

Methodology for Overheating Identification on Induction Motors under Voltage Unbalance Conditions in Industrial Processes

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This paper presents a new methodology to assist the preventive maintenance through the identification and diagnosis of undesired overheating conditions in multiple induction motors installed in industrial facilities. The identification is performed by monitoring the voltage in the electrical system and the temperature characteristic curve of the motor obtained through infrared (IR)-thermography in the presence of voltage unbalance

Keywords: Induction motor, IR thermography, Overheating, Voltage unbalance.

Introduction

Over the past few years, electric machines have been used in different industrial processes in order to reduce both time and production costs¹. Key elements in industrial processes are the induction motors where they represent around 80% of the electrical loads in industry²⁻⁶. Therefore, preventive maintenance on induction motors is a process whose main objective is to identify the presence of a failure condition that can damage the associated machinery if it continues operating under this condition during long-time intervals⁷⁻⁹. The voltage unbalances are the most common industrial electrical problems that affect directly the operation and useful life of the electric motor¹⁰. Several studies have shown that more than 40% of induction motor failures can be caused by short-circuits and unbalanced currents¹¹. Voltage unbalances are produced by uneven distribution of loads over the three phases, and by impedance asymmetries in each one of the three-phase lines cables^{12, 13}. Under voltage unbalance conditions, thermal performance of the motor varies due to the amplitude increase of negative and positive voltage sequence¹⁴, causing abnormal operating conditions^{13, 15}.

In this sense, temperature is used to determine undesirable conditions, showing wear which would be perceived as a lifetime decreasing¹⁶. One technique used for temperature sensing is infrared thermographic analysis, which is a technique for real-time temperature measuring that is used in fault diagnosis of equipment and industrial systems, with the advantage of being non-invasive and has been presented in a wide range of analysis^{17, 18}. Several works focused on the fault diagnosis on induction motors have been carried out, some of these investigations have been related to the thermal behavior in induction motors under voltage unbalance, through thermocouples inside the motor to obtain the winding temperature getting the motor useful life under disturbance conditions¹⁹ and proposing an index relationship of power quality by means of temperature rise²⁰. Otherwise, thermal models have been used for analyzing induction motor thermal behavior under voltage unbalance in power supply²¹⁻²⁵. On the other hand, different studies through thermographic analysis have been made to evaluate thermal performance of induction motor under failure conditions as bearing faults, fan failures, rotor bar breakages, stator unbalance, mechanical unbalance, misalignment and voltage unbalance where automated thermography image segmentation was used.

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In this sense, it would be desirable to have a methodology based on thermography, which provides the necessary help in the identification of motors under critical overheating in the industrial facility, produced by voltage unbalance for assisting preventive diagnosis. The contribution of this paper is the development of an infrared (IR) thermography-based methodology to obtain critical overheating identification of induction motors under unbalanced voltage conditions. This methodology assists to identify susceptible motors to overheating caused by voltage unbalance, producing an alert and estimating a value of overheating in the motor. The proposed methodology is performed through two steps, first the characterization of maximum overheating produced in the induction motor through the induction of unbalanced voltages in the motor, and the second part, assuming an industrial situation in which induction motors, in an industrial process, are monitored with a thermographic camera to acquire thermal gradient of the motor to compare with thermal increase obtained through the first step.

Voltage unbalance

Voltage unbalance is produced through the uneven distribution of loads over the three phases, and by asymmetries in the three-phase line cables impedances^{12, 13, 15}. In order to know the voltage unbalance produced in the power supply of an induction motor, the symmetrical components method^{27, 28} is used. In this method, signals of voltage of the three phases are acquired at the same time, obtaining the symmetrical components (zero, positive and negative) by means of its fundamental components, U_a , U_b , U_c written as complex voltage phasors as follows:

$$\begin{bmatrix} U_0 \\ U_p \\ U_n \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} \quad \dots (1)$$

where U_0 , U_p and U_n , are the zero, positive, and negative symmetrical components respectively, and $a = -\frac{1}{2} + \frac{1}{2}\sqrt{3}j = e^{120^\circ j}$.

The magnitude of the fundamental components U_a , U_b and U_c , can be estimated by means of root mean square (RMS) voltages. Once the symmetrical

components are calculated, the voltage unbalance degree expressed as a percent (% UNB) is given by:

$$\%UNB = \frac{|U_n|}{|U_p|} \times 100\% \quad \dots (2)$$

Proposed Methodology

The proposed methodology has two parts, in first step (Fig. 1a), the characterization of maximum overheating produced in the induction motor through the induction of different unbalanced voltages in the motor power supply is realized. Then, in the second part, induction motors within an industrial process (Fig. 1b & 1c) are monitored to compare with thermal increase obtained through thermal characterization, producing an alert signal to carry out a preventive diagnosis by means of overheating levels due to voltage unbalance presented in the electrical line. In the Fig. 1a, motor temperature is obtained through a thermographic camera, until the maximum level of overheating (thermal steady-state) occurs in the motor due to voltage unbalance injected in the motor power supply, obtaining temperature behavior in presence of a generated voltage unbalance. After that, a linear equation of motor overheating in function of voltage unbalance is obtained, achieving thermal motor characterization due to voltage unbalance, and acquiring a database of overheating. Once the overheating linear profile is obtained, an industrial situation is assumed in which an electrical bus with different loads (single-phase, two-phase and three-phase), including other motors (Fig. 1b). Induction motors are monitored with a thermographic camera and at the same time voltage signals are acquired to calculate the unbalance produced in motor supply (Fig. 1c), through Fast Fourier Transform (FFT) due to that FFT is a processing tool that provides magnitude and phase angle of a signal in continuous time. Temperature of the motor working under unbalance conditions is obtained to compare it with thermal increase obtained through thermal characterization, providing an alert if the motor is exceeding overheating levels to carry out a preventive diagnosis by means of overheating levels.

Experimental setup

In the experiment setup, a three-phase induction motor (WEG 00136AP3E48T) with 220 V, 1 Hp, 60 Hz, 2 poles, is used. The applied mechanical load

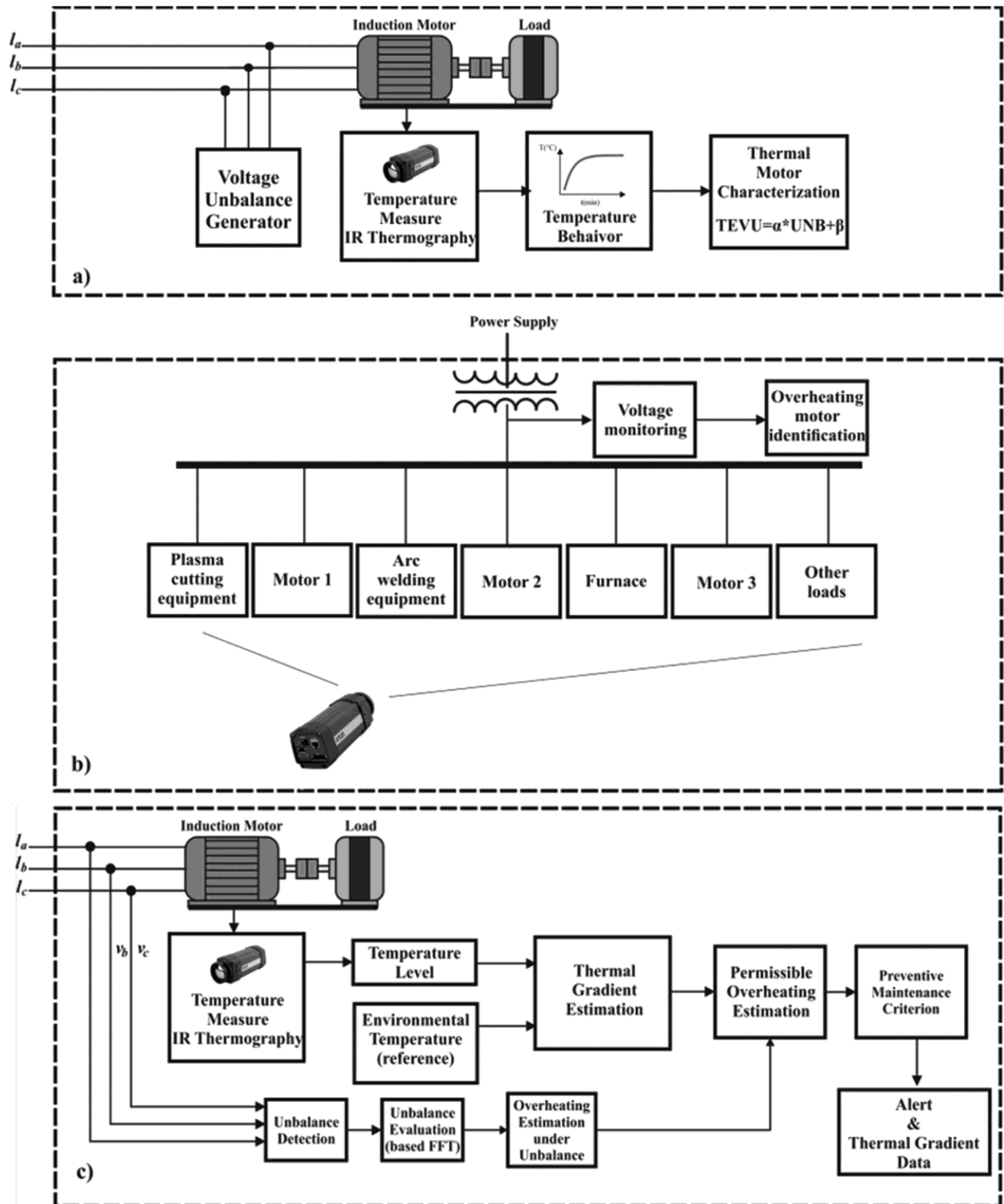


Fig. 1—(a) Induction motor overheating characterization, (b) Industrial process and (c) Monitoring of damage in presence of unbalanced voltage conditions.

corresponds to an alternator and a bank of resistors to obtain the nominal load in the motor, obtaining maximum load conditions recommended for motors operations. To accomplish the development of the proposed methodology in the identification of the voltage unbalances, the current and voltage signals are measured and used to obtain the real voltage unbalance in the motor using three hall-effect sensors model L08P050D15, for current signal acquisition. On the other hand, voltage signals are acquired on each phase by a voltage divider and a precision isolation amplifier model ISO124PND from Texas Instruments Inc., in order to get a galvanic isolation between the power systems and the proposed monitoring system. A 16-bit 4-channel serial-output sampling analog-to-digital converter ADS8341 from Texas Instruments Inc. is used in the data acquisition system (DAS). The DAS has a sampling frequency $f_s = 4$ kHz to obtain 120,000 samples of each phase of current and voltage during 30 seconds for each data window. A field-programmable gate array (FPGA)-based board is used for controlling the data acquisition process. Otherwise, the thermal images are acquired using a thermographic camera model FLIR A310 from FLIR Systems Incorporated. The thermographic camera takes an image every two minutes throughout the entire test. The voltage unbalance conditions are generated by means of variable autotransformers connected to each power supply phase. The acquired current, voltage and temperature data are sent to a personal computer (PC) to be processed afterwards, and to characterize the motor. Voltage unbalance of 4, 4.5, 5.6, 6.31 and 8.4% are considered in order to obtain an unbalance degree inside and outside the recommended levels by the National Electrical Manufacturers Association (NEMA)¹⁵. Different temperature gradients (ΔT) in steady state, (equation 3), are obtained of these voltage unbalance, linking the thermal increment level with the voltage unbalance.

$$\Delta T = TEVU - TEVB \quad \dots (3)$$

where TEVU denotes the Thermal Equilibrium with Voltage Unbalance, and TEVB is the Thermal Equilibrium value obtained with Voltage Balance. The first step to obtain the temperature gradient is the thermography camera calibration according to the established by the manufacturer through the parameters: emissivity (0.95), motor distance (1.8 m), environment temperature (21.8 °C) and reflected

temperature (16.6 °C). Waveforms of voltage by the thermal characterization were generated, where according to equation 1, symmetrical components zero, positive and negative are: $U_0 = 0 + 0i$, $U_p = 258.73 + 149.38i$ and $U_n = 2.05 - 11.96i$. Obtained with $U_a = 181.4V$, $U_b = 158.6V$ and $U_c = 177.3V$ and a phase angle of 0° , 120° and 240° respectively, obtaining an unbalance of 4% for thermal gradient measured by a thermographic camera. The voltage unbalanced was produced injecting different under voltages in the phase B of the motor, generating an adjustment to the consumed current and motor overheating. After reaching thermal equilibrium under nominal conditions, the unbalance is applied to the motor power supply to reach its thermal equilibrium under this condition, where thermal gradient is obtained by means of equation 1. Fig. 2 shows this performance, where red box marked TEVB, shows thermal steady state achieved by induction motor on conditions of nominal current, without any disturbance; on the other hand, red box marked TEVU shows thermal steady state achieved in voltage unbalance presence.

Results and discussion

Fig. 3 shows the measurement regions denoted by four spots S1, S2, S3 and S4, where temperature measurements were carried out. The evolution of the thermograms is obtained and shown from 3a to 3f. The spots present a thermal gradient over the induction motor during its operation with voltage unbalance in the power supply. The thermogram in Fig. 3a shows the beginning of the thermal unbalance characterization with a measurement of temperature in the spots of S1=21.8 °C, S2=21.6 °C, S3=21.5 °C, and S4=21.5 °C, which are the temperatures of steady

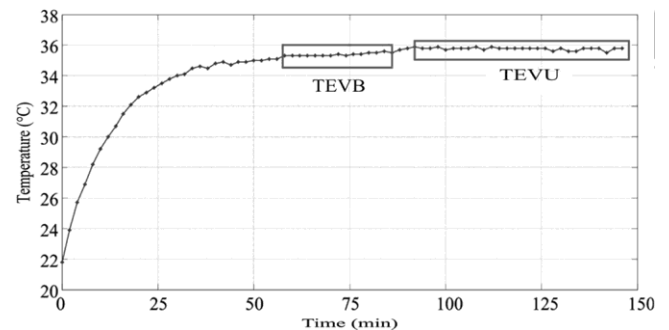


Fig. 2—Thermal equilibrium with voltage balance (TEVB) and thermal equilibrium with voltage unbalance (TEVU) of 4%

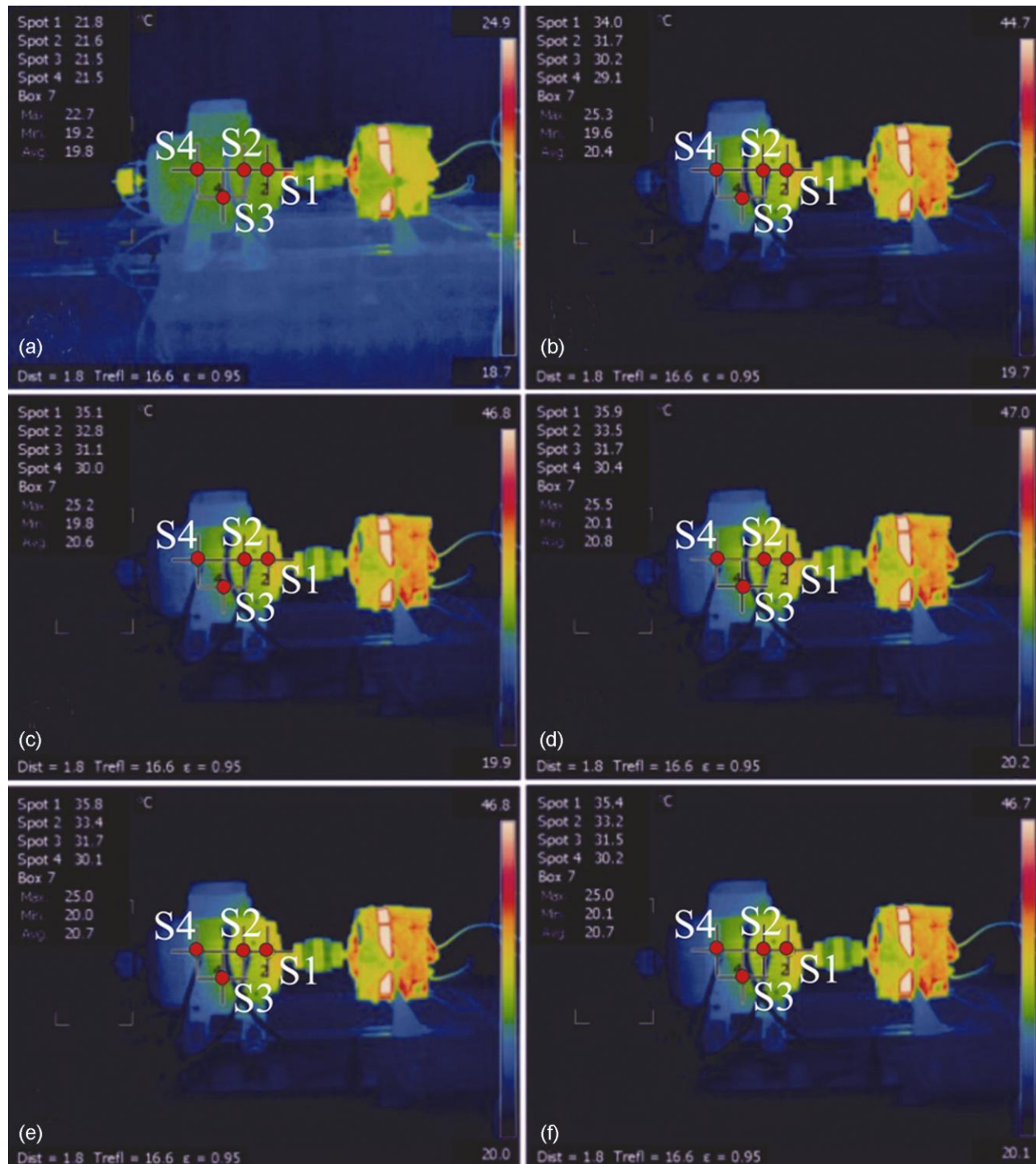


Fig. 3—Thermograms of heating evolution in the induction motor at the times (a) 0 min, (b) 30 min, (c) 56 min, (d) 92 min, (e) 120 min and (f) 146 min

state motor with nominal current. Table 1 shows the time of thermogram measurements and the temperature in the spots S1, S2, S3 and S4. These voltage unbalances affect differently in thermal steady state to any other induction motor of different power,

as is shown in the work of Ching-Ying L. *et al.*¹⁴, where thermal effects due to voltage unbalance in induction motors of 2 and 3 hp are compared. The values that indicate the relationship between the unbalance voltage and heating presented in the three

Table 1—Dynamic Temperature of Spots S1, S2, S3 and S4

Thermogram	Time (min)	Temperature measurement °C			
		S1	S2	S3	S4
(a)	0	21.8	21.6	21.5	21.5
(b)	30	34.0	31.7	30.2	29.1
(c)	56	35.1	32.8	31.1	30.0
(d)	92	35.9	33.5	31.7	30.4
(e)	120	35.8	33.4	31.7	30.1
(f)	146	35.8	33.4	31.8	30.2

Table 2—Tevu Gradient by different levels of Voltage unbalance.

Voltage unbalance [%]	Tevu overheating [°C](thermal gradient)			
	Spot s1	Spot s2	Spot s3	Spot s4
4.0 %	0.4	0.5	-	0.3
4.5 %	0.7	1.0	0.7	0.5
5.6 %	1.3	2.0	1.3	0.5
6.3 %	1.6	2.1	1.7	1.5
8.4 %	5.8	4.4	3.7	3.2

regions of measurement in induction motor are shown in Table 2, where the gradual increase in temperature is shown. This table shows that when the voltage unbalance is greater, the heating produced in the induction motor is also increased. The criterion for the diagnosis of motors that are working in presence of unbalanced voltages is given in Table 2, which provides the TEVU overheating values of the motor produced, depending on the unbalance presented. The operator will use this information to diagnose if a motor is unsafe knowing the operating temperature of the induction motor. The behavior of each of the spots is similar for the unbalances percents, where a heating equation is determined by means of a simple linear fitting, which determines the overheating in local areas S1, S2, S3 and S4 (equations 4-7) and provides the alert when motor is under overheating:

$$\Delta T_{S1} = 1.2UNB - 5 \quad \dots (4)$$

$$\Delta T_{S2} = 0.85UNB - 2.9 \quad \dots (5)$$

$$\Delta T_{S3} = 0.77UNB - 2.9 \quad \dots (6)$$

$$\Delta T_{S4} = 0.65UNB - 2.4 \quad \dots (7)$$

These linear equations are proposed due to their simplicity and adjustment level. The adjustment level is given through the norm of residuals, the values for each spot are: 1.7, 0.4, 0.3, and 0.1 respectively, denoting a higher linear behavior in

the region where the spot number 4 is located. However, the possibility that another order in the equations may offer similar results without affecting the proposed methodology is not discarded. The higher the voltage unbalance levels presented in the power supply of the industry are, the greater the overheating caused by induction motors will be. This provides a good indicator for the detection of motors operating under conditions of voltage unbalance. Those are the equations used to activate the alert indicating high overheating levels equivalent to those produced by voltage unbalance, in this sense region located in the spot S1 (equation 4) was discarded by not present a linear behavior for the easiness of the methodology.

Discussion

Different factors that vary between the characterizations performed experimentally and the motor installed in the industry as calibration parameters of the camera, where industrial environment is an uncontrolled environment which may have variations in motor temperature due to other machines, industrial processes and even the ambient temperature are minimized because the proposed method is based on the change in the motor temperature (ΔT), and not on the temperature level. Different overloading conditions presented in motors lead to a demand for more power, generating a heating effect in the motor. On the other hand, the duration of voltage unbalance neither reaches thermal equilibrium, nor provides levels of constant heating. In this sense, the proposed overheating indicator is effective whenever the level of overheating exceeds the thermal equilibrium level, in this case the proposed methodology is carried out.

Conclusions

The evaluation of thermal behavior in induction motors by means of thermograms for the quantification of voltage unbalance impact is a simple and powerful process that can be used to identify a failure condition in industry. The proposed methodology allows evaluating the impact of different voltage unbalance levels on induction motors, obtaining maximum levels of overheating produced in voltage unbalanced conditions, and their mutual influence through temperature measure in local areas

of the motor with a thermographic camera, besides indicating which motors are in higher risk of damage caused by unbalanced voltage levels in the power supply. TEVU values achieved in the presence of voltage unbalances are good indicators that the motor suffers from overload caused by voltage unbalanced, which can be used in future works to build intelligent diagnostic tools, which can be used to diagnose motors that are in the industry, which exhibit overheating levels due to voltage unbalance. It is important the thermal steady state achieved in the tests because it quantifies the maximum overheating (TEVU) reached in the induction motor due to voltage unbalance. The measurement of the temperature rise can be made by any thermal sensor, however, in this work a thermographic camera was chosen due to its non-invasive system that can be by sensing different points simultaneously, including different motors simultaneously.

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