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Analysis of the Effects of Voltage Unbalance on Three-Phase Induction Motors

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Abstract

The 3-phase induction motors are widely used in mechanical load drive in residential, commercial and especially industrial facilities, where the motor is subject to have a number of malfunctions generated by the power supply. Thus, it becomes crucial to conduct studies that monitor their performance, monitoring the negative impacts generated. This article aims mainly at showing the 3-phase induction motor behavior when subjected to the effects of unbalance on the power supply voltage. It was developed the system architecture for four different experiments in order to make measurements using a power analyzer. For all the experiments a ramp time is adjusted through a soft starter drive (SS) and after that the motor is split. As soon it gets to permanent regime the motor receives power through adjustments of the dynamometer brake voltage and soon after that an unbalance voltage is forced among the phases with the help of a rheostat, in order to analyze the effect on the power factor as well as on the harmonics.

Keywords

Induction Motors, Voltage Unbalance, Power Quality

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1. Introduction

The 3-phase induction motors are widely used in mechanical load drive not only in small-sized consumer units but also in big companies. Considering the great number of motors used in Brazil and consequently analyzing the consumption of energy associated, they are responsible for approximately 68% of industrial energy consumption and 35% of total energy consumption in Brazil. The importance to analyse the induction motor consumption is important to define policies do apply in energy planning [1]. The 3-phase induction motors become crucial when their magnitudes are evaluated against the energy quality [2].

Taking into consideration that their behavior can vary according to the anomaly in the power supply, generate financial losses as well as reduce their lifetime it becomes necessary a behavior evaluation.

The electrical disturbances, which cause low electrical power quality, regardless its cause, can generate relevant losses to energy consumers. In fact, the industries end up being the most affected ones, as the disturbance can cause bad function as well as burn the equipment connected to the electrical power and consequently interrupt a production process [3].

The 3-phase induction motor behavior when subjected to bad functions such as voltage unbalance is largely studied topic in the academic field, taking into consideration the equipment efficiency regarding economic aspects which are relevant and impacted by the losses [4]. It is important to highlight that the energy consumption can be affect for the oversizing motor specification as reported by Ferreira et al. [5].

The voltage unbalance in three phase system is practically

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impossible to be eliminated due to their inherent causes and further this problem is aggravated by the fact that the presence of small unbalance in three phase system will cause the no proportional unbalance in the line current [6].

An unbalanced voltage supply leads to a reduction in the torque of the induction motor. An increase in the motors current forces the user to derate the motor [7].

The unbalance in the supply voltage to the induction motor can result in degradation of motor performance and also shorten the life of the induction motor [8].

Losses can be studied as presented in [2]. Efficiency tests can be performed according to the Brazilian technical standard NBR5383 / 1: 1999, method 2 [9]. This method is similar to the method B of IEEE - 112: 1991 [10], and is performed using a dynamometer, with indirect measurement of additional losses and direct measurement for losses in the stator (I^2R), rotor (I^2R) and core as well as friction and ventilation losses. In this method, the input and output power are measured, and the apparent losses are calculated by subtracting from each other. The additional losses are calculated by subtracting from the apparent losses the remaining loss components, which in turn is obtained by direct measurement of the I^2R losses in the stator and rotor, the iron core losses and the friction and ventilation losses.

Besides these analyses, researches are also carried on in order to verify the effects caused by these unbalances in voltage on the winding temperature, which can affect the lifetime as well as the charging capacity of the induction machine.

It should be taken into consideration that one of the factors that most contribute to the increase in MIT is the power with unbalanced phase. The voltage unbalance can be generated by a number of causes. The main one is the disproportionate monophasic power, being verified in monophasic motors installation as well as a random distribution of phases in lighting systems, where these inappropriate installations generate problems such as Rezende and Samesina [11]:

1 An excessive current increase which has a negative current generating a rotating field contrary to the one produced by the positive sequence, where the interaction of these fields creates beating electromechanical waves in its speed reducing the performance [12-13].

2 Temperature rise above the acceptable limits leading to a reduction in the motor lifetime. Studies show that the rise in temperature of 10°C on the motor temperature insolation reduces to half of its lifetime [14].

3 Reduction in the available conjugated delivered to the power also generated by the existence of the magnetic rotating field contrary to the motor rotating [14].

Voltage unbalance at the fundamental frequency and harmonic distortions are normally present in the supply voltage [15]. The voltage unbalance origin can be represented basically by two types: structural and functional [3], where the structural causes can be generated by:

1 Converters mainly the connected ones in open delta;

2 Transmission lines;

3 Fuse opening in capacitors banks.

Considering that these causes are practically stable due to a small parameter variation in the energy supply. On the other hand, the functional causes are those caused by the presence of unbalanced 3-phase loads as well as by poor distribution of unbalanced monophasic loads where the final consumers are the biggest agents who cause this voltage unbalance. Following some functional causes will be demonstrated [16].

1 phase systems;

2 Induction ovens and 3-phase bow ovens;

3 Electrical welding machines;

4 Traction supply in remote areas;

5 System bad function such as: conductor opening, short circuit, equipment isolation failure;

6 Asymmetric aerial lines and without transposition;

7 Phase converter magnetization current, due to magnetic differences coming from its own construction.

2. Methodology

2.1. The system Architecture

In this part, the requirements of this template will be described step by step. Authors should pay attention to each part so as to get a clear understanding of the basic points. The purpose of the proposed system is to evaluate the behavior of the three-phase induction motor and to obtain the current operating status at the moment of the application of a single phase voltage imbalance, so it is essential to carry out current and voltage readings with the help of a making possible an analysis of specific points of the system.

The methods consist of creating four different experiments and perform measurements with a power analyzer through data acquisition of electrical parameters in the output of a soft-starter (SS). With the obtained data the behavior of the induction motor equipment with unbalanced voltage in one of the feeding phase is described.

For all the experiments a ramp time acceleration of 60 seconds is adjusted. After that, the motor is split and the transitional is analyzed. As soon as it gets in the permanent regime the motor stops operating in null and starts to receive power through the voltage of the dynamometer break adjustments then, on the experiment a voltage unbalance is forced upon the phases with the help of a rheostat. In this experiment, an SS was used for triggering a motor, which is attached to a dynamometric brake. This equipment allows the voltage adjustment simulating a power variation as it can be observed in Figures 1 and 2. The connections between the SS and the power, as well as the inclusion of the energy analyzer in the circuit, are also showed in Figure 1.

The motor used has the following plate data: 1/2 CV 3-phase, 60 Hz, Ip/In=5, 1.700 rpm, 220V, FS=1.15, In= 1.92 A, cos φ = 0.71 e η= 71%. The SS has the following manufacturer data of 4kW and 230V and the power analyzer used was Embrasul model.

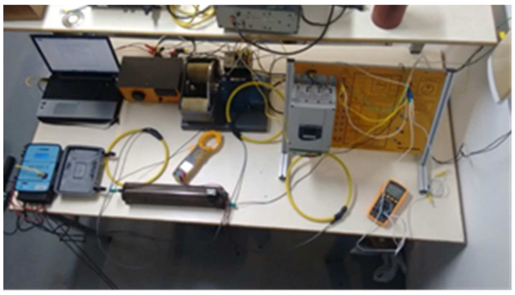

Figure 1. Installation of the SS with power analyzer mounted on the motor supply.

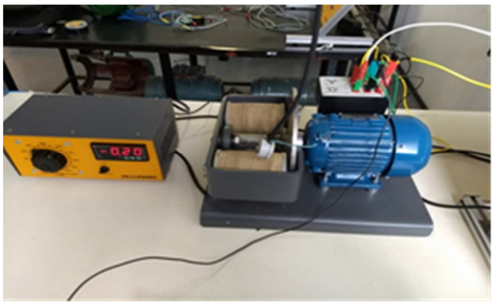

Figure 2. Load used in the tests.

It was installed a rheostat in phase B, in the SS output, as one can notice in Figure 3. Thus, one can provoke a voltage to fall in one of the phases, enabling the study and also the analyze presented.

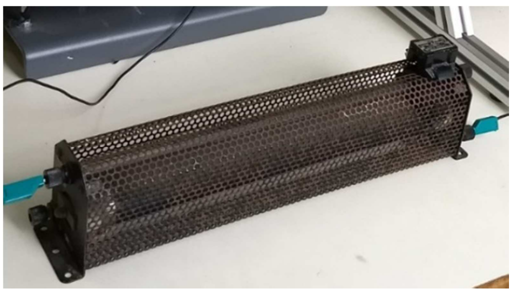

Figure 3. 103Ω and 545W Rheostat.

The PRODIST module 8 [13] highlights that the limit for the unbalance factor for systems with nominal voltage Vn ≤ 1kV is 3%. Equations 1 and 2 are used to calculate the imbalance factor (FD or DF):

$$FD\% = 100\sqrt{\frac{1-\sqrt{3-6\beta}}{1+\sqrt{3-6\beta}}} \quad (1)$$

$$\beta = \frac{Vab^4+Vbc^4+Vca^4}{(Vab^2+Vbc^2+Vca^2)^2} \quad (2)$$

It was installed the energy analyzer in the SS energy output for each case presented throughout this article, so that it becomes possible to evaluate the system parameters behavior such as: current, voltage, power factor, power, harmonic content and the produced wave.

The tests were run with the application of the nominal voltage as well as on an unladen motor (without brake application on the induction motor). Soon after that, the voltage conditions were adjusted on the dynamometric brake for each trial (20%, 40%, 60% e 80% on the equipment scale and also the rheostat was being gradually adjusted decreasing the voltage level on phase B, up to the point which the protection could act by turning it off due to the unbalance and/or critical undervoltage.

2.2. Results and Trail Descriptions

According to [4] among the possible applications of SS, one of the main is to relieve the triggering of high conjugated during acceleration of MIT as well as protect the power supply from the high start current. Some of the beneficial features regarding the SS keys applications are as follow:

1. Adjust the start voltage for a predetermined time;
2. Starting voltage pulse for loads with high starting conjugated;
3. Quick voltage reduction to an adjustable level (hydraulic shock quick reduction in pumping systems);
4. Protection against lack of phase, overcurrent, and undercurrent, etc.

In the experiment performed and described in this work, undervoltage is caused in one of the power phases, with the insertion of a rheostat in series between the SS and the power supply terminals of the motor. The profile of the voltage, current and power factor applied to the system being tested are shown in Figures 4, 5 and 6, respectively, where we note the voltage dip in Phase B.

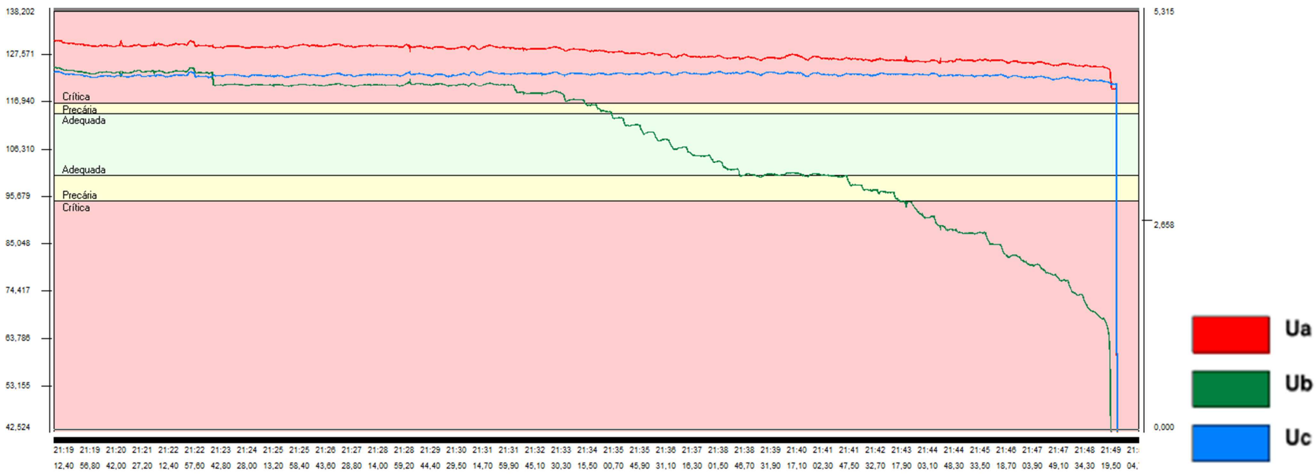

Figure 4. Motor supply voltage profile with undervoltage effect in Phase B.

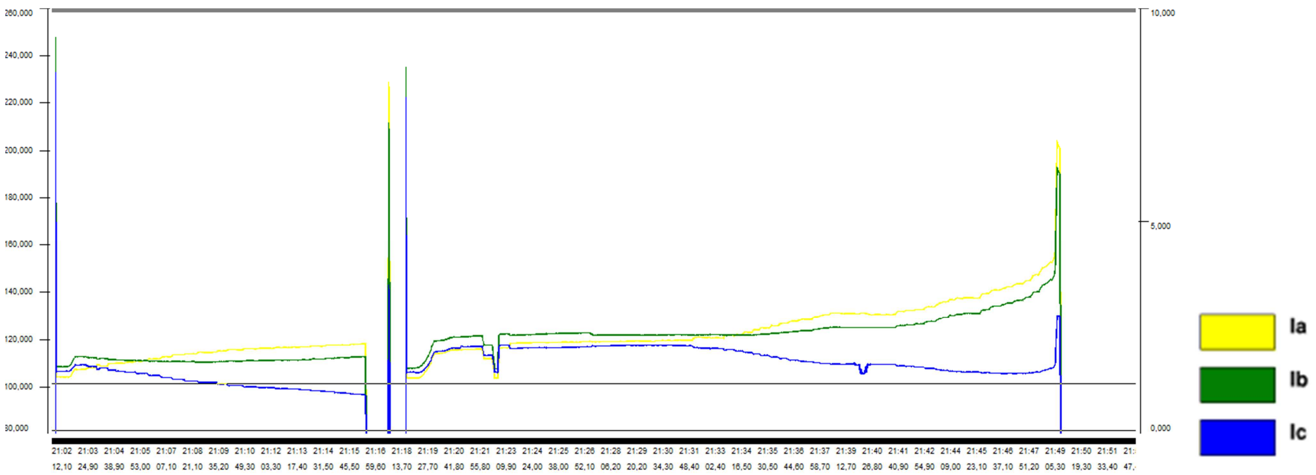

Figure 5. Profile of the motor supply current with the undervoltage effect in Phase B.

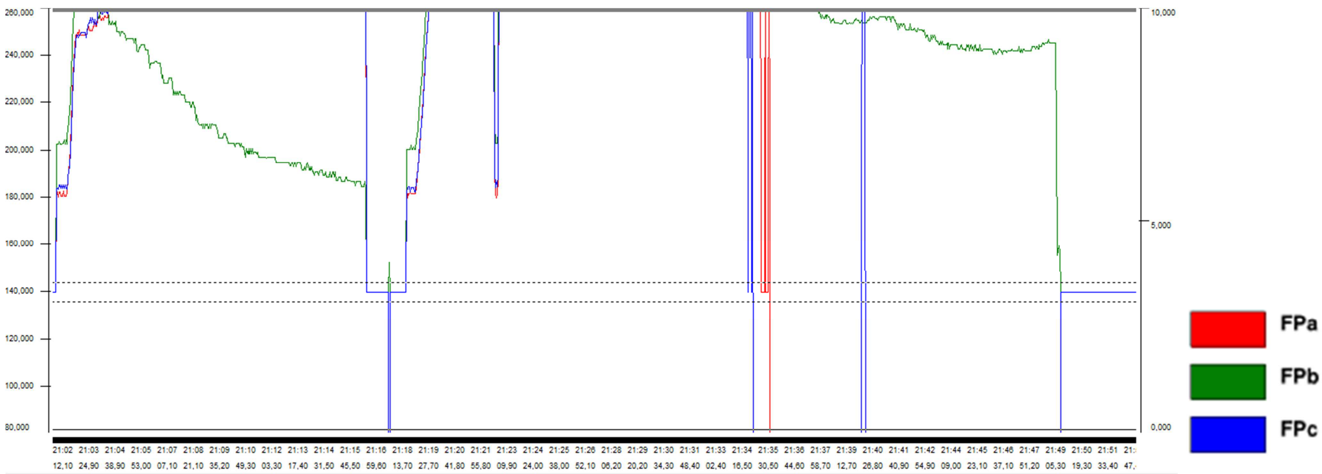

Figure 6. Motor power factor profile with undervoltage effect in Phase B.

It is highlighted in Figure 4 the sinking in the value of the voltage in Phase B in relation to the other phases. In addition, small oscillations are observed during the analysis period. In Figure 5, the motor power supply profiles are shown.

Figure 6 shows the behavior of the power factor, as the voltage unbalance factor is increased can be observed that this increase causes the reduction of the power factor of the motor.

Figure 7 shows an excessively deformed waveform for voltage only in phase B, already characterizing the effects of the sag induced for the tests.

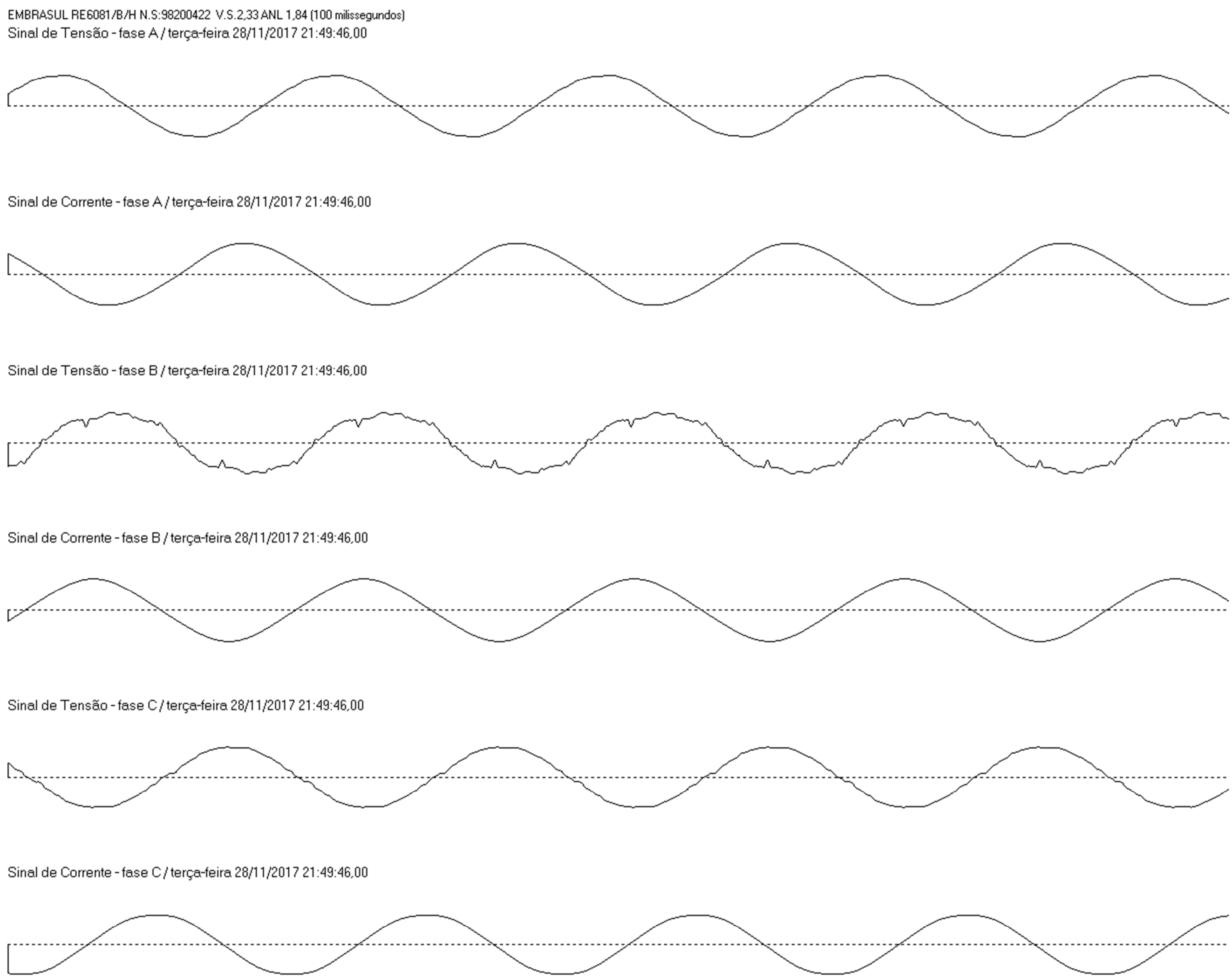

Figure 7. The voltage waveforms at the motor input with the undervoltage effect in Phase B.

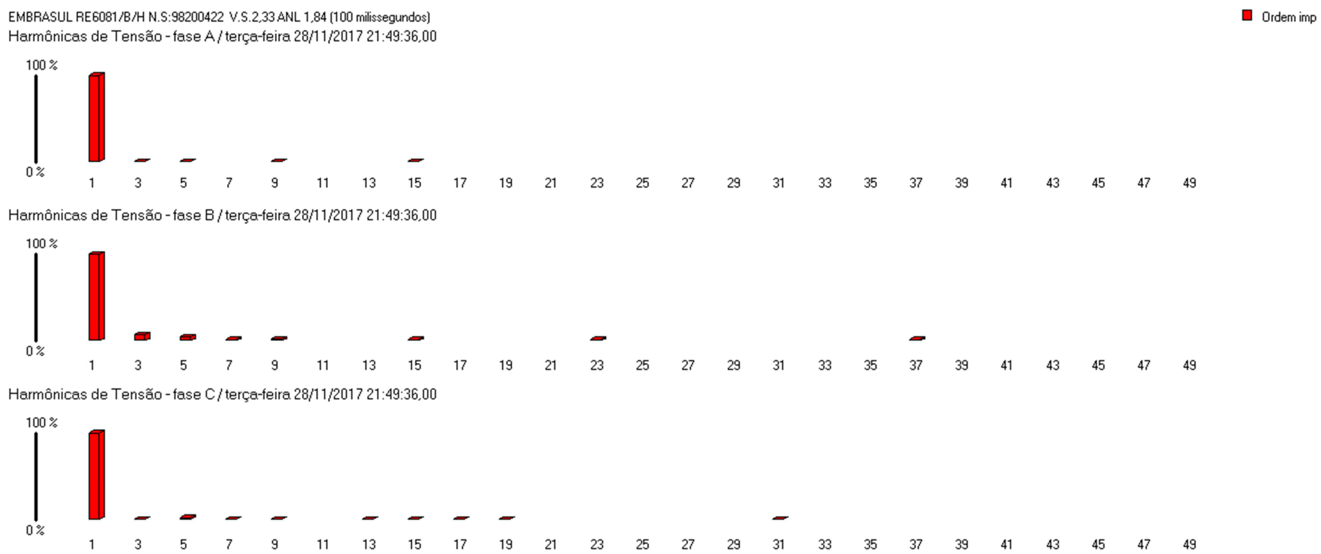

Figure 8. Harmonic components of the motor supply voltages with the undervoltage effect in Phase B.

Figure 8 complements the information presented in Figure 7, since it highlights the voltage harmonic components. Note in Phase B indexes of harmonics of minor orders with significant relevance in the 15th, 23rd, and 37th with lower values. The components are also highlighted: 3rd, 5th, 7th and 9th order.

The first experiment consists of starting the machine without load, considering a ramp of 60 seconds in the start and after the entry into the regime, adjust the voltage on the dynamometer brake to 20%, then the rheostat will be adjusted to cause the voltage drop in phase B and the data is collected until the equipment stops due to protection. This experiment aims to collect data on a cycle of operation of the drive with the load in 20%.

The second experiment consists of starting the machine without a load on the axle, considering a ramp of 60 seconds at the start and, after starting the system, adjust the voltage on the dynamometer brake to 40%, then the rheostat will be adjusted to cause the voltage drop in phase B and the data is collected until the equipment stops due to protection. This experiment replicates the objective of the first experiment but with the stress on the brake at 40%.

The third experiment consists of starting the machine under the same conditions as before, after starting the system, adjusting the voltage on the dynamometer brake to 60%, then the rheostat will be adjusted to cause the voltage drop in phase B and the data is collected until the equipment stops due to protection. As in the first two experiments, the goal is to collect data from a 60% duty cycle of the drive.

The last experiment consists of breaking the machine without a load on the axle, considering a 60-second chute at start-up and, after starting the system, adjusting the voltage on the dynamometer to 80%, then the rheostat will be adjusted to cause the voltage drop in phase B and the data is collected until the equipment stops due to protection. This final experiment collects data from a drive operating cycle with load at 80%. The results obtained by collecting data on power and power factor of the motor are shown in Figures 9 and 10. The second experiment consists of starting from a machine with no load on the axle, considering a ramp of 60 seconds at start and, after starting the system, adjusting a tension on a dynamometer brake to 40% or re-tensioning being adjusted to cause a voltage drop in the phase B and the data is collected until the equipment stops due to protection. This experiment aims to collect data from a drive operating cycle with the voltage on the brake at 40%.

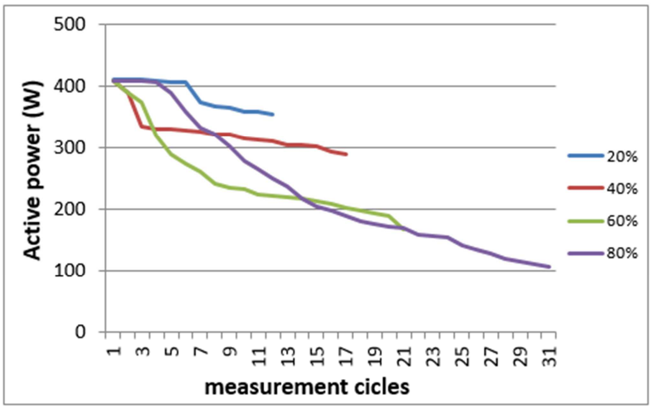

Figure 9. Active power for test conditions.

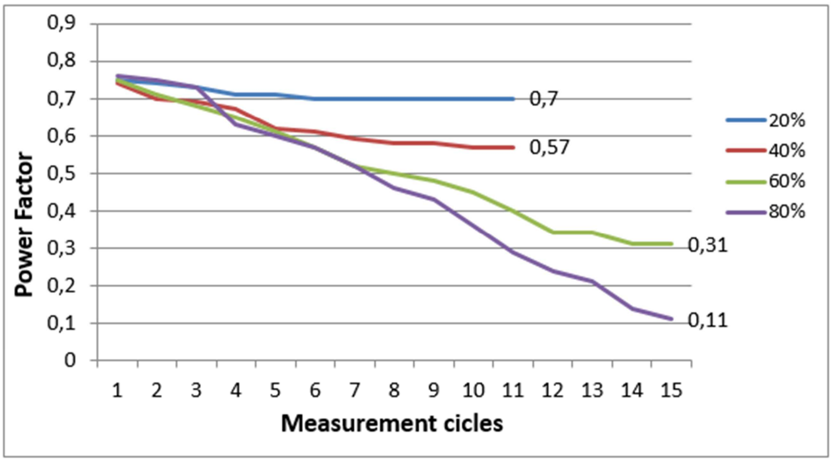

Figure 10. Power factor for test conditions.

In Figures 11 and 12 are presented graphs of the analysis of the presence of voltage harmonics for the initial case where there was no voltage unbalance and for the critical case close to the motor disarming.

In the case without voltage unbalance, it is possible to observe slight variations in the harmonics of 3rd, 7th and 9th orders with FD calculated according to the module 8 of the PRODIST [13] of 1.9%, already in the case near the disarming of the motor one notices a variation immense in the harmonic components with more intense peaks in the 3rd and 5th order, containing some oscillations up to 49 order, containing the imbalance factor of 19.7%, the most critical case.

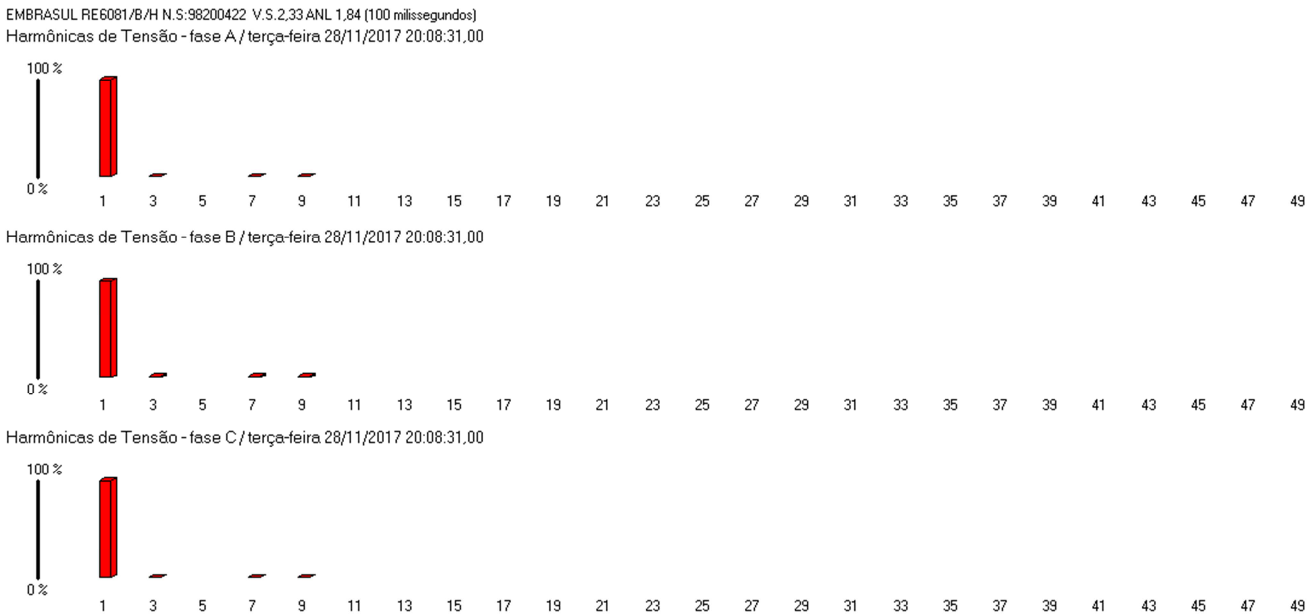

Figure 11. Occurrence of odd harmonics in the voltage without voltage unbalance.

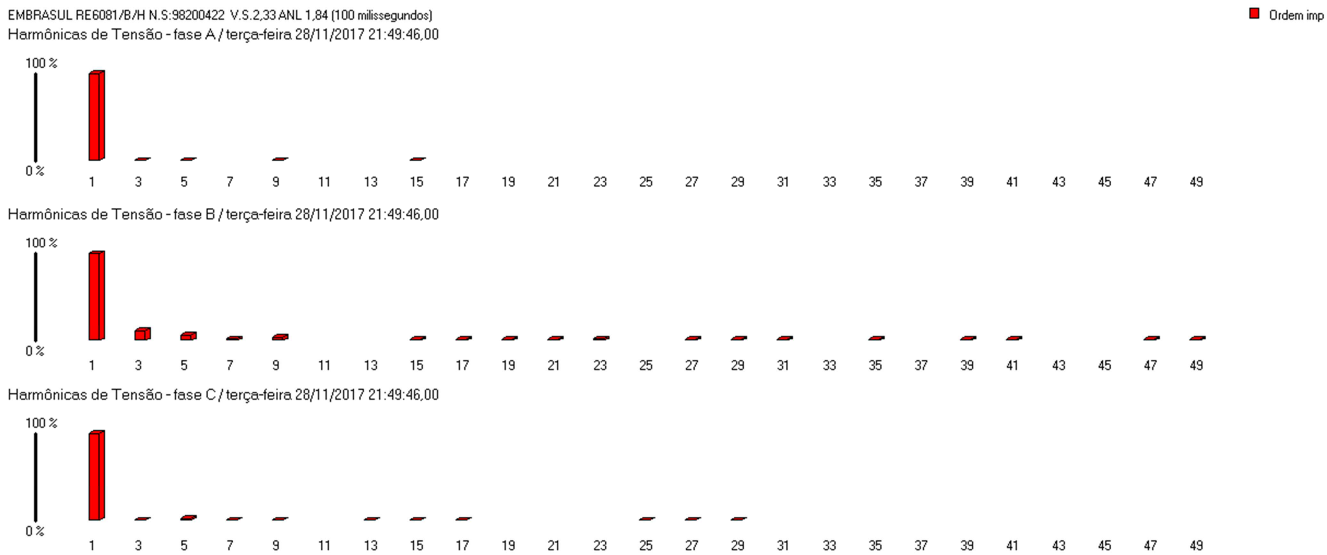

Figure 12. Occurrence of odd harmonics during transient.

The analysis of the factors of voltage unbalance indicated that the increase of the voltage on the dynamometric brake, consequently the increase of load in the motor allowed a greater variation in the voltage drop on the rheostat that implies in a greater value of the imbalance factor, according to Figure 13.

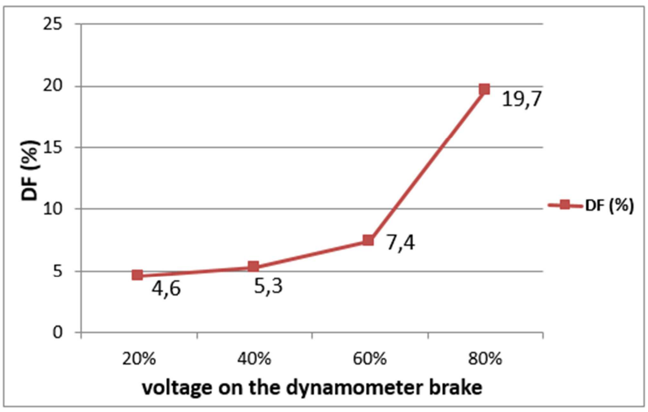

Figure 13. Maximum voltage unbalance factor for each test.

3. Conclusion

The concern should not only be restricted in determining the occurrence of disturbances, but also in the continuous monitoring of the parameters of the electric system to be analyzed. Information must be collected and stored for the purpose of generating data that can be compared over time in order to improve statistical tools. It is aimed at the possibility of arriving at more precise diagnoses.

The achievement of these parameters allows the application of statistical tools for the analysis and visualization of results, which provides information about the behavior of the electrical system at certain time intervals (such as hours, days, weeks, months or years).

This work presented studies concerning the application of undervoltage in one of the phases of the feeding of a three-phase induction motor driven by soft-starter (SS). With this, the behavior of the three-phase induction motor (MIT) can be verified.

The system was submitted to different operating scenarios, so that it was possible to verify the response in the motor parameters. Firstly, a balanced voltage was applied to the motor power supply and thereafter voltage unbalance with sinking in the value of Phase B by the application of a rheostat until the drive device could no longer maintain the normal operating condition of the MIT.

Voltage and current waveforms also showed distortions. It was observed the increase in the level of the harmonics for the odd frequencies of low order and the appearance of the harmonics of odd voltage for high orders.

Thus can be verified that in relation to the behavior of the power versus factor of unbalance shows that with the increase of the factor of imbalance in the feed of the three-phase motor the power of the same one was reduced significantly. Regarding the power factor, for higher voltage unbalance factors the motor power factor also decreases, which is very important.

and necessary to be evaluated especially in industrial installations where the number of induction motors is high, which compromises not only the manufacturing processes but also the billing of the customer by the concessionaire. Also with respect to the presence of harmonics as verified in the results, it was possible to identify a greater presence of harmonics when provoked the voltage unbalance. As the load was applied through the dynamometric brake voltage adjustment in the motor for each experiment it was possible to analyze that the motor withstands a greater voltage drop until disarmed by the SS.

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