Preventive Thermographic Diagnostic of a HV Busbar Disconnector

Predrag Šaraba, Zoran Ljuboje, Božidar Popović and Dražan Krsmanović

***Abstract* — For the purpose of increasing quality, continuity and, at the same time, of increasing reliability and decreasing the losses in an electric power system (EPS), there is an emerging need for preventive diagnostic testing. From the standpoint of an electric power system availability, it is desirable to perform as many tests as possible without a violation of operating conditions of the system itself. The paper presents the thermographic testing of a HV disconnector, as an online testing with the aim of preventive maintenance and condition diagnosis of particular elements, as well as the suggestions for taking adequate measures with the aim of removing potential malfunctions.**

For the testing results to be quality and to give a reliable information, the load of a facility must be bigger that 50% of the nominal power. On the basis of obtained thermograms, the analysis of the disconnector and its contacts is performed, as well as of the contacts towards other elements in the facility.

Key words*: *Paper - thermography, diagnostics, disconnector, availability, preventive.

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I. Introduction

Electric energy consumers require a reliable and quality electric energy supply, and, at the same time, it is the basic requirement imposed to an electric power system (EPS). The operation reliability of an EPS largely depends on the condition (characteristics, age, functionality) of high voltage equipment, due to the fact that the characteristics of high voltage equipment change during exploitation because of different factors. The age and exploitation time also affect the reliability and availability of and EPS. For this purpose, it is necessary to perform the so-called high voltage condition evaluation. The evaluation can be performed on the basis of tests performed in voltage-free conditions (off-line) and the tests which do not require voltage-free conditions (on-line). From the standpoints of efficiency, availability and economy, on-line methods for high voltage equipment evaluation are preferred. Although these methods are less reliable, their application gives an overview on equipment condition pursuant to which preventive activities can be defines and decisions made for taking service activities or additional tests.

A facility in an EPS loses its defined characteristics and functionality during exploitation, what is a consequence of influence of operating conditions, environment and aging during the life cycle. All the facilities and their elements have a lifetime, and they are expected to work within it in accordance with the indicated characteristics, without a greater number of stoppages and cancellations. The function of cancelation intensity change $\lambda(t)$ in time, i.e. the number of cancellations in plants during a life cycle is shown in Figure 1. In practice, the dependence has the form as in the figure, where three areas can be singled out: the area of early cancellations in the period of equipment exploitation after the plant has been put into operation (I), the area of normal exploitation where the number of cancellations is small and relatively constant (II), and, at the end of the life cycle, the area with the increased number of cancellations which occur because of the age of the observed element (III). By aging, the equipment gradually loses its characteristics and properties, so its cancellation occurs more often, and that affects the decrease of availability, facility reliability, and increase of maintenance costs. To act preventively with the aim to eliminate such phenomena, preventive and regular maintenance is performed. [1]

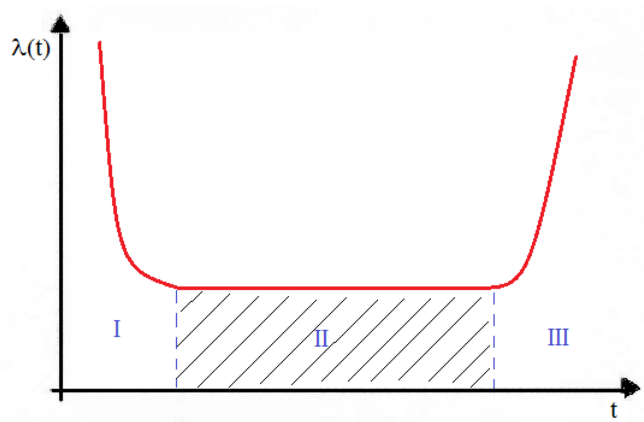

Figure 1. Function of cancellation intensity of an electric power system element.

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Thermographic testing presents a diagnostic on-line testing which is becoming largely applied in monitoring and diagnostics of high voltage plants elements. The problems which occur at the end of a thermographic testing are related to determining of a deadline for servicing the equipment where temperature anomalies have been noticed. Observed in the long term, the temperature anomalies (dissipation) can be used as the indicators of exploited equipment quality, as well as of performed service operations. On the basis of dissipation and features of tested equipment, a decision can be made regarding the service, repair or replacement of each particular element. [2]

II. Physical Properties Of Thermography

Thermography presents the recording of thermal differences in different objects by means of thermographic cameras. This recording registers thermal radiation, and in that an image is converted into the visible part of spectrum. This recording does not require any additional lighting, i.e. the objects invisible to a human eye can be recorded.

When a body heats to a certain temperature, it emits a thermal radiation in the form of electromagnetic waves. Solids and liquids emit a continuous spectrum of electromagnetic waves, and gases emit a discrete or line spectrum. Also, the bodies reflect and absorb the electromagnetic radiation which falls on them.

If a body, at a certain temperature on a given wavelength emits a radiation to a certain degree, the same radiation will be absorbed in the same conditions and to the same degree. If the body completely absorbs the radiation, then it presents the *absolutely black body.*

Let us define the *integral emission capacity* (E_T) which presents a *power flux density*, i.e. the energy emitted by a body heated to the temperature T in the time unit from the surface unit.

If only a small part is extracted from the power flux density, $dE_{\lambda,T}$ i.e. $dE_{\omega,T}$ which is emitted in the wavelength $d\lambda$, that is in the frequency range $d\omega$, we can write that $dE_{\lambda,T} = e_{\lambda,T} d\lambda$, or $dE_{\omega,T} = e_{\omega,T} d\omega$, where the unit $e_{\lambda,T}$, i.e. $e_{\omega,T}$ presents a *monochromatic emissivity* or the so-called *emission capacity.* It follows that:

$$E_T = \int_0^\infty e_{\omega,T} d\omega \tag{1}$$

On the basis of experiments and theoretic calculations in the second half of the 19th century, Stefan-Boltzmann law has been defined:

$$E_T = \sigma T^4 \tag{2}$$

where σ - is *the Stefan-Boltzmann constant* and T is *temperature*.

The experiments have shown that the relation of emissivity and absorptivity is equal and given by the universal Kirchhoff function, i.e. $f(\omega,T) = (e_{\omega,T}) / (a_{\omega,T})$. Because for the absolutely black body the absorptivity is $a_{\omega,T} = 1$, it follows that for the absolutely black body monochromatic emissivity is equal to the universal Kirchhoff function $f(\omega,T) = (e_{\omega,T})_{a.c.t}$. In calculations, it is more suitable to use the Kirchhoff function dependant on frequency $f(\omega,T)$ while in experiments it is more suitable to use the function of wavelength $\varphi(\lambda,T)$. Figure 2 presents an example of experimental results of emissivity of the absolutely black body.

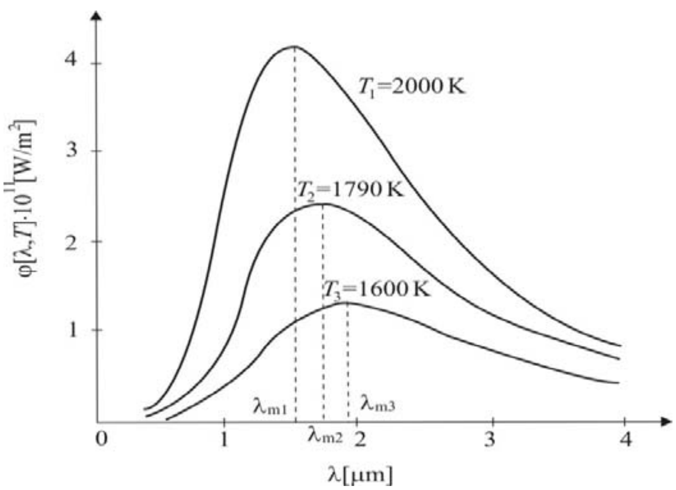

Figure 2. Dependance of emissivity on wavelength for differernt values of temperature.

Among the others, the results in Figure 2 show that with the increase of temperature the maximum of curves moves right, That is defined by the so-called Wien's law: $\lambda_m T = b$, where b is the constant, i.e. Wien's law can be given in the form:

$$\lambda_{\max} = \frac{2898}{T} [\mu m] \tag{3}$$

The explanation of the results in Figure 2, including Wien's law, by using the equation (1) stating that $f(\omega,T) = (e_{\omega,T})_{a.c.t}$ could not be given with the laws of classical physics. On the basis of laws of classical thermodynamics, Rayleigh and Jeans have come to the form of function

$$f(\omega,T) = \frac{\omega^2}{4\pi^2 c^2} kT. \tag{4}$$

The solution from (1) gives the result known as the ultraviolet catastrophe, because it is completely wrong in the ultraviolet part of the spectrum (Figure 3).

In 1900, Max Planck solved the problem with a new theory stating that electromagnetic waves are emitted in the form of electromagnetic quanta of energy, where the value of quantum energy is proportional to the frequency of radiation:

$$\varepsilon = h\nu = \hbar\omega \tag{5}$$

where $\hbar$ is Planck constant. Planck obtained the function given by the expression:

$$f\left(\omega,T\right)=\frac{1}{4\pi^{2}c^{2}}\frac{\hbar\omega^{3}}{e^{\frac{\hbar\omega}{kT}}-1}. \tag{6}$$

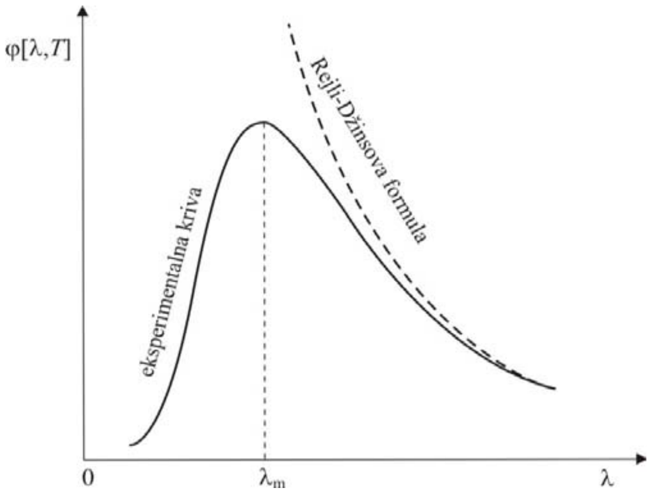

Figure 3. Experimental and Rayleigh-Jeans result

By including this function in the expression (1), solutions are obtained confirming the experimental results (2) and (3).

III. THERMOGRAPHY

A. Operation principle of thermography

Thermographic testing is based on contactless measurement of surface temperatures. The testing is based on the fact that an object which has a temperature above the temperature of absolute zero emits a thermal radiation of spectral band (>0,7 μm). The named radiation becomes visible for a human eye if the body reaches the temperature in the range from 500÷550ºC. Thermographic camera detects the radiations emitted by the heated object and presents it in the form of a thermogram. [2]

Thermographic testing can record the temperature distribution at the visible part of the tested object surface. For the testing results to be quality and offer a reliable information, the load of a facility must be bigger than 50% of nominal power. It is recommended to perform a thermographic testing in cloudy weather, because if the weather is sunny, a reflection may occur because of which the measurement is not useful. It should be taken into account not to neglect the influence of wind which can significantly cool down the place of a potential malfunction, the influence of dust and humidity which absorb the part of the infrared spectrum. [3], [4].

Thermographic testing is performed with the measurement method which is called the method of comparison. The method of comparison is based on the temperature comparison of elements with the same element of another phase under the same load. In a measurement, it is necessary to determine the place of referent temperature, environmental temperature, as well as the current for all three phases. The deviation of the measured temperature from the referent one indicates the malfunction of an object. The temperature excess is determined as the difference between the measured and referent temperature of the place of temperature increase on the object. The attention should be paid to whether the place of operating temperature is of the same material as the place of temperature increase for the emissivity factor to be approximately equal. Thermographic testing is performed on the visible parts of tested elements. There are numerous advantages of using thermographic tests: [5]

- testing is performed during the plant operation,
- availability of the plant is increased,
- malfunction of equipment is located precisely in an early phase,
- unnecessary servicing is avoided,
- repair time is shortened,
- maintenance is improved,
- maintenance costs in the exploitation period are decreased,
- correct determination of control deadlines decreases the number of bigger malfunctions,
- number of plant outages is minimized,
- energy supply quality is increased and losses decreased.

B. Equipment for thermographic testing and thermogram processing

For the needs of electric power plants testing, the cameras of the producer FLIR have been used, models ThermaCAM PM 675 and E40.

Thermographic camera forms a thermal image by measuring the infrared radiation of a certain body or area part.The software, contained by the camera, performs the correction at the conversion of thermal image to an adequate thermogram, which presents the approximation of the exact temperature of the recorded object or the temperature distribution in the area.

The camera measurement range is from -40÷120ºC (range 1), from 80÷500ºC (range 2). The camera accuracy is ±2 % of reading. The permitted operating temperature of the environment is from -15÷50ºC. The measurement is performed pursuant to the manufacturer’s instruction. [6]

FLIR R&D Software 3.3. has been used for the analysis of the obtained thermograms, having the possibility to control the regime of recording the thermograms, setting of conditions regarding the temperature (min, max) of particular zones on a thermogram, warning of an user on the exceeding of set conditions and generating of reports for the selected thermogram. Figure 4 presents the operating environment of the application. [7]

IV. DISCONNECTORS AND THEIR MAINTENANCE

The basic task of disconnectors is a visible and contact separation of a part of a high voltage plant, which is in voltage condition, from the network. The ability to conduct a current in a primary cycle is crucial for the reliability of a high voltage disconnector, and that is violated with the appearance of “bad” connections, contacts and other primary cycle points in which a heating occurs increasing the probability that a damage of disconnector itself will occur together with the interruption of supply for consumers. The named defects are removed by periodic

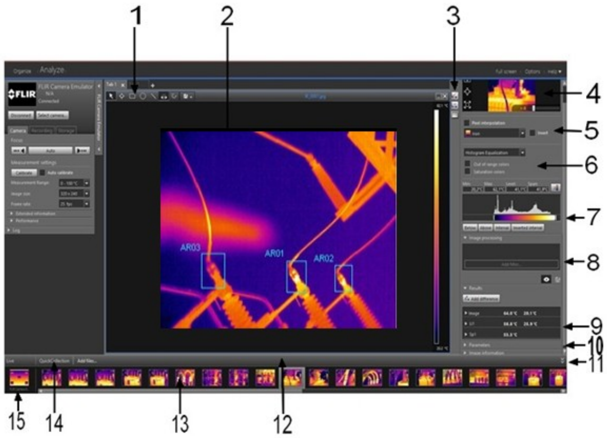

Figure 4. Operating environment of FLIR R&D Software 3.3.

1. *Measurement toolbar*: selection of points or areas for which a thermogram is analysed.
2. *Image window*: overview of a thermogram.
3. *Image Window:* selection of a thermogram, graphs and tables with measurement parameters.
4.-7. *Zoom, Controls, (Pixel interpolation, Color palette, Invert color palette), Image enhancements pane (Histogram equalization, Plateau equalization, Signal Linear, Temperature Linear, Digital Detail Enhancement), Scale pane:* options for setting a thermogram.
8. *Image processing pane*: selection of filters for processing
9. *Results pane*: overview results of all measurements
10. *Display parameters*: focus, calibration, measurement range…
11.-15. *Button, Recording toolbar, Recording snapshot location, Quick Collection pane, Live source control:* management of files.

diagnostic testing and regular maintenance [8]. At the service of a disconnector, it is necessary to disassemble both contact places of disconnectors, clear them properly and lubricate the bearings. The testing of the main current cycles includes the measurement of voltage drops at a disconnector, which must not be higher than the allowed ones. If the voltage drops are too high it is necessary to localize the place of malfunction by moving the current and voltage connectors and repair the places of bad connections.

V. Analysis Of Thermographic Testing

The testing was performed in the transformer substations which belong to the Field Unit (FU) Višegrad. These were TS 400/220/110/35/10 kV Višegrad, FU 110/35/20/10 kV Goražde 1, FU 110/20/10 kV Goražde 2, FU 110/35/10 kV Sokolac, FU 110/35/10 kV Rogatica and FU 110/35/10 kV Foča. The recordings were performed at the distance of 5m from the observed object, and the average emissivity was 0.95. The results present the cases where an increased heating of disconnectors and their belonging contacts occurs.

On the basis of the recording from 2014, the heating at the busbar disconnector F0 at the transmission line TL 110 kV Goražde 2 was noticed in the FU 110/35/20/10 kV Goražde 1. The thermogram of this disconnector is shown in Figure 5.

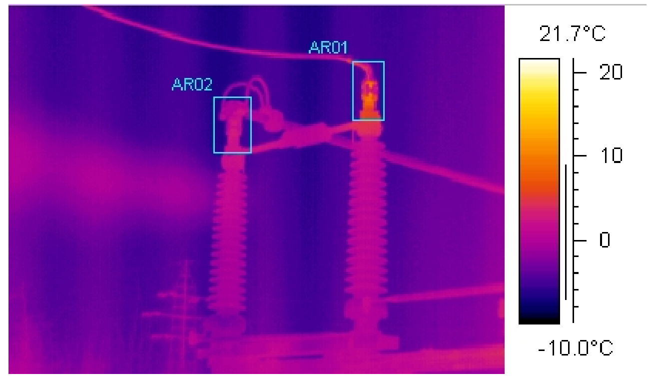

Figure 5. Thermogram of the busbar disconnector F0 in TL 110 kV Goražde 2 in the FU 110/35/20/10 kV Goražde 1

During the recording, the environmental temperature was -3 ^{0}C, and the air humidity was 74% RH. The current per a phase was 100 A. The analysis showed the heating at the contact to the busbar (AR01 area in Figure 5). The temperature was 10.6°C. When it is compared to the environmental temperature and other (AR01, temperature 6 °C), it can be concluded that the heating occurs at the contacts to the busbar and the repairing of the heating place is recommended. After thermographic recordings and noticed heating, the repairing of the heating place was performed. Before the repairing, the voltage drop of 204mV had been measured at the heating place, and after the performed repairing it was 10.25mΩ.

The next heating was noticed at the busbar disconnector in the transmission line TL 110 kV Goražde 2 was noticed in the FU 110/35/20/10 kV Goražde 1. At During the recording, the environmental temperature was -3 ^{0}C, and the air humidity was 74% RH. The thermogram of this disconnector is shown in Figure 6.

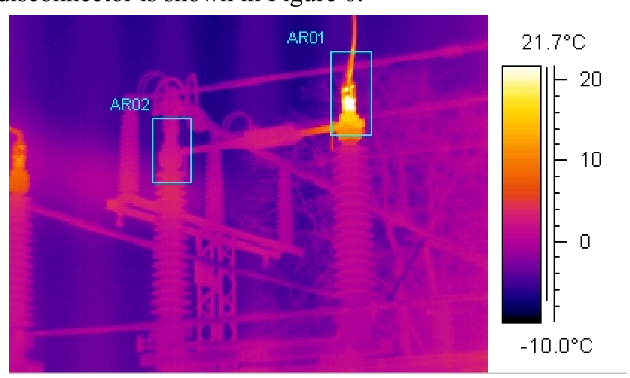

Figure 6. Thermogram of the busbar disconnector F4 in TL 110 kV Goražde 2 in the FU 110/35/20/10 kV Goražde 1

During the recording, .the current per a phase was 100 A. By a detailed analysis of thermogram, an increased heating can be noticed at the contacts to the busbar (AR01). The temperature of a contact was 31.2°C, while by the comparison to the contact on the other disconnector, where the temperature was 7°C, it can be concluded that an increased heating occurs at the contacts between disconnectors and busbars. During the repairing, the voltage drop of 316 mV had been measured at the heating place, while after the removal of the named defect the voltage drop at the contact was 11.35 mV.

During the testing in 2015, the heating on particular disconnectors was noticed in the FU 110/20/10 kV Goražde 2. The analysis of the thermogram showed the heating at the busbar disconnector F0 in the transmission line field transmission line (TL) 110 kV Višegrad. The thermogram of this disconnector is shown in Figure 7.

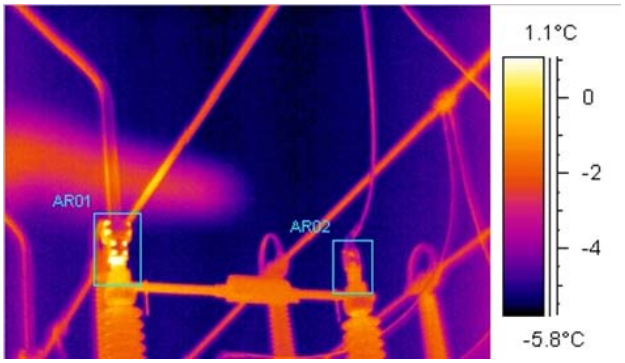

Figure 7. Disconnector F0 in TL 110 kV Višegrad in the FU 110/20/10 kV Goražde 2

During the recording, the environmental temperature was -4°C, and the air humidity was 66% RH. At this part of the facility, the current per phase was 103 A. On the basis of the analysis of the thermogram, it can be seen that there is an increased heating at the contact of the disconnector towards the switch (AR01). The temperature of the contact was 5.8°C. After the heating had been noticed, the repairing of the contact was performed. During that, a voltage drop of 98.8 mV had been measured at the contact. After the repairing (cleaning and tightening of connections), the voltage drop at the same place was 13.1 mV.

The heating at the busbar disconnectors F0 and F4 in the transmission line TL 110 kV Goražde 1 was noticed. The thermograph of this disconnector is shown in Figure 8.

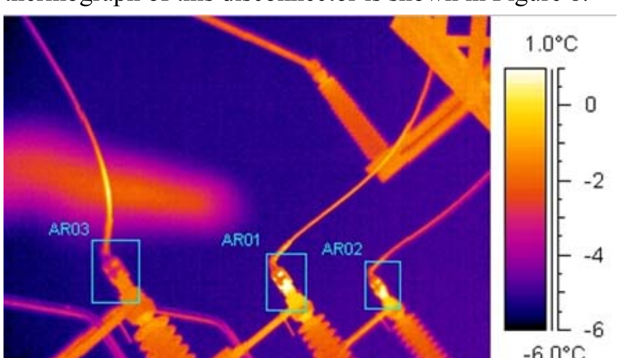

Figure 8. Thermogram of the disconenctor F0 and F4 in TL 110 kV Goražde 1 in the FU 110/20/10 kV Goražde 2

During the recording in this part of the plant, the current per phase was 100 A. The thermogram showed the heating at the contacts of the disconnectors towards the busbar (AR01 and AR02). The temperature of the heated contacts was 1.6°C (AR01), 1.1°C (AR02). During the repairing of the contacts, a voltage drop of 87.5 mV(AR01) and 84.3 mV (AR02) had been measured. After the repairing (tightening of the connections), the voltage drop was 2.01 mV and 1.94 mV.

At the Figure 9 shown thermogram of the disconenctor F8 in TL 110 kV Višegrad in the FU 110/10/35 Rogatica.

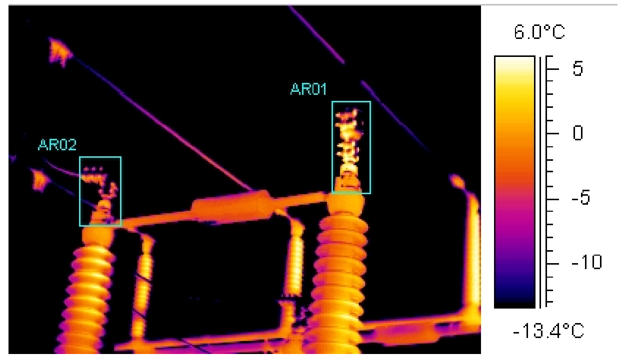

Figure 9. Thermogram of the disconenctor F8 in TL 110 kV Višegrad in the FU 110/10/35 Rogatica

During the recording, the environmental temperature was -9°C, and the air humidity was 38% RH. The current per a phase was 85 A. The analysis showed the heating at the contact to the busbar (AR01 area in Figure 9). The temperature was 7.1°C. When it is compared to the environmental temperature and other (AR01, temperature 1.3°C), it can be concluded that the heating occurs at the contacts to the busbar and the repairing of the heating place is recommended. After thermographic recordings and noticed heating, the repairing of the heating place was performed. Before the repairing, the voltage drop of 256mV had been measured at the heating place, and after the performed repairing it was 2.51mΩ.

The heating at the busbar disconnector F0 in the the transformer field 1, 110 kV in the FU 110/10/35 kV Foča was noticed. The thermograph of this disconnector is shown in Figure 10.

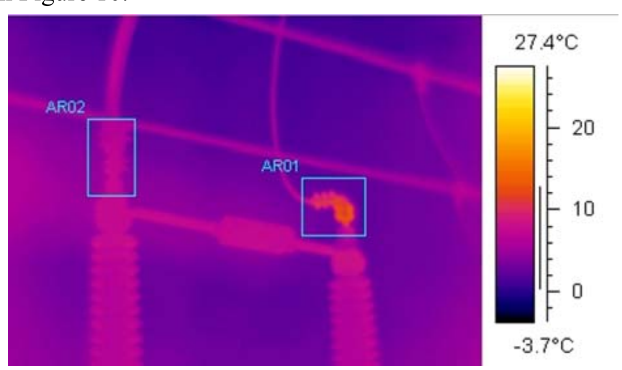

Figure 10. Thermogram of the disconnector F0 in the transformer field 1, 110 kV in the FU 110/10/35 kV Foča

During the recording, the environmental temperature was 5°C, and the air humidity was 75% RH. The current per a phase was 30 A..By the analysis of the thermogram at the contact of the disconnector towards the busbar, the temperature of 13.3°C was measured. If it is compared to the environmental temperature, it is concluded that an increased heating occurs at this contact and is recommended to repair the contact to prevent a bigger heating. At the repairing of the contact, the voltage drop of 127.8 mV had been measured. After the repairing (tightening of the contact) it was 2.14 mV.

VI. CONCLUSION

The application of thermograph as one of the methods in the monitoring of distribution facilities has an increasing significance in the world. The advantage of this method is the fact that a facility is in the operating regime during the testing. By a detailed analysis of thermograms, the heating places can be noticed which may lead to serious damaging of elements in the facility. So, this analysis can locate precisely the elements, contacts which can cause interruptions and outages of the entire facility or its part and thus significantly decrease the availability and reliability. By a precise locating and identification of critical places, interventions can be done promptly and efficiently.

It is noticeable that the heating mostly occur at the contacts of the disconnector, at the contacts of the disconnector towards the switch and busbar, what is manifested by the heating of contacts to the temperatures which significantly deviate from the environmental temperature. The cause of this heating is a big transitional resistance of contacts which can be caused by the oxidation of contacts or bad connections.

To decrease the phenomena, it is necessary to perform regularly the preventive thermographic control (minimally once a year), so that the points in which the temperature increased, possibly leading to the damaging of elements or the entire facility, which may cause a significant material and financial damage both for the producer and the consumer, can be noticed in time.

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