VU with undervoltage; (b) 4% VU with undervoltage; (c) 1% VU with overvoltage; (d) 4% VU with overvoltage.

condition with overvoltage, as shown in Figure 14. Despite the increase in this negative sequence harmonic, it does not impact on the motor synchronous operating speed, for the unbalance degrees analyzed, as presented in Figure 12.

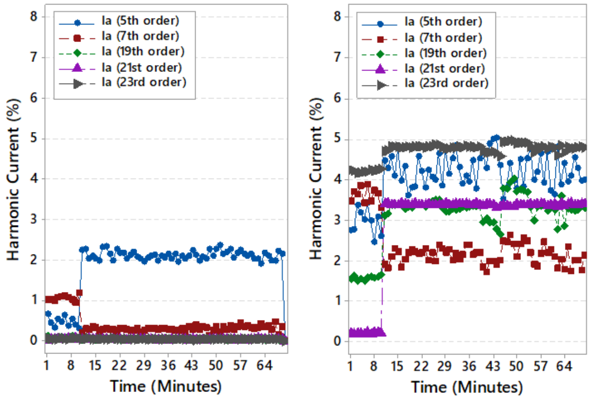
The variation of the 7th positive sequence harmonic current was also analyzed for the three tested electric motors and is presented in Figure 15. Lower percentages of harmonic currents, when compared to the 5th negative sequence harmonic current, are observed. Moreover, this harmonic current did not follow the 5th harmonic growth pattern, undergoing significant abrupt variations when inserting the voltage unbalance. For the IE2 and IE3 class motors, the increase in VU results in a decrease in the harmonic percentage, both for the under- and overvoltage unbalance conditions.

Regarding the LSPMM, presented in Figure 16, voltage unbalance also resulted in a variation of the 7th-order harmonic currents. It is observed that in the case of VU with undervoltage, increases in one of the phases are observed for 1% and 4%, respectively. VU with overvoltage resulted in an increase in two of the phases for 1%, while it resulted in a decrease for 4%. It is further observed that like the 5th negative sequence harmonic, the 7th positive sequence harmonic also presents significant initial abrupt variation in the harmonic magnitude when inserting these voltage unbalance conditions.



(a) (b) (c) (d)

FIGURE 16. Seventh harmonic current variations for phases a-b-c for the IE4 class motor for (a) 1% VU with undervoltage; (b) 4% VU with undervoltage; (c) 1% VU with overvoltage; (d) 4% VU with overvoltage.

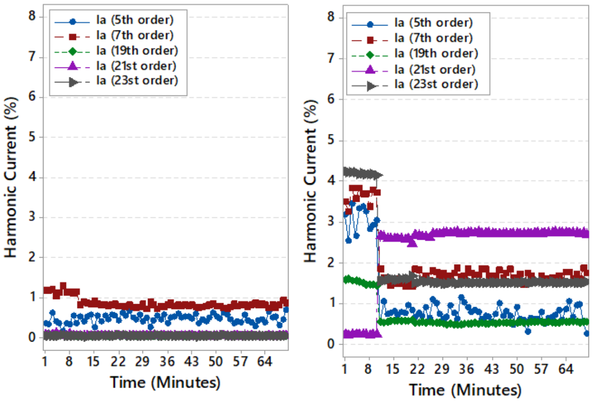


(a) (b)

FIGURE 17. Phase "a" harmonic current variation for 4% voltage unbalance with undervoltage for (a) IE3 and (b) IE4 class motors.

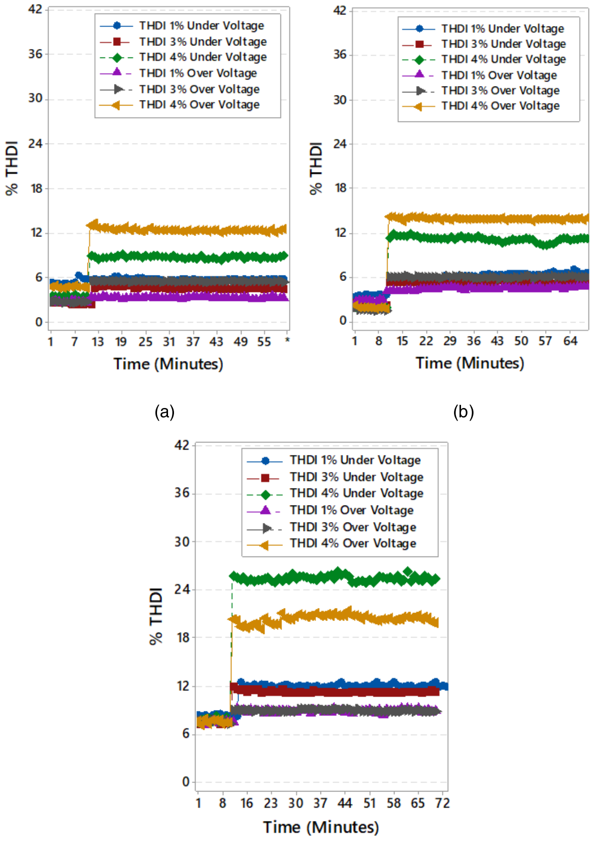
It has been observed that using permanent magnets results in a higher harmonic content, as can be noted for the LSPMM, mainly with higher-order harmonics. To exemplify this point, Figures 17 and 18 present the main current harmonics found for the IE3 and IE4 class motors for 4% voltage unbalance with under- and overvoltages, respectively.

As shown in Figure 17(b), the 19th-, 21st-, and 23rd-order harmonics are present in the waveform before the motor is subjected to VU. Then applying 4% VU with under voltage,



(a) (b)

FIGURE 18. Phase "a" harmonic current variation for 4% voltage unbalance with overvoltage for IE3 (a) and IE4 (b) class motors.



(a) (b)

(c)

FIGURE 19. Total current harmonic distortion for under- and overvoltage unbalance conditions for (a) IE2 SCIM, (b) IE3 SCIM, and (c) IE4 LSPM.

it is observed that the 7th harmonic order component suffers a decrease, while the 5th-, 19th-, 21st-, and 23rd-order components undergo increases, highlighting the 21st order that became very significant with voltage unbalance. Figure 18(b) then shows that with VU and overvoltage, the harmonics in the LSPMM tend to decrease, except for the 21st-order harmonic that increased with this VU condition.

This scenario occurs only for the LSPMM, while the IE2 and IE3 class motors present similar variation pattern, varying only 5th and 7th current harmonics as shown in Figures 17(a) and 18(a).

As a consequence of the current harmonic variation resulting from the voltage unbalance, the total current harmonic distortion also undergoes variations in relation to ideal power conditions. Figure 19 shows the THDI of each motor for each analyzed unbalance condition. In general, the voltage unbalance results in an increase in the total current harmonic distortion rate, which is worse for the LSPMM, which initially shows THDI of up to four times that of classes IE2 and IE3 motors. With the presence of voltage unbalance, these percentages then reach values of up to 24% THDI; more than double that of the IE2 and IE3 class motors. The worst scenarios observed are 4% VU with under- and overvoltage, as shown.

V. CONCLUSION

The search for efficiency in electric motors has led to the implementation of new technologies, resulting in considerable savings in relation to consumption and greater tolerance to the disturbances present in electrical systems in operational terms. The substitution of old/non-efficient motors with high-efficiency motors represents a key aspect in ecological and economical terms. To that end, policies, regulations, incentives, and training represent key elements. The introduction of new technologies also plays a fundamental role to achieve greater efficiencies.

However, in parallel, the IM's response in nonideal power conditions should be observed, in addition to the operational efficiency, considering the common disturbances present in electrical systems. Based on that, the present work presented a comparison of the harmonic response of three different efficiency classes' electric motors in the presence of voltage harmonics and voltage unbalance with voltage variations.

The results showed that the presence of voltage harmonics may result in amplification of current harmonics in electric motors for distortion percentages greater than 8% as well as in significant variations of other harmonic currents in the analyzed electric motors including negative and positive sequence harmonics, which ends up increasing the total harmonic distortion rate of the network. It was also observed how these new harmonics presented higher percentages for the higher efficiency motor analyzed (line-start permanent magnet motor).

This work also presented how the voltage unbalance results in an increase in the current total harmonic distortion for the three technologies, with higher percentages for the LSPMM.

Finally, from the results presented, it is possible to establish some general guidelines that may be considered as recommendations:

- Replacing old/non-efficient electric motors with higher efficiency motors results in better economic benefits for the end user.
- New technologies can represent a challenge for electric utilities mainly in terms of power quality and large-scale uses.

- Regulatory institutions must also observe the power quality impacts of higher efficient motors, so that manufacturers implement solutions to the challenges that the implementation of new technologies in induction motors can bring to the electric power systems.

Despite the observed impacts of voltage unbalance and voltage harmonics on power quality, the analyzed sample (three electric motors) only allows us to conclude in relation to this output power (0.75 kW). In this way, it is important to analyze the effects observed in this work with a larger sample of motors of different powers in accordance with IEC 60034-30-1 to make more general conclusions.

REFERENCES

[1] *US Department–Energy Police Act 1992 (EPAct), Public Law 102-486–Oct. 24, 1992*. Accessed: Jul. 26, 2020. [Online]. Available: https://afdc.energy.gov/files/pdfs/2527.pdf

[2] Official Diary of the Union. *Interministerial Ordinance no 1, of 29 June 2017–National Press*. Accessed: Mar. 8, 2020. [Online]. Available: http://www.in.gov.br/materia

[3] A. Anibal, B. Rob, B. U. Conrad, D. Martin, and H. William. (Feb. 2009). *Motor MEPS Guide*. 1st Edition Zurich Switzerland. Accessed: May 27, 2020. [Online]. Available: https://www.motorsystems.org/files/otherfiles/0000/0100/meps_guide_feb2009.pdf

[4] A. Fytrou-Moschopoulou. (Mar. 31, 2017). *European Commission: Good practice in Energy Efficiency*. Build Up. Accessed: Jul. 19, 2020. [Online]. Available: https://www.buildup.eu/en/practices/publications/european-commission-good-practice-energy-efficiency-0

[5] *Minimum Energy Performance Standards (MEPS)–Policies*. IEA. Accessed: Jul. 26, 2020. [Online]. Available: https://www.iea.org/policies/333-minimum-energy-performance-standards-meps

[6] ANEEL. *Call. 002/2015 Priority Energy Efficiency Project: 'Encouraging the Replacement of Electric Motors: Promoting Energy Efficiency in the Driving Power Segment'*. Accessed: Mar. 8, 2020. [Online]. Available: https://www.aneel.gov.br/sala-de-imprensa-exibicao/-/asset_publisher/XGPXSqdMFHrE/content/chamada-de-projeto-para-incentivar-substituicao-de-motores-eletricos-e-prorrogada/656877?inheritRedirect=false

[7] *Rotating Electrical Machines–Part 30-1: Efficiency Classes of Line Operated AC Motors (IE Code)*, Standard IEC 60034-30-1:2014, Accessed: Aug. 15, 2019. [Online]. Available: https://webstore.iec.ch/publication/136

[8] H. Karkkainen, L. Aarniovuori, M. Niemela, J. Pyrhonen, and J. Kolehmainen, "Technology comparison of induction motor and synchronous reluctance motor," in *Proc. 43rd Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Oct. 2017, pp. 2207–2212, doi: 10.1109/IECON.2017.8216371.

[9] R. M. Pindoriya, B. S. Rajpurohit, R. Kumar, and K. N. Srivastava, "Comparative analysis of permanent magnet motors and switched reluctance motors capabilities for electric and hybrid electric vehicles," in *Proc. IEEMA Engineer Infinite Conf. (eTechNxT)*, Mar. 2018, pp. 1–5, doi: 10.1109/ETECHNXT.2018.8385282.

[10] A. Castagnini, T. Kansakangas, J. Kolehmainen, and P. S. Termini, "Analysis of the starting transient of a synchronous reluctance motor for direct-on-line applications," in *Proc. IEEE Int. Electr. Mach. Drives Conf. (IEMDC)*, May 2015, pp. 121–126, doi: 10.1109/IEMDC.2015.7409047.

[11] A. Tintelecan, A. C.-. Dobra, and C. Marţiç, "Life cycle assessment comparison of synchronous motor and permanent magnet synchronous motor," in *Proc. Int. Conf. Expo. Elect. Power Eng. (EPE)*, Oct. 2020, pp. 205–210, doi: 10.1109/EPE50722.2020.9305636.

[12] C. Li, D. Xu, and G. Wang, "High efficiency remanufacturing of induction motors with interior permanent-magnet rotors and synchronous-reluctance rotors," in *Proc. IEEE Transp. Electrific. Conf. Expo, Asia–Pacific (ITEC Asia-Pacific)*, Aug. 2017, pp. 1–6, doi: 10.1109/ITEC-AP.2017.8080993.

[13] U.S. Department of Energy, Energy Efficiency & Renewable Energy. *Premium Efficiency Motor Selection and Application Guide–A Handbook for Industry*. Accessed: Aug. 15, 2019. [Online]. Available: https://www.energy.gov/eere/amo/downloads/premium-efficiency-motor-selection-and-application-guide-handbook-industry

[14] F. J. T. E. Ferreira, B. Leprettre, and A. T. de Almeida, "Comparison of protection requirements in IE2-, IE3-, and IE4-class motors," *IEEE Trans. Ind. Appl.*, vol. 52, no. 4, pp. 3603–3610, Jul. 2016, doi: 10.1109/TIA.2016.2545647.

[15] J. Muñoz Tabora, M. E. de Lima Tostes, E. Ortiz de Matos, T. Mota Soares, and U. H. Bezerra, "Voltage harmonic impacts on electric motors: A comparison between IE2, IE3 and IE4 induction motor classes," *Energies*, vol. 13, no. 13, p. 3333, Jun. 2020, doi: 10.3390/en13133333.

[16] J. M. Tabora, M. E. De Lima Tostes, E. O. De Matos, U. H. Bezerra, T. M. Soares, and B. S. De Albuquerque, "Assessing voltage unbalance conditions in IE2, IE3 and IE4 classes induction motors," *IEEE Access*, vol. 8, pp. 186725–186739, 2020, doi: 10.1109/ACCESS.2020.3029794.

[17] F. J. T. E. Ferreira, G. Baoming, and A. T. de Almeida, "Reliability and operation of high-efficiency induction motors," *IEEE Trans. Ind. Appl.*, vol. 52, no. 6, pp. 4628–4637, Nov. 2016, doi: 10.1109/TIA.2016.2600677.

[18] A. T. de Almeida, F. J. T. E. Ferreira, and G. Baoming, "Beyond induction motors—Technology trends to move up efficiency," *IEEE Trans. Ind. Appl.*, vol. 50, no. 3, pp. 2103–2114, May/Jun. 2014, doi: 10.1109/TIA.2013.2288425.

[19] A. E. Emanuel and and J. A. McNeill, "Electric power quality," *Annu. Rev. Energy Environ.*, vol. 22, no. 1, pp. 263–303, Nov. 1997, doi: 10.1146/annurev.energy.22.1.263.

[20] H. G. Beleiu, V. Maier, S. G. Pavel, I. Birou, C. S. Pică, and P. C. Dărab, "Harmonics consequences on drive systems with induction motor," *Appl. Sci.*, vol. 10, no. 4, p. 1528, Feb. 2020, doi: 10.3390/app10041528.

[21] C. Debruyne, L. Vandevelde, and J. Desmet, "Harmonic effects on induction and line start permanent magnet machines," presented at the 8th Int. Conf. Energy Efficiency Motor Driven Syst. (EEMODS), Rio de Janeiro, RJ, Brazil, Oct. 2013.

[22] C. Debruyne, S. Derammelaere, J. Desmet, and L. Vandevelde, "Comparative study of the influence of harmonic voltage distortion on the efficiency of induction machines versus line start permanent magnet machines," in *Proc. IEEE 15th Int. Conf. Harmon. Qual. Power*, Hong Kong, Jun. 2012, pp. 342–349, doi: 10.1109/ICHQP.2012.6381217.

[23] *IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems*, IEEE Standard 519-2014 (Revision IEEE Standard 519-1992), Jun. 2014, pp. 1–29, doi: 10.1109/IEEESTD.2014.6826459.

[24] O. E. Faduyile, "Effect of harmonics on the efficiency of a three phase energy efficient and standard motors," M.S. thesis, College Eng., Univ. Tennessee, Chattanooga, TN, USA, 2009. Accessed: Apr. 8, 2021. [Online]. Available: https://scholar.utc.edu/cgi/viewcontent.cgi?article=1400&context=theses

[25] X. Liang and Y. Luy, "Harmonic analysis for induction motors," in *Proc. Can. Conf. Electr. Comput. Eng.*, May 2006, pp. 172–177, doi: 10.1109/CCECE.2006.277368.

[26] W. Abu-Elhaija and A. Muetze, "A voltage unbalance factor coding technique for three-phase induction motors," *Int. Trans. Electr. Energy Syst.*, vol. 28, no. 6, p. e2554, Jun. 2018, doi: 10.1002/etep.2554.

[27] A. B. F. Neves, M. V. B. de Mendonca, A. De Leles Ferreira Filho, and G. Z. Rosa, "Effects of voltage unbalance and harmonic distortion on the torque and efficiency of a three-phase induction motor," in *Proc. 17th Int. Conf. Harmon. Qual. Power (ICHQP)*, Oct. 2016, pp. 943–948, doi: 10.1109/ICHQP.2016.7783350.

[28] C.-Y. Lee, "Effects of unbalanced voltage on the operation performance of a three-phase induction motor," *IEEE Trans. Energy Convers.*, vol. 14, no. 2, pp. 202–208, Jun. 1999, doi: 10.1109/60.766984.

[29] NEMA MG1-2016. *Motors and Generators*. Accessed: Aug. 15, 2019. [Online]. Available: https://www.nema.org/Standards/Pages/Motors-and-Generators.aspx

[30] E. C. Q. Oqueña, P. Peñaranda, and A. Enciso, "Efectos del desequilibrio de tensiones sobre la operación del motor de inducción trifásico: Énfasis en la caracterización del desequilibrio de tensiones y el efecto sobre la potencia nominal [recurso electrónico]," M.S. thesis, Programa de Posgrados de Ingeniería Eléctrica y Electrónica, Universidad del Valle, Cali, Colombia, 2017. Accessed: Oct. 10, 2020. [Online]. Available: https://bibliotecadigital.univalle.edu.co/handle/10893/10287

[31] S. B. Singh and A. K. Singh, "Steady-state performance assessment of induction motor under unbalanced voltage condition," *Electr. Power Compon. Syst.*, vol. 41, no. 13, pp. 1248–1263, Oct. 2013, doi: 10.1080/15325008.2013.817492.

[32] S. B. Singh and A. K. Singh, "Precise assessment of performance of induction motor under supply imbalance through impedance unbalance factor," *J. Electr. Eng.*, vol. 64, no. 1, pp. 31–37, Jan. 2013, doi: 10.2478/jee-2013-0004.

[33] E. El-Kharashi, M. El-Dessouki, J. G. Massoud, A. W. Farid, and M. A. Al-Ahmar, ''The use of the current complex factor to determine the precise output energy of the induction motor,'' *Electr. Power Syst. Res.*, vol. 154, pp. 23–36, Jan. 2018, doi: 10.1016/j.epsr.2017.08.008.

[34] A. L. F. Filho, J. A. A. Cormane, D. C. Garcia, M. V. C. Costa, M. A. G. Oliveira, and F. A. do Nascimento, ''Analysis of the complex voltage unbalance factor behavior resulting from the variation of voltage magnitudes and angles,'' in *Proc. 14th Int. Conf. Harmon. Qual. Power (ICHQP)*, Sep. 2010, pp. 1–7, doi: 10.1109/ICHQP.2010.5625315.

[35] F. Z. Dekhandji, L. Refoufi, and H. Bentarzi, ''Quantitative assessment of three phase supply voltage unbalance effects on induction motors,'' *Int. J. Syst. Assurance Eng. Manage.*, vol. 8, no. S1, pp. 393–406, Jan. 2017, doi: 10.1007/s13198-015-0401-3.

[36] F. Z. Dekhandji and H. Bentarzi, ''Theoretical and experimental investigation of the supply voltage unbalance effects on squirrel cage induction motors,'' *Algerian J. Signals Syst.*, vol. 4, no. 2, pp. 51–60, Dec. 2019, doi: 10.51485/ajss.v4i2.82.

[37] L. Refoufi, H. Bentarzi, and F. Z. Dekhandji, ''Voltage unbalance effects on induction motor performance,'' in *Proc. 6th WSEAS Int. Conf. Simulation, Modeling Optim.*, Lisbon, Portugal, Sep. 2006, pp. 112–117.

[38] S. X. Duarte and N. Kagan, ''A power-quality index to assess the impact of voltage harmonic distortions and unbalance to three-phase induction motors,'' *IEEE Trans. Power Del.*, vol. 25, no. 3, pp. 1846–1854, Jul. 2010, doi: 10.1109/TPWRD.2010.2044665.

[39] M. Kostic, ''Effects of voltage quality on induction motors' efficient energy usage,'' in *Induction Motors-Modelling and Control*. London, U.K.: IntechOpen, 2012. [Online]. Available: https://www.intechopen.com/books/induction motors-modelling-and-control/effects-ofvoltage-quality-on-induction-motors-efficient energy-usage, doi: 10.5772/51223.

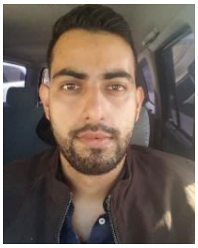
[40] F. J. T. E. Ferreira, A. T. de Almeida, J. F. S. Carvalho, and M. V. Cistelecan, ''Experiments to observe the impact of power quality and voltage-source inverters on the temperature of three-phase cage induction motors using an infra-red camera,'' in *Proc. IEEE Int. Electric Mach. Drives Conf.*, May 2009, pp. 1311–1318, doi: 10.1109/IEMDC.2009.5075373.

[41] User_Administrator. (Jul. 31, 2014). *National Action Plans and Annual Progress Reports*. Energy–European Commission. Accessed: Jul. 26, 2020. [Online]. Available: https://ec.europa.eu/energy/topics/energy-efficiency/targets-directive-and-rules/national-energy-efficiency-action-plans_en

[42] *Database of State Incentives for Renewables & Efficiency?*. DSIRE. Accessed: Jul. 26, 2020. [Online]. Available: https://www.dsireusa.org/

[43] *Next Generation Electric Machines–Project Descriptions*. Accessed: Jul. 26, 2020. [Online]. Available: https://www.energy.gov/eere/amo/next-generation-electric-machines-project-descriptions

[44] A. von Jouanne and B. Banerjee, ''Assessment of voltage unbalance,'' *IEEE Trans. Power Del.*, vol. 16, no. 4, pp. 782–790, Oct. 2001, doi: 10.1109/61.956770.



JONATHAN MUÑOZ TABORA was born in Santa Rosa de Copán, Honduras, in April 1993. He graduated from the National Autonomous University of Honduras (UNAH-VS). He received the master's degree in energy systems with orientations in power electrical systems from the Federal University of Pará (UFPA), where he is currently pursuing the Ph.D. degree. He worked as a Professor with the Department of Electrical Engineering, UNAH-VS. He is currently a participant in two research and development projects (P&D) related to energy efficiency and electrical mobility. His research interests include motor drive systems, energy efficiency, power quality, electrical installations, electrical power systems, and statistics.

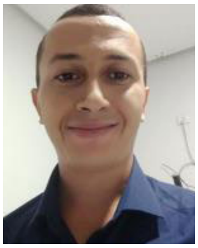
MARIA EMÍLIA DE LIMA TOSTES (Member, IEEE) was born in Recife, Brazil, in 1966. She received the B.Sc., M.Sc., and Ph.D. degrees from the Federal University of Pará, Belém, Brazil, in 1988, 1992, and 2003, respectively. She is currently a Professor with the Department of Electrical and Computer, Federal University of Pará. Her main research interests include power quality, distribution systems, and industrial processes.

UBIRATAN HOLANDA BEZERRA was born in Pereiro, Ceará, Brazil, in October 1950. He received the bachelor's degree in electrical engineering from the Federal University of Pará (UFPA), Brazil, the M.Sc. degree in electrical power system from the Federal University of Itajubá, and the Ph.D. degree in electrical power system from the Federal University of Rio de Janeiro, Brazil. He is currently a Titular Professor at UFPA. His main research interests include power system security assessment, power quality issues, distributed generation, and renewable energies.

EDSON ORTIZ DE MATOS (Member, IEEE) was born in Belém, Pará, Brazil, in January 1953. He received the bachelor's degree in electrical engineering from the Federal University of Pará (UFPA), Belém, in 1978, the M.Sc. degree from the Federal University of Rio de Janeiro, Brazil, in 1980, and the Ph.D. degree in electrical engineer from UFPA, in 2016. His main research interests include electrical power systems, electrical machines, power systems stability, energy efficiency, and power quality issues.

CARLINDO LINS PEREIRA FILHO was born in Belém, Brazil, in 1948. He received the B.Sc. and M.Sc. degrees from the Federal University of Pará, Belém, in 1971 and 2014, respectively, where he is currently pursuing the Ph.D. degree. His main research interests include power quality, stability of power systems, energy efficiency, and regulation of the electricity sector.

THIAGO MOTA SOARES (Member, IEEE) was born in Belém, Pará, Brazil, in February 1985. He received the bachelor's degree in electrical engineering and the M.Sc. degree in electrical power system from the Federal University of Pará (UFPA), Belém, where he is currently pursuing the Ph.D. degree in electrical engineer. His main research interests include power quality issues, energy efficiency, distributed generation, and renewable energies.



CARLOS EDUARDO MOREIRA RODRIGUES was born in Xinguara, Brazil, in April 1993. He received the bachelor's degree in electrical engineering and the M.Sc. degree from the Federal University of Pará (UFPA), Brazil, in 2016 and 2018, respectively, where he is currently pursuing the Ph.D. degree in energy systems. His main research interests include power quality, energy efficiency, and losses in energy distribution systems.

• • •