Influencial factors in thermographic analysis in substations

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Highlights:

- Reliability of results obtained with thermography
- Percentage of load needed to perform thermography
- Waiting time for thermographic inspections
- Importance of tightening torque in generating hot spots

Abstract

Thermography is one of the best predictive maintenance tools available due to its low cost, fast implementation and effectiveness of the results obtained. The detected hot spots enable serious incidents to be prevented, both in the facilities and equipment where they have been located. In accordance with the criticality of such points, the repair is carried out with greater or lesser urgency. However, for detection to remain reliable, the facility must meet a set of requirements that are normally assumed, otherwise hot spots cannot be detected correctly and will subsequently cause unwanted defects. This paper analyses three aspects that influence the reliability of the results obtained: the minimum percentage of load that a circuit must contain in order to be able to locate all the hot spots therein; the minimum waiting time from when an item of equipment or facility is energized until a thermographic inspection can be carried out with a complete guarantee of hot spot detection; and the influence on the generation of hot spots exerted by the tightening torque realized in the assembly process.

Keywords: Hot spot, Predictive maintenance, Substation, Thermography

1. Introduction

Maintenance work in electricity companies has undergone a major evolution since its origins. Initially, only corrective maintenance was carried out: when a fault was produced, it was repaired as quickly as possible. Subsequently, preventive maintenance evolved: the existing maintenance programs were applied periodically without taking into account the particularity of each facility and with the consequent risk of introducing faults into the equipment during its manipulation. Finally, predictive maintenance can now be carried out: either without intervening in the facility whatsoever or intervening only minimally, whereby through comparison of the results obtained with the historical data of the element maintained, conclusions can be drawn regarding its state.

Predictive maintenance is the logical evolution that takes into account not only the quality of service demanded by the customer, but also the existing competition between electricity companies, and the possibility of introducing undesirable defects in facilities and equipment when maintenance is carried out. In addition, predictive maintenance gives us the information needed for intervention in the facilities only and exclusively when necessary and, from an economic point of view, this type of maintenance is the most profitable [1].

These maintenance techniques have been carried out with specific tests on various items of equipment to be maintained in the substations. Therefore, in the transformers, physical-chemical and chromatographic analyses of the oil are carried out, the dissipation factor is analysed, etc. [2]. In the circuit breakers, the displacement and speed of the poles is tested, the consumption of the coils is analysed, etc. [3], [4].

However, one tool is of common application both to the variety of equipment and to the facilities, and is recognized for the benefits that it contributes: thermography [5], [6], [7], [8], [9], [10], [11]. In addition, this tool provides one of the most useful ways of carrying out maintenance due to its low cost, quick implementation, and the effectiveness of its results.

Studies published on thermography have analysed: the factors that affect the temperature reading of thermographic cameras [12]; the equivalent modelling of certain equipment to identify internal defects through thermography [13]; and the relationship of certain parameters that characterize an item of equipment with thermography [14]. However this tool has yet to be studied from the practical point of view of the execution of the measurement process.

The main objective of thermography is to detect the hot spots of the equipment and facilities and then to proceed with their repair with the urgency associated to their criticality. This involves either programming the deenergization of the bay or carrying out work live in order not to influence the quality of the service perceived by the client.

In thermography, an experienced operator is necessary for the inspection of the installation in a fast but effective way; robots have occasionally replaced this operator [15]. In addition, it would be advisable to carry out the thermography when loads are as high as possible, although this is not always possible due to dependence on the work planning, in which case it becomes necessary to extrapolate the temperature measured for the load that is passing at that moment, to the temperature that would be obtained if the nominal current were passed through the inspected circuit.

Since thermography is carried out in each facility with the circuits in different states, a series of frequently assumed conditions are analysed in this study. However, if these conditions are not the case, the results obtained can be distorted and lead to erroneous conclusions regarding the assessment of localized hot spots. Furthermore, since in this work the field thermography operative prevails, the degree of precision of the results obtained is relegated to a secondary plane.

The minimum thresholds of three major assumptions are therefore determined to correctly identify the hot spots: the minimum percentage of load that a circuit must contain in order to be able to locate all the hot spots therein; the minimum waiting time from when an item of equipment or facility is energized until a thermographic inspection can be carried out with complete guarantee of hot spot detection; and the influence that the tightening torque realized in the assembly exerts on the generation of hot spots.

2. Materials and Methods

2.1. Thermography in substations

The environment in which the activity of electricity companies is developed has changed radically in recent years: from a regulated market composed of vertically structured companies of a monopolistic nature to companies with competing independent segments. However, transmission and distribution activities have characteristics of natural monopoly due to their increasing economies of scale since the fixed costs of investment, operation and maintenance predominate over the variable costs. Moreover, it is totally inefficient for two companies to compete in the same territory by duplicating electricity infrastructure.

In this case, market competition is replaced by state intervention through regulatory agencies that encourage companies to carry out an efficient operation, maintenance, and investment plan. As a response to this remuneration for the operation and maintenance of the facilities and the incentives for their improvement, electricity companies have had to improve their maintenance techniques and optimize their programs. Termography constitutes one of the maintenance methods that have given the best responses to this need.

Thermography measures the heat emitted by the surface of a body by means of infrared radiations. This temperature is compared with that of the surrounding surfaces and with those of the same elements of other phases. Depending on the value reached, it can be determined whether the measured point is in a functioning state, and, if is not, then the urgency of its repair to return it to its optimal working condition is indicated. However for thermographic measurements to be taken as reliable, there must be a series of circumstances regarding the condition of the installation, otherwise risks may be masked. It is precisely from these circumstances that the measurements attain reliability and this forms the focus of this paper.

Another issue to bear in mind is that the locations within a substation where there is a greater risk of presenting a hot spot tend to be: at the connection points between the conductors with the facility equipment; and at the connection points from one conductor to another. It is at these points where inspection by an experienced operator must be focused. Since these connections are made through the connectors, these elements are vital for the prevention of breakdowns. Therefore, this paper also focuses on the operating conditions of connectors which, despite their simplicity, can cause many failures in the facilities.

This paper therefore focuses on the field circumstances that enable good thermography to be performed on those elements where the most hot spots appear (the connectors) and on one of the factors that experience has shown generates the most problems: the tightening torque of the connectors. Furthermore, in the case of results from field applications, the extreme accuracy of the laboratory's own results loses importance since field conditions differ from those of the laboratory, and hence measurement precision plays only a secondary role. For this reason, no statistical study has been carried out with the results obtained, as it should have been done in case the objective of the experiment had been to demonstrate rigorously a new hypothesis. In addition, the results obtained in the tests have been increased with a safety margin to obtain the conclusions to be applied in the substations. The measurements of the tests were taken when the temperature was stabilized, which occurred at approximately two hours in all cases. The current that in each test went through the loop, and all its components, has been indicated below and the temperature measurements of the tests have been carried out with thermographic camera.

2.2. Identification of the connectors used in the study

In order to analyse the aspects that influence the attainment of the correct conclusions when the thermographic measurements are made, the connectors that produce the highest percentage of hot spots have been previously identified. Six thermographic inspections were carried out over a period of fifteen months in six substations where there was a wide range of temperatures, and the measures of the intensities that circulated around the circuits were also registered. The number of connectors registered in these substations was 21,027 with a total of 165 hot spots in the six inspections carried out (figures 1 and 2 show the normal and thermal images of two of these hot spots). Once the families of connectors that have the most hot spot problems had been defined, such connectors were used in laboratory tests. These connectors connected: Aluminium (Al) cable with copper (Cu) tube; Al cable with Cu flatbar; Al cable with Cu stud; and Cu tube with Cu flatbar. Both the connectors and the rest of the material used in each of the laboratory tests were new and with the characteristics indicated in each of them. When the inspections were carried out, measurements were taken of the intensities presented by the circuits, and a total of 7,204 values were registered. Figure 3 shows the percentage, compared to the total, of each step of intensities in amperes (A).

Fig. 1: Normal and thermal images of hot spot: Cu tube with Cu flatbar connector.

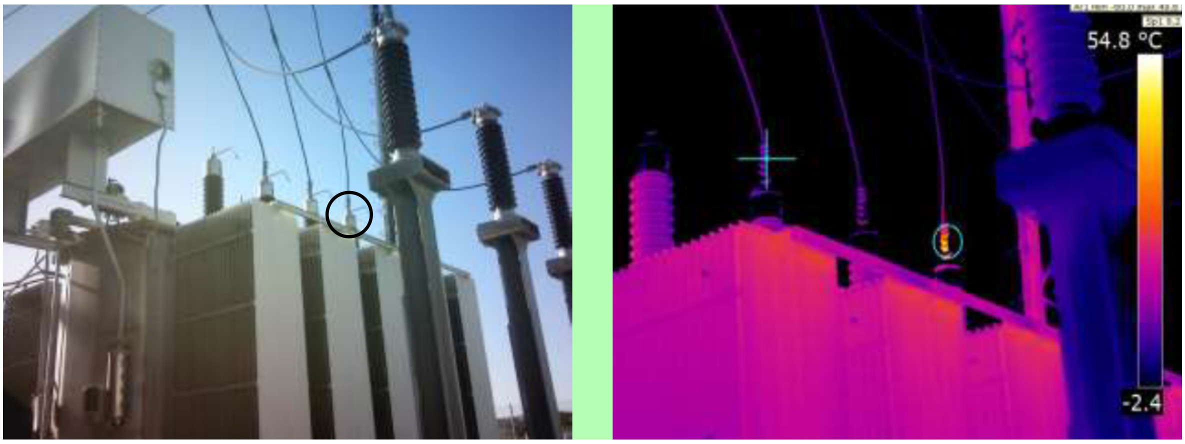

Fig. 2: Normal and thermal images of hot spot: Al cable with Cu stud connector.

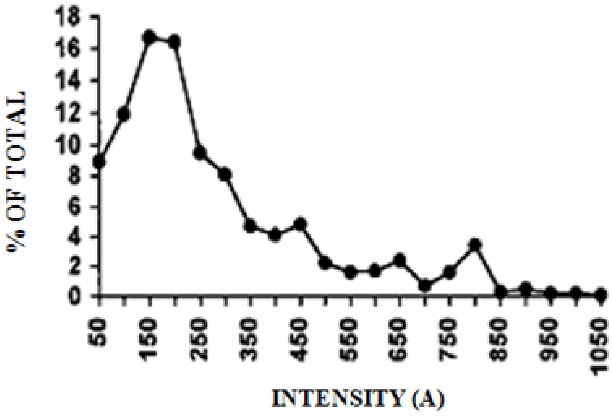

Fig. 3. Percentage, versus the total, of each step of intensities.

Since the objective of this study is to obtain conclusions regarding the optimization of the thermographic inspections and not with respect to the best type of connectors to be used, connectors without any distinction of type or connectors without a previous criterion were used in the tests performed for the analysis of the relevant aspects for taking a good measurements.

3. Results

3.1. Minimum load threshold for hot spot detection

The objective of this test in the laboratory was to determine the minimum percentage of load that a circuit must have in order to guarantee that all the hot spots therein can be located. To this end, data on existing intensities in the facilities and data concerning the families of connectors with the greatest problems was used. By taking into account that the Al cable limited the intensity 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.

The test circuit consisted of four connections connecting a 22-millimeter (mm.) diameter Al cable with a 30-mm diameter Cu tube (Figure 4). To the connection, and on the side of the Al cable, various tightening torques were given proportional to that recommended by the manufacturer for its installation in normal use: 50, 60, 80, and 100%. This test loop was subjected to 50 cycles of thermal aging with an intensity of 900 A, and each cycle was subjected to a period of 75 minutes of heating and 120 minutes of natural cooling. After completion of the aging cycle, the loop was fed so that the desired current values (30, 60, 120, 300, and 500 amperes) would be obtained. The data of the temperature increments for the conductor and the four connectors, for each test, were those indicated in Table I.

	30 A	60 A	120 A	300 A	500 A
Conductor	1.1	3.9	14.5	41.6	82.6
Al with a tightening torque of 50%	1.8	5.5	16.1	43.1	71.8
Al with a tightening torque of 60%	3.9	13.5	39.4	136.2	205.9
Al with a tightening torque of 80%	2.9	9.2	33.5	102.0	218.4
Al with a tightening torque of 100%	0.8	2.3	9.3	30.3	68.6

Table I. Temperature increments of each test to obtain the minimum load threshold (ºC).

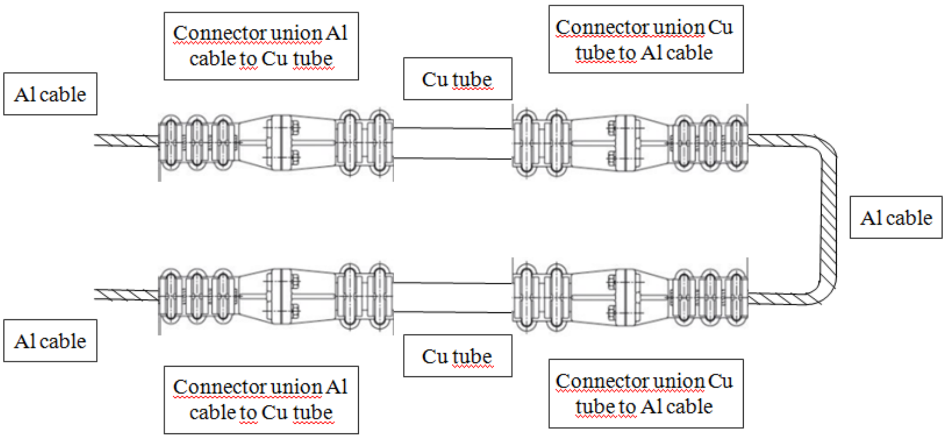

Fig. 4. Test circuit for minimum load threshold for hot spot detection

From this table it can be deduced that the aluminium connection with a tightening torque of 100%, in accordance with the manufacturer's specification, was heated less than the conductor, as expected, because the manufacturers of connectors specify the nominal tightening torque that should be given to each connected element to work properly and therefore without hot spots. The aluminium connection with a tightening torque of 50% was a part that was originally tightened to 40% of its specified tightening and after the tenth cycle had to be re-tightened because it had reached temperatures that endangered the piece. The temperatures reached by this piece are very similar to those of the conductor. In the test at 500 amps the temperature was even lower than that of the conductor itself.

Therefore, there was one connection without hot spots (aluminium with a tightening torque of 100%), another that was at the limit of becoming a hot spot (aluminium with a tightening torque of 50%), and two other connections that had hot spots (aluminium with a tightening torque of 60 and 80%). Table II shows the temperature increases of these two latter connections with respect to the conductor versus the percentage of load. It should be remembered that the tests were performed at 30, 60, 120, 300, and 500 A which is 5, 10, 20, 50, and 83.3% of the value of the nominal load respectively.

Load percentage	5 %	10 %	20 %	50 %	83,3 %
Al with a tightening torque of 60%	3.9	13.5	39.4	136.2	205.9
Al with a tightening torque of 80%	2.9	9.2	33.5	102.0	218.4

Table II. Temperature increases of aluminium connections with a tightening torque of 60 and 80% with respect to the conductor versus the load percentage (ºC).

Adjustment by least squares yields the following lines:

- Al with a tightening torque of 60%: $\Delta T = -3.92 + 1.64\ (I_R/I_N \times 100)$
- Al with a tightening torque of 80%: $\Delta T = -12.64 + 1.70\ (I_R/I_N \times 100)$

where I_N is the nominal current of the test loop and I_R is the intensity of the test.

By calculating the load values at which temperature increases begin to occur:

- Al with a tightening torque of 60%: $I_R/I_N = 2.39$ %
- Al with a tightening torque of 80%: $I_R/I_N = 7.43$ %

Therefore, for a temperature increase to be detected by thermographic equipment, there must be a load of at least 10%. However, if the environmental conditions are not favourable, then this increase might be insufficient.

If the temperature increases that would occur with a load of 20% are calculated with the lines obtained, then:

- Al with a tightening torque of 60%: T = 28.8 %
- Al with a tightening torque of 80%: T = 21.3 %

and sufficient temperature increases are detected even with poor environmental conditions.

3.2. Waiting time for thermography

The objective of this test was to set the minimum waiting time from when a device or facility is energized until the hot spot temperature stabilizes and can be ascertained with certainty, together with the time that it is necessary to wait to ascertain whether the reviewed facility contains hot spots. To this end, as in the previous section, data on existing intensities in the facilities and on the families of connectors with the most problems was used: this test was carried out in the laboratory. Regarding the intensities, and by assuming the same circumstances as in the previous section, the values of 30, 60, and 300 A were chosen.

The test circuit consisted of eight connectors, four of which connected a 22-mm diameter Al cable with a 30-mm diameter Cu tube, and another four joined a 30-mm diameter Cu tube with a Cu flatbar (Figure 5). On the Al cable side of the Al-Cu connections, various tightening torques proportional to that recommended by the manufacturer for installation in normal use were given: 50, 60, 80, and 100%. The same was performed on the side of the Cu tube. On the side of the Cu tube of the Cu-Cu connections, the following tightenings were given: 40, 60, 80, and 100%. Fifty cycles of aging were then applied as described above and the loop was fed so that the desired intensity values would be obtained.

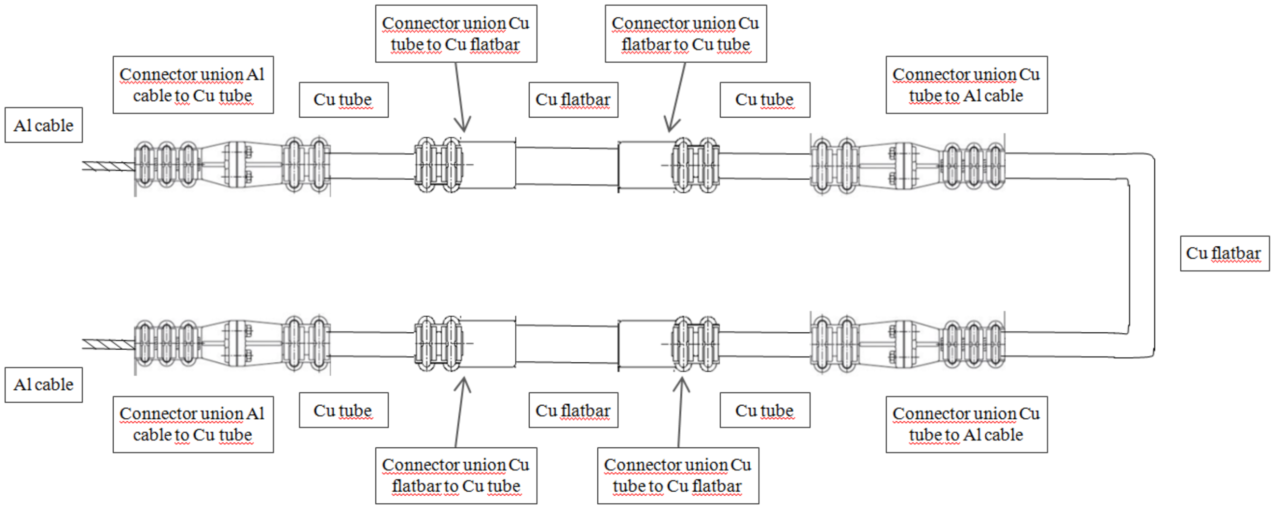

Figure 5. Test circuit for waiting time for thermography

Stabilization was taken to mean that there is no variation greater than one degree centigrade within the last 15 minutes: the error of the measurement with respect to the final stabilization temperature was taken into account to determine the thermal stabilization time.

In the Cu-Cu connectors, no hot spots were generated, even without the specified tightening torque, and the temperature increases were very small, and hence its stabilization was very rapid. Table III shows the stabilization time (in minutes) for the three connectors of Al-Cu without the specified tightening torque, which were those that presented hot spots. Table IV shows the mean stabilization time.

	Error < 5 %	Error < 10 %	Error < 20 %	Error < 50 %	Error < 100 %
30 A	125	125	78	40	28
60 A	121	108	92	62	47
300 A	122	106	89	57	31

Table III. Stabilization time for Al-Cu connectors without specified tightening torque (minutes).

Error < 5 %	Error < 10 %	Error < 20 %	Error < 50 %	Error < 100 %
123	113	86	53	35

Table IV. Mean stabilization time for Al-Cu connectors without specified tightening torque (minutes).

The waiting time from when a facility is energized until the temperature of a hot spot can be accurately measured is therefore approximately two hours (thermal stabilization).

Finally, the time that is necessary to wait to ascertain whether there are hot spots in the inspected facility has been investigated with the data obtained. To this end, in order to ascertain whether these increments could be localized by thermography equipment, it was only interesting to determine the temperature increases between the hot spots and the reference conductor, whereby it can be observed in Table V, Table VI and Table VII that the increments obtained after 15 minutes of the facility being energized are sufficient for detection by thermography equipment, especially when the intensities are high.

	15’	30’	45’	60’	75’	90’	105’	168’
Al with a tightening torque of 60%	1.2	1.5	1.7	2.0	2.1	2.3	2.3	2.7
Al with a tightening torque of 80%	0.9	1.1	1.2	1.3	1.4	1.5	1.4	1.8
Cu with a tightening torque of 60%	1.3	1.6	1.9	2.0	2.2	2.4	2.3	2.8
Cu with a tightening torque of 80%	0.8	1.0	1.1	1.2	1.3	1.4	1.4	1.7

Table V. Test at 30 A: Difference in temperature between the hot spots and the conductor, from when the facility is commissioned, for different tightening torques (ºC).

	15’	30’	45’	60’	75’	90’	105’	120’	135’	150’	165’	180’
Al with a tightening torque of 60%	2.5	4.4	5.8	6.9	7.6	8.2	8.5	8.9	9.0	9.1	9.3	9.6
Al with a tightening torque of 80%	1.5	2.4	3.1	3.8	4.3	4.7	4.9	5.2	5.4	5.4	5.3	5.3
Cu with a tightening torque of 60%	2.6	4.4	5.8	6.9	7.7	8.3	8.5	8.9	9.1	9.3	9.4	9.6
Cu with a tightening torque of 80%	1.1	2.0	2.7	3.4	3.9	4.3	4.5	4.8	5.0	5.1	4.9	4.9

Table VI. Test at 60 A: Difference in temperature between the hot spots and the conductor, from when the facility is commissioned, for different tightening torques (ºC).

	15’	30’	45’	60’	75’	90’	105’	120’	135’	150’	165’	180’	195’
Al with a tightening torque of 60%	15.5	27.5	36.2	46.0	56.1	63.8	68.4	69.7	71.5	72.5	74.2	74.9	75.2
Al with a tightening torque of 80%	7.9	18.4	21.5	25.0	28.5	35.5	40.0	44.1	45.6	46.0	46.4	46.6	46.5
Cu with a tightening torque of 60%	19.9	29.1	50.6	63.3	73.1	83.0	86.1	89.5	91.4	92.8	93.9	94.2	94.6
Cu with a tightening torque of 80%	7.5	18.7	22.9	25.5	29.9	37.2	43.8	49.6	54.6	58.5	60.0	60.2	60.4

Table VII. Test at 300 A: Difference in temperature between the hot spots and the conductor, from when the facility is commissioned, for different tightening torques (ºC).

3.3. Influence of tightening torque

The purpose of this test in the laboratory was to analyse the relationship between the given tightening torque and the generation of hot spots. To this end, a connector belonging to a family of connectors that experienced the most hot spot problems was used in the circuit. In particular, it connected a 22-mm diameter Al cable with an 80 x 50 mm Cu flatbar (Figure 6). On the side of the Al cable, various tightening torques were applied that were proportional that recommended by the manufacturer for its installation: 60, 70, 80, 90, 100, and 110%. In order to simulate the circuit immediately after its commissioning, no aging cycle was applied. Four heating tests were carried out with the following intensities: 300, 600, 800, and 1000 A. The values shown in Figure 7 were obtained.

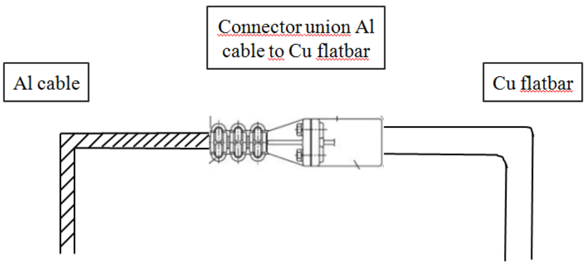

Figure 6. Test circuit for influence of tightening torque in connector Al cable to Cu flatbar

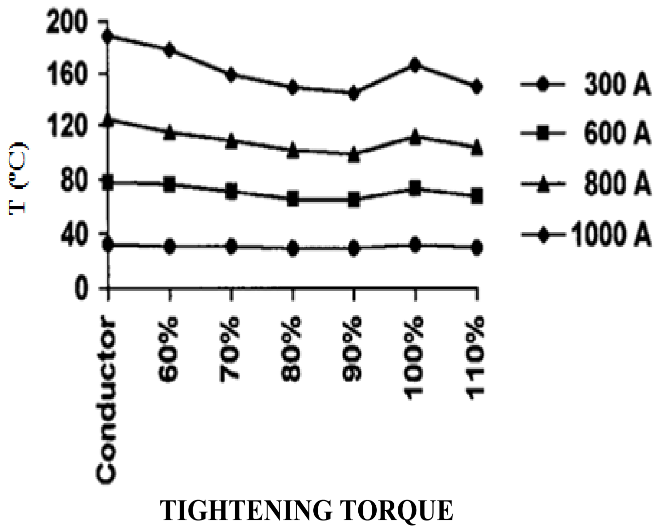

Fig. 7. Temperatures reached in the stabilization, after commissioning, for each connection and with different heating intensities.

In this figure it can be seen that no connection, irrespective of its tightening torque, reaches a higher temperature than that of the conductor, and hence hot spots that may exist and have been generated by poor tightening torque after assembly or repair fail to appear immediately after commissioning the facility.

Subsequently a second loop was assembled that used two of the problem connectors: a straight connector connecting a 22 mm diameter Al cable with a 30 mm diameter Cu stud and a straight connector connecting a 25-30 mm diameter Cu tube with an 80 x 50 mm Cu flatbar (Figure 8). The connectors were subjected to tightening torques of 50, 60, 80, and 100% with respect to that specified. This loop was subjected to 50 cycles of thermal aging with a current of 900 A, and then subjected to five heating tests with the following intensities: 30, 60, 120, 300, and 500 A. Figure 9 shows the stabilization temperatures for the conductor and the Al-Cu connector with different tightening torques and various heating intensities. In Figure 10 the same variable is shown but for the connection of the Cu-Cu connector.

From these figures, it can be concluded that the hot spot generated by poor tightening in the assembly phase can become apparent when the equipment has undergone a certain aging.

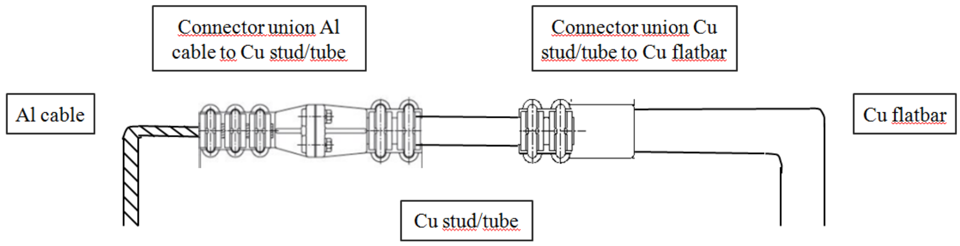

Figure 8. Test circuit for influence of tightening torque in connector

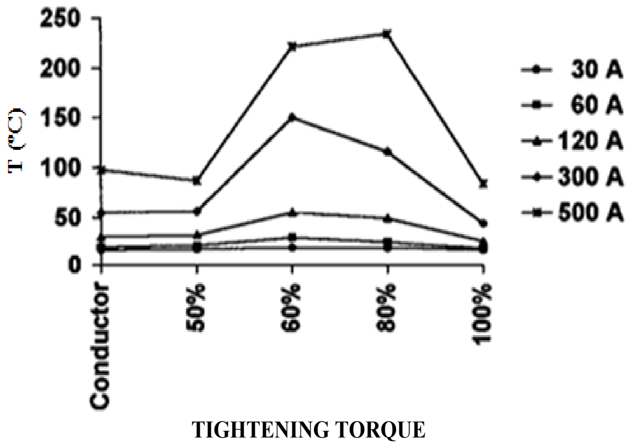

Fig. 9. Stabilization temperatures for the conductor and the Al-Cu connector with different tightening torques and various heating intensities.

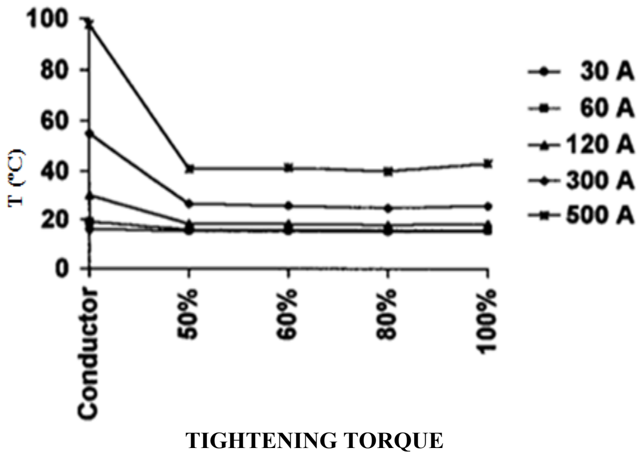

Fig. 10. Stabilization temperatures for the conductor and the Cu-Cu connector with different tightening torques and various heating intensities.

4. Conclusions

Within predictive maintenance, thermography is one of the most effective tools due to its low cost, speed in its realization, and the effectiveness of the results obtained. In this paper, a series of considerations has been analysed regarding the circuits on which thermography is carried out, which must be taken into account in order to draw reliable conclusions on the state of the facility. These considerations include: the minimum percentage of load that a circuit must contain in order to be able to locate all the hot spots therein; the minimum waiting time from when an item of equipment or facility is energized until a thermographic inspection can be carried out with a complete guarantee; the influence that the tightening torque realized in the assembly exerts on the generation of hot spots.

The following conclusions have been obtained:

- The minimum percentage of load that a circuit must have in order to be able to locate all the hot spots therein is 20%.
- Above a 10% load, heating takes place which, depending on various conditions (mainly environmental), can render it possible to detect all hot spots, but never with a total guarantee.
- Below a 10 % load, there is no guarantee that there will be any increase in the temperature of the connector with respect to the conductor.
- The waiting time from when a facility is energized until the temperature of a hot spot can be accurately measured is approximately two hours (On the assumption that stabilization implies that there is no variation greater than one degree centigrade in the last 15 minutes).
- The time to wait from when a facility is energized for the detection of existing hot spots is 15 minutes. This time can be reduced if the load values to which the installation is subjected exceed its nominal load.

- Good compliance with the assembly recommendations of the manufacturers of connectors, in terms of the required tightness, is essential for the prevention of the future generation of hot spots.
- Hot spots that may have been generated by an incorrect tightening after an incorrect installation or reparation in an installation will not appear, except in extreme cases of an incorrect assembly, after its immediate energization.
- The hot spot generated by an incorrect tightening in the assembly phase can appear when the equipment has undergone a certain aging.

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