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Voltage Unbalance Impacts on Temperature of IE2, IE3 & IE4 Class Induction Motors

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Abstract: Energy efficiency actions is a shared policy goal of many governments in the world. In that sense, drive systems represent an important opportunity for energy savings. With an average of 20.1 million installed motors that represents approximately 30% of total energy consumption In Brazil, old motors substitution for new and more efficient technologies is now a reality. The present work analyses the impact of voltage unbalance (VU) with under and over voltage on the line current and temperature of electric motors classes IE2, IE3 and IE4, the latter being a hybrid permanent magnet and squirrel cage motor. To do this, six different unbalance voltage conditions were applied to each motor while measurements were made to capture the main variations for each technology. The results show how the voltage unbalance results in considerable uneven increases in current and temperature in each motor, it was also observed how the hybrid permanent magnet motor shows less dependence on voltage variations, mainly with undervoltage.

Resumo: Ações de eficiência energética são uma meta de política de muitos governos no mundo. Nesse sentido, os sistemas motrizes representam uma importante oportunidade para economia de energia. Com uma média de 20,1 milhões de motores instalados, o que representa aproximadamente 30% do consumo total de energia elétrica no Brasil, a substituição de motores antigos por tecnologias novas e mais eficientes agora é uma realidade. O presente trabalho analisa o impacto do desequilíbrio de tensão com sub e sobretensão na corrente e temperatura de motores elétricos das classes IE2, IE3 e IE4, sendo o último um motor híbrido de ímãs permanentes e gaiola de esquilo. Para isso, seis distintas condições de desequilíbrio de tensão foram aplicadas a cada motor enquanto foram feitas medições para capturar as principais variações de cada tecnologia. Os resultados mostram como o desequilíbrio resulta em aumentos consideráveis de corrente e temperatura em cada motor. Também foi observado como o motor híbrido de ímãs permanentes mostra uma menor dependência as variações de tensão, principalmente com subtensão.

Keywords: Energy efficiency, Induction Motors, Voltage Unbalance, Temperature, Efficiency Classes, Line Start Permanent Magnet Motor.

Palavras-chaves: Eficiência Energética, Motores de Indução, Desequilíbrio de Tensão, Classes de Eficiência, Motor de Imãs Permanentes.

1 INTRODUCTION

In recent years, many countries have started a transition process towards more efficient electric motors, based on local regulations, also known as MEPS (Minimum Energy Performance Standards) (Anibal et al., 2009). Behind these there are countries with emerging economies, which are just beginning to explore new options given the high energy costs, and aiming to delay investments in generation through energy efficiency actions. These facts added to the replacement of old motors has contributed to accelerate the integration of new high efficiency technologies in the industry market.

The introduction of new technologies such as copper rotor motors, synchronous reluctance motors and permanent magnet motors has allowed to achieve greater efficiencies, classified by the IEC 60034-30-1 standard (IEC 60034-30-1:2014, n.d.), last published in 2014, in which the Efficiency class IE4 was defined, with values reaching 96%, it is expected that in the new edition of this standard the IE5 class will be defined.

With more efficient motors present in the market, numerous studies have been carried out to analyze the main strengths and weaknesses of these new technologies, mainly with the main disturbances present in current electrical systems.

Comparisons between Induction Motors (IM) of different efficiency classes have been presented in (A. T. D. Almeida et al., 2012; A. T. de Almeida et al., 2014, 2009; Debruyne, 2014; Ferreira et al., 2018).

In relation to VU, authors in (Abu-Elhaija & Muetze, 2018; NEMA MG1-2016, n.d.; Neves et al., 2016, 2016; Singh & Singh, 2013; Zhang et al., 2017) comment about the negative impacts on efficiency, torque and power factor reduction.

Temperature rise in IM is another consequence of VU, due to the unequal variation of the line currents, unbalanced losses occur within the motor. These losses depend on the degree of unbalance as well as the magnitudes of the voltages present. The degree of VU can be calculated by means of different definitions such as NEMA, IEEE, and IEC (Rodriguez et al., 2015). As a reference, Bonnett in (Bonnett, 1999) shows that for every 10 ° C increase in the temperature of the windings, life expectancy for the motor is reduced by half.

Aiming to analyze the response of these new technologies, an analysis on the impact of VU with under and over voltage in the temperature of IE2, IE3 and IE4 class motors is presented in this study

2 VOLTAGE UNBALANCE IN INDUCTION MOTORS

2.1 Losses in Induction Motors

In the process of energy conversion carried out by electric motors, electrical and mechanical losses occur that depend on the nominal power, the percentage of load as well as the design, materials and technology present, as will be presented later. The distribution of losses for asynchronous induction motors is presented in Figure 1.

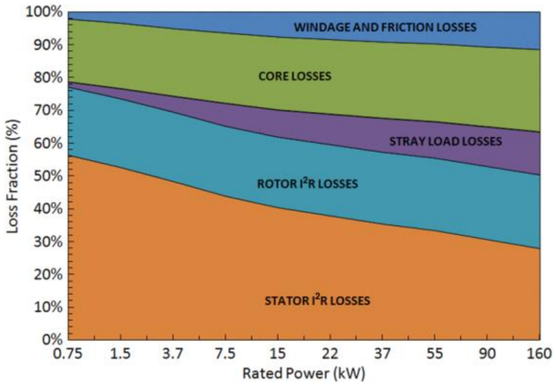


Figure 1. Typical fraction of losses in 50-Hz, four-pole squirrel cage induction motors.(A. T. de Almeida et al., 2014)

Losses are manifested in the form of heat and result in temperature increases in the internal components of the motors. Many studies were carried out in the last 20 years by researchers and manufacturers aiming to reduce the main losses present in electric motors in order to achieve greater operating efficiencies. The studies resulted in improvements in manufacturing processes, in the materials and design of electric motors, as well as with the emergence of new technologies such as copper rotor motors, synchronous reluctance motors and permanent magnet motors and with which greater efficiencies were obtained (U.S. Department of Energy, Energy Efficiency & Renewable Energy, n.d.).

Higher efficiencies mean lower operational losses and therefore lower operating temperatures, in this study the IE2 class motor presents insulation class B (Maximum temperature of 130 °C) while the IE3 and IE4 class motors have an insulation class F (Maximum temperature of 155 °C), so greater tolerance to temperature increases is expected in these new classes.

New technologies such as the Line Start Permanent Magnet Motor (LSPMM have new characteristics, such as synchronous speed, which results in zero slip, so theoretically, no current will circulate in the bars, thus the losses in the rotor will be reduced and consequently the motor temperature. A brief review of its main characteristics is presented in the next section.

2.2 Line Start Permanent Magnet Motor (LSPMM)

The permanent magnet motor has a similar construction with the asynchronous induction motor, the main differences are the synchronous operation and the permanent magnets inside the rotor. These new features bring a number of advantages and challenges. As mentioned, the synchronous speed resulted in zero slippage, where no current is induced on the rotor bars (except for harmonic currents), in this way, the losses in the rotor are considerably reduced and therefore the internal motor temperature

Also the total motor current is the sum of the magnetization current needed to create the magnetic fields and the current due to the load, the presence of permanent magnets contributes to the reduction of the magnetization current due to the creation of magnetic fields who interact with the magnetic fields of the stator, in this way the total motor current is decreased which results in lower total losses and temperature.

However, the presence of permanent magnets in the rotor also results in a distorted waveform and a braking torque during motor start, which results in large vibrations, so this motor is not recommended for applications with frequent stops / starts (Miller, 1984).

2.3 Voltage Unbalance in Induction Motors

Both standards NEMA (NEMA MG1-2016) and the IEC 60034-1(*IEC 60034-1:2017*) coincide in specifying that motors be designed to operate satisfactorily with a voltage variation of plus or minus 10% of a symmetrical three-phase system at nominal frequency as presented in figure 2. 11 This performance is even worse when voltage unbalance, present in all power systems is added.

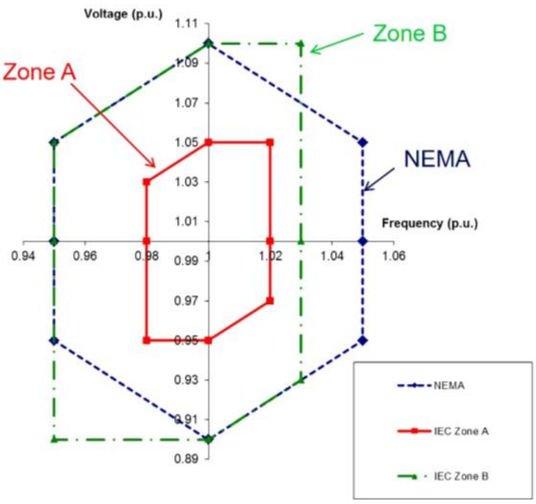


Figure 2. NEMA/IEC Allowable Voltage and Frequency Variations for Motors (*NEMA vs. IEC Motor Standards. "Comparison and Contrast of the Two Design Practices,"*).

The effects of VU on IMs has been extensively documented, unbalanced voltages result in three main components: positive, negative and zero. Positive and negative components 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 & Banerjee, 2001). A small percentage of VU also results in a higher percentage of current unbalance in the order of 6 to 10 times the percentage of VU, which results in large increases in temperature and therefore a reduction in service life.

The National Electrical Manufacturer Association (NEMA) (NEMA MG1-2016, n.d.) defined the unbalance voltage by means of the relation between the maximum voltage deviation from the average line voltage magnitude divided by the average voltage, as presented in (1).

$$\%\boldsymbol{VU} = \frac{\boldsymbol{Máximum\ voltage\ deviation\ from\ average\ voltage}}{\boldsymbol{Average\ Voltage}} \quad \mathbf{(1)}$$

According to NEMA recommendations, to avoid overheating, the three-phase motor needs to be reduced depending on the degree of unbalance. The value by which the power is to be reduced is called the "derating factor", presented in Figure 3.

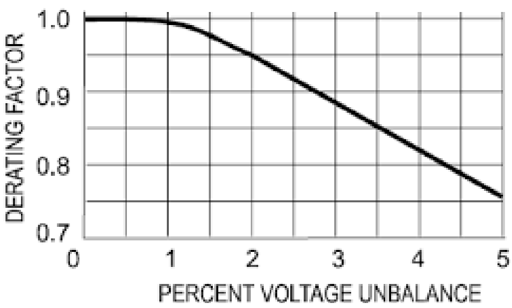


Figure 3. Derating Factor for squirrel cage induction motors due to unbalanced voltage according to NEMA.

3 METHODOLOGY AND RESULTS

3.1 Methodology

Measurements were performed in order to analyze the influence of harmonic voltage unbalance with under and over voltage on the temperature and performance of induction motors classes IE2, IE3 and IE4. Figure 4 shows the general test set up. NEMA definition was selected due to its practicality at the VU degree calculation without the need for a power quality analyzer equipment, or table.

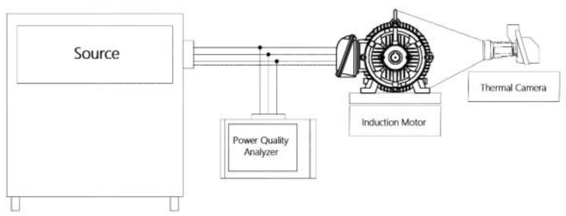


Fig. 4 General Test Setup.

Voltage unbalances were generated using the SUPPLIER three phase AC source model FCATHQ, capable of generate a pure sine signal as well as voltage unbalance, sags and swells and harmonics (up to 50th order) with different distortion magnitudes. To measure the induction motor input parameters the class "A" HIOKI quality analyzer model PW3198-90 was used.

The load used in this work consists of an electromagnetic brake or Foucault brake, which includes two load cells that are connected to the ends of the brake with which it is possible to measure the opposite force produced by eddy currents. When multiplied by the distance to the axis it is possible to find 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 torque of motors. 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
Nominal Power	1 hp	1 hp	1 hp
Nominal Voltages	220 V/380 V	220 V/380 V	220 V/380 V
Speef (rpm)	1730 rpm	1725 rpm	1800 rpm
Nominal Torque (Nm)	4,12	4,13	3,96
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

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

Table 2. Voltage Unbalanced Magnitudes.

% VU	Va	Vb	Vc
1% Under Voltage	117.6 V	107.48 V	127.98 V
3% Under Voltage	120.77 V	128.34 V	116.5 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

To measure the frame temperature was used the FLIR infrared camera model T620, with a calculated emissivity of 0.94. The thermographic images of the motors were captured at two angles every 1 minute. Figure 5 show the angles photographed during the experiments.

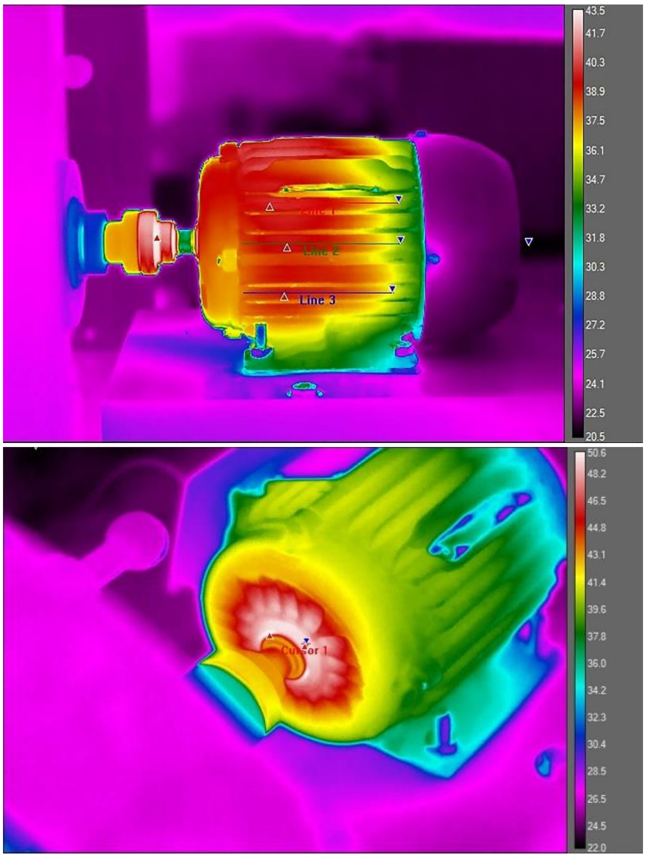


Fig. 5 Thermographic images angles captured for LSPMM.

Regarding the methodology used for the treatment of measurement data and obtaining the results, Figure 6 presents the steps performed in the present work. At first, the tests were performed on the test bench for each of the motors analyzed and then the measurements were made using the Power Quality analyzer equipment as well as the images taken with the infrared camera, considering the measuring points of figures 2 and 3. The next step was to transfer the measurement data from the equipment to the analyzer (HIOKI) and camera (FLIR T620) software. After data analysis, they were converted to CSV format files, compatible for reading in Minitab (Minitab 18) statistical software. In Minitab, the data processed for plotting the results and the statistical analysis made on the study were analyzed.

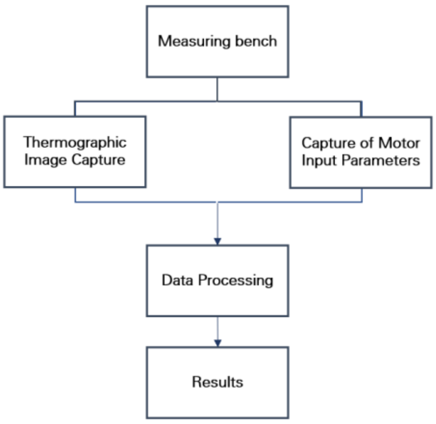
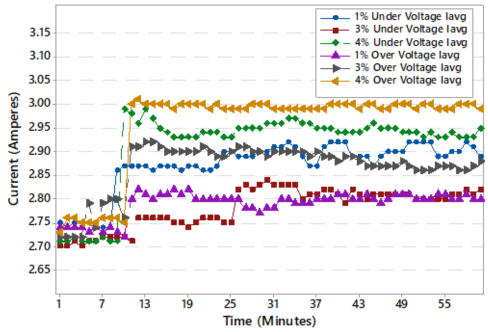


Fig. 6 Flowchart of the methodology used to obtain the results from the measurements.

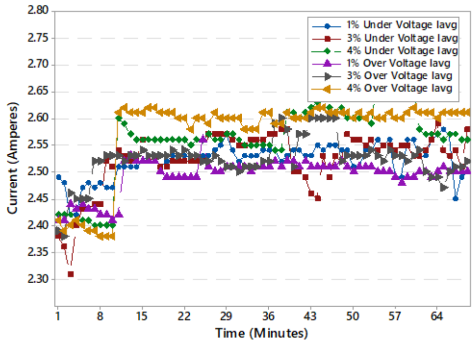
3.2 Results

3.2.1 Current Behaviour

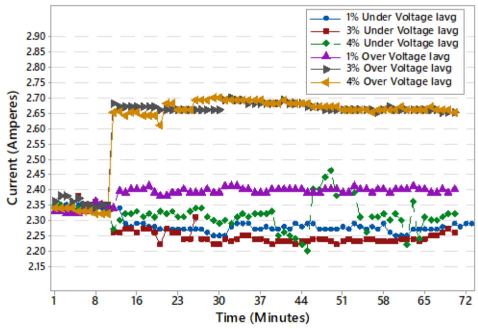
The presence of VU in the supply voltage results in greater unbalances in the line currents, the magnetization current also varies proportionally with the magnitude of the voltages present. In this way the presence of overvoltage results in higher magnetization currents which ends up increasing the total current. However, this scenario depends on the present technology, as presented in Figure 7, where the average variation of the three phases for each VU condition is presented, it is observed that in general the IE2 and IE3 class motors present increases in their current line being the worst scenarios with 4% of VU with under and over voltage, while the IE4 class motor shows the greatest increases for 3 and 4% of VU with overvoltage, it was observed that for this motor the VU with undervoltage results in decreases in the average current.



(a)



(b)



(c)

Fig. 7 Average Current Consumption for under and over voltage unbalance conditions for: (a) IE2 SCIM; (b) IE3 SCIM; (c) IE4 LSPMM.

In electric motors the current is the difference between the supply voltage and the induced voltage, both divided by the equivalent impedance of the motor, however in the LSPMM the induced voltage also depends on the magnetization current generated due to the FMM created in the permanent magnets, so the induced voltage varies less with the variation of the supply voltage. In this way the average current varies according to the magnitude of the supply voltage for the LSPMM.

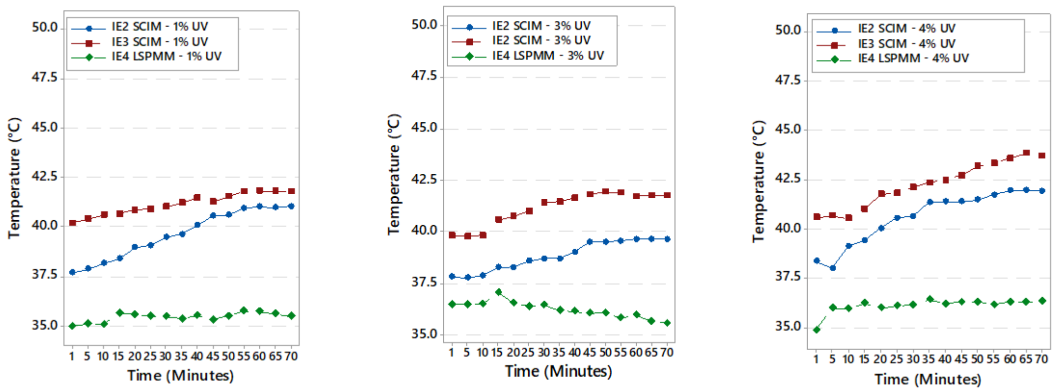
3.2.2 Temperature Rise due to Voltage Unbalance

Voltage unbalance results in increased losses and consequently in the internal temperature of the motor. The improvements implemented in more efficient motors suppose a greater tolerance to temperature due to VU as well as smaller temperature increases. Temperature rise depends on the percentage of unbalance, the voltage magnitudes as well as the present technology. Figures 8 and 9 present the increases in temperature experienced by the IM's under the six unbalance conditions with under and over voltage respectively.

The variation of the temperature with undervoltage in Figure 8 initially shows how the IE4 class has the lowest operating temperature, then the IE2 class motor and finally the IE3 class motor with a temperature of around 40 ° C. It can be seen how 1% unbalance produces uneven increases in temperature in each motor, with class IE2 being the most affected, although the class IE3 motor has the highest temperature. The hybrid motor is not affected by this percentage, varying around its initial temperature throughout the experiment. With 3 and 4% unbalance, the IE2 and IE3 class motors show similar increases in temperature, while the IE4 class motor temperature only increased by 1.3% for 4% unbalance with overvoltage. These results support the current variations observed for this motor in Figure 7 (c) where unbalance with undervoltage resulted in decreases in average current.

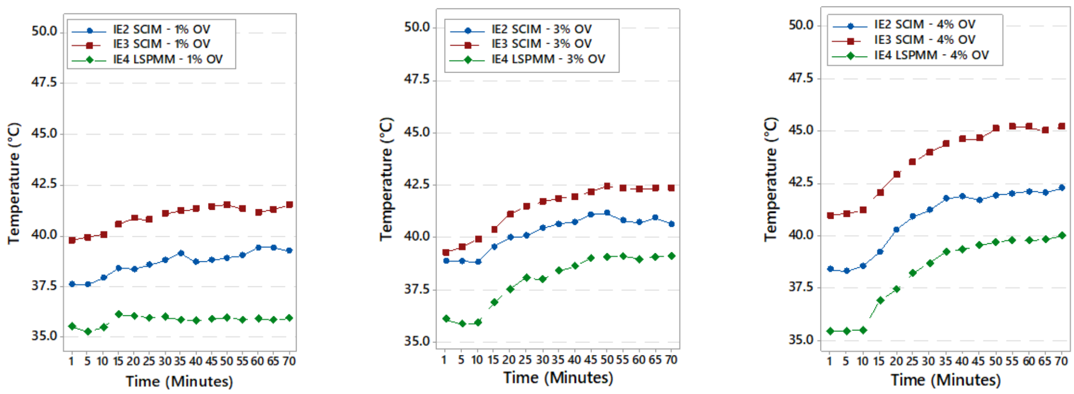
A different scenario is observed for the unbalance with overvoltage, mainly from 3 and 4%, where the IE4 class motor presents the greatest temperature increase (13.3%), while the IE2 class presents the greatest tolerance to this disturbance.

In general, it is observed that the unbalance overvoltage results in greater temperature increases, with the IE4 class hybrid motor being the most affected, while the undervoltage results in temperature increases for the IE2 and IE3 class motors while the IE4 class motor show more tolerance to this disturbance. Table 3 presents



(a) (b) (c)

Fig. 8 Temperature rise for undervoltage unbalance conditions for IE2, IE3 & IE4 Class motors with: (a) 1% UV; (b) 3% UV; (c) 4% UV



(a) (b) (c)

Fig. 9 Temperature rise for overvoltage unbalance conditions for IE2, IE3 & IE4 Class motors with: (a) 1% OV; (b) 3% OV; (c) 4% OV

Table 3. Temperature rise in IM´s with VU

% VU	Induction Motor Class					
	IE2		IE3		IE4	
	UV%	OV%	UV%	OV%	UV%	OV%
0	100	100	100	100	100	100
1	108	104.8	103.4	104.3	101.9	101.6
3	105.1	105.1	105.3	107.9	97.8	109.6
4	108.5	110.7	108.1	110.3	101.3	113.3

4 Conclusion

The present work analyzed the impact of the VU on the temperature of electric motors class IE2, IE3 and IE4. Based on the results obtained, it is possible to conclude how the VU results in increases in both the average line current and the motor temperature, it was observed how not only the percentage of unbalance impacts on these parameters but also the magnitude of the voltages, resulting more damaging the overvoltage unbalance.

The IE3 class motor presented the highest operating temperatures, for both balanced and unbalanced voltages conditions, while the IE4 class hybrid motor presented the lowest operating temperatures for all the scenarios analyzed.

It was observed that the undervoltage unbalance in the hybrid motor did not result in considerable increases in the average current or in the temperature, which demonstrates the contribution of the magnetic fields produced by the permanent magnets in the induced voltage of this motor, being less dependent on the input voltage, for undervoltage conditions.

5 Future Works

For future work, comparisons will be made between different voltage unbalance definitions, considering the definitions of the IEC, IEEE and NEMA, as well as with voltage unbalance and overvoltage conditions individually.

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