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Voltage Unbalance Effect on the Behavior of IE2, IE3 And IE4 Induction Motor Classes

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Abstract: More than 30 million electric motors are sold every year in the world, in the last 20 years the appearance of more efficient electric motors resulted in the replacement of more than 70% of the old motors installed. New technologies are being presented by manufacturers as substitutes for the squirrel cage induction motor (SCIM). Given this scenario, studies should be carried out to analyze the performance of these motors in the same operating conditions to know their main advantages and drawbacks. This study presents a comparison of the performance of electric motors classes IE2, IE3 and IE4 in the presence of voltage unbalance (VU) with under and over voltage. Results show that not only the unbalance percentage present impacts the motor performance, but also the magnitudes of the voltages present. The VU also results in an increase in the harmonics present in each motor, mainly in the permanent magnet hybrid motor, which presents non-linear characteristics.

Keywords: Energy efficient motors; Voltage Unbalance; Efficiency classes; Line-Start Permanent Magnet Motor.

1. INTRODUCTION

Electric induction motors represent an important class of electrical rotating machines in which is widely employed in industrial, commercial and residential facilities. According to (International Energy Agency (IEA); Rodriguez et al., 2015), these machines are responsible for approximately 68% of the industry's total energy consumption in Brazil and 50% of the global electric energy consumption.

As consequence of this situation coupled with environmental concerns, increasing energy costs, mandatory minimum efficiency requirements and others, manufacturers have increased the electric induction motor efficiency by enhancing their constructive characteristics, which results in a decrease of the motor losses along their electrical-mechanical energy conversion. This evolution can be observed by the arise of new categories of electric motors as the premium (IE3) and line-start permanent magnet electric motors (LSPMM or IE4), which attain efficiency up to 97 %.

Although the National Electrical Manufacturers Association (NEMA) (NEMA MG1-2016) recommends that electric motors must be designed to operate satisfactorily with a voltage variation of 10%, this situation may accelerate motor's insulation deterioration over time as well as reduce motor's efficiency, which may become even worse when these motors are subjected to voltage unbalance.

Then, based in this context, (Abu-Elhaija e Muetze 2018; Ferreira et al. 2016b; NEMA MG1-2016; Neves et al. 2016; Singh 2005; Zhang et al. 2017) have documented the negative effect that the voltage unbalance has on electric motor's torque, power factor and efficiency. In (Ching-Yin Lee 1999), it was presented a complete analysis of the over and under voltage unbalance effect on electric motors including, where, according to the experimental results, an under-voltage unbalance usually causes the worst temperature rise on this machine.

Based in this context, this work analyzes the behavior of different electric motor (classes IE2, IE3 and IE4) in the presence of different under and over unbalanced voltages.

2. INDUCTION MOTORS

2.1 MEPS & IEC Efficiency Classes

With more than 30 million motors sold every year in the industrial sector, many countries have established local regulations that ensure the use of energy efficient motors in industrial, commercial and residential sector. These regulations are known as MEPS (Minimum Energy Performance Standards) (A. et al. 2009). In this way, studies and discussions with users and manufacturers (if any) are carried out to guarantee the success of MEPS.

These standards work with the efficiency classes defined by the IEC 60034-30-1 (IEC 60034-30-1:2014) in 2008, in which four efficiency classes are defined: IE1 (Standard), IE2 (high efficiency), IE3 (premium efficiency) and IE4 (super premium efficiency). In Figure 3 countries in the world that adopted MEPS are presented.

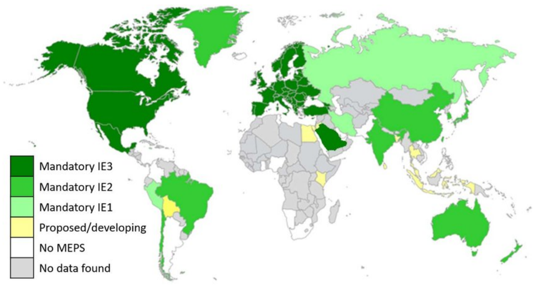


Fig. 1 Countries with MEPS for electric motors (Ferreira et al. 2018).

IE4 motors are not yet mandatory by the MEPS, however, these new technologies such as the Line-Start Permanent Magnet Motor are expected to be the new substitute for the conventional induction motor. Then studies must be carried out to analyze their performance under the same operational conditions of the IE2 and IE3 IM´s. Some of the main improvements in these higher efficiencies IM´s are presented in the next section.

2.2 Improvements in Induction Motors

There are five main losses present in the process of energy conversion of electric motors with percentages that vary according to the nominal power of the motor as well as the percentage of load coupled to its axis: copper losses in the stator (30-50% of total losses), copper losses in the rotor (20-25% of total losses), core losses (20-25% of total losses), friction losses (5-10% of total losses) and dispersed losses (5-15% of total losses) (Almeida et al. 2014; U.S. Department of Energy, Energy Efficiency & Renewable Energy). In that sense, many improvements implemented in recent years in electric motors are aimed at reducing these losses:

- Increase in active materials as well as redistribution of the coils in the stator of the IM's. The use of copper in the stator bars also represents a decrease in losses due to its greater conductivity in relation to aluminum, which in turn results in lower operating temperatures. Technologies such as the LSPMM and the synchronous reluctance motor also result in lower copper losses in the rotor thanks to the synchronous speed, with which, theoretically no current circulates in the rotor bars (except for harmonic currents) (Copper Development Association; Debruyne 2014; Peter et al. 2014)

- The implementation of high quality and amorphous materials for the construction of the core led to the reduction of losses in these high efficiency motors, with decreases of 70-90% compared to traditionally used materials (HITACHI 2018; Peter et al. 2014).

- Stray load losses also depend on load currents, as well as the motor construction. Surface losses and transversal currents between the rotor bars represent more than 70% of these losses and can be reduced with the improvement in the construction of the IM´s (Peter et al. 2014).

2.3 Line Start Permanent Magnet Motor

The permanent magnet and squirrel cage hybrid motor combines the advantages of an induction motor in a synchronous operation. With a squirrel cage which provides self-starting capability and enables synchronous operation at steady state, in synchronous operation no slip is present, so theoretically no current circulates in the rotor bars (except for the currents harmonics). Different configurations of the magnets inside the rotor have been implemented by manufacturers and researchers. The magnetic fields created by the magnets result in the decrease of the magnetization current required, so lower currents and reactive power consumption are obtained in this technology. This decrease added to the synchronous speed results in a decrease in the losses of these motors and therefore higher efficiencies and lower operating temperatures.

However, the presence of the magnets results in a braking torque during the starting of these motors, so large oscillations and difficulties to start with load are some of the main challenges for manufacturers, mainly in applications with frequent stops / starts. The presence of permanent magnets resulted in higher manufacturing costs for this technology, so its initial cost was one of the great disadvantages in relation to its predecessors, making it unattractive for industries despite its notable efficiency consumption. However, in recent years, such initial costs have decreased so that lower paybacks are obtained. Currently in the Brazilian market the cost of an IE4 LSPMM is approximately 1.3 times the cost of an IE3 SCIM, while the IE3 SCIM is approximately 1.3 times the cost of an IE2 SCIM.

Considering that the initial cost of the motor is approximately 5% of energy consumption throughout its useful life, the implementation of better efficiencies IM´s is much more economically attractive. However, previous studies must be carried out before replacing these technologies as will be expanded later.

2.4 Voltage Unbalance

Unbalanced voltages result in three main symmetrical components: positive, negative and zero. Because most of the 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 negative) produce different impacts, one contributing to the resulting torque while the second creating opposite magnetic fields, resulting in greater oscillations, speed reduction as a resulting lower torque (von Jouanne e Banerjee 2001). Presence of voltage unbalance (VU) also results in unbalanced currents in the stator windings. A small percentage of voltage unbalance will result in a much higher current percentage unbalance. Normally, the unbalance of the currents is 6 to 10 times the unbalance of the voltages, which causes the winding to overheat (Ferreira et al. 2016a; Kostic 2012). While the positive sequence component also has a detrimental effect on the machine windings: compared to nominal power conditions, a 5% increase in positive sequence voltage causes an increase of about 12% in motor temperature above the value reference value as shown in (Mendes et al. 2010).

Consequently, the temperature rise of the motor operating at a specific load and the percentage of voltage unbalance will be higher than for the motor operating under the same conditions with balanced voltage. According to NEMA recommendations, to avoid excessive heating, the three-phase motor needs to be reduced depending on the degree of unbalance under such operating conditions. The value by which the power must be reduced is called the "power reduction factor".

Due to the increased tolerance inherent in the additional temperature rise, high efficiency motors are generally less susceptible to voltage unbalance variations as will be presented in the next section.

3. METHODOLOGY

To investigate the voltage unbalance impact on IE2, IE3 and IE4 motors, it was performed some laboratory test on these types of machines. During the tests performed, it was applied under and over voltages unbalances to the three different electric motor classes after they reached the thermal stability. Figure 2 shows the general test scheme built in the laboratory.

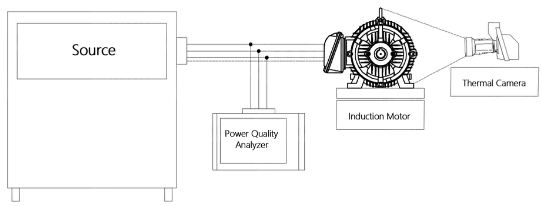


Fig. 2 General Test Setup.

Using the power quality analyzer HIOKI PW 3198, it was recorded some electrical quantities as harmonic current, power factor and current harmonic distortion rate. And, using Flir T620 infrared camera, it was taken some thermal pictures of the three motor. However, it is important to emphasize that this paper will only focuses on the motors' electrical behavior.

During the tests, voltage unbalances were generated using the three phase AC source model FCATHQ manufactured by SUPPLIER. This AC power source is capable of generate a pure sinusoidal signal as well as voltage unbalance, sags and swells and harmonics (up to 25th order).

The load used during the tests consists of an electromagnetic brake or Foucault brake, which includes two load cells that are connected to the ends of the brake in order to measure the opposite force produced by eddy currents. Moreover, if the opposite force is multiplied by its distance to the rotor, it is possible to obtain the torque demanded by the load. For the study a torque of 3.8 Nm was applied to the Foucault brake which represents 92-95% of the nominal motor torque. The nominal data of each motor are presented in Table 1:

Table 1. Induction Motors Parameters

Motor Class	IE2	IE3	IE4
Motor Technology	SCIM	SCIM	LSPM
Rated Power (HP)	1	1	1
Rated Voltage (V)	220 /380	220 /380	220 /380
Rated speed (RPM)	1730	1725	1800
Rated Torque (Nm)	4,12	4,13	3,96
Rated current (A)	2,98/1,73	2,91/1,68	3,08/1,78
Efficiency (%)	82,60	82,6	87,4
Power Factor	0,80	0,82	0,73

During the testes, the IE2, IE3 and IE4 induction motors were firstly subjected to a perfect three-phase sinusoidal voltage of 220 V for 1 hour and 10 minutes so that they reached their thermal equilibrium. In a second moment, over and under voltage unbalances of 1%, 3% and 4% were applied to each motor for a period of one hour until the thermal equilibrium was reached again. It should be noted that only voltage magnitudes were varied, while the voltage phase angles remained constant. Table 2 presents voltage magnitudes for each voltage unbalance.

Table 2. Voltage Unbalanced Magnitudes.

% Voltage Unbalance	Va	Vb	Vc
1% Under Voltage	117.6 V	107.48 V	127.98 V
3% Under Voltage	120.77 V	128.34 V	165.1 V
4% Under Voltage	121.62 V	126.50 V	123.96 V
1% Over Voltage	124.66 V	127 V	129.05 V
3% Over Voltage	129.90 V	139.30 V	127.10 V
4% OverVoltage	140.85 V	119.15 V	131.38 V

The induction motor's electrical quantities as current, harmonic distortion rate of current and the power factor recorded throughout the tests were preprocessed and analyzed using the statistical software Minitab. Fig 4 summaries the steps taken during the tests.

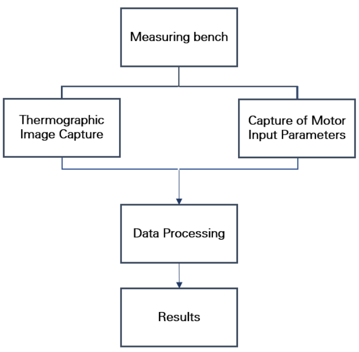


Fig. 4 Flowchart of the methodology used to obtain the results from the measurements.

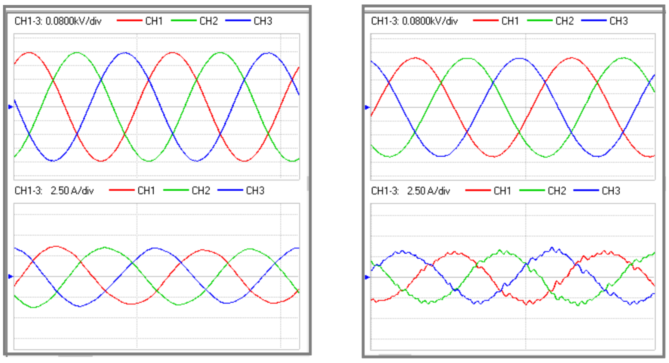
4. RESULTS AND DISCUSSION

The operation of IM's with unbalanced voltages is far from the ideal, where it has been widely commented in the literature that as the percentage of unbalance as the voltage magnitude significantly impacts the motor performance.

4.1 General Considerations and THDI

Due to the synchronous operation of the IE4 motors, their starting is different compared to the conventional ones, mainly due to the braking torque created by the interaction between fundamental fields produced by stator winding and permanent magnets (PM) in rotor. This torque yields large oscillations during the starting, until synchronism is achieved. Moreover, it is important to mention that the presence of unbalanced voltages may increase the time this machine takes to reach synchronism, with the undervoltage unbalance being the worst case.

The presence of permanent magnets in the LSPMM rotor results in a more distorted current waveform compared to the IE2 and IE3 motors. Figure 5 (a) and (b) presents voltage and current waveforms recorded for the IE3 and IE4 IMs, where this noticeable distortion in the hybrid motor is mainly caused by numerous harmonics and inter-harmonics created by the interaction between permanent magnets and stator fields, which considerably increases the percentage and number of harmonics present in the current waveform as shown in Figures 6 and 7 which present the harmonic content of current of the IE3 and IE4 motors, respectively .



(a) (b)

Fig. 5 Voltage (up) and current (down) waveforms for (a) IE3 SCIM; (b) IE4 LSPMM;

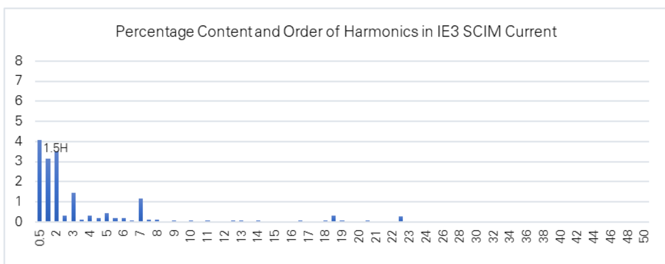


Fig. 6 Harmonic current spectrum IE3 SCIM

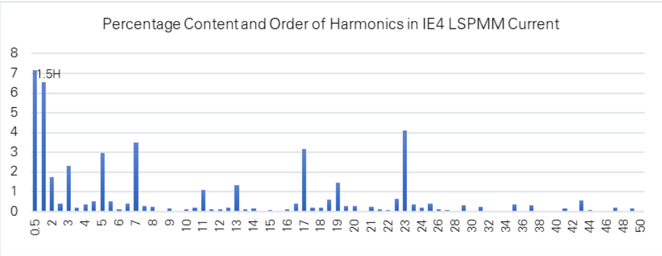
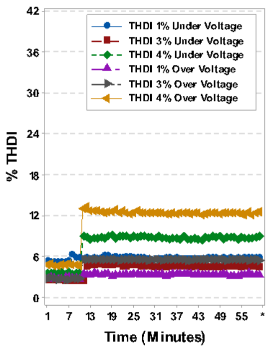


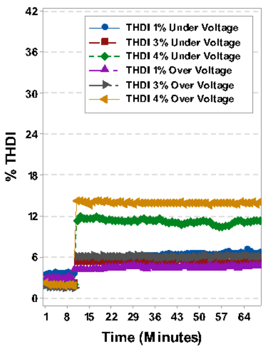
Fig. 7 Harmonic current spectrum for IE4 LSPMM;

The harmonic content present in the LSPMM waveform results in a total harmonic distortion of current (THDI) of about 4 times higher compared to IE2 and IE3 motors. This condition is still aggravated when an unbalance voltage is supplied to these machines, as it can be viewed in figure 8 (a-c) that shows the THDI of the IE2, IE3 and IE4 motors in the presence of the 6 under and over voltage unbalance conditions.

Figure 8 shows that, initially, the THDI of the IE2 and IE3 IM´s is less than 6% while for the IE4 motor THDI is around 8%. However, when the motors were subjected to different unbalance conditions, this rate significantly increased reaching values higher than 24% for the hybrid motor and 15% for the IE2 and IE3 motors. In addition, the worst scenarios observed was 4% of overvoltage unbalance for the IE2 and IE3 motors, and 4% of undervoltage unbalance for the hybrid one.



(a)



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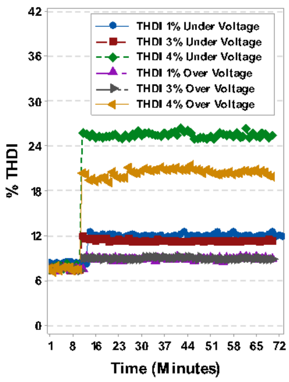


(c)

Fig. 8 Total Harmonic Distortion of Current for under and over voltage unbalance conditions for: (a) IE2 SCIM; (b) IE3 SCIM; (c) IE4 LSPMM.

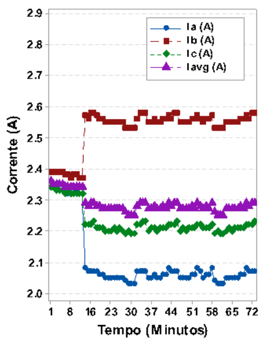
Hence, voltage unbalance provokes a significant increase in IE2, IE3 and IE4 motors' harmonic distortion rate of current, mainly in LSPMM.

4.2 IE4 Motor Currents

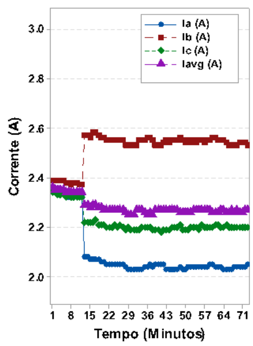
The presence of permanent magnets in LSPMM results in a decrease in the magnetization current necessary to produce the magnetic fields in the air gap, resulting in a lower current when compared to the IE2 and IE3 motors. As consequence, LSPMM presents higher levels of efficiency than the other motor classes.

However, when this type of motor was subjected to voltage unbalances, its currents behavior became unpredictable, where the current in some phases significantly increased and in other decreased, as depicted in Figure 9. Moreover, it is important to highlight that higher is the unbalance degree, higher the motor current becomes in some phases.

Analyzing the current measured when the power source was supplying an unbalanced voltage to the motor, it is also possible to observe that overvoltage unbalances represent a more dangerous condition to the motor's operation than the undervoltage one due to demand more current from the electric grid, except for low VU levels, once that 1% voltage unbalance did not altered the current levels as depicted in figure 9.



(a)



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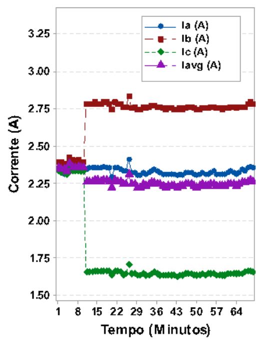

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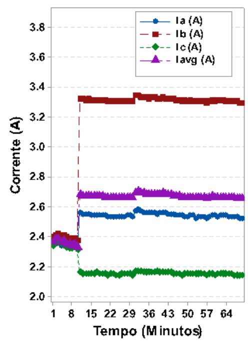
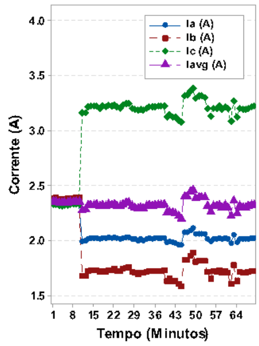
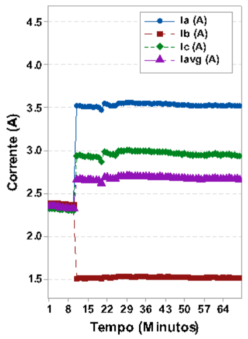


(d)



(e)

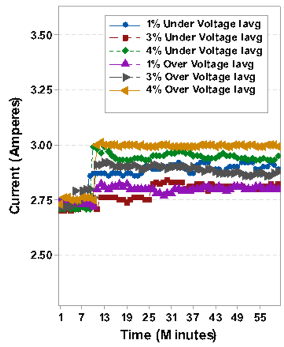


(f)

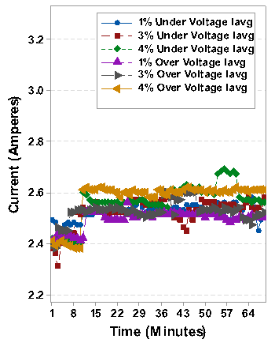
Fig. 9 Line Current recorded IE4 LSPMM with: (a) 1% Under Voltage; (b) 1% Over Voltage; (c) 3% Under Voltage; (d) 3% Over Voltage; (e) 4% Under Voltage; (f) 4% Over Voltage.

Beside the IE4-motor current per phase, figure 9 also showed the average among A, B and C currents for IE4, where it was noted that this current behave exactly as described previously, that is, the overvoltage condition produced higher current levels in relation to the undervoltage one.

Comparing the average value of the A, B and C currents for the IE2, IE3 and IE4 motors under the six VU conditions, it was possible to observe that, for the IE2 and IE3 class motors, the worst scenario found was the 4% unbalance with over and under voltage, respectively. On the other hand, for the LSPMM, undervoltage unbalance resulted in decreases in the average current as shown in figure 10.



(a)



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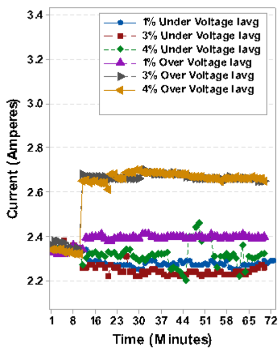


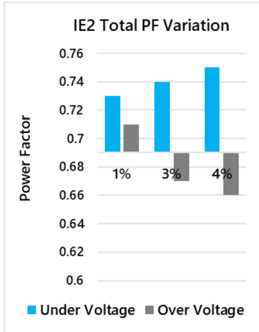
(c)

Fig. 10 Average Current Consumption for under and over voltage unbalance conditions for: (a) IE2 SCIM; (b) IE3 SCIM; (c) IE4 LSPMM.

4.3 Power Factor

The power factor of IM's is also affected by voltage unbalance, as depicted in figure 11 (a-c). According to the graphics presented in figure 11, it was possible to verify that the increase in undervoltage unbalances causes an increase in the IE2, IE3 and IE4 motor's power factor. Moreover, the IE4 motor presented lower power factor values compared to the IE2 and IE3 ones.

And during the overvoltage unbalance condition, it was observed that an increase in the unbalance level dropped the motor's power factor, where the IE4 motor presented the lowest power factor. This fact might be justified by the unusual amount of harmonic produced by this machine.



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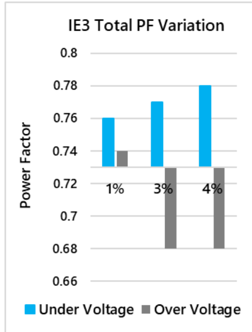

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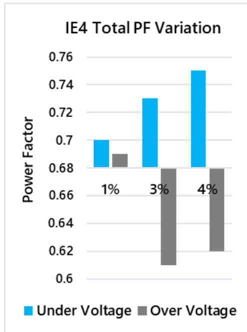

(c)

Fig. 11 Total Power Factor variation with Under and Overvoltage Unbalance for (a) IE2 SCIM; (b) IE3 SCIM; (c) IE4 LSPMM.

5. CONCLUSION

This work aimed to make a comparison among the IE2, IE3 and IE4 motor behavior when subjected to under and over voltage unbalances. Under ideal operating conditions, the LSPMM has lower energy consumption, silent operation and a lower temperature. It was also observed how it presents difficulties in starting, mainly with connected load, so it is not recommended in applications with frequent stops / starts, a distorted current waveform with more and greater harmonics present were also observed so studies should be performed primarily in large-scale use.

Six VU conditions with under and over voltage were analyzed, it was observed that 1% of VU does not result in large variations of the parameters with both under and overvoltage, however the overvoltage unbalance proved to be the most damaging for all motors. Current unbalances of up to 7 times the percentage of VU present were obtained, and that resulted in increases in the average current for each motor. The IE2 class IM turned out to have lower power factor variations due to VU, while the LSPMM was much more affected, mainly with over voltage unbalance.. The IE3 class motor showed a smaller increase with unbalance overvoltage, followed by the IE4 class LSPMM.

REFERÊNCIAS

A. A, R. B, C.U. B, M. D, W. H. Motor MEPS Guide. 2009.

Abu-Elhaija W, Muetze A. A voltage unbalance factor coding technique for three-phase induction motors. Int. Trans. Electr. Energy Syst. 2018;28(6):e2554.

Almeida AT de, Ferreira FJTE, Baoming G. Beyond Induction Motors—Technology Trends to Move Up Efficiency. IEEE Trans. Ind. Appl. maio de 2014;50(3):2103–14.

Ching-Yin Lee. Effects of unbalanced voltage on the operation performance of a three-phase induction motor. IEEE Trans. Energy Convers. junho de 1999;14(2):202–8.

Copper Development Association. Mineral Producer Installing 150 Copper-Rotor Motors Rising Energy Costs Drive Upgrades, Rapid Payback Expected [Internet]. [citado 15 de agosto de 2019]. Recuperado de: https://www.copper.org/environment/sustainable-energy/electric-motors/case-studies/nyco_a6118.html

Debruyne C. Impact of voltage distortion on energy efficiency of induction machines and line start permanent magnet machines [Internet] [dissertation]. Ghent University; 2014 [citado 15 de agosto de 2019]. Recuperado de: http://hdl.handle.net/1854/LU-4383637

Ferreira FJTE, Baoming G, Almeida AT de. Reliability and Operation of High-Efficiency Induction Motors. IEEE Trans. Ind. Appl. novembro de 2016a;52(6):4628–37.

Ferreira FJTE, Leprettre B, Almeida AT de. Comparison of Protection Requirements in IE2-, IE3-, and IE4-Class Motors. IEEE Trans. Ind. Appl. julho de 2016b;52(4):3603–10.

Ferreira FJTE, Silva AM, Aguiar VPB, Pontes RST, Quispe EC, Almeida AT de. Overview of Retrofitting Options in Induction Motors to Improve Their Efficiency and Reliability. 2018 IEEE Int. Conf. Environ. Electr. Eng. 2018 IEEE Ind. Commer. Power Syst. Eur. EEEIC CPS Eur. 2018. p. 1–12.

HITACHI. Development of Motor with Amorphous Metal : Research & Development : Hitachi [Internet]. 2018 [citado 15 de agosto de 2019]. Recuperado de: https://www.hitachi.com/rd/portal/contents/story/amorphous/index.html

IEC 60034-30-1:2014. Rotating electrical machines - Part 30-1: Efficiency classes of line operated AC motors (IE code) [Internet]. [citado 15 de agosto de 2019]. Recuperado de: https://webstore.iec.ch/publication/136

International Energy Agency (IEA). Publications [Internet]. [citado 15 de agosto de 2019a]. Recuperado de: https://www.iea-4e.org/publications

International Energy Agency (IEA). Energy Efficiency 2018 - Analysis and outlooks to 2040 - en - OECD [Internet]. [citado 15 de agosto de 2019b]. Recuperado de: http://www.oecd.org/publications/energy-efficiency-2018-9789264024304-en.htm

von Jouanne A, Banerjee B. Assessment of voltage unbalance. IEEE Trans. Power Deliv. outubro de 2001;16(4):782–90.

Kostic M. Effects of Voltage Quality on Induction Motors' Efficient Energy Usage. Induction Mot. - Model. Control [Internet]. 14 de novembro de 2012 [citado 15 de novembro de 2019]; Recuperado de: https://www.intechopen.com/books/induction-motors-modelling-and-control/effects-of-voltage-quality-on-induction-motors-efficient-energy-usage

Mendes AMS, Quispe EC, López Fernández XM, Marques Cardoso AJ. Influence of the positive sequence voltage on the temperature of three-phase induction motors. XIX Int. Conf. Electr. Mach. - ICEM 2010. 2010. p. 1–6.

NEMA MG1-2016. Motors and Generators [Internet]. [citado 15 de agosto de 2019]. Recuperado de: https://www.nema.org/Standards/Pages/Motors-and-Generators.aspx

Neves ABF, de Mendonça MVB, Ferreira Filho A de L, Rosa GZ. Effects of voltage unbalance and harmonic distortion on the torque and efficiency of a Three-Phase Induction Motor. 2016 17th Int. Conf. Harmon. Qual. Power ICHQP. 2016. p. 943–8.

Peter I, Scutaru G, Nistor CG. Manufacturing of asynchronous motors with squirrel cage rotor, included in the premium efficiency category IE3, at S.C. Electroprecizia Electrical-Motors S.R.L. Săcele. 2014 Int. Conf. Optim. Electr. Electron. Equip. OPTIM. 2014. p. 421–5.

Singh GK. A research survey of induction motor operation with non-sinusoidal supply wave forms. Electr. Power Syst. Res. 1º de agosto de 2005;75:200–13.

U.S. Department of Energy, Energy Efficiency & Renewable Energy. Premium Efficiency Motor Selection and Application Guide – A Handbook for Industry [Internet]. Energy.gov. [citado 15 de agosto de 2019]. Recuperado de: https://www.energy.gov/eere/amo/downloads/premium-efficiency-motor-selection-and-application-guide-handbook-industry

Zhang D, An R, Wu T. Effect of Voltage Unbalance and Distortion on the Loss Characteristics of Three Phase Cage Induction Motor. IET Electr. Power Appl. 18 de outubro de 2017;12.

A comparative assessment of Brazilian electric motors performance with minimum efficiency standards - ScienceDirect [Internet]. [citado 20 de outubro de 2019]. Recuperado de: https://www.sciencedirect.com/science/article/abs/pii/S1364032114007291