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CONSIDERATIONS REGARDING ELECTRICAL EQUIPMENT MONITORING THROUGH INFRARED THERMOGRAPHY

BY

ALIN DRAGOMIR[1,*], MARICEL ADAM[1], SILVIU-MARIAN ANTOHI[1], ADRIAN VÎLCU[2] and ALEXANDRA BODOGA[2]

[1]“Gheorghe Asachi” Technical University of Iași, Faculty of Electrical Engineering, No. 21-23, 700050, Iași, Romania
[2]“Gheorghe Asachi” Technical University of Iași, Faculty of Industrial Design and Business Management, No. 28, 700050, Iași, Romania

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Abstract. In the paper are highlighted the main advantages of wireless monitoring methods present in the market for electrical equipment temperature surveillance. Also, are considerate the mandatory corrections applied to the thermographic image in order to adjust the electrical equipment temperature. In the final part, there are shown the resulted values of an infrared thermography inspection performed in industrial environment, which reveals the thermal stresses identification of the busbar’s connections from a medium voltage switch separator. In addition, the paper present why a highly reflexive surface is not suitable for infrared thermography, and in what manner affects the data obtained from the monitoring devices.

Keywords: infrared thermography, temperature, condition monitoring.

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[*]Corresponding author; *e-mail*: alin.dragomir@tuiasi.ro
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1. Introduction

Knowing the thermal stresses of electrical equipment presents a challenge due to the fact that they can have moving parts and can develop heat due to the conductive paths traveled by current. As a result of the heat generated by the equipment, the temperature increases on the surface of the various component parts, until a permanent regime is reached. At which point all the developed heat is ceded to the environment.

Nowadays, wireless data transmission is undergoing unprecedented development. This is due to the development of wireless sensors that are more dedicated to areas requiring wireless communication. The applicability of wireless communication in the electro-energetic field consists in reducing the identification time of a situation that can lead to abnormal operation or failure of the equipment.

The classification of devices that can monitor the surface temperature of electrical equipment can be done according to the way the sensors are connected to the receiving and data processing unit, such as:

- with direct link between sensors and data collection unit;
- Wireless between sensors and data collection unit.

Monitoring the temperature of the investigated equipment can be done by using wired sensors directly connected to the data collection unit (Adam and Baraboi, 2002; Dragomir *et al*., 2018). They are usually thermocouples, thermistors, integrated circuits, resistance temperature detectors, and represent the most common solution for temperature monitoring used nowadays. Those types of sensors have a slow response time. Due to restrictions on electrical insulation and due to the fact that it requires a large number of conductors to measure temperature at several points, this mode is not preferred to be chosen for monitoring the temperature of the construction elements of electrical equipment.

In turn, the wireless monitoring method between sensors and the data collection unit is classified into two other categories, as follows:

- no contact between the investigated item and the data collection sensor, (Stasiek *et al*., 2006). In this category there are thermal imaging cameras that perform contactless monitoring;
- with contact between sensor and element investigated, but without contact between sensor data collection unit, (Volm *et al*., 2004; Cao *et al*., 2008). These types of sensors can communicate either by means of energy harvested from the electromagnetic field or by frequency due to changes in the structure of a piezoelectric material resulting from temperature change (SAW devices).

The biggest advantage of using wireless technologies is that it is a very affordable way compared to other methods, both technically and economically.

In order to identify the condition of the equipment, one of the methods is to monitor its temperature. Knowing the temperature of the constructive parts of the equipment can help identify an abnormal operation, this being due to the direct influence of thermal stresses on the technical condition.

Heating sources are generally the active parts of the equipment, such as power paths, and the iron cores of its components. With the increase in electrical charge of the conductive paths of the investigated equipment, an increase in temperature is obtained, which is directly proportional to the value of the transited current. It also registers an increase in losses through the joule-lenz effect, which leads to increased overtemperatures in various constructive parts of the electrical equipment.

The sum of the ambient temperature θ_a and the temperature increase recorded due to the electrocaloric effect, recorded in stationary regime ϑ, constitutes the temperature θ of the investigated element:

$$\theta = \vartheta + \theta_a \tag{1}$$

The temperature of the investigated electrical equipment may vary due to several non-stationary regime factors, such as:

- temperature increase due to grid connection until permanent temperature is reached;
- temperature drop due to interruption of mains supply;
- temperature increase caused by short-term overloads;
- temperature increase caused by intermittent operation of some electrical equipment;
- temperature increase caused by a defect in the electrical installation.

The paper highlights the main external factors influencing temperature monitoring by means of infrared thermal imaging. Considering the main factors that determine the heating of the components of electrical equipment, the paper presents a case study on the interpretation of thermographic images taken from the industrial environment.

2. Wireless Devices for Monitoring Electrical Equipment

The development of wireless temperature monitoring systems is continuously developing due to the interest given to them by the industrial and research environment. Due to this development, wireless temperature monitoring systems have become increasingly suitable for the elements to be investigated, have a high accuracy, thus becoming useful in SCADA systems, (Chiriac *et al.*, 2021). Therefore, wireless monitoring systems are better suited for management decisions due to their high availability, (*** Infraspection, 2015).

Below are presented the most common devices used to know the temperature of different constructive parts of electrical equipment found in electrical installations, which use wireless technology for transmitting information.

A. Devices with infrared monitoring

Infrared thermography was one of the most advanced technologies for monitoring the surface temperature of the investigated objects. This technology is used in different countries, of which the electrical field was one of the most developed branches. Knowledge of temperatures is done in a non-contact manner that involves a direct visualization of the investigated element. The accuracy of the measured values directly depends on the influence of disturbances in the sampling of infrared images. In the market of monitoring products there are various models of infrared monitoring devices, this technology has reached a full maturity, which gives confidence to users to use it.

B. Devices using passive sensors of SAW type

Devices using the principle of surface acoustic wave SAW, have seen a remarkable development lately, and this is mainly due to the manner of collecting monitoring information, which does not require electrical power to the sensors, (Chiriac *et al*., 2021). Recent developments have propelled this wireless monitoring technology to the top of preferences for companies that apply monitoring of elements of medium voltage electrical equipment (Cao *et al*., 2008). These devices are not yet at full maturity, constantly knowing optimizations and improvements of the method of information sampling, as well as correction of the acquired signal.

C. Passive devices using RFID sensors

These types of devices use a modern technology that uses to modify an impedance connected to an antenna, which will later transmit RFID signals, so the sensors do not require electrical power (Chen *et al*., 2018). These sensors are still in the early stages of development and will validate their use in all voltage levels. The utility of this technology is of interest in electricity transmission and distribution, where the introduction of additional elements in installations can lead to reducing the level of electrical insulation.

D. Temperature monitoring devices based on active network-type sensors

The temperature monitoring of the components of electrical equipment, especially for the low voltage level, can be achieved by ZigBee technology. Communications between sensors and receiving units of this technology use common protocols used in industry. The sensors can be powered on the principle of energy harvesting, or by battery power (Chiriac *et al*., 2021). Wireless transmission of temperature information is based on units (transmitter, receiver) operating frequency range 2400 ÷ 2500 MHz, (Shinde and Siddiqui, 2018). These monitoring systems have sufficient maturity to be competitive in the market. They are available for purchase, but options are limited due to the small number of manufacturers.

3. Environmental factor considerations within infrared monitoring

When an infrared thermographic image is captured, the temperature value is actually an apparent temperature value θa. The actual temperature θr will always be influenced by external factors, so corrections are necessary to compensate for these shortcomings in order to correctly interpret the recorded thermographic images. In this respect, infrared monitoring devices offer possibilities of direct adjustment on the recorded images, these corrections have the role of adjusting the monitored values according to the working conditions and known properties of the investigated elements.

Moreover, are presented some various external factors which can affect the infrared monitoring.

Emissivity of the investigated object – this factor is compensated by introducing as an investigation parameter in the adjustment settings of thermal imaging cameras. The emissivity value is often not available to the person doing the investigation, but often elements with different emissivity can be identified, it is good to introduce the known value of emissivity of the investigated material. When surfaces to be investigated in infrared with an emissivity value below 50% are known, additional elements are needed to make a correct measurement, (*** Suceava, 2022). This factor is very important because emissivity is the basis for constructing the thermographic image of the investigated element.

The reflexivity of the elements found in infrared thermographic imaging is another important factor. If the reflexivity value is higher than 50%, a correct value can no longer be found, because the infrared camera algorithm requires to compensate for reflections by declaring the reflected temperature (thus an erroneous value will be rendered).

Transmissiveness (transparency) – in infrared monitoring it is considered to be a disturbing factor when it is desired to know the temperature of two overlapping elements when the element in front of the infrared camera lens has a considerable transparency. In this situation, if the temperature of the element behind the investigated element has a higher temperature, it will influence the temperature value captured by the device. This disturbing factor is not considered in the algorithm of infrared cameras, remaining to be compensated later from compensation calculations.

Image resolution in correlation with distance to investigated elemental: The infrared thermographic image is more accurate the closer we are to the investigated elemental. If we remove the infrared camera lens from the investigated elemental, due to the limitation of digital infrared photography, namely the limitation of the number of pixels, it will be more difficult to interpret a precise value, here large errors occur. As a rule, the influence of this factor is limited by the algorithm of infrared cameras for limited distance values.

Ambient humidity: a low value of this parameter favors a more accurate monitoring, this disturbing factor is successfully compensated by the algorithm of infrared monitoring devices.

Ambient temperature of the investigated element: the higher its value, the higher the value of the investigated element will result. In the case of current donor paths, the temperature value on their surface when traveled by current is made up of the sum of the ambient temperature value and the overtemperature, (Dragomir *et al*., 2021). This factor is considered in the algorithm of infrared monitoring devices.

Apparent temperature θ_a, is displayed on the infrared monitoring camera, and can be determined with the relationship:

$$\theta_a = (\varepsilon + \rho + \tau) \cdot Kp \cdot \theta_r \tag{2}$$

where ε represents the emissivity of the material; ρ the reflection value of the elements; τ temperature by transmission; *Kp* complex coefficient of correction of temperature values for: environment, humidity, distance to the element. Temperature transmission through the investigated element does not occur too often in cases of monitoring, therefore it will be neglected. The correction factor *Kp* may constitute a maximum of 5% of the true value, according to (Dragomir *et al*., 2021), it is inferred that the apparent temperature monitored by the infrared device will consist of the actual temperature θ_r influenced by emissivity and reflexivity.

From equation (2), results:

$$\theta_a = (\varepsilon + \rho)\theta_r \tag{3}$$

The sum of emissivity and reflexivity equals 1 (100%), therefore if emissivity has small values, then reflections will have large values. High accuracy in infrared monitoring of the temperature of the investigated elements is obtained when the emissivity of the material is higher than 60%. For undesirable situations where the investigated surfaces have emissivity less than 50%, a detailed analysis of the results is required, according to (*** Suceava, 2022).

For a correct interpretation of the severity of the overtemperatures detected in infrared thermographic images, post-processing activities are required, which will calculate and compensate the temperatures identified in the elements of the investigated electrical equipment. At this stage, corrections will be made regarding the degree of electric current load of the investigated elements, as well as the level of wind influence in the case of outdoor investigations, (Andrusca *et al*., 2021), only after these final adjustments will the identified defect be correctly framed.

The sensors of infrared monitoring cameras are suitable for performance in certain ambient temperature ranges. Other factors that can affect sensor lenses are: dust, oxidizing gases or vapors, which often cause inaccuracies in measurement. Noise, electromagnetic fields or vibrations are other conditions that should also be considered before starting the infrared investigation procedure. In these situations, a protective housing, forced ventilation or cooling can protect the sensor and ensure accurate measurements. These measures and methods are available from most infrared camera manufacturers.

Fiber optic sensors, in which the optical head is separated from the sensor electronics by a fiber optic cable, provide a solution around electromagnetic fields or in other harsh environments. In applications involving hazardous materials (e.g. vacuum chambers), the sensor is mounted to investigate the enclosure with controlled environment through a special window. Window materials can transmit the wavelengths used by the sensor. For example, in low-temperature applications, the window can make the target invisible to the eye because it is often made of an opaque material such as germanium or amorphous material that transmits infrared radiation. If the operator needs to see through the window, windows with zinc selenide or barium fluoride are recommended.

Finally, we can say that infrared monitoring offers an easy way to investigate the surface temperatures of the elements of electrical equipment that are of interest, but to do this we must resort to advanced knowledge of interpreting infrared thermographic images and adjust them according to the situation present at the time of investigation.

4. Case Study- Infrared Monitoring of busbar connections

When investigating temperatures in medium voltage cells on the route of electrical installations and equipment, the dielectric insulation capacity must not be affected, (*** Suceava, 2022). Therefore, infrared technology is currently used to monitor the thermal stresses of electrical equipment within medium voltage power cells. In the case study presented, a monitoring of a medium voltage cell, 20 kV, from the component of the Suceava transformer station with voltage levels 400/220/110/20 kV was performed.

At the time of investigation, all necessary conditions were met to capture as accurately as possible the temperatures of the investigated elements. Thus, it was aimed to directly interrogate the element of the electrical equipment, also with a capture as perpendicular as possible to the investigated element. Also, emissivity and reflexivity corresponding to the investigated materials were considered.

Therefore, the connecting bars are made of aluminum, which are painted so that they can be easily identified when it comes to the component phases in the three-phase distribution. Given that the emissivity of the paint is of much better values compared to that of the aluminum bar, as input size for the thermal imaging camera were declared the emissivity of the paint, value 0.95, to the detriment of the aluminum bar (emissivity 0.68).

The reflected temperature was considered the ambient temperature, 19ºC, since possible reflections may indicate ambient temperature. The distance to the investigated element was considered 1.5 m, considering that the resolution of the thermal imaging camera used, Flir T650sc, is 640x480 pixels. The relative humidity of the air at the time of investigation was 55%.

Therefore, after conducting infrared investigations inside a medium voltage cell, a thermal defect was identified at the connection bar on the L3 phase, belonging to a medium voltage separator.

Following the analysis of Fig. 1, from the visible spectrum it can be interpreted that everything seems to be in place for all three phases.

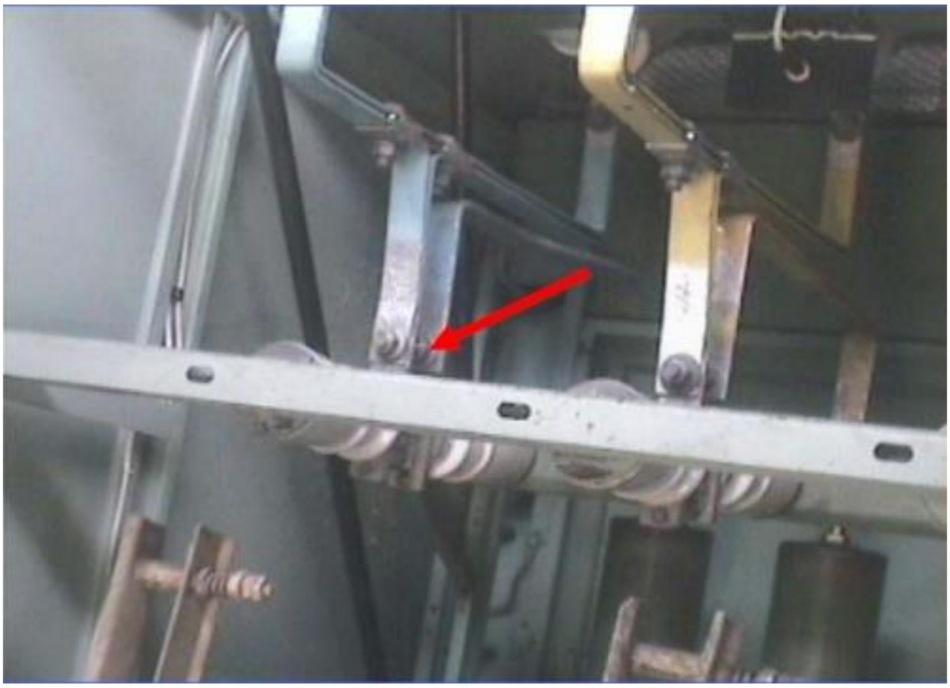

Fig. 1 – Connection bars on the three phases of the medium voltage separator under investigation.

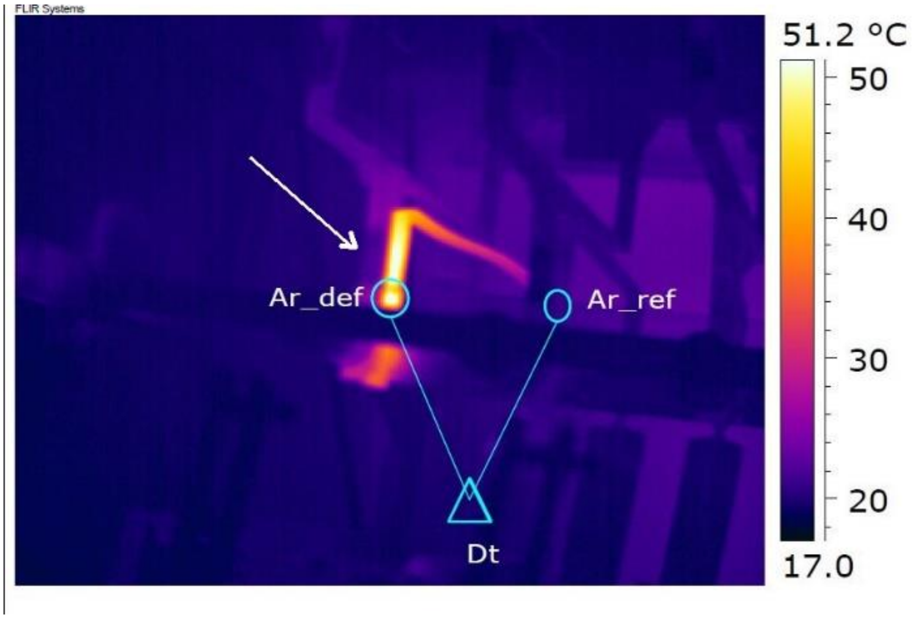

Fig. 2 – Infrared view of the connecting bars on the three phases of the medium voltage separator under investigation.

However, from the analysis of the infrared thermographic image Fig. 2, the fault area is identified, in which it is clearly highlighted as a hot zone. This area is identified on the L3 phase, where the recorded surface temperature is much higher than the temperature of the other two phases. The connection bars are made of painted aluminum. From Fig. 1, it can be noticed that above the connection area of each connection bar is identified an unpainted part used for various monitoring of the equipment and from which the material of manufacture of the connecting bar (red arrow) can be identified. Due to the high reflexivity of the aluminum of which the bar is constituted, in Fig. 2 (white arrow), it can be seen that, regardless of the temperature of the connection bar, the infrared investigation camera records temperature values reflected in those areas. This indicates the importance of an investigated element having a high emissivity, otherwise the surface reflexivity of the investigated element.

Therefore, due to the high reflexivity of aluminum, we can say that the monitored connection bar is correctly investigated due to coating with a high emissivity material (paint), which helps to correctly identify temperatures with infrared thermal imaging camera.

In order to assess the severity of the identified defect, the Dt criterion is used, which involves comparing the temperature of the detected defect with the temperature value of another component element of the investigated equipment that is considered to be in optimal operating conditions. This implies applying the relationship, according to (*** Suceava, 2022), as follows:

$$Dt = A_{r_{def}.max} - A_{r_{ref}.max}\ [^0\mathrm{C}] \qquad (4)$$

where $A_{r_{def}.max}$ – represents the fault area, the maximum temperature value, and $A_{r_{ref}.max}$ – is the maximum temperature value of the similar reference element area.

Thus, for the investigated case, we have: $A_{r_{def}.max} = 53\ [^0\mathrm{C}]$, respectively $A_{r_{ref}.max} = 21\ [^0\mathrm{C}]$, resulting by applying the relationship (4), the value of:

$$Dt = 32\ [^0\mathrm{C}] \qquad (5)$$

Moreover, by applying also the current load correction, taking into account that at the time of the inspection, the electrical installation was only 20% loaded, a final corrected value is obtained, according to (*** Suceava, 2022), results:

$$Dt_{100\%} = 197\ [^0\mathrm{C}] \qquad (6)$$

Finally, identifying this defect, immediate action will be taken to correct the identified problem consisting of imperfect electrical connection to the bolt / nut that secures the attachment of the strap to the movable brooch of the separator.

The temperature difference from the similar connection considered as reference is about 32°C at 20% load. Applying the correction related to current loading, a temperature difference of 197°C is obtained, resulting severe heating level, thus falling within the CRITICAL gravity level, the identified defect.

5. Conclusions

Wireless monitoring devices are suitable when properly fitted with the system and its characteristics in order to achieve optimal results. Thus, in order to identify the correct technical condition of the investigated equipment, it is necessary to use appropriate wireless monitoring devices, for which the parameters corresponding to the investigation scenario are known.

In the paper were presented several wireless monitoring methods used to investigate thermal stresses of electrical equipment elements.

Many elements of electrical equipment have surfaces with high reflexivity, which are difficult to monitor with infrared thermographic investigation devices. By defining correction parameters, it cannot be guaranteed that this disadvantage will be covered. Following the study of that, it was identified that when using infrared investigation devices to monitor the thermal stresses of the elements of electrical equipment, it is essential that the emissivity of the surfaces of the monitored elements is higher than 60%.

When the surface with low emissivity is covered by an element with higher emissivity, then infrared investigation of this surface will give a more accurate value of the monitored temperature.

As resulting from study case analyzed in this paper, is not sufficient just to evaluate the temperature at the moment of investigation, is mandatory to do the engineering corrections and calibrations as postprocessing the infrared thermal images, in order to make a correct decision regarding the gravity of thermal anomalies identified.

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CONSIDERAȚII PRIVIND MONITORIZAREA ECHIPAMENTELOR ELECTRICE PRIN TERMOGRAFIE ÎN INFRAROȘU

(Rezumat)

În lucrare sunt evidențiate principalele avantaje ale metodelor de monitorizare wireless prezente pe piața supravegherii temperaturii echipamentelor electrice. De asemenea, sunt avute în vedere corecțiile obligatorii aplicate imaginii termografice în vederea reglării temperaturii echipamentului electric. În partea finală sunt prezentate valorile rezultate în urma unei inspecții termografice în infraroșu efectuate în mediu industrial, care relevă identificarea solicitărilor termice ale conexiunilor barei colectoare de la un separator al comutatorului de medie tensiune. În plus, lucrarea prezintă de ce o suprafață extrem de reflexivă nu este potrivită pentru termografia în infraroșu și în ce mod afectează datele obținute de la dispozitivele de monitorizare.