DETECTION OF STATOR WINDING INTER-TURN SHORT CIRCUIT USING THERMOGRAPHIC ANALYSIS

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Abstract. *The electrical machines are subject to failures that, depending on their importance in plant and manufacturing of its kind, can cause physical damage, economic and social significance. Among all existing electromechanical systems, there is a numerical supremacy of the induction three phase electric motors. Nowadays with the high productivity, any non-scheduled stops (corrective not planned maintenance) cause great damage. Therefore, an improvement in the use of appropriate techniques of maintenance becomes essential. The objective is the development of new applications for the technique of predictive thermography and the viability assessment in thermography analysis for detection of stator winding inter-turn short circuit through the conventional techniques. By InfraCAM Thermographic Camera, the thermograms were collected, which used to analyze the failure. Thermograms could detect the temperature rising of the motor from short circuit before it happens. Actually, thermography it is a technique that can achieve great results in the diagnosis of this failure, because when a induction motor short circuit has been a considerable increase of the temperature of that even if thermography is a technique that has a more simplified analysis in comparison with the traditional, and is very widespread in the industrial environment*.

Keywords*: Induction Motor; Short Circuit; Thermography.*

1. INTRODUCTION

Induction motors are a critical component of many industrial processes and are frequently integrated in commercially available equipment and industrial processes, Mehala (2007).

With a high productivity, any non-schedule stops (corrective not planned maintenance), can cause huge damage. However, the maintenance techniques improvement is essential. Met the existent techniques, improve them and develop new technologies mean a better quality of maintenance and consequently less time hours in maintenance stops, Brito (2002).

The thermography is a technique for inspection, "not destructive", which is based on detection of infrared radiation which is emitted naturally by the body with intensity proportional to its temperature, allowing us to make measurements of temperatures, "without physical contact" with the equipment to be inspected.

The analysis thermography allows better planning, reducing the manpower and resources involved, it allows identification of overheating in the premises "without the interruption of the production process." These results are presented in the form of thermal images, called thermograms (Thermal Digital Image), which allows us to pre examine them at the time of measurement.

Thermography Inspection System consists of the set of resources for achieving the tasks of predictive analysis in the fields of electrical networks, mechanical equipment, steam networks, furnaces, reactors and processes. The basis for this systems is given by the equipment operator.

The reports are integral parts of a program of prevention of losses, where the analysis of the severity of found problems and recommendations for their elimination or reduction are developed by the maintenance area.

Analyzing scientific and technical work related to detection of asymmetries in the stator in the literature, it was noted that the last three years the detection of faults of short circuit between turns of one phase has attracted much interest in the scientific community. However, the researchers are still starting. In published papers, few results are presented, both on experimental simulations, which validate the proposed methods, Baccarini (2005).

In this paper, is a contribution to the study and characterization of a short circuit between turns on electric motors through thermography. This paper made feasible the use of thermography for detection of stator winding inter-turn short circuit through the conventional techniques.

2. FAULT DETECTION USING TERMOGRAPHY

All objects around us are constant sources of thermal energy in the form of invisible radiant energy, the infrared. When an object heats it radiate more energy from its surface. The human is able to feel the radiation, but can not see it. However, the temperature of a body depend on many other parameters beyond the radiation, the values of temperature are also evaluated according to the body emissivity. According RoMiotto (2007), the emissivity is a measure of the capability of an object to absorb, transmit and emit infrared energy. The technique capable of making visible the radiation is called infrared thermography, Ferreira (2002).

In motors, Fig. 1, generators and transformers, the thermograph should be applied so as correlated with other techniques, such as analysis of vibration. For the diagnosis of potential electrical failures, the infrared thermography on the assumption that the power of those machines that do not leave in the form of work in some form is becoming lost in the middle and being dissipated by joule effect. These thermographic analysis are both quantitative and qualitative as allow users to monitor the aging of the machine and diagnose faults from other partial short circuit between turns, partial failure of insulation, cooling, Rezende Filho (2007).

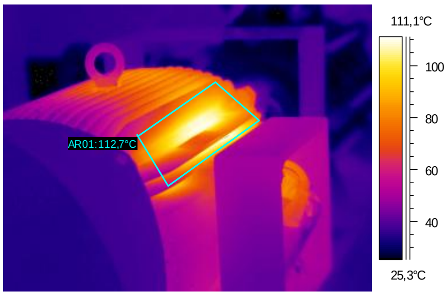

Fig. 1. Induction motor thermogram.

2.1. Stator Winding Inter-Turn Short Circuit.

The studies of induction motor behavior during abnormal conditions and the possibility to diagnose these conditions have been a challenging topic for many electrical machine researchers. The major faults of electrical machines can broadly be classified as the following, Vas (1993):

• Stator faults resulting in the opening or shorting of one or more of a stator phase windings,
• Abnormal connection of the stator windings,
• Broken rotor bar or cracked rotor end-rings.
• Static and/or dynamic air-gap irregularities,
• Bent shaft (akin to dynamic eccentricity) which can result in a rub between the rotor and stator, causing serious damage to stator core and windings.

Deterioration of winding insulation usually begins as an inter-turn fault involving a few turns of the winding. The fault current, which is of the order of twice locked-rotor current, causes severe localized heating and the fault rapidly spreads to a larger section of the winding, Tallam *et al.* (2003). Thus, the detection of faults between turns is especially important because it believes is the start for the occurrence of other faults in windings, such as short circuit between coils of one phase and between coils of different phases, and short circuit between phase-ground, which can result in irreversible losses of the stator core, Boqiang *et al.* (2003).

The time evolution of stator winding inter-turn short circuit, Fig. 2, for all other failures can not be estimated because it depends on the operating conditions of the induction motor, Baccarini (2005).

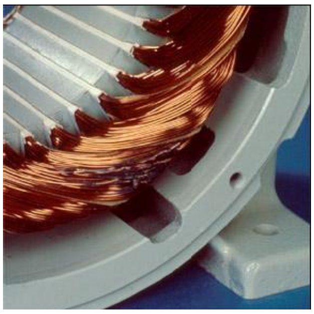

Fig. 2. Inter-turn short circuit.

2.2. Application of Thermography for Detection of Stator Winding Inter-Turn Short Circuit.

The thermal radiation, or infrared, is energy that propagates in space as electromagnetic waves. This radiation is in the infrared range of the electromagnetic spectrum that is classified in bands according to the wavelength (λ) of radiation. The categories of waves ranging from radio waves (wavelength higher and lower energies) to the gamma (wavelength lower and high energy), Silva *et al.* (2006).

Fig. 3 presents the region of the spectrum that is relevant, i.e., the infrared region, which extends the wavelength of 1 mm up to 770 nm, the limit to visible light.

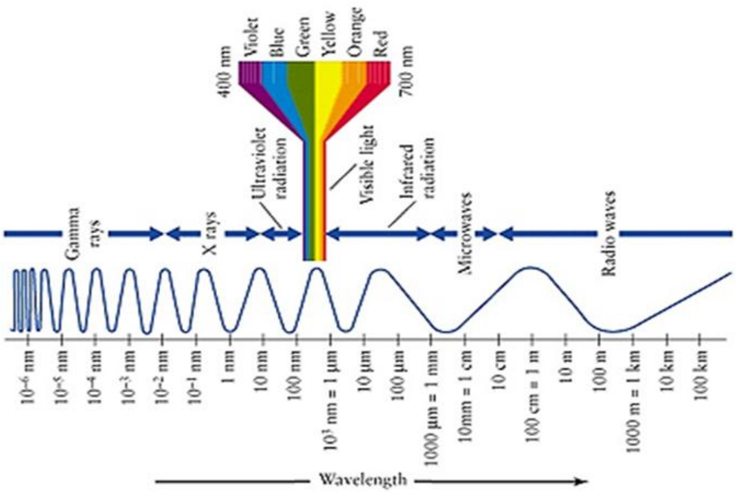

Fig. 3. Electromagnetic Spectrum.

In Eq. (1), has been the wavelength that is related to two other parameters of electromagnetic waves: the frequency and energy of the photon, where $\boldsymbol{\nu}$ is the wave frequency [Hz], **c** is the speed of light in vacuum [2.998 x10^8 m/s] and the wavelength **λ** [m].

$$\nu = \frac{c}{\lambda} \tag{1}$$

In Eq. (2), has been the photon energy, where **E** is the photon energy [J] e **h** is the Planck constant [6.626 x10^{-34} J.s].

$$E = h \, . \, \nu \tag{2}$$

The Eq. (2) is the hypothesis of the Planck black body, where it admitted that the radiant energy was emitted and absorbed how much energy (**h** × **ν**), but this hypothesis was considered artifice of calculation only. It was in 1905 that Einstein, investigating the photoelectric effect, suggested the quantum nature of light and the quantization of energy in small packages, the photons, given by Eq (2), also called the equation of Einstein. As the frequency remains constant, as is the parameter that characterizes the wave, the speed of propagation and wave-length change proportionally when the waves traveling in different materials. Each body that has its temperature upper the absolute zero emits heat radiation and it is precisely this energy that is captured by the infrared cameras to obtain thermal images of bodies, Silva *et al.* (2006).

Every material emits radiation in a way, and a black body that is able to absorb and emit all the radiation in all wavelengths. In Eq. (3), has been the spectral distribution of radiation emitted by a black body described by Max Planck where, $\mathbf{W_{\lambda b}}$ is the spectral radiance of black body at a wavelength of **λ** [Watt/m².µm], **k** is the constant of Boltzmann [1.381 x10^{-23} J/K] and **T** is the absolute temperature of black body [K].

$$W_{\lambda b} = \frac{2\pi h c^3}{\lambda^5 (e^{hc/\lambda kT} - 1)} \times 10^{-6} \tag{3}$$

The total spectral radiance of the Black body, or Stefan-Boltzmann law, Eq. (4) is the integration of λ = **0** to λ = ∞, where $\mathbf{W_b}$ is the total spectral radiance of Black body [W/m²] and **σ** is the Stefan-Boltzmann constant [W m².K^4].

$$W_b = \sigma . T^4 \tag{4}$$

The importance of establishing equations for the spectral distribution of black body comes from the fact that it set a maximum limit whole spectral of emittance of a source. An object, or source, real does not have the same emission of black body radiation behavior, and its curve of spectral of emittance is limited by the corresponding black body in the same temperature of the object, Silva *et al.* (2006).

The emissivity is a factor that decreases the total emittance spectrum of a real object related to the energy emitted by the black body at the same temperature. The emissivity of the object, **ε (λ,T)** is calculated by Eq. (5) where $\mathbf{W_o}$ is the total spectral radiance of a real object and $\mathbf{W_b}$ is the total power of radiation emitted by black body in the same temperature of the object.

$$\varepsilon(\lambda,T) = \frac{W_0(\lambda,T)}{W_b(\lambda,T)} \tag{5}$$

Then, considering the emissivity of the material in Eq. (6) has been the total spectral radiance of a real object.

$$W_o = \varepsilon(\lambda,T).\sigma.T^4 \tag{6}$$

The continuous checking the temperature of a rotating machine is indispensable in the predictive maintenance. Actually, a change in any temperature of rotating machine is indicative of change in the behavior of the same. For these reasons, the temperature is a parameter that should be taken into account in any scheduled maintenance at any level.

2.2.1. Monitoring Process.

The radiation measured by the camera depends on the temperature on the emissivity of the body that is being examined. Therefore the information of the emissivity of the camera is crucial to an accurate estimate of the temperature of the radiant flux measured. Usually the values range from 0.1 to 0.95. For highly polished surfaces have emissivities less than 0.1, and oxidized surface values are greater than 0.95, Silva *et al.* (2006).

Besides the emissivities, other parameters of the analyzed object should be inserted in the camera as reflected temperature, air temperature, distance between camera and object, and relative humidity. The reflected temperature is a temperature which is admitted for all emitting surface in the adjacent environmental to the object under study. While the air temperature, is the atmosphere between the object and camera. The distance between the object and camera and the relative humidity are inserted in order to calculate the attenuation that the radiation has to reach the lens of the equipment, Silva *et al.* (2006).

The infrared camera when focus an object it's receive radiation emitted not only by the object, but also the adjacent environment, reflected by the surface of the object. Both radiations are partly decreased by the atmosphere during the measurement. A third contribution is added, that is the radiation emitted by the atmosphere. This process is showed in Fig. 4, Bezerra *et al.* (2006).

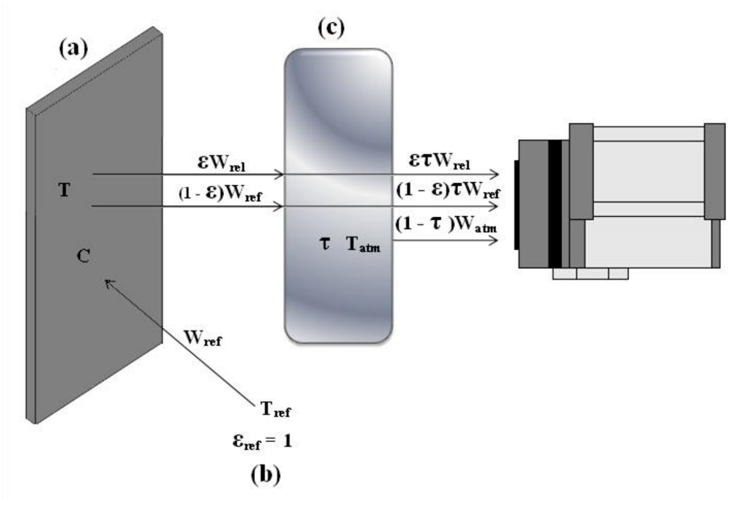

Fig. 4. Thermography measurement representation, (a) Analyzed Object (b) Adjacent Environment (c) Atmosphere.

However, the radiation measured by the camera does not only depend on the temperature of the object but also the temperature and emissivity of the object. This radiation is also of the external environment which is reflected in the object, Bezerra (2006).

3. EXPERIMENTAL SET UP

The experimental set up, Fig. 5, was assembled in the *Experimental Research Laboratory* of the Federal University of São João del Rei - UFSJ, Department of Electrical Engineering, was used for the study of the failure.

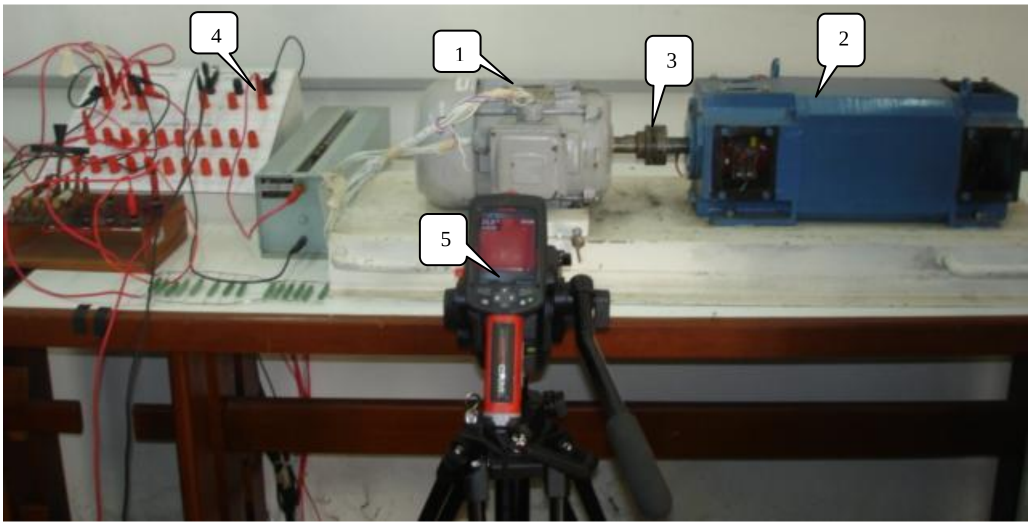

Fig. 5. View of the experimental setup.

The stator winding inter-turn short circuit was introduced in a three-phase induction motor **{1}**, WEG (GF 12087), 3 CV, 1730 rpm, 220 V, 60 Hz, 4 polar regions, category N, 28 slots, bearing SKF 6205-2Z , insulation class B, 1.15 FS, Ip / In 7.5, IP 55, 13.8 A. A DC generator **{2}** was used as system load and is coupled to the induction motor through a flexible coupling **{3}**, it is possible to change the load by a panel of resistive loads and can the short circuit through the panel **{4}**.

The thermograms were collected by the thermographic camera *FLIR Systems InfraCAM* **{5}**. The information contained in the thermographic camera were downloaded to the computer through the QuickView software support, allowing thus detailed analysis in an environment more friendly.

For the simulation of stator winding inter-turn short circuit, was extracted ten leads in two coils of two distinct phases, which can make the closing of three turns in the same coil, which represents the beginning of failure. Furthermore, the short-circuit current was controlled by a resistance to not exceed twice the rated current. So has almost been made degradation of insulation tests that is the beginning of a problem that may evolve into short-circuit. The photos in Fig. 7 show the front and side view of the stator, where the white cables are derivations and black cables are the terminals for the closing and power of the three phases. These leads were placed externally on a panel of terminals to facilitate the control of current of short circuit, the power and application of induction motor load in the DC generator. Before the test it was made the dynamic balancing and laser alignment, verifying too possible mechanical looseness. This procedure allows the thermograms collected are representative of the induced fault.

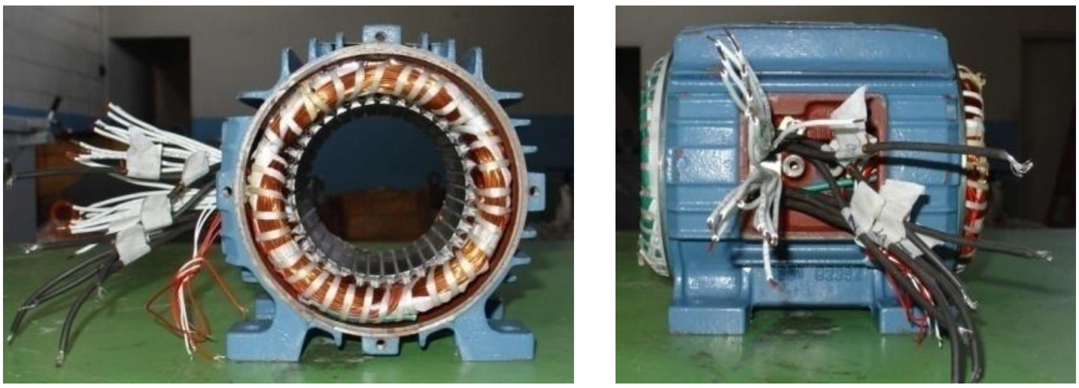

Fig.7. View of the stator three-phase induction motor which was rewinding to allow short-circuit between coils in the same slot.

3.1. Detection of Initial Stator Winding Inter-Turn Short Circuit with Magnetic Flux.

The failure evolution time of stator winding inter-turn short circuit to the other failures can not be estimated because it depends on the operating conditions of the induction motor. What is known is that the speed of development is fast, so the continuous monitoring of the induction motor to detect the fault really important, Sottile *et al.* (2000).

According to Thomson (2001), there may be a time of operation of the induction motor before the inter-turn short circuit evolve to short-circuit between phase-ground and phase-phase, therefore the development of detection systems failures.

It is possible to state that the presence of an abnormality in the circuit of the rotor and/or the stator circuit will provide a disturbance in the density of magnetic flux through the iron of the machine, causing a change in the spectrum of reference and can be identified through analysis of components of frequencies, Lamim Filho (2007).

According Nandi (2000), the 21° harmonic of the power supply (1260 Hz) is always present when there is a fault in the stator. After comparison of various spectra of magnetic flux, it was found that the harmonics 19° and 21° of the power supply were more excited by the inclusion of the short circuit. These harmonic frequencies are considered as characteristics of faults, Lamim Filho (2007).

The magnetic flux spectra were collected using equipment from CSI UltraSpec 8000, through the flux coil CSI A03430A.

Fig. 8 shows the spectrum of magnetic flux for the induction motor in the condition without fault.

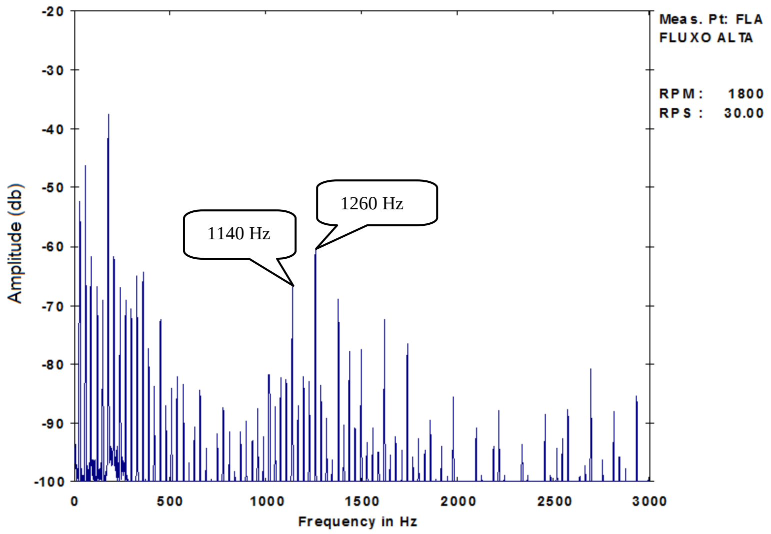

Fig. 8. Flux spectrum without motor fault.

Fig. 9 shows the spectrum of magnetic flux for the induction motor with three turns short circuited.

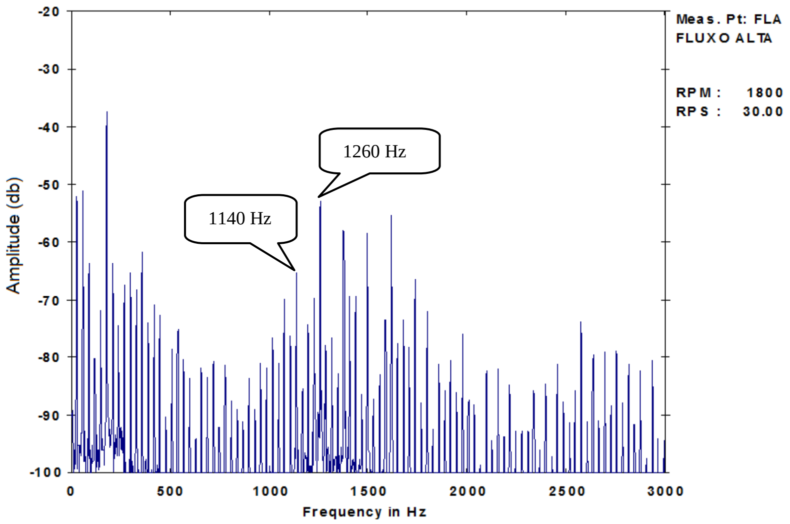

Fig. 9. Flux spectrum with three turns short circuited.

Fig. 10 shows the spectrum of magnetic flux for the induction motor with six turns short circuited.

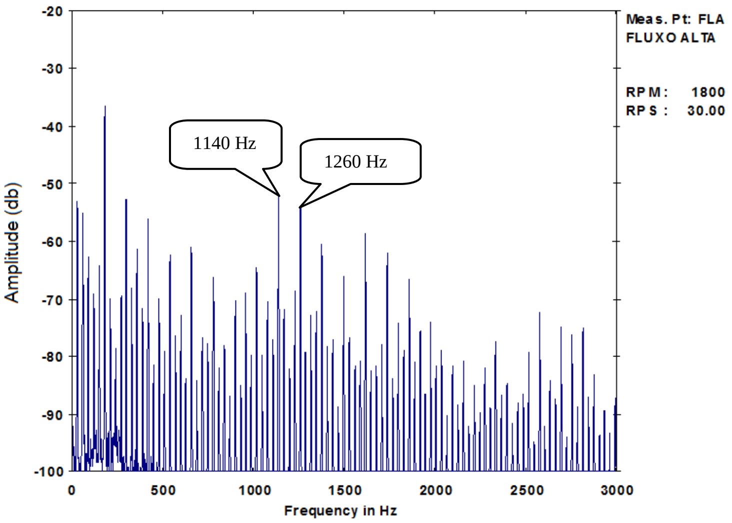

Fig. 10. Flux spectrum with six turns short circuited.

3.2. Experimental Results with the Thermographic Camera.

For the realization of the experimental tests the thermographic camera was configured with emissivity of 0.85, after-match the temperature of the camera to a thermocouple and being sure of temperature collected. Relative humidity and environmental temperature were preserved. The relative humidity was monitored by a wet bulb thermometer and it was around 75%. During the experimental testes was kept a distance between the induction motor and camera of 0.60 m.

Before the beginning of the measurement, wait 2 hours up to stabilize the induction motor temperature, as shown in Guedes (1994), Fig. 11.

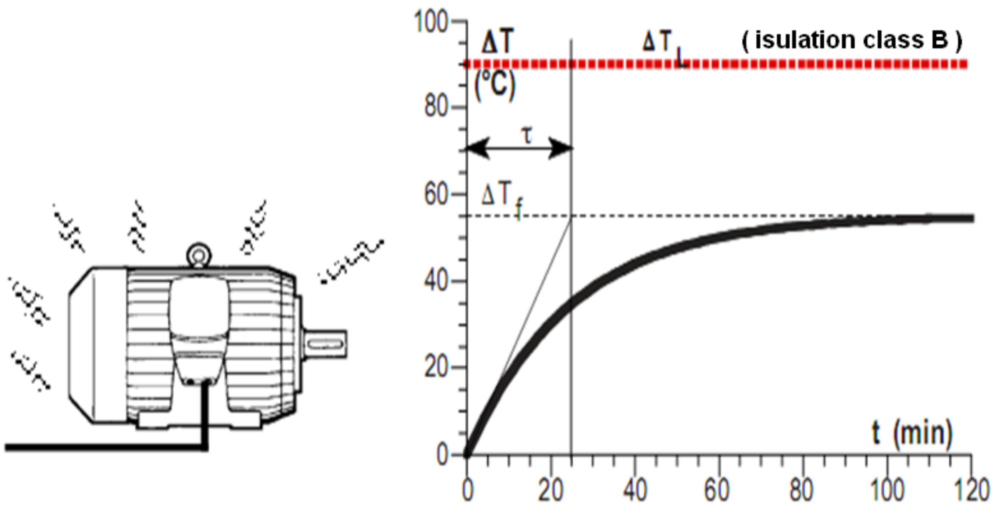

Fig. 11. Curve of temperature for an induction motor insulation class B.

Thermograms were collected in various conditions: without faults, short circuit between three turns and short circuit between six turns. Therefore, it was possible to verify the elevation of temperature, comparing the motor short circuited with the condition without failure, Fig 12. The dark area on the induction motor represents the area where there was a greater heating. On top view thermogram has shown the area of highest elevation of temperature. It's possible to observe the increase of 8.41% in the level of temperature with short-circuit comparing to the test without failure.

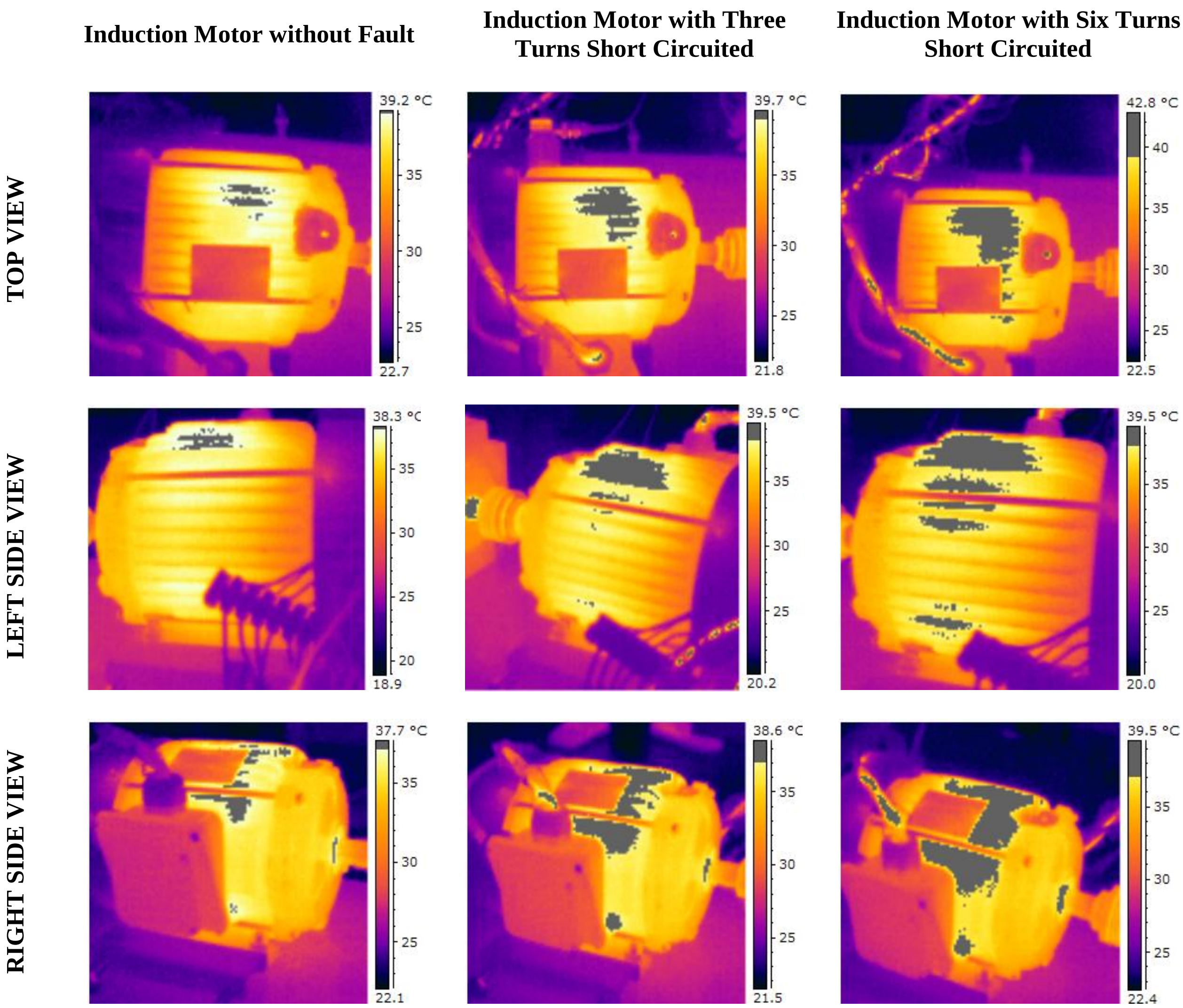

Fig. 12. Thermograms of Induction Motor.

4. CONCLUSION

The results show that the use of thermography in the detection of stator winding inter-turn short circuit is a tool of great help. Together with other techniques of predictive maintenance, this tool makes the inspection process much faster, because can detect heat points or regions, with temperatures above the normal operating condition.

With thermography can check a large number of machines in a short time interval, and thus the analysis of magnetic flux can be performed only on the machine that had a high temperature, confirming the inter turn short-circuit. If the same inspection was done only with the magnetic flux, the whole process would be more expensive because the time required would increase significantly. In the case of short circuit the reduction of the time analysis becomes even more important because the development of a short circuit is very fast.

Thus, the predictive maintenance has another ally, and that makes the process more efficient and effective, increasing the reliability and availability of equipment, avoiding the non-schedule maintenance stops.

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