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Conducting Thermographic Inspections in Electrical Substations: A Survey

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Abstract: Liberalization of the electricity market has forced the use of economic and efficient maintenance techniques. Thus, it is necessary to extend the useful life of the facilities in a perfect state of service, and with quality supply for customers. Furthermore, thermography is a maintenance technique that can be implemented quickly, has low cost, and is very effective in terms of the results provided. For this reason, it is very widespread within the electricity sector. As substations are critical facilities within the electrical supply, thermographic inspections are carried out on them very frequently. However, to ensure that the results obtained are reliable, a series of requirements must be met. A compilation of the complete process of the performance of a correct thermography in substations is shown. The factors that affect performing a correct thermographic inspection are indicated. These can be procedural, technical, and environmental. In addition, conditions for conducting thermographic inspections and the action to performed on a hot spot are indicated. The hot spot is usually identified with a current and wind speed other than nominal; these two variables can mask the true severity of the hot spot. For this reason, the extrapolation of the detected temperature to the nominal current conditions and in the absence of wind is carried out using a proposed formula. Finally, two examples of application of the proposed formula and the recommended action on them are exposed.

Keywords: infrared thermography; nondestructive evaluation; defect detection; defect criticality; substation

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1. Introduction

1.1. Context

The importance of sustainability is clearly reflected in the declaration of the Sustainable Development Goals of the United Nations [1]. In addition, the sectors considered as priorities for the achievement of these goals can be identified by analyzing them. Thus, energy is one of the most repeatedly mentioned goals. It appears in goals 7, 11, 12 and 13. Goal 7 is dedicated to affordable and clean energy; Goal 11 focuses on achieving sustainable cities; Goal 12 is based on a responsible production; and Goal 13, on climate action. Electricity is one of the most important sources of energy; therefore, it becomes an essential element to be able to achieve the aforementioned goals.

To play that crucial role, power companies must be efficient. However, the sector has undergone great changes in the last 30 years. This transformation has affected almost all countries. Some have made the modifications before others, but all have followed the same path. Companies that were vertically integrated and monopolistic have become competing companies with separate activities [2]. However, this has not happened in all company sectors, but only in generation and commercialization. In them, it is the market mechanism that marks the competition. By contrast, transmission and distribution continue to be considered natural monopolies due to the economies of scale they produce. In addition, developing this type of facility in parallel has been considered to not result in improving the quality of service or in efficiency [3].

Market competition is replaced by state intervention in these new transmission and distribution monopolies. This is done through regulatory agencies. They are responsible for ensuring that electricity companies are efficient in the operation and maintenance of their facilities and carry out the necessary investment plans. However, this efficiency cannot come at the cost of a reduction in the established quality of service [4]. Furthermore, many facilities are considered critical, mainly substations [5]. For this, a remuneration is recognized for the activities of the electricity companies, among them the maintenance of the assets [6]. In this way, the lengthening of its useful life and its good conservation for service are encouraged. Therefore, maintenance is deemed to be of relevant importance.

1.2. Substation Maintenance

The assets of the facilities are subject to different types of maintenance. Corrective maintenance is the one used exclusively in low voltage, consisting of repairing or replacing the damaged element, depending on its cost. Preventive maintenance is the one that is carried out every certain interval of time: a series of established activities are carried out on the element in question. In this way, possible defects that are in the early stages can be identified and repaired before they get worse. On the contrary, it has the drawback that, if the equipment is intervened unnecessarily, a defect may be introduced during handling. Condition-based maintenance analyzes the main parameters of the element and acts on it only if it is considered necessary. In this case, many parameters must be monitored, which can be expensive. Reliability-centered maintenance, in addition to considering the condition of the element, takes into account its importance and the economic consequences that the failure may cause.

Substations, as one of the most critical facilities of electric companies, must be maintained in accordance with the required quality criteria. Within them, batteries, circuit breakers, and power transformers are the most important elements. The former, because they are the ones that feed the protection and telecommunications circuits; the second, because they open and close the energized circuits, with the consequent arc created in these maneuvers; and the latter, because they are the essential components of the substations, since they are responsible for the voltage changes in the circuits, and this is the goal of most substations.

Battery maintenance is carried out, considering it as a single element due to its small size [7] and analyzing its internal functioning by thermography [8]. Unlike the battery, the circuit breaker is a more complex piece of equipment, so its components are examined in its maintenance: SF_6, which is used as a dielectric to extinguish the arc [9], although other types of nonpolluting compounds are also being studied [10]; the state of its mechanical parts, through speed and pole displacement [11] and coil consumption [12]; or detecting the presence of hot spots [13]. The power transformer is the most complex element of the substation and, in its maintenance, its components are also examined: the state of the oil, both in its main tank [14], or as a consequence of having been contaminated from the on-load tap-changer (OLTC) [15]; its mechanical behavior, both of the main coils [16] and of the OLTC contacts [17]; the existence of partial discharges [18]; detecting turn-to-turn faults [19] and using acoustic methods [20]; looking for the presence of the possible hot spots [21]; or assessing the technical condition of the transformer [22]. A state of the art of maintenance in power transformers is shown in [23].

The maintenance techniques applied to each piece of equipment are usually specific to each one. However, thermography is common to all. Moreover, it is also used for the maintenance of facilities [24], usually carried out with human resources, although it can be also carried out with fixed cameras [25] or autonomous systems [26]. In addition, when reviewing the maintenance of electrical installations, thermography is one of the most widely used techniques for all equipment and facilities [27].

1.3. Research Motivation

The importance of substations as critical facilities has been highlighted, as well as the need to extend the useful life of electrical facilities as an incentive for the remuneration of utilities. In addition, the way to ensure that facilities are in perfect condition and safe for both people and equipment is through maintenance. Among the different maintenance techniques, thermography is one that stands out in particular. However, for this, it must be done properly. Furthermore, the factors that mask their results must be eliminated.

For all these reasons, it is of great interest to have a global vision of the complete cycle of the thermography process in substations: from its realization in the field, followed by the processing of the measurements and ending with the recommendation to eliminate the detected defect. It is this complete cycle that this work tries to cover.

1.4. Aim of the Research

The object of the manuscript is two-fold. On the one hand, a compilation of the complete process of performing a correct thermography in substations is made. On the other hand, a formula to extrapolate the temperature of the identified hot spot to the nominal operating conditions is presented. This formula is obtained from those already proposed in the literature but combining the factors that can most affect a substation under the most unfavorable conditions. An example of its application in the field is also shown. With the values obtained from the application of the formula, an action on the element is recommended according to existing standards. In this way, the complete cycle of performing thermography in substations is compiled.

The manuscript is structured as follows: the main factors that affect the performance of a correct thermography are exposed in Section 2; Section 3 presents a formula to determine the temperature that the hot spot will reach under nominal conditions and in the absence of wind; Section 4 shows some examples of application of the formula to hot spots detected in the field; finally, the conclusions are presented in Section 5.

2. Performance of a Correct Thermography

Thermography is a non-destructive maintenance technique that is applied in different sectors. The electricity sector is one of them, and its use is very widespread. It is applied to all types of facilities and voltages. Through thermography, points are located that reach an abnormal temperature, known as hot spots. These points are identified in both the equipment and facilities. The connections between elements are the places where they usually appear. They are mainly caused by a loose connection or an incorrect tightening torque at the time of assembly. This anomaly can cause a deterioration of the element and cause a breakdown. The connections are made through the connectors.

Thermography has advantages such as being able to perform the inspection with the facility energized; low cost; fast execution; and effectiveness of the results. For all these reasons, it is a highly appreciated maintenance technique. In addition, it must be kept in mind that the important thing about thermographic inspection is the identification of hot spots, with the accuracy of the values in second place in importance. This is because, as this is a work carried out in the field, levels of precision similar to those of laboratory tests cannot be expected.

Another thing to keep in mind is that a medium-sized power company may have around a thousand substations. In each of them, thermography can be performed on about a thousand elements. Usually, at each substation, a thermographic inspection can be performed two or more times a year. Therefore, the number of points to be inspected can exceed one million per year.

2.1. Factors Influencing Thermographic Inspection

To carry out a correct thermography inspection, a few factors that influence the accuracy of the results obtained must be considered. These factors can be procedural, technical, and environmental [28]. The procedural factors are those that are a consequence of the thermography inspection. It must be performed by a qualified operator with sufficient experience [29]. The most important technical factors are the emissivity of the inspected elements, the current that circulates through the circuit, the distance to the target element, and the specifications of the camera used. Regarding environmental factors, the most influential are the ambient temperature, rain, the wind, and the solar radiation [30].

With respect to technical factors, a sufficiently precise camera must be used to perform the thermography at a certain distance. It must be borne in mind that the operator cannot approach the elements to which thermography must be performed, as they are energized equipment located at a certain height. For this reason, a thermographic camera with a lens that allows sufficient resolution and image increase should be used. The resolution will allow sufficient image quality and precision to detect the hot spots at the safe distances to which the thermography must be made. In addition, thermal imaging cameras compensate for these factors to provide the correct values of the measurements. To do this, it is necessary to introduce the required parameters with values that are as close as possible to reality, since otherwise the results obtained may differ greatly from the actual values measured.

It must be considered that an exact emissivity value for the equipment inspected in a substation cannot be obtained. This is because of the presence of very diverse elements whose emissivity will change over time as it ages, until it stabilizes. In addition, they are equipment subjected to high voltage, and, for that reason, they are not normally accessible. Therefore, it is not possible to use any of the methodologies that allow for obtaining an exact value. Furthermore, it would be necessary to obtain this value for each element, and for each time the thermography inspection was to be carried out (which can happen several times a year). For this reason, when thermography inspections of all substations of an electrical utility are to be carried out, it is impossible to carry out all the preparations prior to the inspection. In fact, thermography cameras have an emissivity table for the operator to include the exact value of the element, if known, or assign the value of the group to which it can be associated, such as matte, semi-matte, semi-matte glossy or glossy.

Wind is one of the environmental factors that influence the measurement during thermography inspections. To correct its influence, methods that manage to obtain the exact value have been designed. However, some of them are not applicable in substations. Other weather conditions, such as rain, hail, fog, or storm, are not considered in this work. The reason is that substations are facilities with energized equipment in a delimited area and subject to safety distances. For this reason, and due to safety reasons, when those atmospheric conditions exist, maintenance work cannot be carried out. Therefore, thermographic inspections cannot be carried out under such conditions.

International standards [31,32] include parameters with conservative values that are recommended for use. Subsequently, these values are included in the procedures of each of the electrical utilities. Although these standards are not specifically for substations, their values apply to them because they are defined for electrical equipment subjected to similar conditions. Regarding the value of the emissivity, although 0.5 values have been used in North America, these values have subsequently changed to values between 0.7 and 0.9, finally setting at the same value recommended in [32]: 0.8. Another parameter to be also considered is the absorptivity, having its value of no less than 0.8, and must be used with an emissivity of no more than 0.1 below absorptivity. The value normally used is also 0.8, so both the emissivity and the absorptivity are given the same value. About wind speed, a value of 0.6 m/s is recommended, which can be considered conservative, and a solar radiation of 1000 W/m^2. Evaporative cooling does not usually occur, so it is not recommended.

With these recommendations, electrical utilities set their inspection procedures with conservative values of the parameters that influence the measurements. In this way, the parameters are established for all elements of all substations, regardless of the year in which the thermographic inspection is carried out. Thus, the thermography job performed by the operator in the substations is easier and faster [33].

2.2. Conditions for Conducting Thermographic Inspections

Substations are high voltage electrical facilities. Thermographic inspections are performed with the facility energized. In it, the distances between elements are smaller than in other facilities. Therefore, a series of requirements must be met to carry out the work: the personnel who can work must be qualified; and with adverse environmental conditions, the work cannot be carried out (wind, fog, rain, hail, or storm).

The operator who performs the thermography has a plan of the substations to be inspected during the day. Depending on the time of day, the week of the year, and even the day of the week, circuit load conditions will vary at each substation. The most favorable condition for the detection of hot spots is when the nominal current circulates through the element. This current is the maximum that can circulate through that circuit and corresponds to the facility working at full load. However, that cannot always happen. Therefore, a series of minimum requirements must be met in the inspected element for the correct detection of hot spots [34]: the current that circulates through it must be greater than 20% of the maximum that can circulate; the measurement must be performed at least 15 min after being energized; and the tightening of the connections recommended by the manufacturer must be met. Otherwise, hot spots may not be identified and lead to erroneous conclusions.

To detect hot spots, a minimum current circulating through the element is necessary. That load is set at 20% of the rated current. Having been crossed by the current, the element acquires the service temperature. At some point after the current begins to circulate, the service temperature is acquired and stabilized. For this reason, at least 15 min must pass from powering on. Subsequently, the change in the current that passes through it does not have as much influence as the one produced since it is de-energized. This is because current variations in a substation are usually not abrupt. Another important requirement that must be met is that the tightening torque of the element connections be those recommended by the manufacturer. Poor tightening can cause incorrect detection of the hot spot.

Regarding the load, probably when the thermographic inspection is carried out, the nominal current does not circulate. However, it can be reached at any time. In addition, it must be considered that the higher the current through the element, the higher the temperature. Therefore, the results obtained with a given current must be extrapolated to the case in which the nominal current circulates.

2.3. Action to Be Carried out in a Hot Spot

The purpose of maintenance techniques is to keep the equipment in operating condition, avoid possible failures, and maintain safety conditions for people and facilities. In this way, its useful life is increased. The results obtained will allow one to decide what actions to be taken. Basically, they can be reduced to three: the equipment parameters are adequate, and therefore there is no action to take; there is some variation in the parameters that indicate that more continuous monitoring of the equipment is necessary; or the results of the parameters lead to perform an intervention on the equipment to return it to its normal service condition. Something similar happens with thermography.

The goal of thermography as a maintenance technique is not to acquire knowledge of the temperature of an identified hot spot. The goal is to discern whether to take any action on it. Table 1 shows the actions suggested by the American National Standards Institute [35]. It is based on the temperature difference between the hot spot and a reference. The reference can be the temperature of the ambient air or that of another point with similar characteristics, such as that corresponding to another electrical phase. In each case, the ΔT ranges are different, being lower when the difference is between the hot spot and another element. The recommendations vary between a possible defect to observe, a follow-up of the hot spot through thermographic inspections with different time frequencies, or immediate repair to avoid a major defect.

Table 1. Actions suggested by the American National Standards Institute based on the temperature difference.

Temperature Difference (ΔT) Based on Comparisons between Similar Components under Similar Loading	Temperature Difference (ΔT) Based on Comparisons between Component and Ambient Air Temperatures	Recommended Action on the Component
1–3 °C	1–10 °C	Possible deficiency; warrants investigation
4–15 °C	11–20 °C	Indicates probable deficiency; repair as time permits
-	21–40 °C	Monitor until corrective measures can be achieved
>15 °C	>40 °C	Major discrepancy; repair immediately

Another important issue to remember is that the precision of the measurements takes second place in terms of priority because it involves field inspections, which would not occur in laboratory tests.

2.4. Hot Spot Temperature Corrections

Almost all factors that influence thermographic inspection are fixed in the procedures of the electric companies. In this way, the operator can carry out the inspection relatively quickly without having to change them. It must be remembered that the objective is the detection of hot spots to take the correct actions on them. Therefore, the accuracy of the temperature is of secondary importance, since the values of the parameters entered are on the side of security.

However, there are two factors that are usually modified. These modifications are not made in the field, but later when the field results are processed. They are the current that circulates through the circuit and the wind speed at the time of inspection.

To correctly identify a hot spot, a minimum current must circulate through it. However, the element is dimensioned so that the nominal current flows through it. When the operator performs the thermographic inspection, the current that passes through it is usually lower than the nominal one. With the measured temperature, the recommended action of Table 1 would be obtained. However, as the higher the current, the higher the temperature, and when the nominal current circulates through the element, the temperature of the hot spot will be higher. Therefore, the recommended action with the measured temperature may not be correct since the hot spot temperature may be higher.

Something similar occurs with wind speed, but in reverse: the higher the wind speed, the lower the temperature of the identified hot spot. Therefore, the hot spot and the action to be considered may be masked. In the presence of wind at the time of inspection, a point that does not reach the threshold of being considered a hot spot can be considered when there is no wind. Thus, the action to consider should be when there is no wind, since this is a circumstance that can occur at any time. That moment can be when the circuit is also at maximum load.

To prevent the decision taken from being the correct one, an extrapolation of the measured temperature to what it would reach when the nominal current circulates and, in the absence of wind, must be made. Thus, the recommended action would be the correct one when the installation is fully loaded and in the absence of wind.

2.5. Worksheet with the Recommended Action to Carry Out

When performing a thermographic inspection in a substation, four data of interest need to be collected to elucidate the recommended action to be taken on the element: ambient air temperature, hot spot temperature, current through the element, and wind speed. With this information, the detected temperature can be extrapolated to the most unfavorable conditions: the nominal current circulates through the element and the wind speed is zero. The difference in this new temperature with that of the ambient air when the inspection was carried out allows the recommended action of Table 1 to be identified.

A worksheet with the relevant information about the hot spot is elaborated upon. At a minimum, it must contain the following data of the element in which it was found: identification data of the element; position of the hot spot on the element; thermographic and visible images; current flowing through the element, wind speed and ambient air temperature at the time of inspection; temperature detected at the hot spot; extrapolated hot spot temperature; recommendation of action on the element. In this way, the operator will be able to decide the right time to act and the possible scope of the action.

3. Extrapolation Formula

An extrapolation of the temperature measured when the inspection was performed must be performed to identify its real importance. It is enough to focus on the factors that have the most influence and to which the electricity companies do not give standard values for all their facilities. It should not be forgotten that electricity companies set common values for all their facilities and thus do not have to change them from one substation to another or within the same substation. Furthermore, those values and the results obtained are always on the side of security. These factors are basically two: on the one hand, the temperature detected with the current measured when carrying out the inspection must be extrapolated to what it would reach when the nominal current circulated; on the other hand, the same must be done when instead of existing wind speed at the time of the inspection, its speed was zero.

The extrapolation to the nominal current is done by the following equation [36]:

$$\frac{\Delta T_R}{\Delta T_N} = 1.0537\frac{I_R}{I_N} - 0.055 \quad (1)$$

where ΔT_R is the temperature increase of the hot spot with respect to the ambient temperature when the measurement was made; ΔT_N is the temperature increase of the hot spot with respect to the ambient temperature under nominal current; I_R is the circulating current at the time of inspection; and I_N is the nominal current.

Hence, the increase in temperature due to the fact that the nominal current circulates through the circuit is:

$$\Delta T_N = \frac{\Delta T_R}{1.0537\frac{I_R}{I_N} - 0.055} \quad (2)$$

A theoretical measure of the temperature obtained in the field is presented in [37]:

$$\Delta\theta = 4.906 \cdot 10^{-5} \cdot I^2 - 1.241 \cdot X_{WS} + 6.626 \cdot 10^{-3} \cdot X_{SR} - 1.428 \cdot X_R + 13.079 \quad (3)$$

where $\Delta\theta$ is the measured temperature of the hot spot, I the current at the time of the measurement, X_{WS} the wind speed, X_{SR} the solar radiation and X_R the rain. In this way, the temperature of a point in the electrical circuit is calculated. However, of the weather variables present in the equation, only the wind speed is applicable in a substation because, for safety reasons, maintenance in a substation cannot be carried out in the presence of rain. Solar radiation is similar between substations in the same area and is usually defined in the standards of electric companies. Furthermore, it is the current through the circuit that primarily sets the temperature that the hot spot reaches. This can also be seen from the coefficient corresponding to solar radiation in Equation (3).

With respect to the influence of the current, it should not be forgotten that the objective is to find the temperature that a hot spot would reach under nominal conditions, which is shown with Equation (2). However, Equation (3) shows the temperature of a point that is crossed by a current I. That is why the influence of I in Equation (3) is not considered and, on the other hand, it is considered in Equation (2). Something similar happens with the added constant in Equation (3). It becomes necessary for the objective intended by that equation, but not for what is sought in this work.

Therefore, using Equation (3), the extrapolation at zero wind speed is defined by the following equation:

$$\Delta T_V = 1.241\ v \tag{4}$$

where ΔT_V is the increase in temperature of the hot spot due to the absence of wind; and v is the wind speed when the inspection was carried out.

Therefore, considering the most unfavorable load and wind conditions, the increase in the temperature of the hot spot over the ambient air temperature is obtained as follows [38]:

$$\Delta T = \frac{\Delta T_R}{1.0537\frac{I_R}{I_N} - 0.055} + 1.241\ v \tag{5}$$

where ΔT is the temperature increase above the ambient air temperature.

Obtained this increment from Equation (5), the recommended action is determined from Table 1.

4. Application of the Proposed Formula in the Field

4.1. Actions in the Field

Thermographic inspection in the field must be carried out by a qualified operator from a safety point of view of safety. For this, appropriate training to work in substations has had to be received. From a technical point of view, the operator must be accredited to carry out thermographic inspections. Therefore, training must have been received to handle thermographic equipment, to know the factors that affect the inspection and to know how to interpret the results [39,40]. In addition, he must know the company's technical procedures for action. They include, among others, the values of the factors that must be used in all substations and the conditions under which thermographic inspections cannot be carried out.

After field inspections, the operator must determine the plan of action. With the information collected in the field and the use of Equation (4), the recommended action is obtained. Thus, the information of the temperature that would reach the hot spot at full load and without wind is calculated. Finally, the maintenance schedule at the repair points to be repaired can be planned with the written report. All the information necessary for the maintenance operator to carry out the intervention in the hot spot will be perfectly defined in it. Among them, visible and thermal images; element in which it is located; corresponding phase; and recommended action.

4.2. Field Results

The formula proposed in Equation (4) has been applied to hot spots detected in the field. In that way, the correct action to take has been identified. In fact, hot spots where it was necessary to act would have had another recommendation if it had not been applied, which could have caused an untimely failure.

Figure 1 shows the hot spot detected in a transformer bushing connector of a 66/15 kV transformer. The values of the parameters when the inspection was carried out were the following: hot spot temperature: 26 °C; ambient air temperature: 10 °C; current: 200 A; wind speed: 1 m/s. The nominal current of the circuit is 720 A. As the difference between the temperatures of the hot spot and the ambient air is 16 °C, Table 1 indicates the *probable deficiency* and the recommended action: *repair as time permits*. However, to know the temperature of the hot spot under the nominal conditions of the facility, Equation (5) must be applied. Thus, the extrapolation is to a current of 720 A and no wind is made. In that case, the hot spot would reach a temperature of 68 °C and the recommended action is *repair immediately* (Table 1). Following that recommendation, the hot spot was repaired and the need for immediate repair was confirmed. This confirms the need to extrapolate the hot spot temperature to correctly identify the severity of the problem.

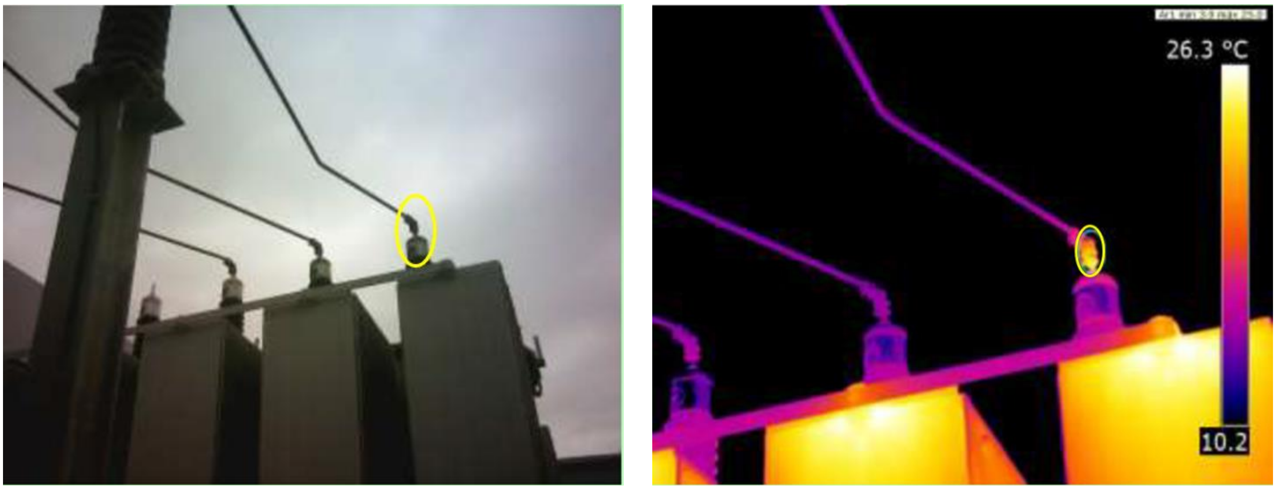

Figure 1. Visible and infrared images of a hot spot in a 66 kV transformer bushing connector.

Figure 2 shows the case of a hot spot on a 66 kV wall bushing connector. The parameters measured during the thermographic inspection were the following: hot spot temperature: 50 °C; ambient air temperature: 32 °C; current: 200 A; wind speed: 1 m/s. The nominal current of the circuit is 720 A. The difference between the temperatures of the hot spot and the ambient air is 18 °C. Therefore, Table 1 indicates *probable deficiency* and the recommended action: *repair as time permits*. However, Equation (5) indicates that the hot spot would reach 77 °C when extrapolating the temperature to the nominal conditions of the facility and without wind. In this case, the recommended action from Table 1 is to *repair immediately*. According to that recommendation, the hot spot was repaired immediately, and its severity was confirmed. This reaffirms the need to extrapolate the hot spot measurement obtained to its nominal condition values, and that, by design, can be achieved.

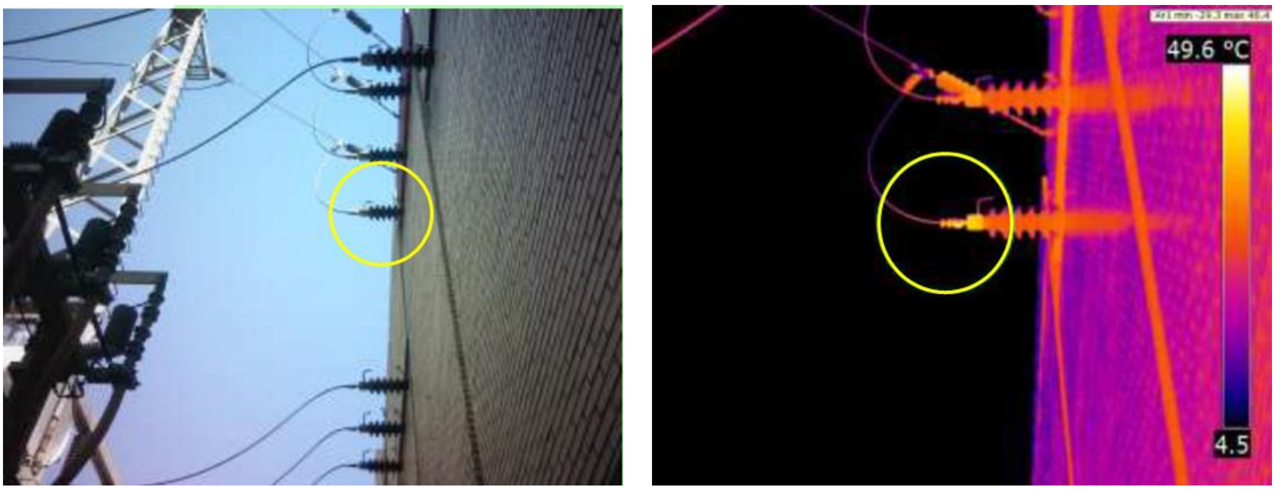

Figure 2. Visible and infrared images of a hot spot in a 66 kV wall bushing connector.

5. Conclusions

Thermography is one of the most effective and widespread maintenance techniques in different sectors. One of them is the electrical sector, and it is used in all kinds of facilities and voltages and, in particular, in substations, which are one of the most critical facilities. A compilation of the factors that affect the performance of a correct thermographic inspection, conditions to carry it out properly and actions to be carried out in a hot spot are presented. Regarding the procedures, the operator must be qualified from the point of view of safety, have the required training, and have previous experience. With regard to technical factors, adequate thermographic equipment should be used. Finally, the environmental factors must be such that they allow access to the substation for the inspection. This is because the substation is a high-voltage facility with particular characteristics under which maintenance is prevented in adverse environmental conditions. As for the values of the factors that affect thermography, the same are usually used for all the facilities. These are set by the internal procedures of the companies. In them, the international standards are collected, varying those that the company itself considers appropriate.

For the correct identification of the hot spot, two additional aspects to consider have been identified: the maximum current of the circuit and the wind speed. When performing the inspection, the facility may not be under its nominal conditions. However, they can be reached. In addition, the contingency of the nonexistence of wind can occur. Therefore, a formula for extrapolating of the hot spot temperature to the conditions of nominal current and zero wind speed has been proposed. It is based on existing results in the literature, but which, to the authors' knowledge, have not been combined for practical use.

In addition, examples of the application of the proposed formula to field results and a table with the recommended actions to follow as a consequence of the extrapolated temperature of the hot spot has been presented.

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