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Assessing Voltage Unbalance Conditions in IE2, IE3 and IE4 Classes Induction Motors

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ABSTRACT Brazil has started an energy transition process through more efficient electric motors. The new legislation determining the IE3 Class as the minimum efficiency level in commercial electric motors became valid in August 2019. Currently, four induction motor classes are defined by the IEC 60034-30-1, with the IE4 class being the most efficient, and in the same way, proposals to achieve IE5 efficiency class are available in the market. Considering the upcoming new technologies, it is necessary to know the impact of power systems disturbances in IM's in view of future substitutions. This paper presents a detailed analysis of the impact of different percentages of under and over voltage unbalances on the temperature and performance of electric motors classes IE2, IE3 and IE4. Results show that the IE4 hybrid motor presents non-linear characteristics, being observed this motor shows less dependence on voltage variation, mainly undervoltage unbalance. An analysis of how this phenomenon impacts on the current harmonic distortions in the induction motors operation is also developed through Spearman's correlation matrices. Finally, models that represent the temperature increase of each motor with different voltage unbalance conditions are presented.

INDEX TERMS Energy efficiency, electric motors, permanent magnet motor, temperature measurements, power quality.

I. INTRODUCTION

The implementation of energy efficiency actions, policies and incentives to promote greater environmental and energy economies represent key factors for a sustainable future. Industry is one of the sectors with the greatest opportunities for energy efficiency, with approximately 300 million installed motors representing more than 50% of global electricity consumption [1], [2]. As part of the minimum efficiency policies and requirements, manufacturers and researchers have advanced in the use of high-quality materials and processes as well as more efficient but unexplored new technologies as the line-start permanent magnet motor (LSPMM).

The IE0 class (non-regulated motors) and IE1 class (standard efficiency motors) represent almost 60% of electrical consumption by drive systems [1], [3]. Annually, around 30 million new electric motors are sold [1], with the implementation of incentives by governments, old/non-efficient motors can be replaced by much more efficient technologies which will result in positive impacts for the environment.

The introduction of new technologies added to a good energy efficiency action plan can result in savings of up to 26% of industry energy used according to recent studies [4]. This has led to more than 80 countries to implement energy efficiency actions through Minimum Energy Performance Standards (MEPS), appropriate to each country considering the presence or not of motor-manufacturing industries, to define the minimum efficiency classes for electric motors and from there, define the ecological, energy and economic savings to be achieved.

Brazil has also joined these actions through the Energy Optimization Project for Driving Systems, created within the PROCEL industry program [5], which aims at two main objectives, encouraging the use of higher efficiency motors and optimizing the systems already installed. Published in

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June 2017, it establishes the new energy efficiency regulation for electric motors and determines the minimum performance level in IE3 according to the IEC 60034-30-1 [6] in the power range from 0.16 to 500 kW, from 2 to 8 poles, this regulation came into force in August 2019 and is valid for all motors manufactured or imported, whether new or used, while for the commercialized motors the deadline started in March 2020 [7].

The industry in Brazil is responsible for more than 43% of the total energy consumption, the electric motors in operation use 68% of industry energy consumption, therefore, approximately 30% of the electrical energy in the country is used by electric motors [8]. In this way, the implemented energy efficiency actions can mean significant savings in economic and ecological terms.

More efficient motors result from the implementation of improvements in the design, construction and materials used [9], thus inevitably the disturbances in the electrical systems will impact differently each technology to a greater or lesser degree. Despite the great benefits that efficiency classes substitution can bring, induction motors (IM's) efficiency and performance not only depend on its construction and technology but also on the supply conditions. Because the power quality in real electrical systems are far from ideal, efficiency in electric motors also departs from its ideal value according to the service conditions. The impact of these disturbances not only has an economic consequence due to the increase in consumption, but also affects the power quality, the power factor, as well as decreases the motor lifetime due to increases in temperature.

Considering the new minimum energy performance in Brazil and anticipating new editions, this work presents, through experimental tests, a comparison between induction motors classes IE2, IE3 and IE4, analyzing the main improvements obtained between efficiency classes under ideal operating conditions as well as with the presence of under and over voltage unbalances in the supply voltage.

The results of the proposed experimental tests will allow to observe the response of each technology in ideal conditions and against different degrees of voltage unbalance, from the economic, technical, power quality and temperature points of view.

II. BRAZILIAN INDUCTION MOTOR REGULATION

In August 2019, the new energy efficiency regulation for electric motors came into force, which determines the minimum performance level in IE3 according to Government Ordinance No. 1 [7]. With the implementation of premium efficiency motors, Brazil joins China, North America, the European Union and Japan. By 2030, economies of up to 1.830 TWh/ year and a total accumulated savings for around 1.830 TWh/ year and a total accumulated economy of more than 11 TWh according to the Brazilian Ministry of Mines and Energy are expected [3], [10]. Analyses and suggestions on new policies for induction motors, considering the life cycle cost and the best available technologies in the market for the induction motors, are presented in [11]–[13].

Despite the benefits that the new regulation brings with the minimum efficiency level, motor already installed are not included in the ordinance. Brazil has around 20.1 million electric motors installed in the residential, commercial and industrial sectors [14], the average-life of electric motors varies in the range of 10-20 years according to the nominal power, as well as the operating conditions and energy supply power quality. In industry there is a large number of motors operating above their life expectancy, this is due to the fact that they were probably repaired more than once, and studies show that the losses in efficiency can vary from 3 to 7.5% with each rewinding [14], [15].

The public call No. 002/2015 [16] promotes the replacement of old or reconditioned electric motors with more modern and more efficient motors using a limited bonus system to replace three-phase IM's manufactured until 2009 and with power between 0.75 kW and 250 kW and single-phase electric motors with power equal to or larger than 0.75 kW. The bonus percentage is defined by the electric utility, which must submit the amounts for approval by ANEEL [17].

The initial cost of the electric motor represents approximately 5% of the operation cost throughout its lifetime, and improvements in efficiency come with increases in the initial value of electric motors, mainly when new technologies are implemented, such is the case of the IE4 class line start permanent magnet motor (LSPMM). Although initially the value of these motors was up to 2 times the value of the IE3 squirrel cage induction motor (SCIM), which increases the investment payback, over the years its value was decreasing until reaching values of 1.3 times the costs of the SCIM [18] being more profitable for replacement in the industry.

In this way, users can choose between paying a lower initial value or obtaining greater efficiency by paying an additional cost. Annual cost savings in U.S. dollars ($) obtained with the substitution can be calculated with equations (1-3) [19]:

$$\begin{aligned} \boldsymbol{kW_{saved}} &= \boldsymbol{P_{out}L\left(\frac{100}{E_{OM}} - \frac{100}{E_{NM}}\right)} && (1)\\ \boldsymbol{kW_{savings}} &= \boldsymbol{kW_{saved}hr} && (2)\\ \boldsymbol{Total\ Savings} &= \boldsymbol{12\,(kW_{saved})\,(monthly\ demand\ charge)} \\ &\quad \boldsymbol{+\,(kWh_{savings})(energy\ charge)} && (3) \end{aligned}$$

where kW_{saved} is the kilowatt reduction in motor input power, P_{out} the motor nameplate rated power in kW, L the motor load, $\mathrm{E_{OM}}$ and $\mathrm{E_{NM}}$ are the old motor and new motor efficiencies respectively, hr is the annual operating hours, $kWh_{savings}$ the annual energy savings. Total annual cost savings is calculated using equation (3), using a monthly demand charge of $0.08/(kW-month) and an energy rate of ($0.086/kWh). To analyze the difference between the IE3 and IE4 class motors, the savings in US$ over the average life of these motors for substituting the IE1 class motor were calculated using a $P_{out} = 37$ kW, a L = 0.75 and hr = 8,000 and also considering the substitution bonus, and results are presented in figure 1. It can be seen how the class IE4 motor, despite having a higher initial cost results in large economies of more than 4 times its initial cost, while with the IE3 class motor the savings reach 3 times the market cost.

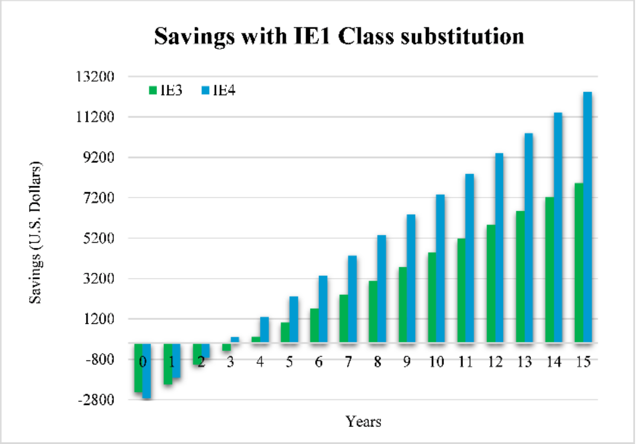


FIGURE 1. **Energy savings with IM's IE3 and IE4 classes replacing an IE1 IM class.**

III. ENERGY EFFICIENT MOTORS

The global energy transformation requests more efficient electric motors with economically viable prices for the replacement of old motors in industry. This transformation started more than 20 years ago with the improvement of materials and processes where high efficiency and super premium efficiency motors emerged. Then and in order to obtain efficiencies greater than those achieved with the SCIM, manufacturers had to go beyond conventional induction motors, including new technologies such as copper rotor motors, synchronous reluctance motors as well as permanent magnet motors [19]. These technologies present significant decrease in losses through factors such as synchronous speed, lower joule losses among others and through which super premium efficiency (IE4 Class) and proposals for the IE5 class were achieved according to the IEC 60034-30-1 [6].

A. LOSSES IN INDUCTION MOTORS

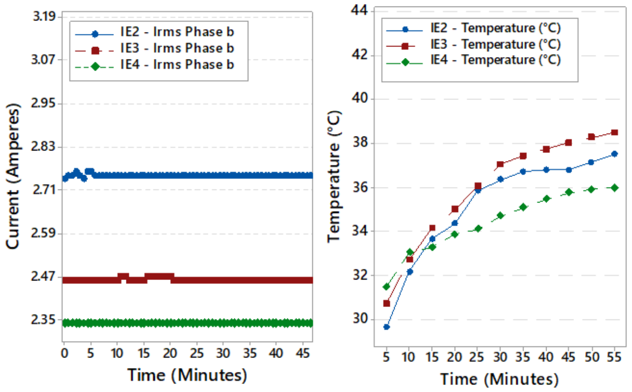
Losses in the electric motors depend mainly on the percentage of load and vary according to the motor nominal power. Ohmic losses represent up to 80% of the total losses for low-power IM's, while for large machines they are reduced to about 55% [19], [20]. Due to that, the main efforts by manufacturers and researchers have been focused on the main losses and the ways to reduce them [21]. Ohmic losses were reduced with more copper wiring in stator and higher slot fill [22]; core losses were reduced by using magnetic materials of high quality [23]; stray load losses with improvements in the motor geometry; and windage and friction losses were reduced with an appropriate design of cooling fan and the reduction in the bearing/seals friction [9]. Consequently IM's have experienced numerous advances in relation to efficiency, reaching values close to 96%, as is the case of the IE4 class Line Start Permanent Magner Motor (LSPMM).

B. COMPARISON BETWEEN SCIM AND LSPMM

The LSPMM has a similar design to the SCIM, with the difference of the presence of permanent magnets inside the rotor, which can adopt different configurations according to the manufacturer's criteria [24]. One of the first outcomes in the LSPMM operation, is the difficulty to start with connected load, this due to the presence of permanent magnets, which create a counter torque, resulting in oscillations according to the percentage of load connected to the motor shaft [25], [26].

However, when synchronous operation is reached a silent operation, as well as lower consumption and operating temperature are obtained. To analyze the operational improvements in high efficiency motors and looking for future substitutions between technologies, the IE2, IE3 and IE4 class motors were compared under the same operating conditions, and the results are presented in the following.

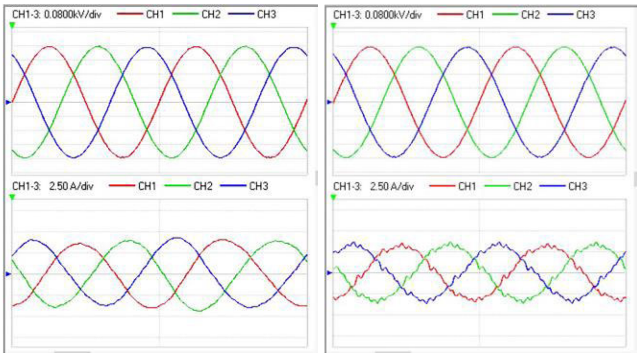
The IE4 class LSPMM has a lower total current compared to the IE2 and IE3 class SCIM motors, as presented in Figure 2 (a). Total current in IM's is the sum of two components, the current due to the load connected and the magnetizing current, necessary to create the magnetic fields in the air gap. The presence of permanent magnets contributes to the reduction of the magnetization current, which in some cases can be up to 50% of the nominal motor current [27, p. 153], reducing the stator winding losses. Another characteristic of the IE4 class LSPMM is the synchronous speed, with which theoretically no current flows in the rotor bars, reducing the ohmic losses and consequently the operating temperature, as observed in Figure 2 (b).



(a) (b)

FIGURE 2. **(a) Total current and (b) temperature in IE2, IE3 and IE4 class motors [28].**

Although the presence of permanent magnets results in lower operating currents and temperatures, it also results in impacts on power quality. Figure 3 presents the voltage and current waveforms for motors classes IE3 (a) and IE4 (b) under ideal feeding conditions. It can be seen how the IE4 class LSPMM presents non-linear characteristics, with



(a) (b)

FIGURE 3. Voltage (up) and current (down) for (a) IE3 SCIM; (b) IE4 LSPMM.

a distorted current waveform, resulting in a current total harmonic distortion (THDI) of up to 4 times that of classes IE2 and IE3 motors, as presented in figure 4.

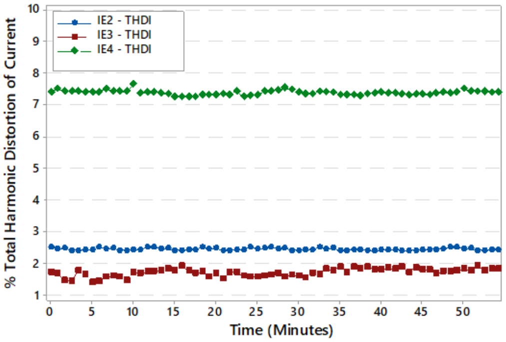


FIGURE 4. Total harmonic distortion of current for IE2, IE3 and IE4 class motors [28].

Harmonics result in different impacts on electrical system components and loads, according to the harmonic order and percentage magnitude. To analyze this aspect, current harmonic were measured in the current waveforms of IE3 and IE4 class motors as presented in figures 5 and 6. Even, odd and interharmonics are found in the current waveforms of both motors, however the IE4 class LSPMM presents higher percentages as well as a greater number of harmonics including high frequency harmonics of up to order 50. Researchers and manufacturers see the LSPMM as a future substitute for SCIM, however studies should be conducted primarily for large-scale use.

The decrease in current flow results in less energy consumption for the IE4 class LSPMM. Figure 7 (a) presents the total power consumed for each motor under the same operating conditions. Regarding the power factor, although the literature comments on the benefits of permanent magnets in improving this parameter [29], for this rated power of 0.75 kW, the class IE3 motor presented a better power factor than the class IE4 motor, and a lower power factor was found for IE2, as presented in figure 7 (b). However, it was observed that for higher loads percentage, the LSPMM motor presented has higher power factor in relation to the IE2 and IE3 classes IM's. According to the literature in [30, p. 61], [31, p. 1], interior the permanent magnets in the rotor (as in this case) also results in lower power factors, due to the rotor saliency, however it can be improved with a suitable design of the magnets inside the rotor.

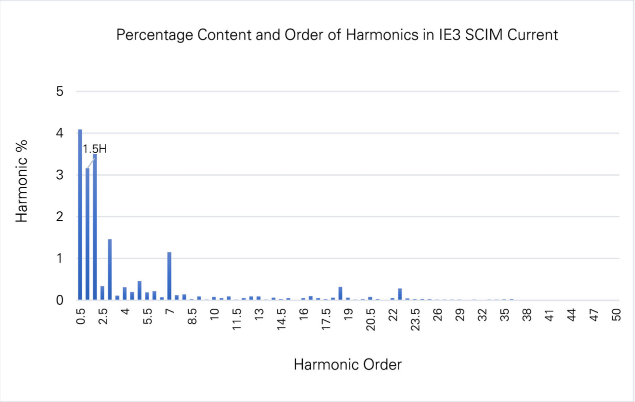


FIGURE 5. Harmonic current spectrum for IE3 SCIM.

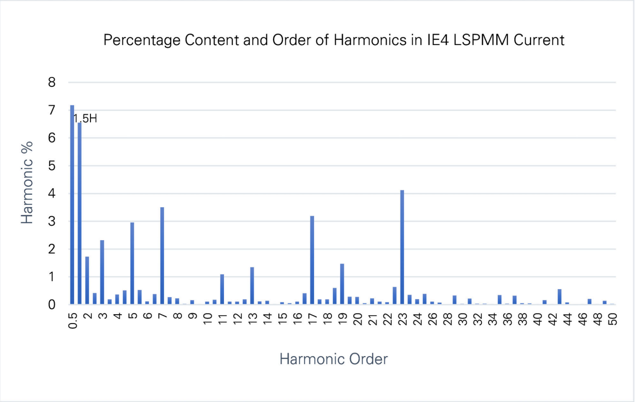
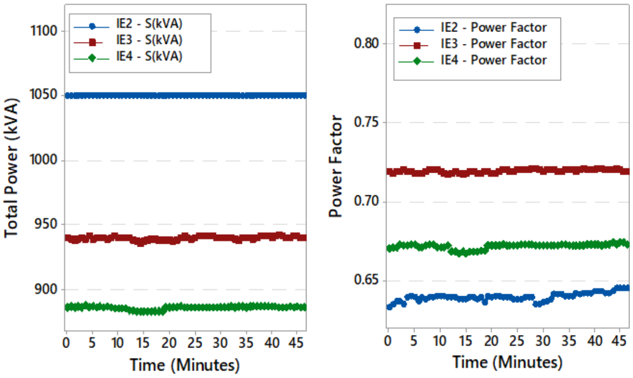


FIGURE 6. Harmonic current spectrum for IE4 LSPMM.



(a) (b)

FIGURE 7. (a) Total power and (b) power factor IE2, IE3 and IE4 class motors.

Finally, this section showed how in relation to energy efficiency, the LSPMM class IE4, presents great savings in relation to consumption, when compared to the IE2 and IE3 class motors. However, from the point of view of power quality, it shows higher harmonic contents, due to which manufacturers and researchers must seek a better balance between both areas (energy efficiency and power quality) to guarantee the best transformation process with the introduction of new technologies in view of futures substitutions.

IV. VOLTAGE UNBALANCE IN INDUCTION MOTORS

Voltage Unbalance (VU) is a phenomenon present in all electrical systems. Due to the numerous negative impacts, visible for unbalances greater than 1%, the National Electrical Manufacturers Association (NEMA) [32] recommends to derate motors power output above that percentage, according to its definition.

A lot of research has been carried out analyzing the impact that the voltage unbalance has on the performance of IM's. The presence of VU in the supply voltages results in three main components: positive, negative and zero, the most damaging being the negative sequence-voltage component, a small negative sequence voltage produces large negative sequence currents, resulting in large currents unbalances and consequently, increased losses and temperature rise in the electric motor. Also its negative effects on torque reduction, power factor and efficiency variation have been documented in [33]–[38].

Due to the numerous damages that this disturbance represents in the IM's, different standards have defined the maximum limits allowed for this phenomenon, including NEMA, IEEE and IEC [32], [39], [40], each one with different considerations.

In relation to the temperature, the VU results in uneven increases in current, increasing joule losses and thus the operating temperature [32], [33], [35]–[37], [41], [42]. In [43], experimental results show that unbalance with under voltage results in the largest temperature increases.

Considering the new outlook which promotes the substitution of old and non-efficient electric motors by high efficiency motors, it is necessary to compare the performance of these new technologies in the presence of power systems disturbances. Based on that, this work presents through experimental tests the response in temperature and performance of electric motors classes IE2, IE3 and IE4 in the presence of different under and over unbalanced voltages.

V. METHODOLOGY

Measurements were performed in the Amazon Energy Efficiency Excellence Center (CEAMAZON) in the Federal University of Pará (UFPA), to analyze the influence of voltage unbalance with under and over voltage on the temperature and performance of induction motors classes IE2, IE3 and IE4. Figure 8 shows the general test set up.

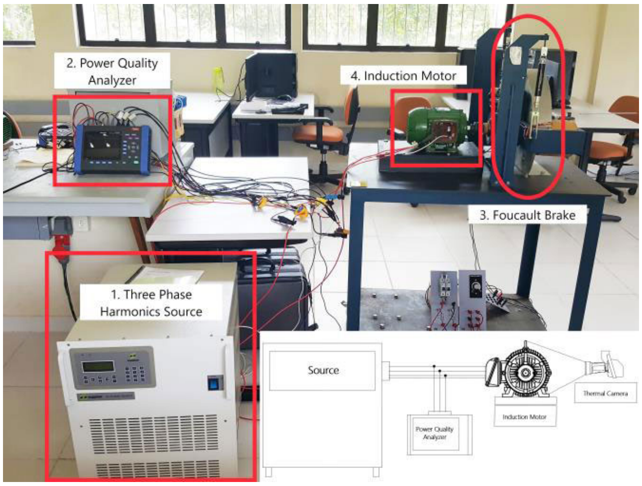


FIGURE 8. General test setup [28].

Voltage unbalances were generated using a three phase AC source model FCATHQ^{TM} (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. Then electric load used in this work consists of an electromagnetic brake or Foucault brake (3), 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 IE2 class motor nominal torque. (4). The nominal data of each motor are presented in Table 1:

TABLE 1. Induction motors parameters [28].

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

At first, the induction motors were subjected to a 220 V perfect three-phase sine voltagefor 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 definition 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 phase angles remained constant. Table 2 presents voltage magnitudes for each voltage unbalance.

To measure the frame temperature, it was used the FLIR^{TM} infrared camera model T620, with a calculated emissivity

TABLE 2. Voltage unbalance magnitudes.

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

of 0.94. The motors thermographic images were captured at two angles every minute for an hour period. Figure 9 shows the angles photographed during the experiments.

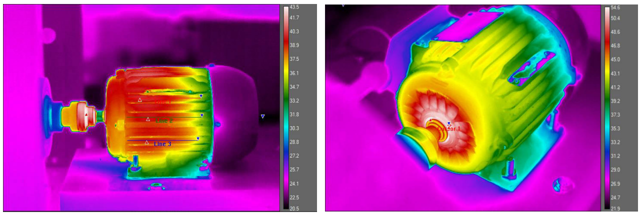


FIGURE 9. Thermographic images angles captured for the LSPMM [28].

Regarding the methodology used for the treatment of measurement data and obtaining the results, Figure 10 presents the steps performed for the study. At first, the six voltage unbalance condition were inserted in the supply voltage of each of the analyzed motors on the test bench 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 figure 9. 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 [44]. In Minitab, the data processed for plotting the results and the statistical analysis made on the study were analyzed.

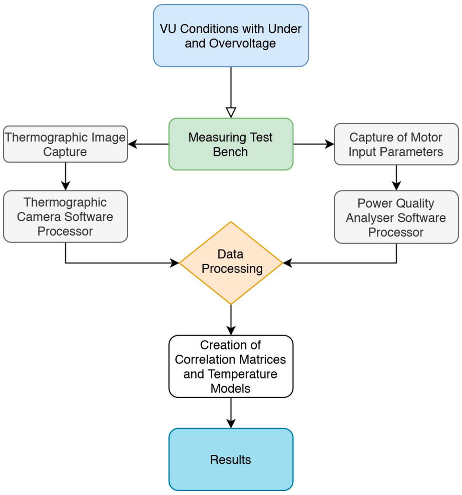
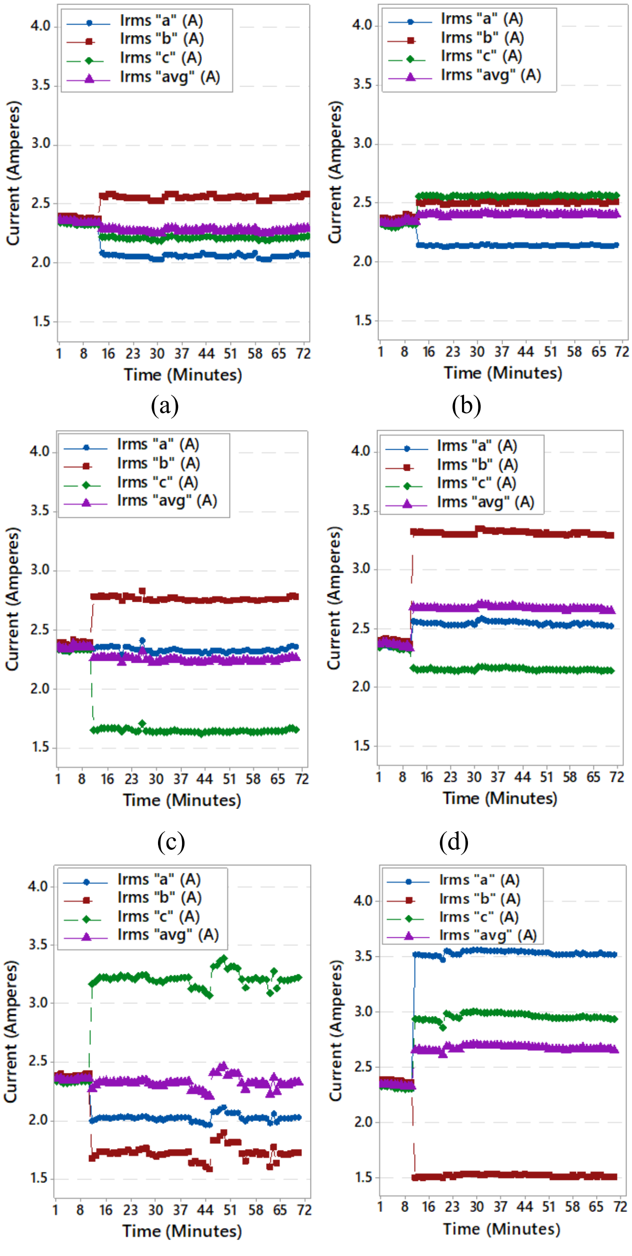


FIGURE 10. Flowchart of methodology used to obtain the results from the measurements.



(a) (b)

(c) (d)

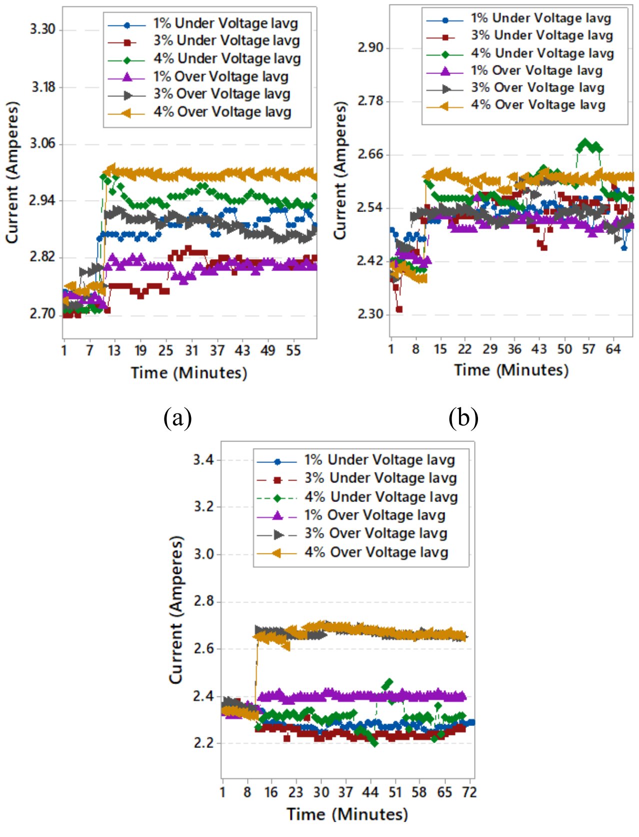
(e) (f)

FIGURE 11. Line and average current for VU in 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.

VI. RESULTS AND DISCUSSION

A. CURRENT BEHAVIOUR

The presence of VU in the supply voltage results in greater unbalances in line current, and magnetization current also varies proportionally with the induced voltage magnitude.



(a) (b)

(c)

FIGURE 12. Average current for under and over voltage unbalance conditions for: (a) IE2 SCIM; (B) IE3 SCIM; (c) IE4 LSPMM.

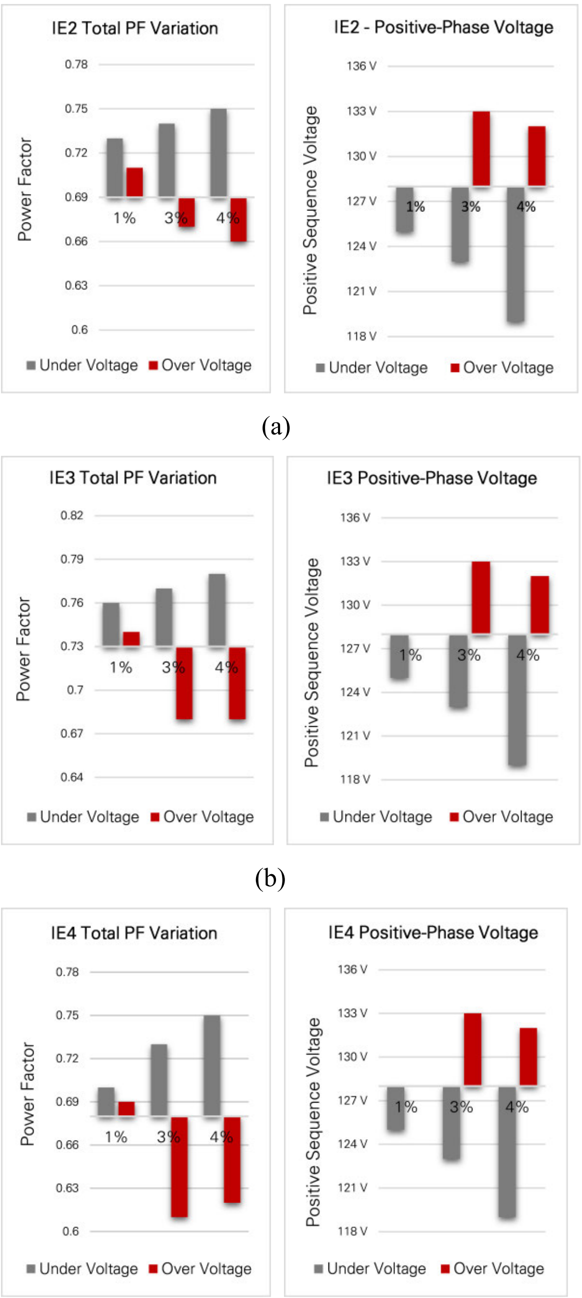
In this way over voltage results in higher magnetization currents which ends up increasing the total current, however in the LSPMM the induced voltage also depends on the magnetization current generated due to the MMF created in the permanent magnets [45], so the induced voltage varies less with the variation of the supply voltage. In this way, the average current varies according to the supply voltage magnitude for the LSPMM. Figure 11 presents phase currents variation for the IE4 class motor in the six VU conditions, and figure 12 presents average current variation for the IE2, IE3 and IE4 Class motors. Unbalance with under and over voltage results in unbalances of up to 10 times the existing VU for the analyzed conditions.

Some conclusions are related to the observed currents:

(1) Voltage unbalance with under voltage results in higher phase currents in relation to over voltage in the IE2 and IE3 SCIM's,

(2) The average current with both under voltage and over voltage shows an increase in relation to the balanced condition.

(3) For the LSPMM, VU with under voltage results in decreases in phase currents and therefore the average current, while over voltage produces an increase like in the SCIM's.



(a)

(b)

(c)

FIGURE 13. Power factor and positive-phase voltage variation with under and over voltage unbalance for: (a) IE2 class SCIM; (b) IE3 class SCIM; (c) IE4 class LSPMM.

Although the LSPMM presents lower average currents, compared to the IE2 and IE3 class SCIM, it also presents the highest current unbalances in 5 of the 6 VU analyzed conditions, while the IE2 class SCIM presents the lowest current unbalances in 4 of the 6 VU analyzed conditions.

B. POWER FACTOR

The power factor is inversely proportional to the positive sequence component, and it is increased with the presence

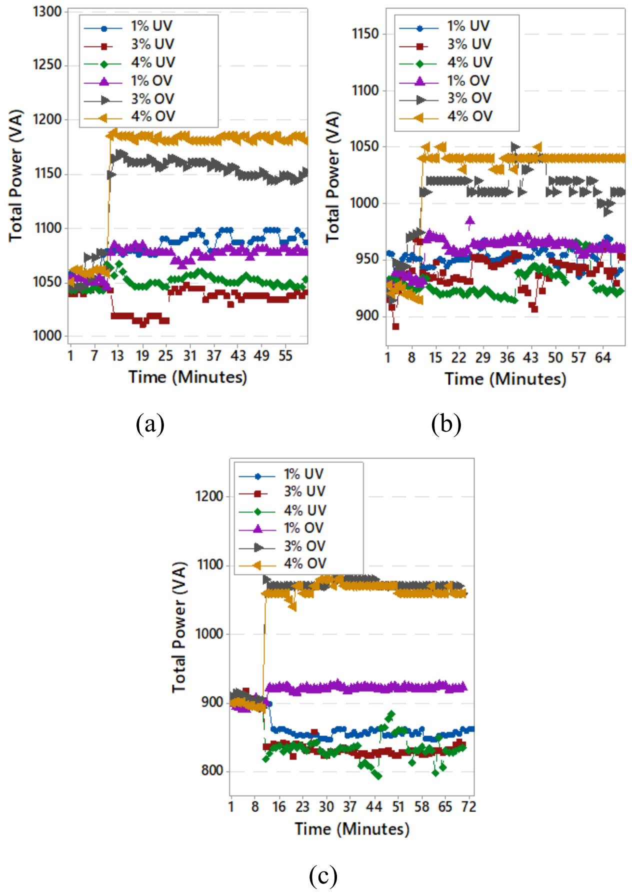


FIGURE 14. **Total power variation with under and over voltage unbalance for: (a) IE2 class SCIM; (b) IE3 class SCIM; (c) IE4 class LSPMM.**

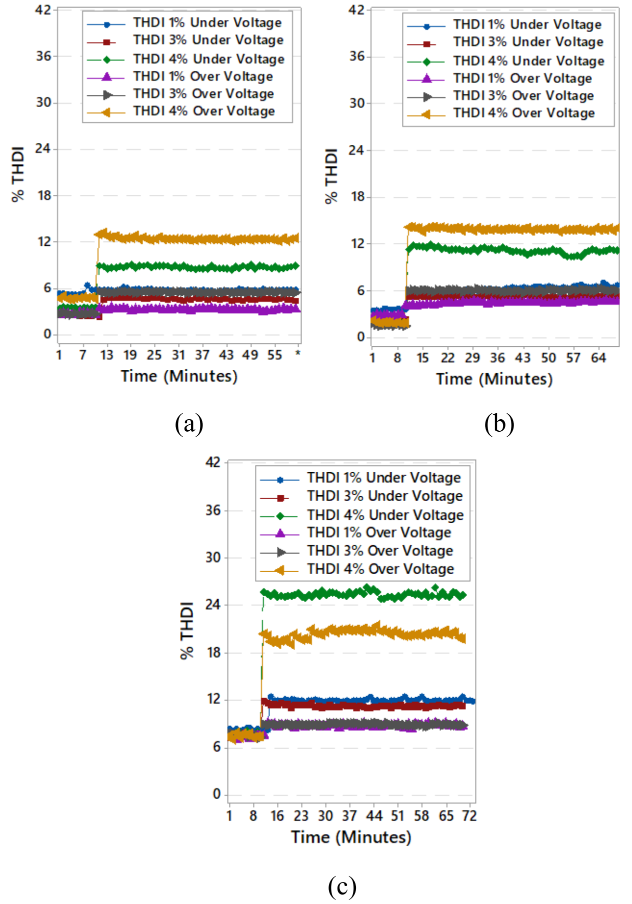


FIGURE 15. **Current total harmonic distortion for under and over voltage unbalance conditions for: (a) IE2 SCIM; (b) IE3 SCIM; (c) IE4 LSPMM.**

of VU undervoltage, while the VU with over voltage results in large decreases in this value according to the VU percentage [46]. Figure 13 shows the variation of this parameter with VU and the inverse relation with positive sequence phase voltage in the IE2, IE3 and IE4 Class motors.

C. TOTAL POWER

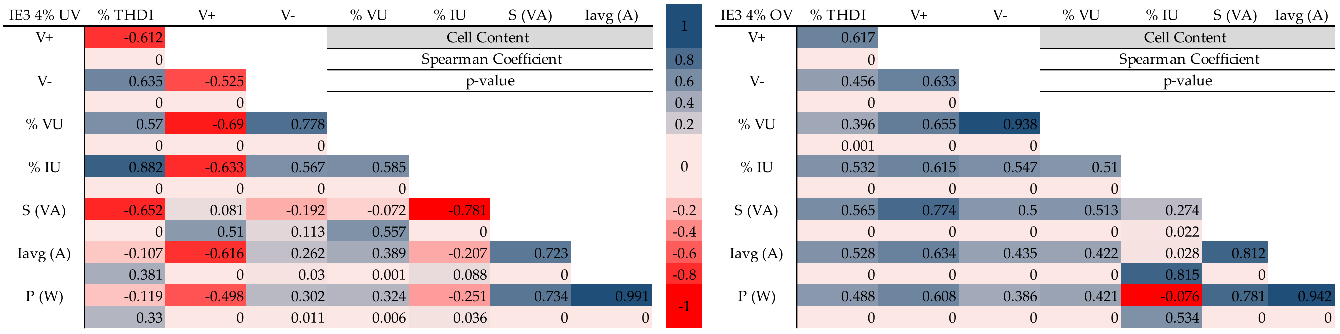
For voltage unbalance conditions, the total power absorbed by IM's is the sum of the total power of positive and negative sequences [38]. In general, unbalances with under and over voltage result in increases in the total power consumed for SCIM Classes IE2 and IE3, while for the LSPMM VU with under voltage results in decrease in consumption for the same load percentage as presented in figure 14.

In relation to motor consumption, as was initially observed in Figure 2, the LSPMM demands lower input currents, mainly due to the magnetic fields created by the permanent magnets, which contributes to the reduction of the magnetizing current, and therefore in the total current. The decrease in the input voltage of the LSPMM, results in a decrease in the induced voltage, which translates into an even lower magnetizing current. In this way, phase currents are reduced as presented in Figure 11, and therefore, the total consumption. Then, in the section below will be presented that this condition results in greater currents total harmonic distortions, as shown in Figure 15.

D. CURRENT TOTAL HARMONIC DISTORTION

It was observed in figure 4, that the presence of permanent magnets in the LSPMM resulted in a THDI up to 4 times that of SCIM classes IE2 and IE3, and this condition is aggravated when an unbalance in the supply voltage is added. Figure 15 (a-c) presents the variation of this parameter with under and over voltage unbalanced conditions. Voltage unbalance results in a growth in the current total harmonic distortion (THDI) for the analyzed motors. The increase depends on the percentage of unbalance present as well as on the voltage magnitudes. For the IE2 and IE3 class motors the worst scenarios are observed for 4% VU with over and under-voltage, respectively. A similar scenario is observed for the IE4 class LSPMM, with higher increases for the undervoltage conditions.

Aiming to analyze the VU influence in the current total harmonic distortion (THDI), a correlation analysis was developed in Minitab 18, considering the THDI, the positive and negative sequence voltages ($V+$), ($V-$),



IE3 4% UV	% THDI	V+	V-	% VU	% IU	S (VA)	Iavg (A)
V+	-0.612						
	0						
V-	0.635	-0.525					
	0	0					
% VU	0.57	-0.69	0.778				
	0	0	0				
% IU	0.882	-0.633	0.567	0.585			
	0	0	0	0			
S (VA)	-0.652	0.081	-0.192	-0.072	-0.781		
	0	0.51	0.113	0.557	0		
Iavg (A)	-0.107	-0.616	0.262	0.389	-0.207	0.723	
	0.381	0	0.03	0.001	0.088	0	
P (W)	-0.119	-0.498	0.302	0.324	-0.251	0.734	0.991
	0.33	0	0.011	0.006	0.036	0	0

Cell Content
Spearman Coefficient
p-value

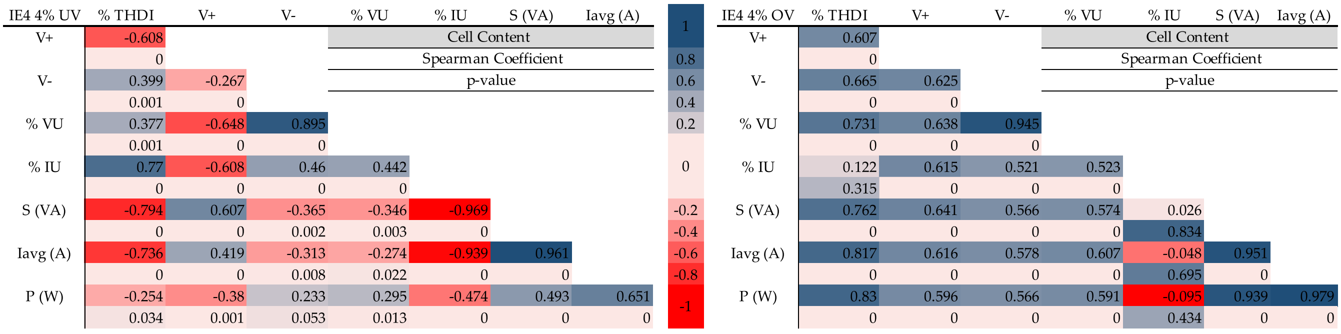
(a)

IE3 4% OV	% THDI	V+	V-	% VU	% IU	S (VA)	Iavg (A)
V+	0.617						
	0						
V-	0.456	0.633					
	0	0					
% VU	0.396	0.655	0.938				
	0.001	0	0				
% IU	0.532	0.615	0.547	0.51			
	0	0	0	0			
S (VA)	0.565	0.774	0.5	0.513	0.274		
	0	0	0	0	0.022		
Iavg (A)	0.528	0.634	0.435	0.422	0.028	0.812	
	0	0	0	0	0.815	0	
P (W)	0.488	0.608	0.386	0.421	-0.076	0.781	0.942
	0	0	0	0	0.534	0	0

Cell Content
Spearman Coefficient
p-value

(b)

FIGURE 16. Correlation matrix for IE3 Class SCIM motor parameters in the presence of VU with: (a) 4% under voltag; (b) 4% over voltage.



IE4 4% UV	% THDI	V+	V-	% VU	% IU	S (VA)	Iavg (A)
V+	-0.608						
	0						
V-	0.399	-0.267					
	0.001	0					
% VU	0.377	-0.648	0.895				
	0.001	0	0				
% IU	0.77	-0.608	0.46	0.442			
	0	0	0	0			
S (VA)	-0.794	0.607	-0.365	-0.346	-0.969		
	0	0	0.002	0.003	0		
Iavg (A)	-0.736	0.419	-0.313	-0.274	-0.939	0.961	
	0	0	0.008	0.022	0	0	
P (W)	-0.254	-0.38	0.233	0.295	-0.474	0.493	0.651
	0.034	0.001	0.053	0.013	0	0	0

Cell Content
Spearman Coefficient
p-value

(a)

IE4 4% OV	% THDI	V+	V-	% VU	% IU	S (VA)	Iavg (A)
V+	0.607						
	0						
V-	0.665	0.625					
	0	0					
% VU	0.731	0.638	0.945				
	0	0	0				
% IU	0.122	0.615	0.521	0.523			
	0.315	0	0	0			
S (VA)	0.762	0.641	0.566	0.574	0.026		
	0	0	0	0	0.834		
Iavg (A)	0.817	0.616	0.578	0.607	-0.048	0.951	
	0	0	0	0	0.695	0	
P (W)	0.83	0.596	0.566	0.591	-0.095	0.939	0.979
	0	0	0	0	0.434	0	0

Cell Content
Spearman Coefficient
p-value

(b)

FIGURE 17. Correlation matrix for IE4 Class LSPMM motor parameters in the presence of VU with: (a) 4% under voltage; (b) 4% over voltage.

the percentage of voltage and current unbalance (% VU), (% IU), total power (S), average current (Iavg), and active power (P). Figures 16 and 17 present the correlations matrix.

In general, correlation analysis results in a number between −1 and +1, called the correlation coefficient. Coefficient value indicates the relationship between the variables, the higher the coefficient, the greater the correlation. For this case and after finding a nonlinear relationship between some variables, Spearman's correlation method was used. In the correlation matrix the upper cell shows the Spearman coefficient while the lower cell shows the p-value, useful for rejecting the null hypothesis when compared to the significance level (0.05 assumed).

It is observed in Figures 16 and 17, that the parameters have inversely proportional relationships (negative Spearman coefficients) with respect to THDI for under voltage unbalance, and directly proportional in the case of over voltage unbalance (positive Spearman coefficients). For under voltage unbalance, the THDI is inversely proportional to positive sequence voltage (V+) and directly proportional to negative sequence voltage (V−). The percentage of current unbalance (% IU) also shows directly proportional relationships with respect to the THDI except for the case of over voltage in the LSPMM.

For the VU with over voltage, it is observed that the THDI varies proportionally with the positive sequence (V+) and negative sequence (V−) voltages, the percentages of voltage and current unbalances also show this behavior. The THDI also varies inversely proportional to the consumption in VA in the case of VU with under voltage, and directly proportional with the VU with over voltage. It is also observed how THDI presents higher correlations with the average current of the IE4 class hybrid motor, different to the IE3 class motor.

E. TEMPERATURE INCREASE DUE TO VOLTAGE UNBALANCE

The improvements implemented in the LSPMM result in lower operational temperatures in relation to IE2 and IE3 class motors in ideal supply conditions. In VU conditions, large current unbalances are created, which increases the losses in the motor and therefore the inner and outer temperatures. To analyze the VU impact with under and over voltage on the motor temperature, thermographic images representing the increase of this parameter in the motor end shield were captured, the results for each VU condition for the LSPMM are presented in figures 18 and 19. The photographs show how 1% of VU with under and over voltage does not result in visible increases in the LSPMM temperature, which justifies that it is not necessary to derate motor output power

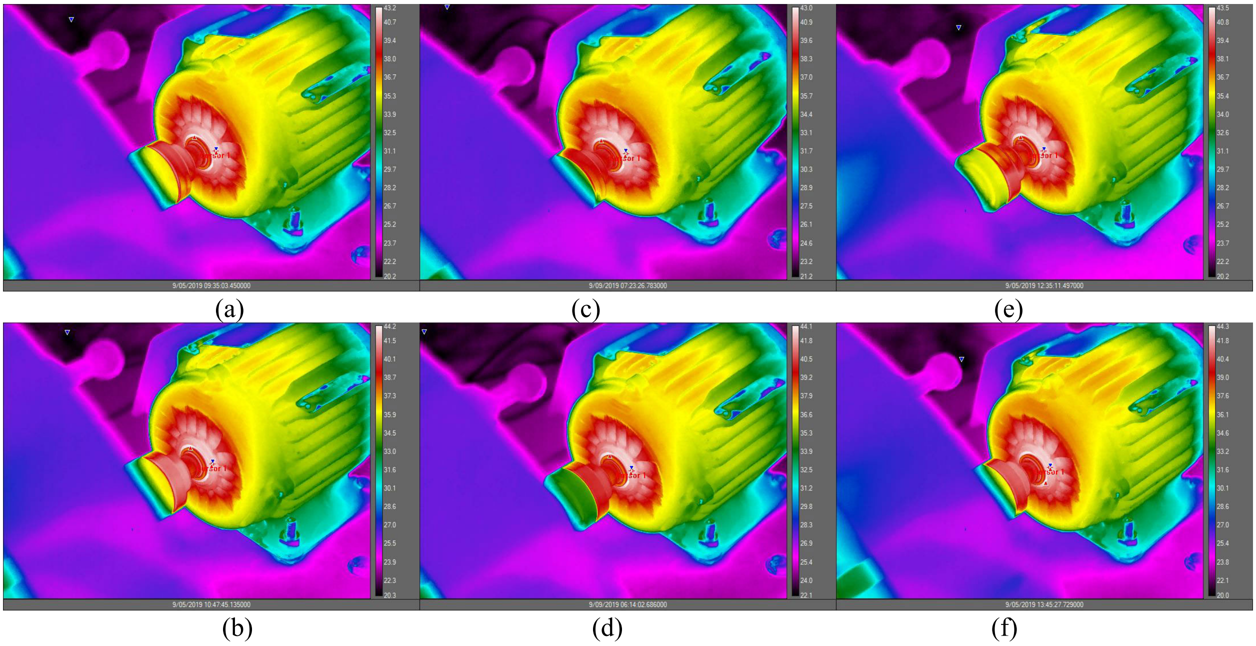


FIGURE 18. Frame temperature with: 1% under voltage (a & b); 3% under voltage (c & d; 4% under voltage.

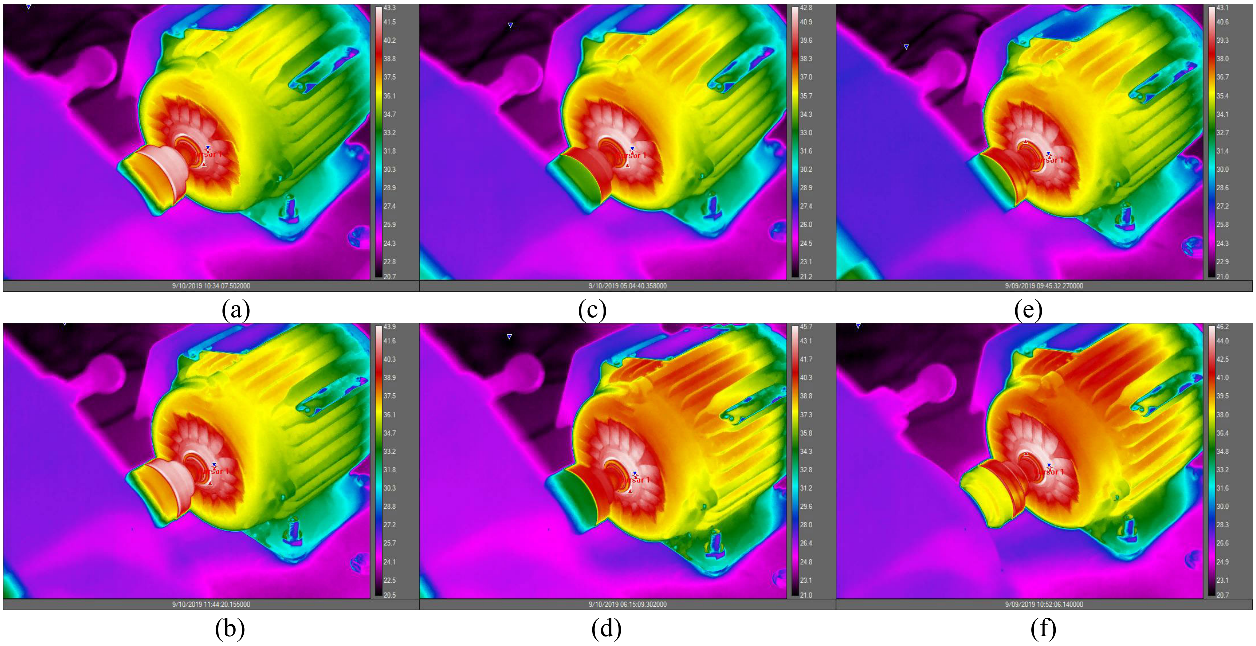


FIGURE 19. Frame temperature with: 1% over voltage (a & b; 3% over voltage (c & d); 4% over voltage (e & f).

for this VU condition according to NEMA [32]. The worst visible scenarios correspond to unbalances of 3% and 4% with over voltage (Figure 19, c-f) turning out to be more damaging to the temperature of this motor than the VU with under voltage.

Temperature variation for the three IM's in the six conditions analyzed are presented in Figure 20. Within the three technologies, the IE2 class motor has insulation class B (maximum temperature of 130 °C), while the IE3 and IE4 class motors have insulation class F (maximum temperature of 155 °C), which means that higher tolerance for temperature increases is expected. However, the results show that the IE4 and IE2 class motors have the lowest operating temperatures, below the IE3 class motor.

In the case of the IE4 class motor, it can be seen in Figure 20 (a, c and e) that the VU with under voltage does not result in considerable increases in its operating temperature. This comes from the fact that in this case the current average magnitude did not increase, resulting in small temperature variations. This scenario changes with unbalance with over voltage, in which the LSPMM presents the highest temperature increases, mainly for cases of 3% and 4% of unbalance over voltage.

In relation to the IE2 and IE3 class motors, similar increases for the conditions with unbalance with under and over voltage, the VU with over voltage resulted as being more damaging. A summary of this parameter variation is presented in Table 3.

TABLE 3. Temperature rise in induction motors with voltage unbalance.

	Induction Motor Class					
	IE2		IE3		IE4	
% VU	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

F. TEMPEATURE MODELS FOR VU IN IE2, IE3 AND IE4 CLASS MOTORS

As it was observed, VU resulted in increases in the operating temperature according to the unbalance percentage. In the graphs presented in figure 20 it is observed how the temperature exhibits a certain increase pattern until reaching the thermal equilibrium with the new unbalance percentage. To analyze the influence of this disturbance on the temperature of each technology, a regression model was used for each percentage of VU using the Minitab 18 statistical software, which uses least squares estimation to fit linear and quadratic terms in the models between two variables (X_i, Y_i). In (4) a linear model is presented.

$$Y_i = \alpha + \beta X_i \tag{4}$$

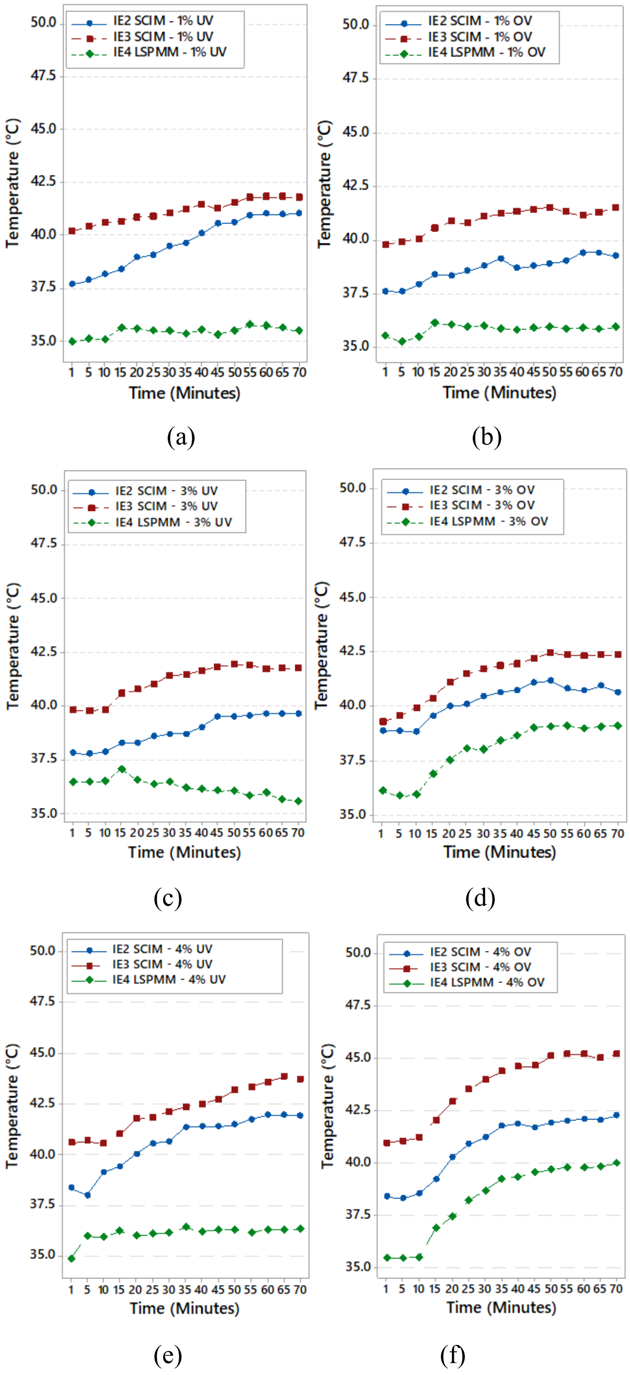
To calculate the coefficients, it is sought that the sum of the square distances between the measured points and the line model, in equation (4), is minimized, as presented in equation (5) [47].

$$\min_{\alpha,\beta} \sum_{i=1}^{n} e_i^2 = \min_{\alpha,\beta} \sum_{i=1}^{n} (y_i - \alpha - \beta x_i)^2 \tag{5}$$

To obtain a good estimation between the analyzed variables, thermographic images were made every minute in each unbalanced condition to have a higher precision in the created models.

Equation 7 presents the temperature change in (°C) over time until the thermal equilibrium is again reached for the IE4 Class hybrid motor when subjected to 4% VU with over voltage.

$$Temp\,(^{\circ}C) = 35.54 + 0.178t - 0.001485\,t^2 \tag{6}$$



(a) (b)

(c) (d)

(e) (f)

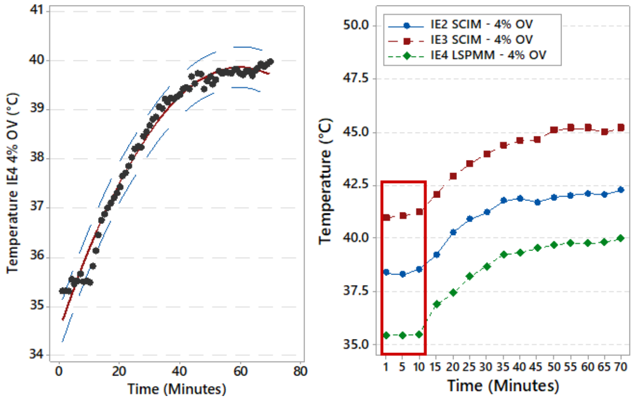
FIGURE 20. Temperature increase in IE2, IE3 and IE4 class IM's with: (a) 1% under voltage; (b) 1% over voltage; (c) 3% under voltage; (d) 3% over voltage; (e) 4% under voltage; (f) 4% over voltage.

where t is the time in minutes. For the model presented in (4), an adjusted $R^2 = 0.9841$ is obtained, and also presenting values less than 0.05 for the p-value. Figure 21 (a) presents the IE4 LSPMM prediction curve for the 4% over voltage unbalance, where the red fitted line shows the predicted temperature for 4% VU unbalance with over voltage and the blue dashed lines show the 95% prediction interval. It is noted that the initial measured temperature values are not quite well

TABLE 4. Summary of temperature models for voltage unbalance in IM's classes IE2, IE3 and IE4.

% VU	IM Class	Equation Model	Adjusted R^2
1% UV	IE2	$T\ (°C) = 37.40 + 0.07935\ t - 0.000348\ t^2$	97.98%
	IE3	$T\ (°C) = 40.10 + 0.04367\ t - 0.000304\ t^2$	92.20%
	IE4	$T\ (°C) = 35.10 + 0.01631\ t - 0.000141\ t^2$	45.94%
3% UV	IE2	$T\ (°C) = 37.49 + 0.05009\ t - 0.000239\ t^2$	94.65%
	IE3	$T\ (°C) = 39.37 + 0.08460\ t - 0.000722\ t^2$	96.94%
	IE4	$T\ (°C) = 36.64 - 0.002836\ t - 0.000188\ t^2$	80.84%
4% UV	IE2	$T\ (°C) = 37.59 + 0.14810\ t - 0.001310\ t^2$	95.58%
	IE3	$T\ (°C) = 40.15 + 0.07319\ t - 0.000284\ t^2$	97.44%
	IE4	$T\ (°C) = 35.94 + 0.007334\ t$	78.00%
1% OV	IE2	$T\ (°C) = 37.63 + 0.03913\ t - 0.000208\ t^2$	90.46%
	IE3	$T\ (°C) = 39.68 + 0.06225\ t - 0.000551\ t^2$	95.83%
	IE4	$T\ (°C) = 35.53 + 0.02125\ t - 0.000259\ t^2$	31.79%
3% OV	IE2	$T\ (°C) = 38.28 + 0.10270\ t - 0.000983\ t^2$	93.85%
	IE3	$T\ (°C) = 38.94 + 0.12250\ t - 0.001094\ t^2$	98.42%
	IE4	$T\ (°C) = 35.22 + 0.13000\ t - 0.001079\ t^2$	97.12%
4% OV	IE2	$T\ (°C) = 37.52 + 0.15880\ t - 0.001360\ t^2$	96.24%
	IE3	$T\ (°C) = 38.94 + 0.12250\ t - 0.001094\ t^2$	97.77%
	IE4	$T\ (°C) = 35.54 + 0.17810\ t - 0.001485\ t^2$	98.41%

* Where t represent the time in minutes for every VU condition.



(a) (b)

FIGURE 21. (a) Prediction plot for temperature model with 95% of prediction interval; (b) Highlighting initial motors temperature measurements before applying unbalanced voltage supply.

fitted by the regression model, presenting larger temperature residuals between values of measured temperature (T_{measured}) and predicted temperature (T_{fitted}). This is because these measured temperature points correspond to the first 10 minutes after starting to bring the motors to a thermal equilibrium condition, before applying the unbalance voltage supply. This condition is illustrated in Figure 21 (b) for IE2, IE3, and IE4 classes motors.

To assess the proposed model accuracy, temperature residuals are plotted in figure 22. Positive value for the residual (on the vertical axis) means the predicted temperature was lower than the measured temperature, and negative value means it was higher, zero means the prediction was correct [48]. It is observed that residuals are mostly clustered around zero, not exceeding temperature mismatches of ±1 degree. Also, for this case, the calculated R^2 value was 98.41%.

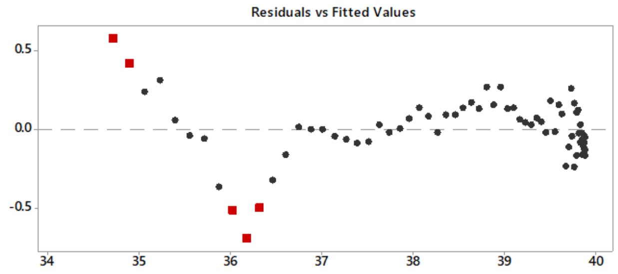


FIGURE 22. Residuals versus fitted or predicted temperature values.

This analysis was performed for the creation of temperature versus time models for each VU analyzed. Figure 23 presents the adjusted R^2 values for each created model, and Table 4 presents the results corresponding to the created models. SCIM classes IE2 and IE3 presented greater temperature increases in the six VU conditions analyzed, also presenting a similar increase pattern, due to which the models created present good approximation of the temperature variation over time until the thermal equilibrium is reached. A different scenario was observed for the LSPMM, which presented considerable increases only for the 3% and

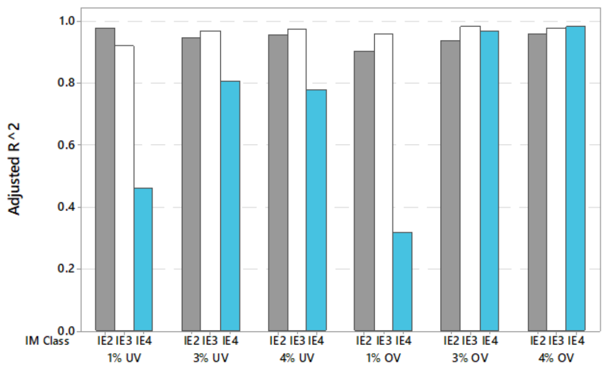


FIGURE 23. **Adjusted coefficient (adjusted R2) for generated models presented in Table 4.**

4% unbalances with over voltage, this is reflected in the adjusted R^2 value, where the models best represent this variation, with values above 97 %.

Table 4 shows each of the temperature models for each unbalance condition and for each motor analyzed. In general, it is observed that almost all models have a quadratic term, useful for modeling the temperature curvature, until the thermal equilibrium is reached again. In these equations, the first coefficient corresponds to the motor's initial temperature, after reaching thermal equilibrium with balanced voltages; the second term determines the rate of temperature increase over time. The third negative sign coefficient is useful to flatten the curve, until the thermal equilibrium is reached.

VII. CONCLUSION

Considering future substitutions between technologies, this work presented a detailed analysis of electric motors classes IE2, IE3 and IE4 responses, under ideal power supply conditions, as well as having under and over voltage unbalances, also considering unbalances impacts on power quality and temperature, through an statistical analysis. Some recommendations can be made based on the experimental tests carried out in this work.

The IE2 and IE3 class SCIM's presented similar operational characteristics, therefore, at the time of substitution, no additional considerations other than efficiency performance is necessary to be carried out.

For the IE4 class LSPMM, however, it was observed through the experimental tests how it can handle higher loads within its nominal values, when compared to the IE2 and IE3 class motors, which can result in a lower consumption at the time of replacement for the same load. However, for the IE4 class LSPMM some operational differences were observed, which must be considered at the time of substitution

Once the LSPMM reaches synchronism, its speed remained constant during all the experiments, due to which this motor is recommended in applications with fixed speeds. It was also observed that at the starting time this motor presented difficulties due to the braking torque in permanent magnets, in this way, it is not recommended in applications with frequent start and stop cycles.

In large scale uses, the IE4 class LSPMM current harmonic content must be also considered, due to the higher harmonic content found in its waveform which is increased with the presence of disturbances such as voltage unbalance.

Results also show that the power factor of the LSPMM motor is less than that of the IE3 class motor for this rated power, and load condition, so the construction characteristics as well as PM rotor configurations must be analyzed in order to get a higher rotor saliency, related to this parameter [30, p. 61], [31, p. 1]. In large-scale uses, the LSPMM current harmonic content must be also considered primarily in networks with high percentages of voltage unbalance or voltage harmonics.

The presence of voltage unbalance conditions results in higher current unbalances and harmonics for the IM's, which produces uneven losses and temperature increases. Power factor also varies inversely to the positive sequence voltage, increasing for undervoltage and decreasing for overvoltage unbalance conditions. In relation to consumption, unbalances with under and over voltage result in increases in the total power consumed for SCIM Classes IE2 and IE3, while for the LSPMM VU with under voltage results in decrease in consumption for the same load.

A novel harmonic analysis was also presented using Spearman's correlation matrices. It was o observed how the THDI is inversely proportional to the positive sequence voltage component and directly proportional to the negative sequence voltage component for the undervoltage unbalance condition. While for the overvoltage unbalance condition turned out to be directly proportional to both positive and negative sequence components.

Finally, novel models representing the temperature variation in IE2, IE3 and IE4 class motors were developed for six voltage unbalance conditions with under and overvoltage. It was observed that large approximations in relation to the experimental data were obtained for the IE2 SCIM and IE3 SCIM, while for the IE4 Class LSPMM the models presented greater approximations for voltage unbalances greater than 3%.

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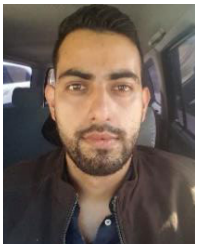

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