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Application of infrared thermography to failure detection in industrial induction motors: case stories

D. Lopez-Perez and J. Antonino-Daviu

Abstract – **Infrared thermography has been extensively applied over decades to areas such as maintenance of electrical installations. Its use in electrical machinery has been mainly circumscribed to the detection of faults in static machines, such as power transformers. However, with regard to the predictive maintenance of rotating electrical machines, its use has been much more limited. In spite of this fact, the potential of this tool, together with the progressive decrease in the price of infrared cameras, make this technique a very interesting option to, at least, complement, the diagnosis provided by other well-known techniques, such as current or vibration data analysis. In this context, infrared thermography has recently shown potential for the detection of motor failures including misalignments, cooling problems, bearing damages or connection defects. This work presents several industrial cases that help to illustrate the effectiveness of this technique for the detection of a wide range of faults in field induction motors. The data obtained with this technique made it possible to detect the presence of faults of diverse nature (electrical, mechanical, thermal and environmental); these data were very useful to either diagnose or to complement the diagnosis provided by other tools.**

Index Terms— **induction motors; fault diagnosis; infrared imaging; bearing faults; camera; cooling.**

I. INTRODUCTION

I NFRARED thermography is a well-known technique in the electrical engineering area. Over decades, it has been a very useful tool for regular inspections of electrical installations and distribution lines [1-4]; for instance, infrared cameras have been applied to the detection of defects in electrical panelboards, power cables, electric switchgear or power meters, among many others. In the area of condition monitoring of electrical machines, infrared thermography has been a preferred option for the detection of occasional faults in power transformers operating in substations, power plants and industrial facilities [5-10]. Indeed, intelligent fault diagnosis methods based on image processing have been proposed in the literature, based on the analysis of infrared images of transformers [11-12]. Excellent review works that deepen into the use of infrared thermography for electrical equipment inspection and other applications can be found in

[1-3].

The use of infrared thermography in the area of condition monitoring of electric motors is much more limited. In D.C. machines, infrared thermography is a useful tool to detect possible defects in the commutator as well as in the brushes system [13], which are weak points from a maintenance point of view. Furthermore, some works propose the technique for detecting faults in the field winding of such machines [13]. In wound rotor induction machines and in synchronous motors and generators, infrared data analysis can provide very interesting information about the condition of the slip rings-brushes system, indicating possible asymmetries or defective contacts [14]. For most of these machines, infrared thermography is commonly used in standard off-line tests, as the core ring test (or loop test) to detect core inter-laminar insulation failures [15]. However, in general terms, the application of this technique has been often circumscribed to the detection of defective connections, usually external to the machine itself [16-17]; the infrared technique has been also used to detect problems such as shaft misalignments [26]. Some works have even widened the use of infrared thermography to analyzing the effect of possible motor faults on the kinematic chain [27], while other have proposed the incorporation of this technique in regular maintenance and inspection of electric motors [28] .

In spite of the previous facts, infrared thermography seems a very interesting option taking into consideration that most of the motor faults usually lead to temperature rises (either general or located in specific regions) that may be detected via infrared data analysis. On the other hand, despite infrared cameras came with excessively high costs only a few years ago, today there are infrared data acquisition devices with very affordable prices and with advanced features (such as high image resolution or possibility of acquiring images during transient regimes).These facts confer this technique with a huge potential, since it can easily become an excellent information source for the condition monitoring of rotating electrical machines. In the case of induction motors, the technique may be very useful, especially for large induction motors, the cost of which can easily amount to $1-2 million and whose unexpected failures can entail losses of several million $ [18]. In these machines, the infrared thermography may play an excellent role to diagnose certain failures or to complement the diagnostic conclusions obtained with other techniques such as vibration or current data analysis [19, 20], as will be shown in this paper.

As a matter of fact, recent works have proposed the combination of infrared data analysis with the analysis of currents (both in steady-state and in transient regime) in order to reach a more reliable conclusion about the condition of

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certain parts of the machine [20]. In these works, it was proven, via laboratory tests, that the infrared thermography technique could be especially useful for the complementary diagnosis of bearing failures or cooling problems, among others.

This paper presents several case studies referred to the use of infrared thermography in field motors operating in a petrochemical plant [21]. The results included here are a part of a more general study that was intended to diagnose the condition of a set of motors with different sizes and operating conditions; in twenty of them, the infrared technique was showing evidence of diverse anomalies. The interesting conclusions of the study revealed that the infrared technique was able to diagnose or provide very useful information for the diagnosis of faults of very different nature such as bearing lubrication problems, incorrect belt tightening, deficient cooling, damaged bearings or defective connections, among others. The paper is structured as follows: Section II reviews the foundation of the infrared thermography technique; Section III presents the results obtained after applying the technique to the field motors as well as the discussion of these results; finally, in Section IV, the conclusions of the work are summarized.

II. INFRARED THERMOGRAPHY

Basically, the infrared thermography technique allows the visualization of the superficial temperatures of an object with high resolution and in a non-invasive way, i.e., not needing any contact with the object [20]. The physical basis of the method relies on turning infrared radiation measurements (captured via an infrared detector) into temperature measurements. This is carried out by measuring the radiation emitted by the object surface within the infrared portion of the electromagnetic spectrum and by subsequently translating these measurements into electrical signals. The infrared detectors are the core of the infrared thermography systems which are classified into different categories (thermal vs. semiconductor) depending on the detector employed [1]. An infrared camera basically consists of the optical components (lens, mirrors, etc.), detector elements, cooling system and associated electronics [1]. Infrared cameras have strongly evolved over the last few decades, from the initial versions based on scanning mirrors to modern models relying on focal plane arrays (FPA) [1, 30-31]. An excellent revision of the operation of different infrared sensors, as well as of the available technology in the field can be found in [32].

As mentioned in [3], there are certain factors that exert influence when applying the infrared thermography technique. These factors can be classified into procedural (which concern the thermographer), technical (emissivity of the inspected equipment, load variation, distance from the inspected object, infrared camera specifications) and environmental (ambient temperature, humidity, wind or other convection, solar radiation, etc…) [3]. All these factors should be considered when carrying out an inspection even if the temperatures can be measured accurately [34]. An interesting analysis of the influence of each particular factor under a practical perspective can be found in [3].

According to the energy source over which the infrared inspection is carried out, two possible infrared readings exist:

direct and indirect. Direct readings are obtained when measuring the radiation from the main energy source point while indirect readings are those that are done in neighboring or close points, where the heat has been transmitted via conduction, radiation or convection. Some authors define direct readings as those where there is little or no thermal insulation between the infrared camera and the energy source, while indirect readings are those where there is a considerable thermal insulation between both elements [22]. Fig. 1 illustrates the differences between direct (Fig. 1 (a)) and indirect (Fig. 1 (b)) infrared thermography.
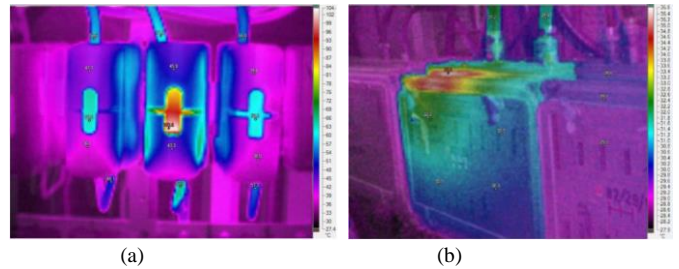

(a)   (b)
Fig. 1. Direct (a) versus Indirect (b) infrared readings.

On the whole, dynamic equipment or components, such as motors, bearings, gear reducers, etc… are analyzed via indirect infrared readings since the fault is started inside the equipment. Hence, it is necessary to assess these elements by taking into consideration both constructive, environmental and operational aspects in order to determine incorrect temperatures or heat transfer trends or patterns that would inform about the presence of developing failures. Fig. 2 shows an example of the evolution of the measured temperature values (weekly intervals) by means of direct and indirect infrared readings for the same fault.
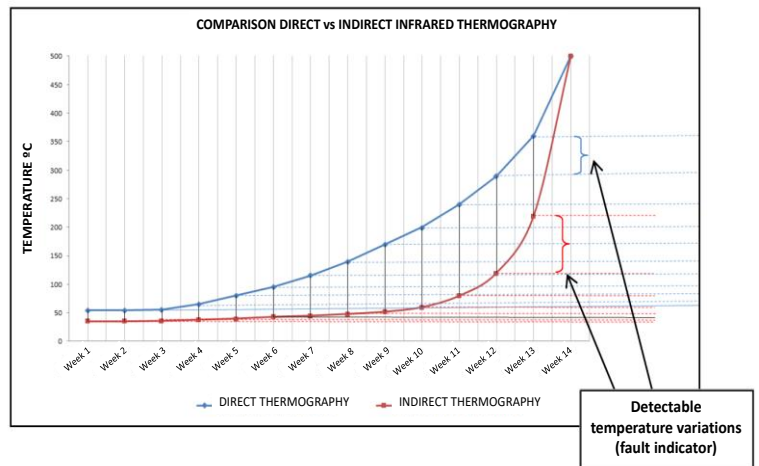

Fig. 2. Direct and Indirect thermography curves.

In order to clearly confirm the presence of the fault, a fault indicator based on infrared thermography must be established so that it must be robust enough to be able to set a reliable alarm threshold and it must show a progressive variation versus the evolution trend that enables to establish appropriate time intervals between successive measurements. In general, indirect infrared readings have fault indicators that show exponential evolutions, so if the time intervals between

successive measurements are too long, the fault can develop before it is detected.

With regard to the fault indicator, there are two ways of applying the infrared thermography to rotating electrical equipment: quantitative and qualitative [3]. The first one considers the fault indicator in absolute terms (i.e. absolute temperature of the equipment) while the second one considers relative temperature values of a point with regard to other parts under similar operating conditions [3]. Qualitative infrared analysis is widespread in many industrial applications [34] and, often, it relies on the use of the ΔT criterion [35-36] which, according to the NETA Standard [37], evaluates the temperature rise above a defined reference that can be either the ambient air temperature, the temperature of an analogue component under similar conditions or the maximum permitted temperature of the component [3]. Depending on the obtained ΔT, a recommended maintenance action is given (see, for instance Table I, which displays the suggested actions based on the temperature rise according to the NETA standard [37]). Other available standards such as ASTM-E1934 [38] or NFPA70-B [39] also provide equivalent guidelines for infrared inspection.

TABLE I. THERMOGRAPHIC SURVEY SUGGESTED ACTIONS BASED ON ΔT IN ELECTRICAL EQUIPMENT ACCORDING TO NETA [37]

Temperature difference (ΔT) based on comparisons between similar components under similar loading.	Temperature difference (ΔT) based upon comparisons between component and ambient air temperatures.	Recommended Action
1ºC - 3ºC	1ºC – 10ºC	Possible deficiency; warrants investigation
4ºC - 15ºC	11 ºC – 20ºC	Indicates probable deficiency; repair as time permits
----	21ºC – 40ºC	Monitor until corrective measures can be accomplished
>15ºC	>40ºC	Major discrepancy; repair immediately

Qualitative infrared analysis has provided good results for inspection of electrical equipment, especially switchgear, cables or static machines. In these cases, comparison with other components under similar operating conditions is often feasible. As [3] points out, the advantage of qualitative thermography is that it is a practical procedure to establish whether or not there is a failure and, also, whether the emissivity has a minor impact on the results [35].

However, in the case of rotating electrical machines, such as electric motors, its application may not be so straightforward. In electric motors, the temperature rise (alarm threshold) to consider if there is failure or not will vary depending on a number of factors related to both the constructive characteristics of the machine and the operational conditions; each machine or component may have different temperature alarm thresholds. More specifically, the qualitative infrared-based diagnosis of electric motors will be based on factors such as: threshold values defined by the manufacturer, duty cycle, environmental factors, operation

conditions (load, supply voltage, etc…) and previous experience. Some thermographers prefer to build their own testing specification chart based on their experience, which can be partially based on the available standards [3].

In the present work, the set of motors that were inspected were operating under rather stable conditions (both environmental and operating) and their sizes were rather similar. This allowed the plant engineers to establish some approximate temperature thresholds for each motor part or component (see Table II). These thresholds were approximately based on the ΔT criterion guidelines shown in Table I. If these alarm thresholds were surpassed, this would become an indication of a possible anomaly in the motor, so that further analysis should be carried out.

Note that, in many cases, the temperature distribution of the surface -thermal pattern- also gives very important information; sometimes, although the temperature thresholds are not surpassed, the thermal pattern can inform on the development of a certain fault in the motor. In this regard, the experience of the thermographer plays an important role for detecting these deviations in the thermal patterns in comparison with previous inspections.

TABLE II. GENERAL ALARM THRESHOLDS ADOPTED FOR DIFFERENT DIAGNOSED COMPONENTS OF THIS WORK BASED ON OWN AUTHORS EXPERIENCE

Element	Temperature Threshold
Motor frame	>70 ºC
Gears (reducers, multipliers, etc..)	>80 ºC
Bearings	>70 ºC
Couplings	>80 ºC
Belt transmissions	>90 ºC

All the previous facts show the potential of the infrared thermography technique to indicate an abnormal operation of certain parts of the machine, which can indicate a fault or can advise the application of other techniques (currents, vibrations) to confirm the presence of the damage. There are four main possible sources of abnormal temperature values or irregular heat transmission patterns: electrical, mechanical, environmental or thermal. Each of them can respond to different faults or anomalies in the machine, as shown in Table III [25]. Therefore, the potential range of failures or anomalies that may be detectable with infrared thermography is of unquestionable value to consider it an interesting information source for the diagnosis.

TABLE III. SOURCES OF ABNORMAL TEMPERATURES AND THEIR POSSIBLE CAUSES

Origin	Fault/anomaly
Electrical	Harmonic distortion, voltage unbalances, incorrect supply voltage, erroneous motor selection, connection defects, shorted turns, broken rotor bars…
Mechanical	Misalignment, operational overload, transmission problems, bearing faults with thermal emission…
Environmental	Dust, winding insulation humidity, lubricant contamination, dirtiness…
Thermal	Deficient cooling, incorrect lubricant refrigeration…

III. CASE STORIES: APPLICATION TO FIELD MOTORS

A survey was carried out based on the infrared inspection of a group of motors operating in a petrochemical plant. In twenty of these machines, the infrared thermography technique was showing the presence of abnormal temperature values or irregular thermal patterns that informed about the presence of diverse types of anomalies and faults. These anomalies had different origin, namely; twelve were attributed to mechanical problems (deficient bearing lubrication (8), damaged bearings (1), deficient belt tightening (1) and operational overload (2)), six were due to electrical causes (defective connections (4), winding problems (1) and rotor damages (1)), five had thermal origin (obstructed cooling channels (5)), and one was due to environmental factors (oil contamination).

In this section, the most representative cases are detailed; they help to illustrate the potential of the infrared thermography for the detection of different types of failures and anomalies. All measurements were taken with the same infrared camera (model Fluke Ti-100) and maintaining similar distances with respect to the analyzed machine in successive revisions. The motors included in this paper were operating at a fixed speed and were operating at rated conditions during the inspections. The room temperature was registered in each measurement so that the measured values could be properly normalized. On the other hand, the emissivity in each case was calculated using a tape with known emissivity obtaining an approximate value of 0.94.

A. Motor 1: Lubricating pump motor (deficient cooling)

This motor was a L.V. machine that was driving a pump for bearing lubrication. The infrared inspection revealed a motor overheating, since the frame temperatures were reaching values above 70ºC in some points (Fig. 3). After a more detailed analysis of the motor, it was observed that the cooling air flow was insufficient; the cause was an obstruction of the cooling channels that was produced by product wastes. The cooling channels and fins were properly cleaned and the subsequent infrared inspection revealed an abrupt decrease in motor frame temperatures up to values around 30-40ºC with the motor operating under similar conditions as in the first inspection (see Fig. 4). Hence, in this case, infrared thermography enabled to detect the source of the problem.
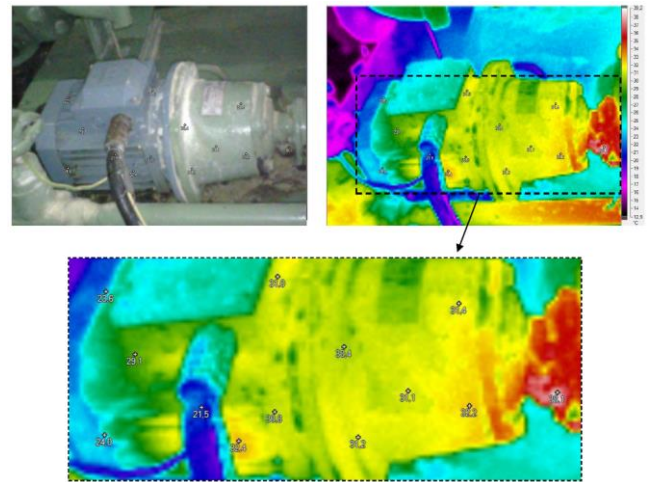

Obstructed cooling channels
Abnormal temperatures on the motor frame.
Origin of the fault: deficient cooling
Fig. 3. Infrared inspection of Motor 1: deficient cooling.

Fig. 4. Infrared inspection of Motor 1 after cleaning.

B. Motor 2: Blower motor (deficient bearing lubrication)

In this case, the inspected element was a bearing of a motor that was driving a blower. An initial infrared inspection revealed an excessive heating of the bearing. This can be noted in Fig. 5 which shows superficial temperatures above 90ºC (and even 100ºC) in the bearing region. We can also observe the deposit of product waste over the bearing cage. The bearing was properly cleaned and a new inspection was carried out. However, no significant temperature drop was detected. Therefore, it was finally decided to re-lubricate the bearing. This measure was much more effective, as a new infrared inspection revealed: the temperatures were not higher than 60ºC in the bearing region for the motor operating under similar conditions (Fig. 6).

It is important to emphasize that, in the past, this motor had an episode of catastrophic failure caused by problems in the bearings: in 2010, the lack of proper bearing lubrication was not properly detected via vibration analysis; finally, this fact led to the collapse of the bearings and to the damage of the stator insulation (see Fig 7). This is an illustrative case that shows how the infrared thermography may provide very interesting information for the diagnosis in situations where other techniques may fail.

In order to prevent the occurrence of this type of bearing lubrication problems, the plant engineers proposed not only the use of the infrared technique to detect such anomalies in advance, but they also suggested the lubrication of the bearings by means of ultrasounds; this lubrication method may bring interesting benefits, such as the reduction of the possibility of an inexact lubrication, amongst others. Moreover, the accurate study of this failure enabled to plot a P-F curve associated with bearing faults; this curve shows, for the corresponding fault, the minimum detectable alarm level for each considered technique. This curve is plotted in Fig. 8 and shows how primary bearing defects (wear, indentations, smearing, corrosion…) are best detected via infrared thermography and ultrasounds while vibrations and oil analysis are best suited for the detection of secondary defects.
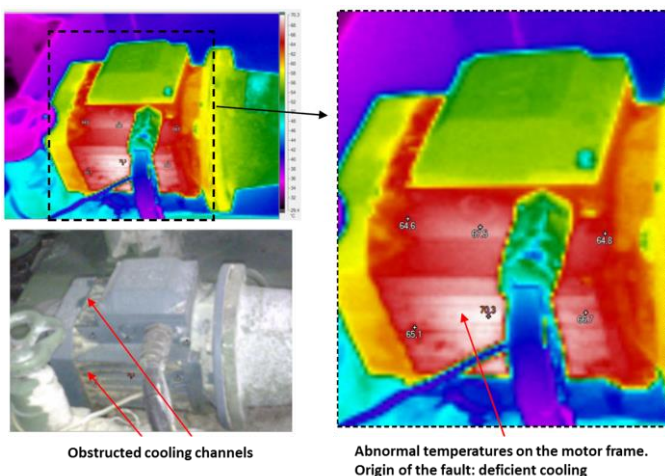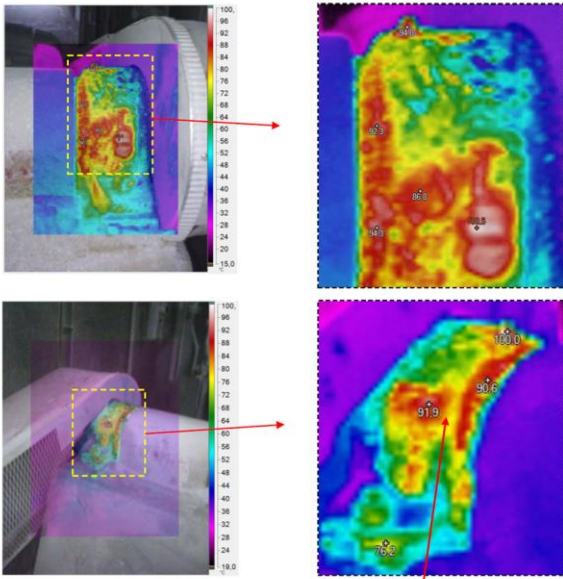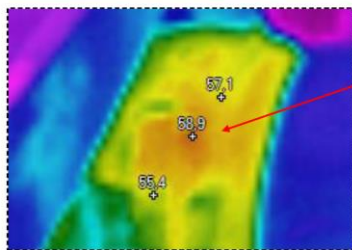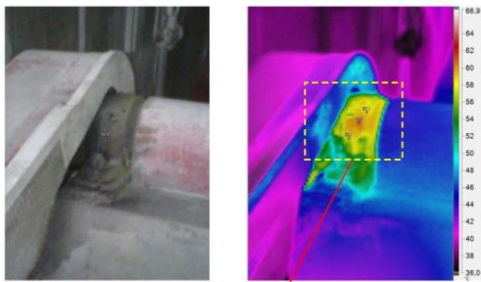
Fig. 5. Infrared inspection of bearing of Motor 2: deficient bearing lubrication.

Fig. 6. Infrared inspection of bearing of Motor 2 after re-lubrication.

Fig. 7. Insulation damage occurred in 2010 in the same motor due to catastrophic failure of the bearings.
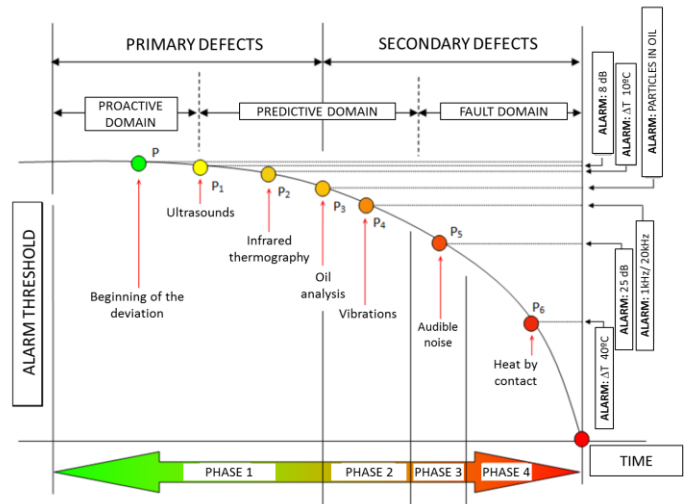

Fig. 8. Developed P-F curve for bearing faults as a function of alarm levels

Anyway, this field case has shown the usefulness of the infrared technique to detect bearing problems that lead to abnormal levels of heat transmission. This was also proven by another of the field inspections carried out in the survey which enabled to detect similar faults in other bearings.

C. *Motor 3: Deodorization fan motor* (insufficient belt tightening)

The inspected motor in this case was an L.V. machine driving a fan for deodorization purposes. Oddly enough, the infrared inspection revealed a very high heat dissipation in the belt transmission system (see Fig. 9), with a maximum temperature of 129.8 °C that was read on the pulley. The deficient tension leads to belt slip on the pulley and increases the heat dissipation due to the friction, which results in decreased efficiency and a reduction of the belt service life.

To solve the problem, the belts were properly tightened and, afterwards, a new inspection was carried out. Fig. 10 shows the new thermal map after the belt tightening that reveals much lower temperatures in the transmission system (30°C in average lower than in the previous case).
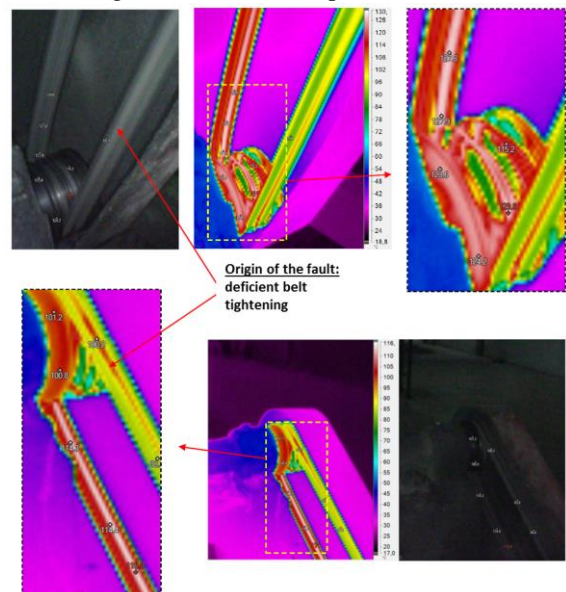

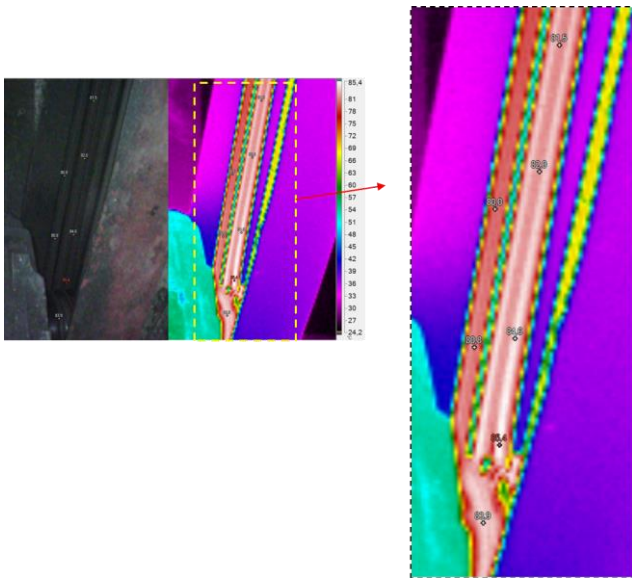Fig. 9. Infrared inspection of Motor 3: deficient belt tightening.

Fig. 10. Infrared inspection of Motor 3 after belt tightening.

D.Motor 4: Motor driving a blower (defective connection)

The inspected motor was an L.V. machine driving a blower. The infrared inspection revealed an excessive heat dissipation that was localized in the upper part of the frame, close to the motor terminal connection box, as shown in Fig. 11. The temperatures there reached high values (76.8 °C).

While the motor was switched-off, the winding resistances were measured, obtaining very similar values. The connections were checked and a weak connection was found as well as a partial damage in one of the terminals (Fig. 10, top). After replacement of the terminal and after fixing the connections, the new infrared inspection showed lower temperature values (Fig. 12, bottom).
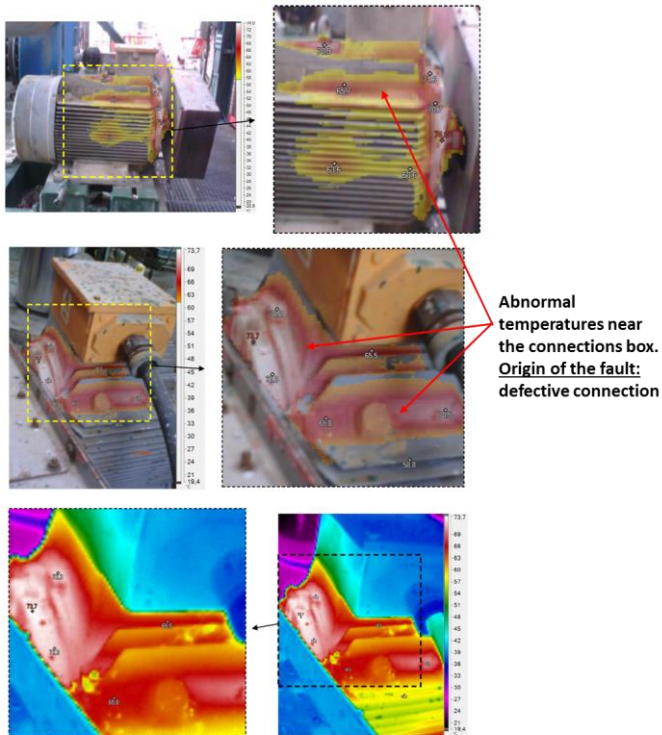

Fig. 11. Infrared inspection of Motor 4: defective connection.
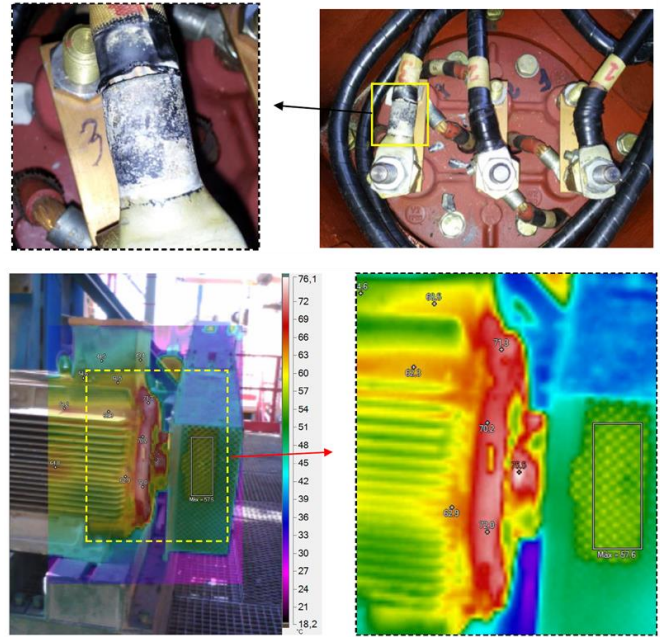

Fig. 12. Defective connection and terminal in motor connection box (top) and Infrared inspection of Motor 4 after repair (bottom).

E. Motor 5: Cooling tower fan motor (winding asymmetry)

In this case, the considered motor was driving a fan of a cooling tower. The infrared inspection of that motor (Fig. 13) showed a significant heating in the motor frame (85.2 °C in the surface and, probably, above 100 °C inside the motor). No cooling anomalies were found during the inspection. As a first measure, the bearings were re-lubricated and repaired in a workshop but no temperature drop was observed.

Then, the motor terminal box was inspected and only a little temperature difference between connections was found. The winding resistance of each phase was measured with an ohmmeter and the results were very interesting (see Table IV, which compiles the results of the measurements): a significant winding asymmetry was detected between phases, leading to a Max Delta R value of near 9%. This could indicate internal high resistance connections, broken turns or internal shorts. This may be the potential cause of the abnormal heat dissipation. A motor re-winding was finally suggested.

Hence, the advantage of the technique in this case is that it informed about the existence of an anomaly in the stator winding, suggesting the adoption of further maintenance actions. Note that these anomalies are not always easily detectable with other techniques (e.g. current analysis), therefore, the information provided by infrared thermography may be very interesting to prevent eventual catastrophic consequences.

TABLE IV. MEASURED VALUES OF WINDING RESISTANCE IN EACH PHASE

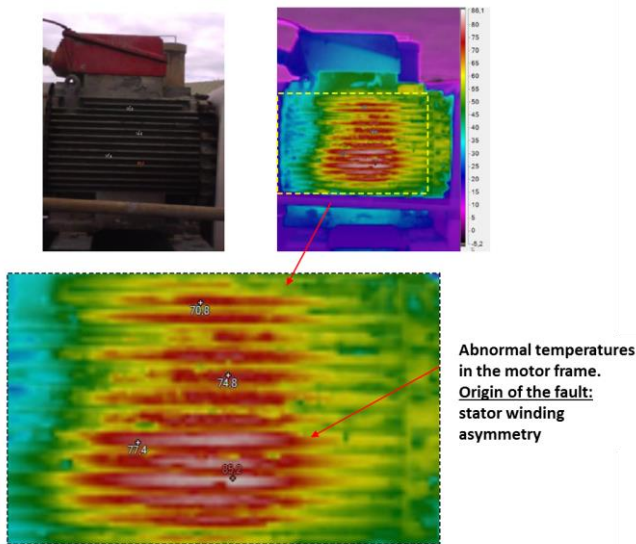| Resistance	Measured value
R_R	87.80 mΩ
R_S	100.04 mΩ
R_T	87.70 mΩ

Fig. 13. Infrared inspection of Motor 5: winding asymmetry.

IV. CONCLUSIONS

Infrared thermography is a well-known technique in the electrical engineering area. However, its industrial use in the area of condition monitoring of induction motors is still scarce. This is not coherent with the extraordinary potential of this technique that can provide very useful information about the presence of different faults in machines; this may be very useful to either determine the motor health when there is no other diagnostic method available or to complement the diagnosis provided by other techniques (currents/vibrations analysis).

This work has presented some industrial case stories extracted from a more general survey that was carried out in induction motors operating in a petrochemical plant. The infrared inspections of these motors enabled to detect several types of failures in the inspected motors that had rather different causes. The results and discussions included here show that this technique was able to detect faults such as bearing lubrication failures, problems in the transmission system, defective connections, cooling system problems and even to give some clues about the presence of stator winding problems. Note that, in most of the analyzed cases, the study of alternative quantities, such as vibrations or currents, did not make it possible to detect the presence of the anomaly in the machine, a fact that, in the past, led to failures of catastrophic consequences. All these results prove the potential of this technique and the importance of incorporating it within induction motor predictive maintenance programs.

Note that every technique (current, vibration analysis…) is likely to create false alarms caused by a variety reasons, and infrared thermography is not an exception. In this sense, motor overheating can be caused by reasons that are not related to a fault, such as operational overload. However, even under these conditions, previous works [19-20] have reported the appearance of different thermal patterns that can be used to discriminate between motor failures and other anomalies that are not related to the motor. In this regard, the thermographer expertise to interpret the thermal images accurately plays a crucial role; in order to avoid this dependence on the user, expert systems based on artificial intelligence techniques are being developed to enable an automatic interpretation of infrared images and reach a diagnosis of the condition discriminating between faults and other effects [29].

Future works will deal with the analysis of the robustness and reliability of the proposed strategy with respect to uncertainty and disturbance affecting the monitored processes, taking into consideration the issues explained in [23-24], among others.

V. ACKNOWLEDGMENT

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