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THE MAJOR PREDICTIVE MAINTENANCE ACTIONS OF THE ELECTRIC EQUIPMENTS IN THE INDUSTRIAL FACILITIES

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Abstract. ***In modern low-voltage electrical installations, the predictive maintenance of the major electrical equipments involved in the power delivery process (transformers) or in the conversion of the electrical energy (especially electric motors) becomes mandatory. Thus, a high level of reliability and safety is assured for both the electric facility and operators. The proactive maintenance is to be non-invasively performed and mainly requires an infrared (IR) thermographic inspection and power quality analysis of the installation loads. A vibration investigation is also necessary for the motor drive systems. The paper critically studies the first two main maintenance procedures revealing their main characteristics, performances and limits. A case-study presents a 1000 kVA distribution transformer that supplies a bakery facility that comprised mainly heaters and inductions motors as loads.***

Keywords: thermography, predictive maintenance, thermal camera, power distribution transformer.

1. INTRODUCTION

Thermography inspection is considered by the predictive maintenance as one of its simplest and the major tool. The infrared thermography uses electronic optical devices to non-invasively detect and measure the thermal radiation emission corresponding to a temperature surface. Radiation is the movement of heat that occurs as radiant energy (electromagnetic waves) moves without a direct medium of transfer. Modern infrared thermography is performed by using electronic optical devices to detect and measure radiation and correlate it to the surface temperature of the structure or equipment being inspected [1-6]. The term "thermography" originally comes from the initial words meaning "temperature picture". The roots of thermography can be credited to the German astronomer Sir William Herschel who, in 1800, performed experiments with sunlight [1].

The predictive or proactive maintenance compares the tendency of all measurable technical parameters of an equipment to its technological limits, to detect, analyse and correct any malfunctions before they occur. The predictive approach can be applied to any equipment, if it's possible to measure various parameters (mechanical, thermal, electrical) that characterize its operation. In electrical and power engineering, most of the times, the predictive maintenance is achieved by [1-13]:

- ***monitoring electrical parameters*** of the investigated installation - accurate measurements of the quality parameters for the received and consumed power
- ***the evaluation of the thermal stress*** - thermal inspection
- ***monitoring of the mechanical stress*** - (vibration analysis) - mandatory for the equipment, that has moving parts (motors, generators, etc).

Figure 1 presents the above-mentioned principles, who illustrate the possible devices with which the three types of the investigations are realized [8-13].

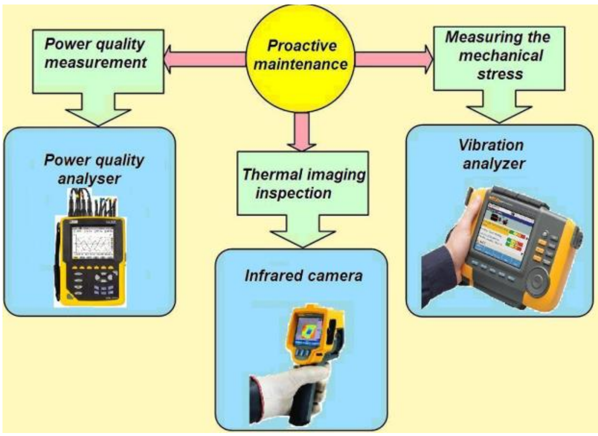


Figure 1. The main components of predictive maintenance in the electrical engineering [11, 12].

The accomplishment of a such a procedure involves considerable investment in high precision equipment and tools that can provide data that can be further processed, analysed (using computing systems), and finally properly interpreted by the qualified personnel.

If these instruments are used correctly a relatively rapid payment of the investment can be achieved with positive effects (increased reliability, cost savings, etc.) on the technological process served by the investigated installation. An important part of the predictive maintenance service is addressed to the non-invasive examination of the thermal stresses of electrical equipment by infrared thermography inspection (IR thermography - infrared).

This method allows viewing and generating in real time thermal maps ("thermal images", thermograms), of the technical systems, which are under investigation. The thermal imaging activity is performed using specialized equipment, called thermal imaging cameras (Figure 2).

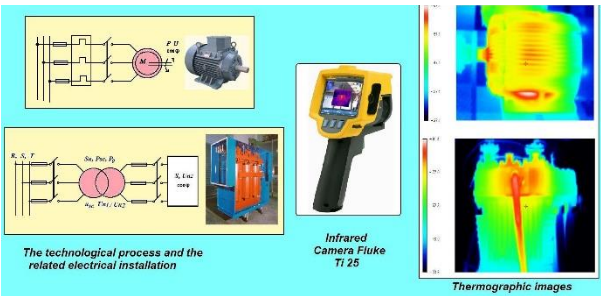


Figure 2: Thermal images for various investigated electrical equipment [11, 12].

By examining the thermographic images, it can be determined the areas with temperatures above the normal (which can lead to damage) or the causes of low-efficiency operation of the inspected equipment. Professional thermal imaging cameras can measure temperatures from -40 ° C to + 1500 ° C with a precision of up to 0.05 ° C.

2. PHYSICS OF THE THERMAL INSPECTION AND INFRARED CAMERA FEATURES

One of the most important conditions for the safety operation of any electrical installation consists in the correct selection of the equipment’s and their maintenance under the established parameters, in terms of heating evacuation (in all operating modes – liner or non-linear regimes), as well as of the current conducting parts which connect them. Heat transfer is also carried out in electrical installations from warm to cold areas in three ways: through **conduction, convection and radiation** [13-16**].**

- Propagation of heat by **thermal conduction** is the process of the heat transfer from a higher temperature region to a lower temperature region within an environment or between two different physical environments. Heat transmission through conduction is made based on Fourier’s law and is given by the following relationship:

$$q = -\lambda grad\theta \qquad (1)$$

where q represents the density of the thermal flow [W/(m·grd)] and λ is the thermal conductivity [W /m].

- **Thermal convection** transmission is based on the heat exchange between the surface of a body and a fluid medium with which it’s in contact. When the fluid movement is due only to the weight difference between the hot and the warmest layers of the fluid, the convection is natural, and when the fluid movement is accelerated by pumps or fans, we talk about an artificial (forced) convection. In case of the heat exchange from the surface of a body with temperature θ_c to a fluid with the temperature $\theta_a < \theta_c$, the heat flux density q_c at the surface of the body is expressed with the general relation:

$$q_c = \alpha_c(\theta_c - \theta_a) \qquad (2)$$

where α_c is the thermal transmissivity by convection [W/ m·grd].

- The thermal exchange between bodies with different temperatures who are on the path of the radiant energy (electromagnetic waves) is called **thermal transmission through radiation**. Heat transfer by radiation occurs only in transparent environments for electromagnetic waves with a wavelength between 0.4 and 340 microns. The density of the heat flux q_r is given by the Stefan - Boltzmann law:

$$q_r = \varepsilon C_0\left(T_c^4 - T_\alpha^4\right)[\text{W/m}] \qquad (3)$$

where T_c is the absolute temperature of the radiating body [K], T_α is the absolute temperature of the environmental (ambient) environment [K], C_0=5.77 [W/mgrd^4] and ε is the radiation coefficient.

The thermography generates, with the aid of a suitable camera (thermal imaging camera), a thermal image obtained exclusively because of heat transfer through radiation between the inspected body and the environment, in the spectral field called infrared. This is a band of the electromagnetic radiation spectrum located between the visible zone and the radio waves. The infrared cameras detect radiations with wavelengths between 8-14 µm (Figure 3).

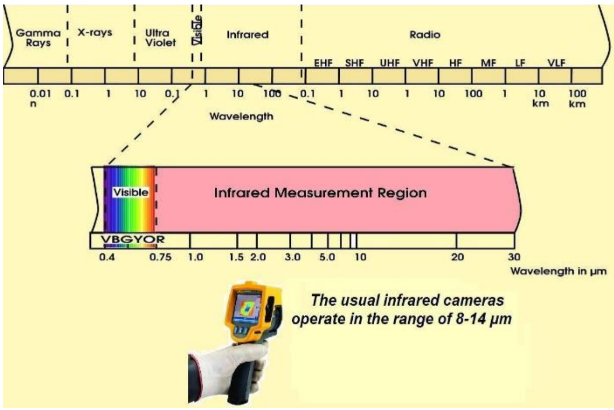


Figure 3. Measuring range of IR infrared cameras with infrared detection [5].

The thermal image is a structured distribution of representatives’ data of the infrared radiation from the investigated structure. Examples of thermal imaging in electrical installations are shown in Figure 4.

It should be noted that anybody that is at a temperature above 0 K (-273° C) emits thermal energy in the form of infrared radiation. The infrared radiation intensity is a function of the body temperature and its emissivity. This is quantified by a non-dimensional number with values between 0 and 1 representing the ratio between the total emission power of any body and the total emission power of the black body. To measure the temperature correctly, the emissivity must be set by the operator depending on the material of the object under investigation. There are certain databases that contain this type of information [13-16].

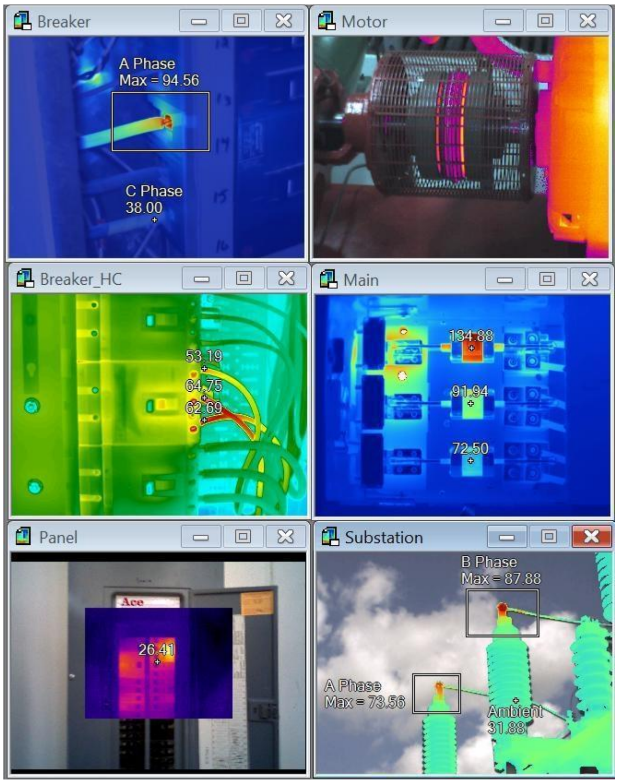


Figure 4. IR thermal images of an equipment currently used in power electrical installations [8].

Thermal imaging cameras measure the electromagnetic radiation emitted by bodies using many specialized sensors (between 19200 and 76800), convert it and then display it as thermal imaging. The sensors can detect a temperature difference of 0.8 to 0.05°C, depending on the sensitivity of the camera. The main parameters that define the performance of a modern thermal imaging camera [13-16]:

- **Temperature range**: represents the interval of the temperature values that the camera can detect and display.
- **Noise Equivalent Temperature Difference (NETD):** the smallest temperature difference that can be identified by the thermal imaging camera.
- **Field of view (FOV):** It is described as an angle (in geometric degrees) and defines the surface that can be captured with a thermal imaging camera. The field of view depends on the incorporated detector in the thermal imaging camera and on the lenses type.
- **Instantaneous Field of View (IFOVgeo):** Measures the ability of a detector to show the smallest details. The geometric resolution is specified in the „*mrad*" and defines the smallest object which, depending on the measurement distance, can be individualized on the thermal image. On the thermal image, the size of this object corresponds to a pixel.
- **Instantaneous Measured Field of View (IFOVmeas):** It represents a parameter that shows the tiniest object whose temperature is still to be precisely measured by an infrared camera. This is usually 2-3 time bigger the smallest identifiable object (IFOVgeo).

The owners of these reports will interpret the results obtained from IR image analysis. The most common position detected by thermal imaging is represented by portions of circuit with accidentally increased resistance (weakened electrical contacts, local loss of electrical properties). Additionally, the overloads and potential short -circuits are very easy to identify due to thermal inspections in different electric panels of electrical installations.

Thermographic images often indicate the improper function of the safety components or the malfunction of other parts of the electrical installation. Sometimes, for a complete interpretation, it is necessary to compare the actual current thermographic image with the images who were previously taken, which also involves a logical (chronological) organization of images. In Figures 5 and 6 are schematically illustrated the previously described procedure using the professional thermal imaging camera Fluke Ti25 [7] and the SmartView software [8]. Lately, the development of these tools has allowed far-reaching investigations into the operation of large-scale electrical equipment and power classes. It should be stressed out that, in the predictive maintenance cases, the thermal imaging report is an extremely valuable document, which correlated accordingly with other documents of the maintenance analysis (energy quality and vibration analysis), impose some measures on short, medium or long term for inspected electrical installations equipment's. Therefore, it must be done with professionalism and responsibility [11, 12].

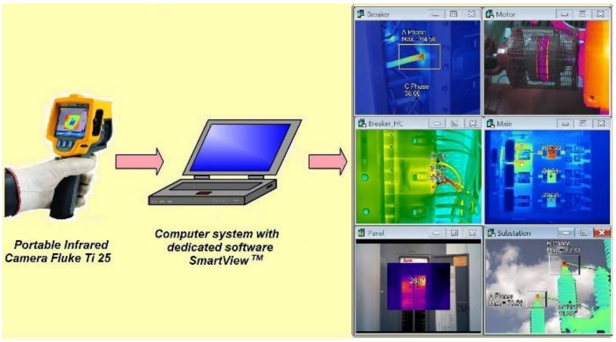


Figure 5. IR thermal images obtained with Fluke Ti25 and processed with Fluke SmartView ™ software [8, 12, 13].

The Fluke SmartView™ software makes it possible to adjust the essential parameters in a picture taken off by the camera, such as emission level, reflection of the reflected temperature, color palette, etc. Lately, the development of these tools has allowed great investigation into the operation of large-scale electrical equipment's and power classes. For a high accuracy in the measurement of different electric devices' temperature, the numerical processing of the thermographic images allows also Reflected **Temperature Compensation (RTC).** This is especially important for objects with low emissivity. This is done using a correction factor introduced by the dedicated software. In most of the cases, the reflected temperature is identical with the ambient temperature [13-16].

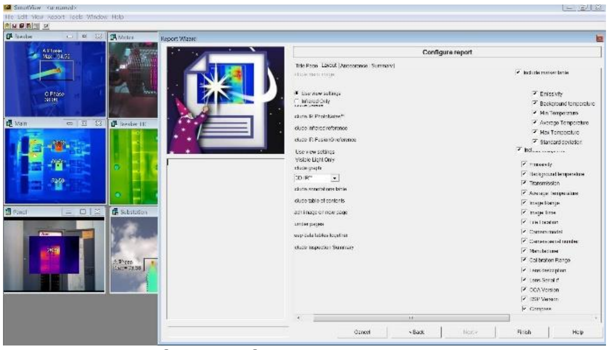


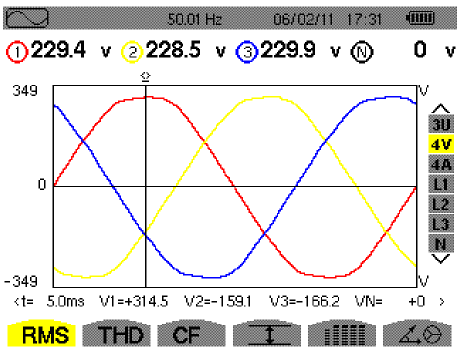
Figure 6. The format of a customized thermal inspecting report using the Fluke SmartView ™ software [5].

3. PREDICTIVE MAINTENANCE OF A POWER DISTRIBUTION TRANSFORMER

The electric energy of an industrial facility with a continuous production processes is supplied by a three-phase power distribution transformer of S_n = 1000 kVA and voltage steps U_{1n}/U_{2n} = 6/0.4 kV - Figure 7. The machine rated data are indicated in the Appendix.

Figure 7. The investigated transformer.

The main power quality parameters at the transformer are measured at the machine secondary part (low-voltage windings) with a C.A 8335 Qualistar Plus power quality analyzer [9]. The most import of them are: root mean square (RMS), Total Harmonic Distortion (THD), distorsion factor (DF), crest factor (CF) and Harmonic loss factor (KF) and voltage flicker (PLS) [17-19]. According to their values, presented in Figure 9, the transformer operates under normal condition



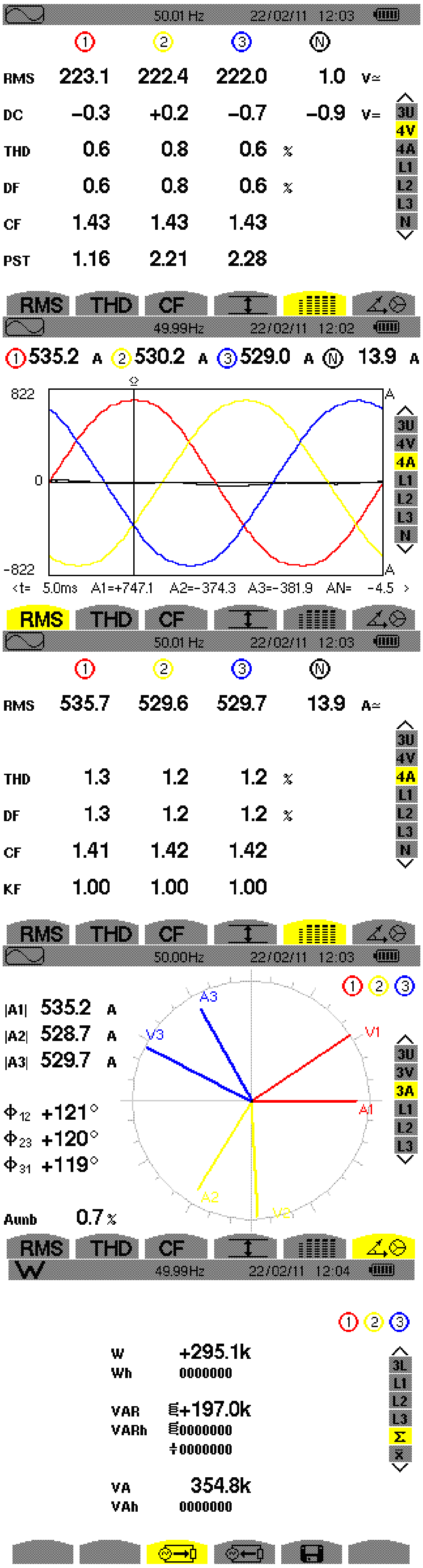


Figure 8. The main power quality parameters measured at the low-voltage side of the investigated transformer.

The available measured data allows the evaluation of the transformer load.

$$\beta = \frac{S}{S_n} \approx \frac{I_2}{I_{2n}} = \frac{535.7}{1443.37} = 0.37. \quad (4)$$

The losses of active and reactive power in the transformer as well as of the active and reactive absorbed powers from the network are determined with the relations [11]:

$$\begin{aligned} \Delta P_T &= \Delta P_0 + \beta^2 \Delta P_{sc} = \\ &= 2.3 + 16 \cdot (0.37)^2 = 4.49 \text{ kW}, \\ \Delta Q_T &= \Delta Q_0 + \beta^2 \Delta Q_{sc} = \\ &= 13 + 60 \cdot (0.37)^2 = 21.21 \text{ kVAr}, \end{aligned} \quad (5)$$

with:

$$\begin{aligned} \Delta Q_0 &= \frac{i_0}{100} \cdot S_n = \frac{1.3}{100} \cdot 1000 = 13 \text{ kVAr}, \\ \Delta Q_{sc} &= \frac{u_{sc}}{100} \cdot S_n = \frac{6}{100} \cdot 1000 = 60 \text{ kVAr}. \end{aligned} \quad (6)$$

The absorbed from the network active P_1 and reactive power Q_1 are to be evaluated in terms of the secondary winding measure active P_2 and reactive Q_2 powers respectively and the above computed losses:

$$\begin{aligned} P_1 &= P_2 + \Delta P_T = 295.1 + 4.49 = 299.59 \text{ kW}, \\ Q_1 &= Q_2 + \Delta Q_T = 197 + 21.21 = 218.21 \text{ kVAr}. \end{aligned} \quad (7)$$

The variation of active and reactive power losses with the transformer load factor are indicated in Figure 9 and Figure 10 respectively, while Figure 11 represents the corresponding Sankey diagrams [11].

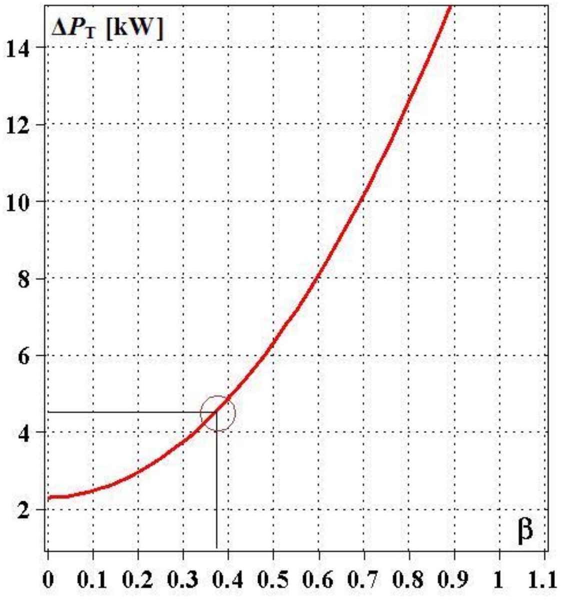


Figure 9. The variation of active power losses with the load factor β.

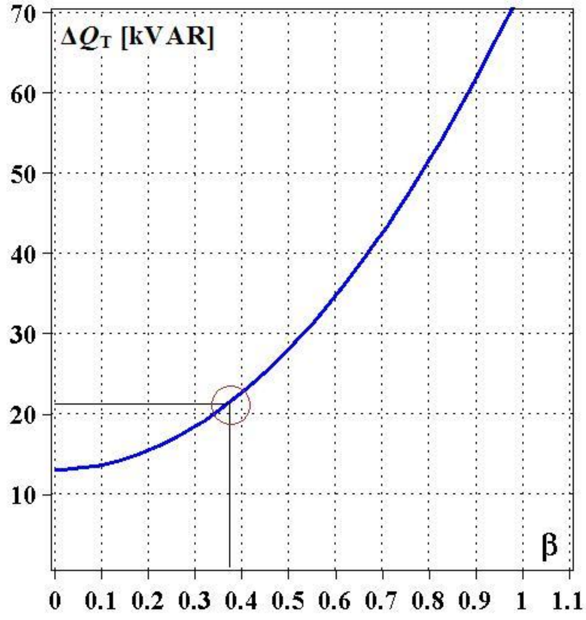


Figure 10. The variation of reactive power losses with the load factor β.

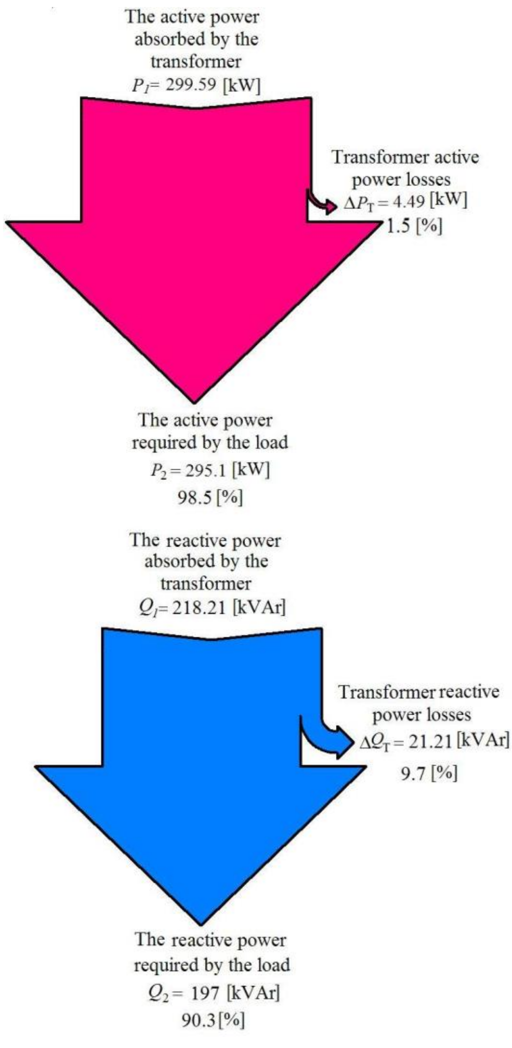
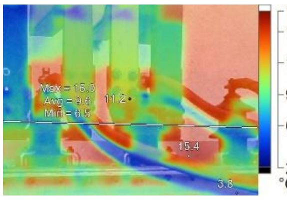
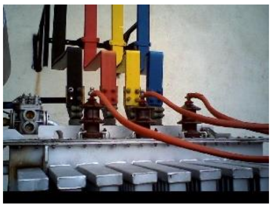


Figure 11. Sankey diagrams for the circulated active and reactive power

To better illustrate the aspects outlined above, in the next section will be presented various thermal images of different electric part of the analyzed transformer and its main electric panel. They are obtained with the professional Fluke Ti25 thermal imaging camera [7, 8]. Using the SmartView™ software provided by the manufacturer some remarks could be made regarding the thermal regime, the maximum temperatures and the temperatures of the equipment surround area.

3.1 Thermal demand of low voltage cables for Transformer





Transformer connectors *Visible Light Image*

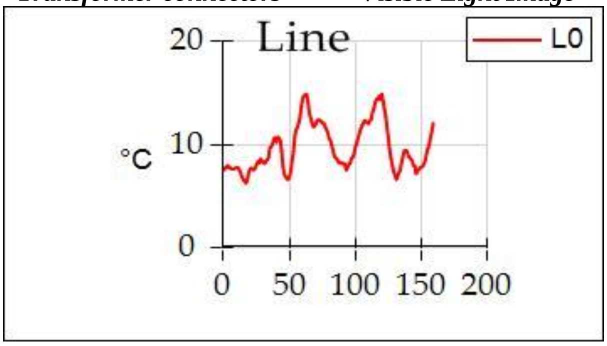


Image Info

Background Temperature	19.0°C
Emissivity	0.95
Average Temperature	10.3°C
Image Range	3.8°C to 15.4°C
Camera Model	Ti25
Camera Serial Number	Ti25-08120648
DSP Version	1.2.7
OCA Version	1.2.7.0
Manufacturer	Fluke
Lens Description	20mm
Lens Serial Number	-
Image Time	1/20/2011 12:39:19 PM
File Location	C:\ Transformer\ IR000253.IS2
Calibration Range	-22.0°C to 125.0°C

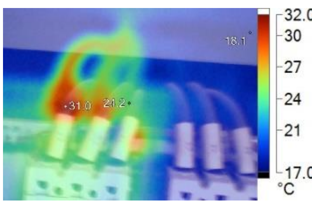
Main Image Markers

Name	L0
Avg.	9.6°C
Min.	6.5°C
Max.	15.0°C
Emissivity	0.95
Background	19.0°C
St.Dev.	2.46

Name	Centre point	Hot	Cold
Temperature	11.2°C	15.4°C	3.8°C
Emissivity	0.95	0.95	0.95
Background	19.0°C	19.0°C	19.0°C

One can notice that connectors of and the surrounding components of the transformer have normal temperatures, that are lower than 40° C. The cables from the primary and secondary winding of the transformer have also normal temperatures.

3.2 Protecting equipment of the transformer – Contactors from the general electric cabinet



Contactors *Visible Light Image*

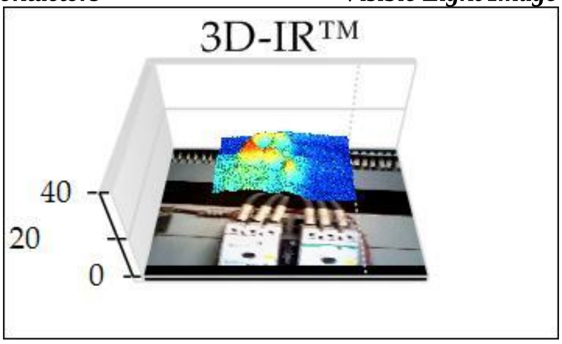


Image Info

Background Temperature	19.0°C
Emissivity	0.95
Average Temperature	21.6°C
Image Range	18.1°C to 31.0°C
Camera Model	Ti25
Camera Serial Number	Ti25-08120648
DSP Version	1.2.7
OCA Version	1.2.7.0
Manufacturer	Fluke
Lens Description	20mm
Lens Serial Number	-
Image Time	1/20/2011 12:13:03 PM
File Location	C:\ Transformer\ IR000243.IS2
Calibration Range	-22.0°C to 125.0°C

Main Image Markers

Name	Centrepoint	Hot	Cold
Temperature	24.2°C	31.0°C	18.1°C
Emissivity	0.95	0.95	0.95
Background	19.0°C	19.0°C	19.0°C

It is also easy to remark that the temperatures of the operating contactors lies within the acceptable limits.

Many similar pictures and data are being taken with a portable inferred camera obtaining an non invasive and efficient thermal map of the equipment. They could signal the potential problems that usually fail from a classical maintenance procedure (visual, electric and mechanical inspections).

4. CONCLUSIONS

Proactive or predictive maintenance of the electric components from different electric installations becomes mandatory to preserve the equipment's' operating parameters under their rated values. Additionally, the whole cost of the retrofitting action is to be considerable diminished due to the predictive maintenance by avoiding failure of major (very expensive) devices such transformers. The paper outlines the main proactive maintenance requirements and focuses on one of its components: periodical thermal inspection. Thermal imaging has major advantages over many other thermal stress diagnosis techniques because thermal scanning does not require direct contact with the test equipment or installation. Flaws, operating problems and the disposition to failure are detected quickly without stopping the operation. Thermal scanning is a non-invasive procedure and can be repeated whenever is needed. The inspection is done quickly; it's a safe procedure and provides a detailed thermal analysis with high measurement accuracy. Thermal imaging analysis allows recording, storage, evaluation and electronic processing of data from inspected equipment / installations. Due to its benefits and widespread applicability in the industrial field, the global energy regulatory bodies are beginning to require the use of predictive maintenance thermography as a condition for energy auditing. The procedure of investigating in-service operating equipment is illustrated on the oil-type 1000 kVA transformer that serves an industrial facility.

5. APPENDIX

The main parameters of the inspected transformer are presented in Table 1.

Table 1. Technical data of the analysed transformer

Transformer data	Value
Rated power (*Sn*)	1000 kVA
Rated voltage from the primary winding (U_{1n})	6 kV
Rated voltage from the secondary winding (U_{2n})	0.4 KV
Rated current in the primary winding (I_{1n})	96.225 A
Rated current in the secondary winding (I_{2n})	1443.37 A
Transformer vector group	Dy05
No load power losses (P_0)	2.3 kW
Rated short-circuit losses (P_{sc})	16 KW
The magnetizing current (i_0)	1.3 %
The short-circuit voltage (u_{sc})	6 %

6. ACKNOWLEDGMENTS

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