A novel method to correct temperature problems revealed by infrared thermography in electrical substations

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Highlights:

- Extrapolation of the results obtained with thermography analysis
- Influence of current on thermography diagnosis
- Relationship between current and temperature
- Recommended actions on hot spots detected

Abstract

The need to monitor and know the state of electrical facilities and their associated equipment has become of crucial importance to ensure the continuity of electrical power supply. To this end, scientific advances result in new measuring instruments that allow diagnosing the state of electrical equipment and thus preventing failures. Infrared thermography is one of the most used methods in predictive maintenance of electrical facilities in high, medium, and low voltage. Its application in electrical substations is especially relevant due to the key role of these facilities in the power supply chain of most of customers. Its low cost, rapid implementation, and the effectiveness of the results obtained make it possible to perform thermography diagnosis several times a year if necessary. However, at the moment of taking thermography images, the electrical facility may not be subject to the maximum electrical current that can circulate through it, and, consequently, the results of the diagnosis may be erroneous since the temperature reached is not the maximum, i.e., a detected hot spot that is determined as non-problematic can become so in the nominal conditions of the facility. The need to extrapolate the results obtained according to certain current to the situation where the maximum current circulates is thus evident. In this paper, a formula is proposed to extrapolate the temperature obtained with certain current to the temperature that should be reached with higher currents, closer to the maximum values of the facility. The proposal is based on experimental data obtained from laboratory thermography tests and it was successfully used in the field.

Keywords: Infrared thermography, Non-destructive testing, Hot spot, Predictive maintenance, Electric Substations

1. Introduction

A medium-size electrical utility may have more than 1,000 substations, more than 100,000 transformer stations, and more than 300,000 km of lines, giving rise to a transmission and distribution network subject to severe regulatory constraints in terms of the quality of supply that should be given to its customers. In addition, the increasing awareness of society regarding the limited energy resources and the need for continuity of power supply provide insight into the importance that maintenance and asset management have reached within electrical utilities [1]. From a technical point of view, the characteristics of the substation equipment has been studied both internally and externally. Internally, to know the state of its main components and perform maintenance actions if necessary. Regarding the external characteristics, it is focused on extending the useful life and keeping the equipment in optimal operating conditions.

Among all the equipment used in substations, batteries, breakers, and power transformers are typically considered the most important elements. Batteries are typically of lead-acid type and feed the protection and the communication systems that are of crucial importance to ensure the security of the installation. Improving its design is of utmost importance and for this it is necessary to know the distribution of the current inside. Infrared thermography is an easy and inexpensive method to achieve this [2]. Circuit breakers are responsible for opening the electrical circuit when needed. The interruption of the electrical current results in an arc with high energy dissipation in a small volume. The sulphur hexafluoride (SF_6) is an excellent electrical insulator that is commonly placed inside the breaker to effectively open the circuit [3]. Power transformers form the backbone of substations since most of these installations are used for transforming the voltage to a new value. Among all the studies that address the internal characteristics of transformers, the analysis of the oil stand outs due to the key importance of checking its insulation condition [4].

Regarding the studies carried out externally to the substation equipment and facilities, they are focused on determining maintenance actions. A battery is typically considered as a single element for maintenance purposes since it is not too complex and due to its small size [5]. However, circuit breakers [6,7] and power transformers are considerably more complex, and thus the assessment is focused only on certain components or performing a particular technique. A review of most common techniques used for knowing both the internal and external state of a transformer is provided in [8], where thermography stands out [9]. But thermography diagnosis is a tool that is also used for the maintenance of facilities [10]. It has even been experimented with carrying out the thermographic inspection by means of an autonomous system [11].

Therefore, from a practical point of view, infrared thermography diagnosis is a tool that is used for both equipment and installations maintenance [12]. It is very appreciated, specially by electric companies, because of the benefits it provides [13], and, in fact, there is a Standard Guide for the examination of equipment with infrared thermography [14]. It is also one of the most useful ways of carrying out maintenance, not only due to its low cost, rapid implementation and the effectiveness of the results obtained, but also because of the benefits associated with the possibility of conducting tests with the equipment in service, which is very important for the quality of supply offered to customers, as the continuity of power supply is not affected. The main advantage of infrared thermography is the possibility of identifying hot spots within the facility. These spots are abnormal temperature increases due to a defect in the device, which cause material deterioration and subsequent failure. Such failures are unexpected and not only leave clients without service, but also may cause material damage and, what is more, personal injury. Therefore, hot spots must be identified as soon as possible in order to repair the associated defect.

Recently, in [15] the conditions that must be satisfied in the facilities have been analysed so that hot spots can be correctly identified, and the results can be considered as valid for diagnosis. However, even if the required conditions are fulfilled to correctly identify the hot spots, it is necessary to extrapolate the results obtained with certain current to those that would be obtained with the maximum current that can circulate. This relation has been analysed for fuses in [16], introducing two correction factors that are applied to the measured temperature to obtain minimum and maximum values that delimit the temperature that would reach the hot point with the maximum load. It has also been studied in [17] for electrical facilities with constantly changing load. In this case, the sum of the currents measured at different times, affected by correction factors, has been used to estimate the temperature with the maximum load. In [18] it is proposed a relation between the temperature of the hot spot detected by infrared thermography and the one that may be reached in case higher currents flow. Such relation is given by an exponential function whose coefficient may vary in a range 1.46 to 1.6, which are taken from [19]. However, these values are only valid for some devices up to 10 kV. In a similar way, the IEEE standard [20] presents the equations that establish the use of the maximum capacity of bare overhead conductors according to their characteristics and the conditions of use. The reason why these standards exist for power lines, and not for electrical substations, is due to the social and environmental issues involved in the construction of a new line. Therefore, the need to take advantage of the maximum capacity of power lines arises. A comparison between standards is shown in [21]. However, to the best of the author's knowledge, the relation between the temperature given by a infrared thermography test at any load conditions and the temperature that would be reached at nominal load has not been reported in the specialised literature.

Logically, it is advisable to conduct the thermography diagnosis when loads are as high as possible; however, this is not always possible since it will depend on the planning of the maintenance work. Indeed, it is not practical for operators to wait certain time until the nominal conditions of the substation are reached because load changes are usually slow during normal operation and operators may wait for hours. For this reason, in this paper a formula is proposed to extrapolate the temperature obtained with certain current to the one that would be obtained with higher currents, closer to the maximum values of the installation. Furthermore, it should be noted that the objective of this work is to obtain a tool that allows to identify hot spots that could be problematic later, when the substation works at full load and higher currents circulate. According to the detected hot spot, the relevant maintenance decisions are taken without altering the usual diagnostic practices in electrical substations. During this process, the accuracy of measurements plays a secondary role, provided that the correct maintenance decisions are taken.

The paper is organised as follows. Section 2 addresses the use of infrared thermography in electrical substations and the equipment most likely to present hot spots. In Section 3, the test circuit used for measurement purposes in the laboratory is presented, and a formula that relates the current to the temperature is deduced. Section 4 presents some examples of the application of the proposed formula in the field. Finally, Section 5 presents the conclusions of the paper.

2. Infrared thermography inspections for maintenance in electrical substations

Transmission and distribution activities have characteristics of natural monopolies. In this case, the competition that the market should produce is replaced by the intervention of the State through regulatory bodies. The function of these organisations is to encourage companies to carry out an adequate operation and maintenance, and to develop an efficient investment plan. As a result of the incentives of the regulation to extend the lifetime of facilities and in order to increase profits while achieving the high quality supply required by the regulator, companies have had to improve their maintenance techniques as well as optimise their maintenance programs, which are the maintenance tasks that periodically have to be performed on the equipment of the facilities. Among these improvements, infrared thermography is one of the predictive maintenance techniques from which greater performance has been derived, since it allows to identify faulty equipment while the continuity of power supply is not affected.

The purpose of infrared thermography is to measure the heat emitted by the surface of an object by means of infrared radiations, which allows to determine the temperature of the surface. This temperature is compared with that of the surrounding surfaces and with those of the same elements of other phases to detect hot spots and assess their severity. Depending on the temperature of the equipment, its operating state is determined. In case it is not in optimal conditions and depending on the temperature reached, it is decided according to the urgency whether or not the equipment must be repaired to return it to an optimum state of operation.

In order to conduct a correct thermography inspection, several factors that influence the accuracy of the results obtained must be taken into account. These factors can be procedural, technical and environmental. The procedural factors refer to the consequences derived from the procedure of the thermography inspection, which must be carried out by a qualified operator with sufficient experience. 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 the environmental factors, the most influential ones are the ambient temperature, the rain and wind conditions and the solar radiation.

Electrical utilities usually have hundreds or even thousands of substations to inspect several times a year using thermography. In the substation, the elements that undergo thermographic inspection far exceed 1,000 as well. Therefore, the points that must be inspected in the substations of a power company exceed one million per year. Therefore, any simplification that allows to reduce the time that operators spend will lead into benefits. International standards [20,22] include technical parameters with conservative values that are recommended for use. It is worth mentioning that, although these standards are not specifically for substations, the values here defined apply to them because the electrical equipment is subject to similar conditions. Subsequently, these values are included in the particular procedures of the electrical utilities and are identical for all substations [23]. In this way, it is avoided to constantly change parameters' value depending on the facility and the date of the year in which the inspection is carried out. In consequence, thermography inspections in substations are simplified whereas security is not affected because precision plays a secondary role in this maintenance process.

Electrical substations have intrinsic characteristics that do not occur in other electrical installations: only qualified personnel can work in them; they have very high voltages and, consequently, the safety distances to the energized elements are greater than in other installations; inspection or maintenance work cannot be carried out when there are certain adverse weather conditions, such as fog, wind, rain, hail or storm. Due to these climatological limitations to carry out maintenance work, the load of the circuits is the factor that most influences thermography. The influence corresponding to adverse weather conditions can even be neglected, since thermographic inspections are not carried out under these circumstances.

In an electrical substation, a large number of incidents take place at the connection points of the equipment to the conductors that connect them to other equipment or to the busbars (Fig. 1). For this reason, that connectors are the most critical components in substations, since most of the hot spots and subsequent fault usually take place there [24]. Insufficient tightening torque and untightening are the main reasons why hot spots appears, as they lead to a bad connection because tightness must remain close to manufacturers value. Therefore, detecting hot spots in connectors before a fault occurs become crucial.

In order to correctly detect a hot spot in the connectors of a substation, several requirements must be met [15]: a) the element must conduct a non-negligible current, over the 20% of the maximum; b) it is necessary to wait a certain amount of time since the element is energised so that the problematic temperature to be detected is reached (i.e., 15 minutes); c) the assembly recommendations of the manufacturers of connectors, in terms of the required tightness, must be fulfilled in order to avoid creating future hot spots. Note that the hot spot caused by an incorrect tightening in the assembly phase can appear when the equipment has reached certain ageing.

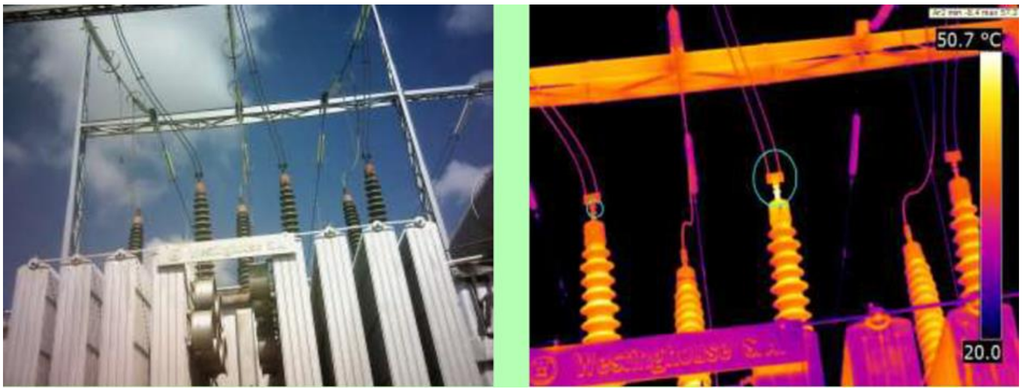

Fig. 1: Visible and infrared images of a hot spot in a 66/15 kV power transformer.

2.1. *Qualitative analysis of hot spots*

The purpose of the maintenance of an electrical substation is to extend the useful life of their components, keeping them in perfect operating conditions. Depending on the results obtained from the maintenance diagnosis, several different situations may arise: a) the equipment has all its parameters within the margins considered correct. In this case no action is required, the equipment will remain in service and it will be maintained again according to the periodicity marked by its maintenance plan; b) a slightly modified parameter is detected that suggests the convenience of supervising its evolution and shortening the period of time until the next maintenance diagnosis; c) a defect or an out-of-limits parameter is detected that could affect the integrity of the equipment or the facility. It suggests the convenience of some remedial action to return it to its optimum state of service.

In the specific case of the maintenance diagnosis based on infrared thermography analysis, once the hot spots have been detected, the proper maintenance decision will be made according to the temperature of the hot spot identified. Notice that the ultimate purpose of thermography is not only to determine the correct temperature of a problematic hot spot, but to decide the actions to implement on the equipment in which the hot spot has been detected, depending on the temperature reached. Table 1 shows the actions suggested by the American National Standards Institute based on the temperatures detected in hot spots [25], where two columns regarding temperature difference are identified. The measured temperature of the hot spot is compared with that of another element with similar characteristics, e.g., similar elements located in the remaining electric phases, or with the ambient temperature. This is the difference between the temperature of the hot spot and the reference taken (ΔT). Depending on whether ΔT is calculated with respect to another element or with respect to the ambient temperature, the temperature ranges established for rating the hot spots are different. In the case of the comparison with another element, ΔT is smaller than when calculating the difference with respect to air temperature. As ΔT increases, the recommended actions can range from a possible deficiency in the equipment, which should be investigated, to an immediate repair of the hot spot detected. Other actions include a recommendation for repairing as soon as possible or an exhaustive follow-up of the hot spot until repaired. The monitoring of the hot spot will consist in controlling it more thoroughly by carrying out thermography analysis at short interval of time until it can be completely repaired.

As indicated above, the temperature reached by a hot spot depends on the current that circulate through the element at the time of measurement: the higher the current, the higher its temperature. A minimum current of the nominal (maximum) current is required in order to correctly identify a hot spot. However, if the hot spot is detected when a relatively low current is circulating, it can be incorrectly identified and therefore the recommended action may not be appropriate. In order to avoid the dependence between temperature and the circulating current, and to get the hot spot correctly determined, it is necessary to assess the temperature that the hot spot would reach under nominal current. Note that the accuracy of the measurements, taking into account the measurement conditions in a substation in contrast to a laboratory test, is of relative importance provided that the decisions made based on field measurements are correct.

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
1 ºC – 3 ºC	1 ºC – 10 ºC	Possible deficiency; warrants investigation
4 ºC – 15 ºC	11 ºC – 20 ºC	Indicates probable deficiency; repair as time permits
---	21 ºC – 40 ºC	Monitor until corrective measures can be accomplished
> 15 ºC	>40 ºC	Major discrepancy; repair immediately

Table 1. Suggested actions suggested by the American National Standards Institute based on temperature rise.

2.2. *Connectors used in electric substations*

As connectors are the elements of the substations in which the hot spots mainly appear and considering that different types of connectors are usually used in substations, a campaign of field measurements was carried out to determine the connectors most likely to create problems. For fifteen months six thermography inspections were conducted in six different substations selected considering the wide range of temperatures throughout the year. In addition to detecting existing hot spots, surface temperatures and circulating currents were measured, registering a total of 7,204 values (Fig. 2 shows the percentage of measurements with a certain current level in Amperes). The number of connectors registered in these substations was 21,027, with a total of 165 hot spots detected. The connectors in which more hot spots were detected are those that connected the following elements: Aluminium (Al) cable with Copper (Cu) tube; Al cable with Cu flatbar; Al cable with Cu stud; and Cu tube with Cu flatbar.

The connectors used in the laboratory to obtain the relationship between the current and the temperature of hot spots were selected based on the above campaign of field measurements. It is worth mentioning that the aim of the study was not to determine the best type of connectors to be used in an electrical substation.

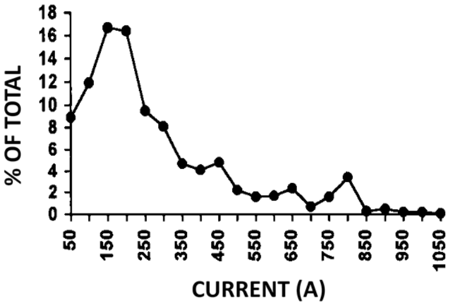

Fig. 2. Percentage of field measurements depending on the circulating current.

3. Current – temperature relationship in connectors

The purpose of the test was to relate the temperature of the elements of a circuit with the current that circulates through them. As it was addressed in section 2, connectors present most of the hot spots due to insufficient tightening. Therefore, the following test was focused on this issue. Also, the most problematic connectors determined in the previous section and the normal range of currents in substation equipment were used. Taking into account that the Al cable limits the currents of the test loop in the laboratory to 600 A, the values chosen to perform the tests were 30, 60, 120, 300 and 500 A, which represent 87.4% of the total values obtained in the inspections. Furthermore, as one of the main causes of the appearance of hot spots in connectors is an incorrect tightening, the connectors of the test circuit were subject to different tightening torques, fractions of the recommended by the manufacturer for correct use.

All the material used in the test circuit was new and consisted of four connectors to connect an Al cable with a diameter of 22 mm, to a Cu tube of 30 mm (Fig. 3). Tightening torques of 50, 60, 80, and 100% of the correct torque were applied on the side of the Al cable. Besides, the test loop was subject to 50 cycles of thermal ageing with a current of 900 A, each cycle composed of 75 minutes of heating and 120 minutes of natural cooling. After completing the ageing cycle, the loop was fed with the desired current (30, 60, 120, 300, and 500 A).

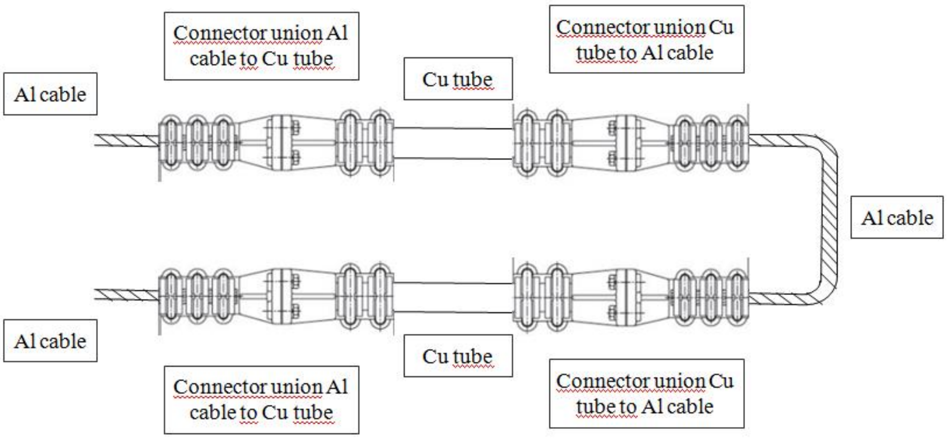

Fig. 3. Laboratory test circuit.

The circuit described above was used to measure the temperature of the connectors, once the temperature stabilises approximately two hours after applying the test conditions. The temperature measurements were taken with a thermography camera. Table 2 presents the temperature reached by each current along with ambient temperature. Table 3 presents the temperature increases of Al connections with respect to the ambient temperature (ΔT_R) under different load conditions (I_R).

	30 A	60 A	120 A	300 A	500 A
Al with a tightening torque of 50%	16.8	20.9	31.8	56.6	87.1
Al with a tightening torque of 60%	18.8	28.9	53.7	130.2	197.2
Al with a tightening torque of 80%	17.9	24.4	49.2	107.6	232.9
Al with a tightening torque of 100%	15.8	17.6	25	43.8	83.9
Ambient temperature	15	15.8	15.7	14.5	25.3

Table 2. Temperatures for each current (ºC) and different tightening torques.

	30 A	60 A	120 A	300 A	500 A
Al with a tightening torque of 50%	1.8	5.1	16.1	42.1	61.8
Al with a tightening torque of 60%	3.8	13.1	38	115.7	171.9
Al with a tightening torque of 80%	2.9	8.6	33.5	93.1	207.6
Al with a tightening torque of 100%	0.8	1.8	9.3	29.3	58.6

Table 3. Temperature increments of Al connections with respect to the ambient temperature (ΔT_R) under different load conditions (ºC).

As the aim of the paper is to determine the temperature that hot spots would reach if the nominal current circulated through the connectors, a formula that allows extrapolation is to be computed. Since 500 A was the maximum current that can circulate through the test loop when the measurements were made, it is considered as the nominal load. ΔT_N is the temperature increase of the Al connections with respect to the ambient temperature under nominal current, and the measured current is I_N. Table 4 shows the normalised values ($\Delta T_R/\Delta T_N$) of the measured temperature increments, along with the average values, for different tightening torques and normalised currents (I_R/I_N).

	30 A	60 A	120 A	300 A	500 A
Al with a tightening torque of 50%	0.029	0.083	0.261	0.681	1
Al with a tightening torque of 60%	0.022	0.076	0.221	0.673	1
Al with a tightening torque of 80%	0.014	0.041	0.161	0.448	1
Al with a tightening torque of 100%	0.014	0.031	0.159	0.5	1
Mean value	0.020	0.058	0.200	0.576	1
I_R/I_N	0.06	0.12	0.24	0.6	1

Table 4. Normalised values of temperature increments under different tightening torques and currents.

In order to visualise the type of relationship between the temperature and the current flowing through the element, Fig. 4 shows the measured values according to the conditions of each test, i.e., tightening torque and normalised current.

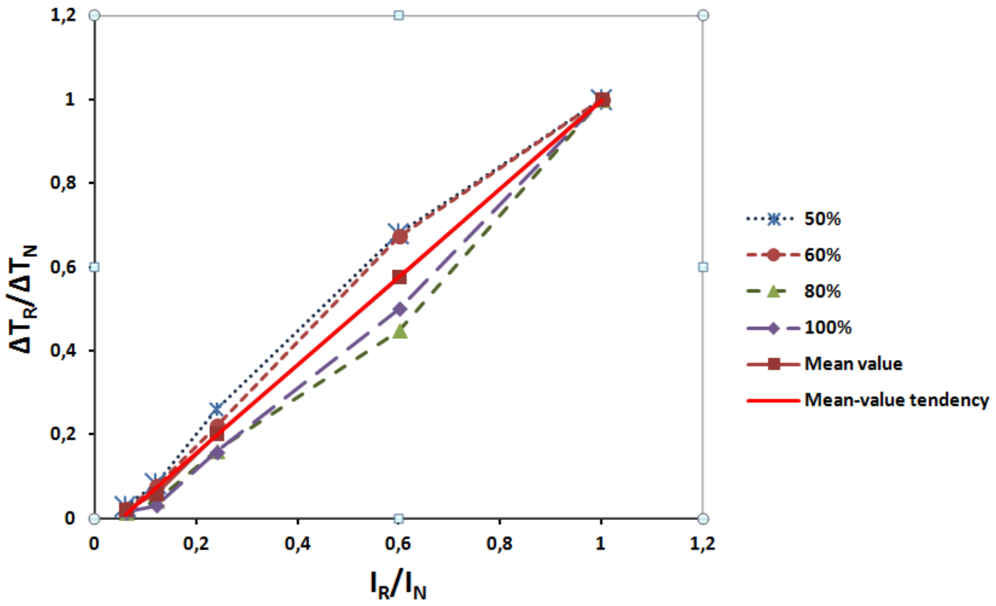

Fig. 4. Normalized temperature increments ($\Delta T_R/\Delta T_N$) versus the current for each tightening torque.

Fig. 4 reveals a linear dependency between the normalised temperature increments, $\Delta T_R/\Delta T_N$, and the circulating current, along with a certain, though small, dependence with respect to the tightening torque. In consequence, a linear approximation can be made based on the mean values of the normalised temperature increments. The equation that relates $\Delta T_R/\Delta T_N$ and I_R/I_N is the following:

$$\frac{\Delta T_R}{\Delta T_N} = 1{,}0537\frac{I_R}{I_N} - 0{,}055 \qquad (1)$$

In order to check the degree of reliability of the model adjusted to a data set, the coefficient of determination R^2 will be obtained, as well as the residual variances S^2:

$$R^2 = \frac{(\sum(x-\bar{x})(y-\bar{y}))^2}{\sum(x-\bar{x})^2\sum(y-\bar{y})^2} \qquad (2)$$

$$S^2 = \frac{\sum(x-y)^2}{n} \qquad (3)$$

where x are normalised values of temperature increments under different tightening currents; $\bar{x}$ is its mean value; y are the values obtained with Eq. (1); $\bar{y}$ is its mean value; and n is the number of elements in the sample.

Table 5 presents the measured values of Table 4 compared to the values obtained with the linear approximation, Eq. (1), including two new columns with the values of R^2 and S^2. Note that all values of the coefficient of determination R^2 are greater than 0.98, in other words, more than 98% of the variability of $\Delta T_R/\Delta T_N$ is explained by I_R/I_N through the adjusted linear model of Eq. (1), for each of the curves of the different tightening torques. Likewise, the residual variances of the curves represented by the linear equation are in all cases less than 0.004, and their standard deviations are thus less than 0.064. This implies a high level of adjustment between the observed values and the values provided by the linear approximation.

The error obtained for each current, regardless of the tightening torques, has also been analysed. The residual variance S^2 of $\Delta T_R/\Delta T_N$ with respect to the linear relationship obtained for each stream is used, as shown inTable 6. In all cases, the residual variance is less than 0.002, except for a current of 300 A, with a value of 0.085. Therefore, there is also a high level of adjustment from the point of view of each current, regardless of the tightening torques.

In consequence, Eq. (1) will serve to extrapolate the temperature measured in the connector with a certain level of load, to the temperature that the same connector would reach when its nominal current circulates.

	30 A	60 A	120 A	300 A	500 A	**R^2**	**S^2**
Al with a tightening torque of 50%	0.029	0.083	0.261	0.681	1	**0.980**	**0.0031**
Al with a tightening torque of 60%	0.022	0.076	0.221	0.673	1	**0.992**	**0.00199**
Al with a tightening torque of 80%	0.014	0.041	0.161	0.448	1	**0.983**	**0.0038**
Al with a tightening torque of 100%	0.014	0.031	0.159	0.5	1	**0.993**	**0.0018**
Mean value	0.020	0.058	0.200	0.576	1	**0.9995**	**6.61E-05**
Mean-value tendency	0.008	0.071	0.198	0.577	0,999		

Table 5. Coefficient of determination R^2 and residual variance S^2 of $\Delta T_R/\Delta T_N$ with respect to the linear relationship obtained for each tightening torque.

Current (A)	S^2
30	0.0002
60	0.0006
120	0.0015
300	0.0085
500	1.69E-06

Table 6. Residual variance S^2 of $\Delta T_R/\Delta T_N$ with respect to the linear relationship obtained for each current.

	30 A	60 A	120 A	300 A	500 A
Al with a tightening torque of 50%	218.9	71.4	81.4	72.9	61.9
Al with a tightening torque of 60%	462.2	183.4	192.0	200.4	172.1
Al with a tightening torque of 80%	352.7	120.4	169.3	161.3	207.9
Al with a tightening torque of 100%	97.3	25.2	46.9	50.8	58.7

Table 7. Temperature increments with respect to the ambient temperature, obtained by applying Eq. (1), that would be reached if the nominal current circulated through the elements (ºC).

As an example, Table 7 presents the extrapolated temperatures increments, with respect to the ambient temperature, corresponding to the nominal current, obtained by applying Eq. (1) to the measured values in Table 3. Thus, when a current of 500 A circulates through the circuit, the real and the extrapolated values are almost coincident: when applying Eq. (1) with a tightening torque of 50%, the temperature increase above ambient temperature is 61.9 ºC (Table 7), while the value obtained in the tests is 61.8 ºC. Similar errors are obtained with the rest of tightening torques, being in all cases 0.13%.

Regarding the other current values, it must be taken into account that, as indicated above, in order to locate all the hot spots in a circuit, the minimum percentage of load that must circulate is 20%. Therefore, and considering that the nominal current of the circuit was 500 A, it is only necessary to focus on the extrapolated values of the columns of 120 A and 300 A in Table 7. For a current of 120 A and a tightening torque of 50%, the temperature increase obtained with the nominal current of 500 A is 61.8 ºC (Table 3). And the value obtained using Eq. (1) is 81.4 ° C (Table 7). That is, with Eq. (1), a temperature increases higher than that measured in the tests is obtained. The same occurs when the results obtained with a current of 300 A and a tightening torque of 50% are analysed. A similar result is obtained for currents of 120 and 300 A, and tightening torque of 60%. This can also be appreciated when analysing Fig. 4: the curves corresponding to tightening torques of 50 and 60% are found above the mean-value tendency curve, so Eq. (1) provides a higher value than actually obtained in the tests.

The same comparison can be made with the values provided by Eq. (1) for currents of 120 and 300 A with tightening torques of 80 and 100% (Table 7) and the corresponding temperature increases of Table 3 when the nominal current circulates. In this case it is observed that the values obtained with Eq. (1) are lower than measured. This can also be seen in Fig. 4.: the curves corresponding to tightening torques of 80 and 100% are below the mean-value tendency curve, so Eq. (1) provides a lower value than obtained in the tests.

Consequently, for tightening torques of 50 and 60%, the decisions taken based on the values obtained by extrapolation are on the side of security in terms of identification and adoption of maintenance measures for problematic hot spots. On the contrary, for tightening torques of 80% and 100%, the extrapolated temperature values are somewhat lower than the real ones. In any case, it must be remembered that the purpose is to correctly classify the detected hot spot, and, for high tightening torques, the decision adopted is still correct. Therefore, in all cases the recommendations adopted (Table 1) when considering the temperatures provided by the extrapolation formula coincide with the recommendations obtained by considering the real temperatures measured in the tests.

Regarding Eq. (1), it should be noted that it has been obtained from laboratory and aging test conditions, trying to reflect field conditions. In addition, connectors and conductors commonly used in electrical facilities have been used. Therefore, the equation is applicable in any electrical facility that uses connectors as the main connection elements between equipment.

4. Application of the proposed formula in the field

4.1. Actions in the field

The realization of thermography in substations must meet a series of requirements so that it can be done correctly. In this environment, a well-trained operator is essential. From a safety point of view, he must be a qualified worker to be able to work within the facility. Regarding training, he must have taken the courses that accredit him as an operator authorized to carry out thermographic inspections. In them, he receives training on how to act in the installation, handling of the equipment, factors to consider and results obtained in the field [26,27]. In addition, he must know the internal procedures of the company. These procedures contain the information necessary to carry out a good thermography. They include: the values recommended by international standards and norms to be used in thermographic inspections, adapted to the company if necessary, and which will be the same for all facilities; the meteorological conditions under which access to the substations is allowed to carry out thermographic inspections; the minimum current that must circulate through the circuit to be inspected; the time that must have elapsed since the circuit has been energised; the safety distances to be respected in substations; the scope of the review to be performed; the report to be made after the inspection, with the identification of the hot spots detected and their severity; the recommendation of the action to be carried out.

The thermographic camera to be used must allow images to be captured with sufficient quality and precision to detect hot spots at the safety distances that must be respected in substations. Images of hot spots are recorded in the camera's memory. Both visible and infrared images are recorded. After the field work, all the registered information is *downloaded* and Eq. (1) is applied. In this way, the temperature of the hot spots detected with the current circulating in the circuit at that time is extrapolated to the temperature that it would reach if the nominal current circulated. Next, the corresponding report is prepared with all the information. And, as a final result, the recommended action is obtained. This recommendation will go to the maintenance staff who will be responsible for acting appropriately on hot spots.

4.2. Results in the field

The application of the proposed formula in electrical substations has made it possible to clearly identify the action to be taken on the detected hot spots. In fact, it has also allowed to identify hot spots on which it was necessary to act, although the actual temperature reached with the circulating current during the inspection was not problematic.

For example, Fig. 5 shows a hot spot in a 66 kV disconnector. The nominal current of the circuit is 720 A, but 200 A circulated at the time of measurement. The temperature of the hot spot was 51 ºC and the ambient temperature 12 ºC. Taking into account that the temperature difference between the hot spot and the ambient temperature is 39 °C, *to monitor this hot spot* is the recommended action by the American National Standards Institute (Table 1). However, in case the current of the circuit increases up to 720 A, according to Eq. (1), the temperature of the hot spot would be 164 °C above the ambient temperature, which will certainly cause a breakdown in the equipment. Therefore, this hot spot should be classified *as repair immediately* according to Table 1. In fact, its severity was confirmed when the device was repaired. For this reason, it is crucial to pay attention to the importance of analysing the severity of the hot spot detected with the nominal current circulating through the circuit, because it is the maximum current that can circulate, and not with the current at the time of the inspection.

In the same way, Fig. 6 shows the hot spot detected in the connector of a 220 kV current transformer. The nominal current of the circuit is 800 A, but 400 A circulated at the time of measurement. The temperature of the hot spot was 27 ºC and the ambient temperature 12 ºC. Therefore, according to the American National Standards Institute (Table 1), the temperature difference indicates *probable deficiency*. In this case, if 800 A circulated through the circuit, the temperature of the hot spot would be 32 °C (Eq. 1), so the recommendation is *to monitor until corrective measures can be accomplished* (Table 1).

5. Conclusions

Infrared thermography is one of the most effective tools in the predictive maintenance of electrical facilities. Through it, hot spots are identified, which are the locations where faults normally occur. Once a hot spot is detected, it is of crucial importance to make the right decision regarding the maintenance action to be taken to avoid a possible breakdown. However, the temperature of the hot spot detected during the thermography analysis depends on the current circulating through the circuit, which may be lower than the maximum current that can circulate through the element. In order to be able to make an adequate assessment of the action to be performed, it is necessary to extrapolate the temperature that the hot spot detected would reach under nominal current.

In this paper an extrapolation formula has been obtained for the temperature of the hot spot as a function of the current. It allows to evaluate the temperature that would be reached if the nominal current circulated through the circuit. Furthermore, the maintenance actions to be implemented when a hot spot is detected, depending on the temperature that it would reach under nominal load conditions, have been presented. The accuracy of the linear approximation adopted between temperature and current has been evaluated using the coefficient of determination and residual variances, demonstrating the validity of the proposal for the adoption of adequate maintenance actions based on the measurements during the thermography analysis. Finally, the proposed formula has been used in the field, and the recommended actions for the detected hot spots confirm the proposed procedure to avoid damage to the inspected electrical substation.

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Fig. 6. Visible and infrared images of a hot spot in a 220 kV current transformer.

Fig. 5. Visible and infrared images of a hot spot in a 66 kV disconnector.

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