

Review

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Review Paper

Thermographic Measurements in Electrical Power Engineering—Discussion on How to Interpret the Results

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Abstract: An important issue concerning the inspection of the technical condition of electrical power components and systems is thermal imaging investigation. This paper presents how the thermograms obtained from these measurements should be interpreted correctly according different standards and how operators should react when a specific anomaly is detected. It is also a review article in which all currently applicable international standards are referred to. The motivation of the article relates to the fact that these standards seems to be too general and not cover all practical situations even though in many countries thermal imaging diagnostics of overhead lines or overhead outdoor and indoor power stations has been used for years on the basis of industry standards or good practices. The purpose of writing this article is precisely to encourage and provoke the global community of metrologists, scientists and engineers involved in thermographic measurements to discuss, strengthen efforts and establish relevant international standards for the interpretation of thermograms containing the relevant temperature anomalies.

Keywords: electrical power system; thermographic measurements; standards in thermovision measurements; thermographic diagnostic; interpretation of thermograms

1. Introduction

Wherever any cause generates heat, thermal imaging measurements become an indispensable diagnostic tool [1–4]. Thermal imaging can be effective method for tracking various processes whose course is associated with changes in emissivity or temperature over time or with variations in the thermal images of individual objects [5,6]. To assess, for example, the type of damage in electrical installation on the basis of thermograms, it is additionally necessary to carry out numerous tests and comparative analyses. A comparison with X-ray methods comes to mind here, where, without being a specialist, it is not possible to properly interpret an X-ray image. In the field of thermal imaging measurements, as in X-ray, specialization is also required, taking into account the characteristics of the individual fields of application and the ability to perform examination, and interpret correctly the results [7,8].

In general, it can be said that thermal imaging measurements in power engineering among others, are used for [9]:

- detection of cracks and material inhomogeneities,
- detection of thermal bridges in the insulation of electric furnaces, overheating points due to damage to the insulation of chamber furnaces, continuous furnaces, melting furnaces, dryers, boilers and pipelines,
- testing of internal combustion engines and turbines,
- wind turbines integrity testing,

- tests on electroenergetics elements to determine heat distribution and assess the components cooling conditions [1,2],
 - surveillance of operation and detection of overheating points on rotating machinery and equipment, bearings, gears, shafts, couplings, drive belts, chains, conveyors, compressors, pumps [3,4],
 - detection of overheating points in electrical equipment and installations, such as fuses, contacts, switches, overhead and cable lines, substations, transformers, thyristors, motors, insulators, electrical circuits [10–12],
 - testing photovoltaic panels and installations [13].
 - In the process of inspecting and assessing the condition of power line components, thermal imaging measurements can furthermore be used to, among other things:
 - detecting overloads, damage or partial ruptures of cables,
 - detection of load asymmetry,
 - detection of leakage occurring on the insulation surfaces,
 - the ongoing monitoring of the correct functioning of transformers.
- It should be noted that the lists given above is not fully exhaustive. The fault reason can be:
- insulation deterioration and aging [12],
 - surface or internal cracks,
 - external pollution,
 - excessive ambient temperature,
 - weak mechanical connection,
 - partial short circuits,
 - eddy current,
 - cooling system failure,
 - wear of electric brushes.
 - semiconductor failure (photovoltaic panels) [12].

It is not possible to include a full description of possible applications within the limited framework of this article. Some of these examples particularly related to electrical power engineering are discussed in more details below. The examples given are only a modest illustration of the area and it is to be believed that specialists in the respective fields of knowledge will be able to considerably expand the field of application of thermal imaging measurements. Furthermore, it should be emphasized that thermal imaging measurements are a complementary method to other diagnostic methods [10,11,14].

2. Discussion on Thermal Imaging Diagnostics in Electrical Power Engineering

Some examples of applications of thermographic testing in electrical power engineering are given in Figure 1. The places with increased temperature are caused by weak connection - Figure 1a,1b and 1d - or leaking effects – Figure 1c. One of the most commonly used measurements is that of connectors on 110, 220 and 400 kV transmission lines. The subjects of the tests are the lashing clamps on the immunity poles - Figure 1d - and the mid-span connectors. Thermal imaging methods can also be used to determine the location of overheating at a disconnected or pressed connection of a line wire. The use of a helicopter to fly around the line makes it possible to inspect a significant length of electric line at one time and obtain results in a relatively short time.

When applying IRT (InfraRed Thermography) to the condition monitoring and diagnostics it is strongly recommended that severity assessment criteria be established [15]. In practice no singular severity assessment criterion is universally applicable to the variety of situations needed to be considered. These criteria can be general categories that identify temperature levels, versus levels of criticality or applied to specific components. First approach is checking the measured temperature is lower or not that absolute temperature limit given in the technical documentation for tested element. It should be noted that the temperature of line components is very much influenced by atmospheric conditions changing the heat transmission between object and surroundings. For example, Figure 2 shows the effect of wind on the temperature difference between the clamp and the conductor. It can

be seen that the wind velocity has a significant effect on the temperature difference for the same current load. For example, for current load $I=500$ A and wind speed $v=7.2$ m/s, i.e. almost 26 km/h, the temperature rise can be six times lower than for no wind conditions. Another weather factor causing similar effects are rainfall or snowfall. Therefore, conclusions based on the temperature reading without taking into account other factors may lead to incorrect assessments and decisions. Furthermore, there are also other relevant factors related to the drawback of thermography like influence of emissivity of the surface of tested object on temperature readings, reflected radiation of other objects, small difference between object and ambient temperatures, air transparency decreased by fog, some contaminating gases or smokes.

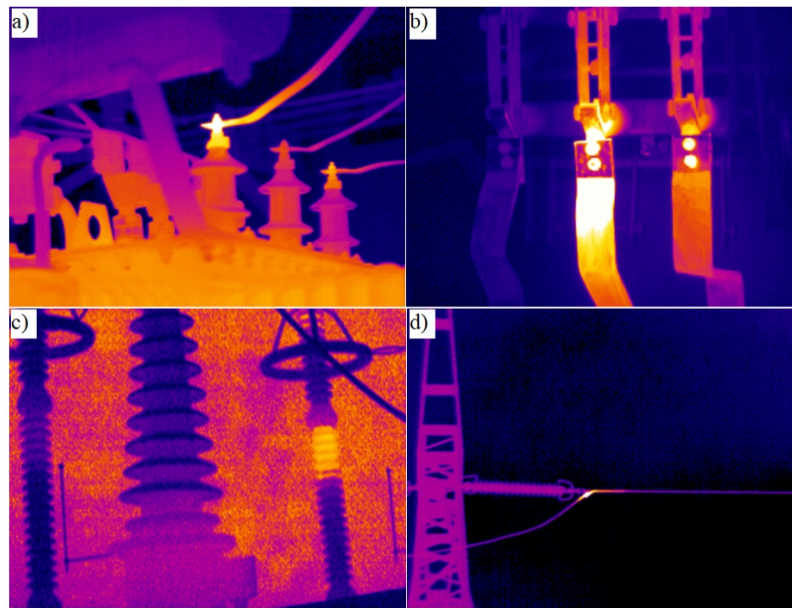


Figure 1. Overheated screw connection clamps on: **a)** transformer insulator, **b)** knife switch; **c)** location of insulation weakening point; **d)** overheating of lashing bracket on immune pole.

Thermal imaging measurements are most often used to determine the condition of an electrical wires after many years of use, when, due to ageing effects, it becomes covered with a oxide or contamination layer of relatively high emissivity. In the case of thermal imaging measurements carried out on a new line, the thermogram obtained does not fully reflect the thermal condition of its components. There are much greater differences in emissivity coefficients and stronger radiation reflections in the new elements, recorded by the camera on the thermogram. This often masks the real technical condition. This causes considerable difficulty in relying on absolute maximum permissible temperature criterion [15] due to high uncertainty of such measurement. In paper [16] ambient, rated and maximal temperatures for different material used to build the electrical components as PVC), polyethylene, silicone rubber, connectors and terminations (copper, copper alloy or aluminum), fuses, coils and relays are given and discussed.

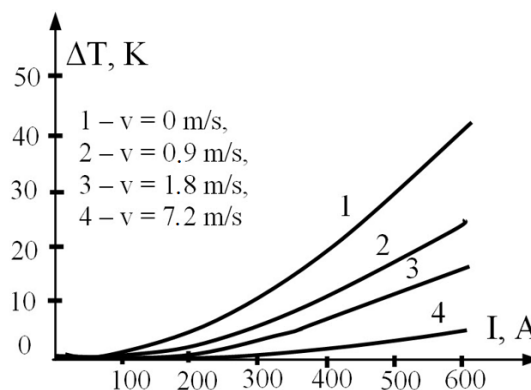


Figure 2. Dependence of the temperature difference ΔT between the wire and the clamp on the current flow at different wind speeds v , m/s [17].

Therefore, it is most often not the temperature of the power line element under test that is important, but the temperature difference between a damaged and a good element. Another solution is comparing measurement with historical data taken for the same environmental and operational conditions. Generally, these difference temperature criteria are usually reported as the temperature rise of the anomaly above the temperature of a defined reference. By taking multiple measurements of similar components over time, statistical analysis can be used to set operational limits for trending and predicting the temperature performance [15].

There will be discussed some approaches taken from published papers an standards. Practical criteria for evaluating the results of measuring the temperature differences between a good and an overheated clamp (contact or joint) are given in Table 1 [17]. Based on these criteria, it can be determined whether there is a need for immediately replacement or repair (IMM), it can be done later, for example during next scheduled maintenance (UR). Determining the line load is crucial, as the temperature rise is proportional to the square of the current rise: $\Delta T \sim (\Delta I)^2$ and high temperature can be accepted as being normal for high currents. For correct assessment we need to consider percentage of nominal current load, wind speed and registered by IR camera temperature rise. As discusses previously due to effect of object cooling by wind, for higher wind speeds the lower temperature differences are indication for technical review an maintenance. For example, for a measured temperature rise of $\Delta T=20K$ at a 40% of a rated load, if the load is twice as high - 80%, the temperature rise will be 4 times higher and will be $\Delta T=80 K$.

TABLE 1. Assessment of the need to repair clamps (contact or connection) and power line conductors [17]. abbreviations: IMM - immediately, UR – urgently.

Line load in % of nominal load	Assessing the condition of a component for need of replacement or repair							
	Wind speed < 2 m/s				Wind speed > 2 m/s			
	10 - 30 K	31 - 50 K	51 - 70 K	> 70 K	10 - 20 K	21 - 35 K	36 - 50 K	> 50 K
40 - 60	UR	IMM	IMM	IMM	UR	IMM	IMM	IMM
60 - 80	UR	IMM	IMM	IMM	UR	IMM	IMM	IMM
> 80	UR	UR	UR	IMM	UR	UR	UR	IMM

2.1. Low-Voltage Installations

Slightly different recommendations and criteria presented in Tables 2, 3, are given in the work [18]. The study assumes that the load remains constant for at least 45 minutes before measurements are taken and meantime in work [19] 15 minuts is suggested as being enough to obtain steady state and constant temperatures. The German VDE standard [20] states 15-30 min for low-voltage and 15-60 min for high-voltage oinstallations up to 20kV. As we see there exist a least few proposals on it and therefore this issue is needs further analysis and discussion.

In addition, the measurements should be carried out at the time of the highest possible current load. The measurements can not be performed if tested element is conducting a negligible current, i.e. under 20% of nominal load according to the authors [19].

Three general indications are commonly accepted, signalling the need to repair the equipment, i.e. if:

- for a symmetrical three-phase load, a temperature difference between clamps on three neighbouring phases $\Delta T > 3 K$,
- clamp and ambient temperature difference $T - T_{\circ} > 35 K$,
- clamp temperature $T > 70\text{ }^{\circ}\text{C}$.

In many situation the condition on nominal load is not met. Furthermore the temperature rise is affected by condition of heat transfer to the surroundings. These both factors are considered in work

[18] and two methods are recommended for determining the severity of overheating. To apply them, the value of the current load I of the installation must be known.

Table 2. Assessment of the need to repair the clamps and conditions of a low-voltage installation based on the calculation of the temperature rise ΔT_n for the nominal load I_n [18]. abbreviations: IMM - immediately, UR - urgently, O – observe

Fault class	ΔT_n , K	Recommendations
1	> 30	IMM
2	$5 - 30$	UR
3	< 5	O

Method 1. Table 2, is used in three-phase systems for symmetrical loading of each phase line. The measured temperature difference between the overheated and good phase ΔT , for the current load I , is converted into a temperature difference ΔT_n , corresponding to the nominal load in according to the formula:

$$\Delta T_n = \Delta T \left(\frac{I_n}{I} \right)^k \quad (1)$$

where:

$k = 1.6 \div 2.0$ - exponent depending on heat transfer conditions, i.e. weather condition: $k = 1.6$ - good, $k = 1.8$ - fairly good, $k = 2.0$ - poor heat transfer conditions.

Method 2. The second method is used in single-phase and three-phase installations when there is load asymmetry in individual phases. It can be used to determine whether the permissible temperature has been exceeded at a given clamp, for a given load I . In this case, the reference temperature is the ambient temperature T_o .

If overheating occurs in a closed switchboard (panelboard switchgear), the switchboard must be kept closed until the temperature of the overheated clamp reaches a constant value. The switchboard is then opened and the temperature of the overheated terminal is measured immediately. The measured temperature difference between the overheated phase temperature T and the ambient temperature T_o , for the current load I , is converted into a temperature difference ΔT_{on} , corresponding to the rated load I_n , according to the formula:

$$\Delta T_n = (T_n - T_{on}) = (T - T_o) \cdot \left(\frac{I_n}{I} \right)^k \quad (2)$$

where:

T, T_o - clamp and ambient temperature for the current load I , K,

T_n, T_{on} - clamp and ambient temperature for rated load I_n , K.

The permissible values of ΔT_n are specified in Table 2.

In paper [21] another, this time linear formula has been obtained for the temperature of the hot spot as a function of the current. It allows to evaluate the temperature that would be reached if the nominal current circulated through the circuit. The drawback of it is that heat conditions are not considered as previously.

2.2. High-Voltage Installations

In this case, a distinction is made between two types of clamps: shielded and uncovered. The values for permissible temperature rise are given for them in Table 3. What can be surprising in contrast to the low-voltage installations the another fault classes are defined. Instead of 3 classes only two are proposed – the last class "observe" is removed. This is justified by more difficult condition for technical inspections and finally higher costs and even fully confirmed by experience of the authors of this manuscript conducting this kind of inspections for power transmission lines in Poland.

Table 3. Assessment of the need to repair clamps and conductors of high-voltage power lines based on the calculation of the temperature rise ΔT_n for the rated load I_n [18]. abbreviations: UR - urgently, NSSI – during the next scheduled service inspection

Fault class	Shielded connection		Exposed connection	
	$\Delta T_n, K$	Recommendations	$\Delta T_n, K$	Recommendations
1	> 3	UR	> 20	UR
2	1 – 3	NSSI	< 20	NSSI

Example

Let us consider the measurement situation shown in Figure 3. We will test the middle phase as its temperature is much higher than right-side reference pahase. According to equation (1), let us assume the most unfavorable value of $k = 2$ - bad heat transfer conditions and that:

- there is a 50 % load on each phase

$$\Delta T_n = (69.1 - 52.0) \left(\frac{1}{0.5} \right)^2 = 68.4 \text{ K}$$

Considering the values given in Table II, the result obtained indicates that repairs should be carried out immediately ‘IMM’.

- there is a 100 % load on each phase

$$\Delta T_n = (69.1 - 52.0) \left(\frac{1}{1} \right)^2 = 17.1 \text{ K}$$

Considering the values given in Table II, the result obtained indicates that repairs should be carried out urgently ‘UR’.

- there is a 200 % load on each phase

$$\Delta T_n = (69.1 - 52.0) \left(\frac{1}{2} \right)^2 = 4.3 \text{ K}$$

Considering the values given in Table 2, the result obtained already indicates the need to observe ‘O’ for this pair of electrical wires.

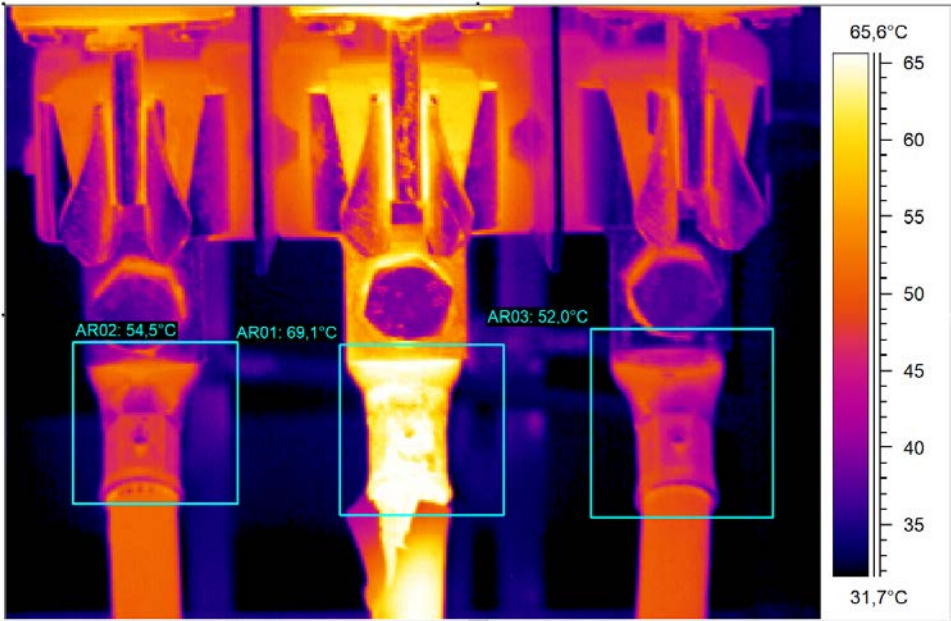


Figure 3. Thermogram showing mid-phase superheating.

For low- and high-voltage installations, certain deviations from the values of permissible temperature increases ΔT_n indicated in Tables 1, 2, 3 are acceptable as fitted to the technical and financial circumstances. These factors are the possibility of obtaining higher loads (which is associated with an increase in the temperature of the junction), the technical and organizational feasibility of shutting down the field (daily service operations, weather conditions), financial consequences of failure or shutdown for maintenance. As stated in the introduction, the main purpose of this article is to encourage discussion with a view to developing relevant international standards for the interpretation of thermograms obtained from thermovision measurements and how operators should react when a specific anomaly is detected. This is because it appears that the guidelines in this respect given, for example, in other standards as an example provided in [22] - Table 4, seems to be really insufficient and not covering real life occurring situations. The most questionable seems to making decision on criterion with low temperature levels as 1-3 K presented in Tables 3 and 4. The measurements of so low differences is difficult with high uncertainty due to limited accuracy of IR camera, comparison to reference object working in the same conditions and load. The key issue, as mentioned in the standard itself, are qualifications of the person performing the electrical inspection that must be thoroughly trained and experienced concerning the apparatus and systems being evaluated as well as knowledgeable of thermographic methodology [22].

Table 4. Suggested actions suggested by the American National Standards Institute based on temperature rise [22].

Temperature difference ΔT based on comparisons between similar components under similar loading	Temperature difference ΔT based upon comparisons between component and ambient air temperatures	Recommended action
1 - 3 K	1 - 10 K	Possible deficiency, warrants investigation
4 - 15 K	11 - 20 K	Indicates probable deficiency, repair as time permits
-	21 - 40 K	Monitor until corrective measures can be accomplished
> 15 K	> 40 K	Major discrepancy, repair immediately

An even different interpretation of the anomalies obtained from thermal imaging measurements is presented in the works [20,23] - see Table 5. These recommendation are obligatory for example only in selected countries like Germany and open question is how do they correspond to others presented in above tables. Are they more realistic being better suited to practical cases? Obviously, relying on first class reported as $0 < \Delta T < 10$ K is more resist and protecting against false indication for maintenance – unjustified and costly shutdowns and repairs.

Table 5. Interpretation of the anomalies obtained from thermal imaging measurements according to the works [20,23].

Fault class	Temperature rise ΔT , K	Recommended action
1	$0 < \Delta T < 10$ K	There is no need to take any action, but observe
2	$10 < \Delta T < 35$ K	Eliminate the weak point at the next shutdown - rectify if possible

3	$35\text{ K} < \Delta T < 70\text{ K}$	Eliminate of the weak point during the next planned maintenance, but within maximum 6 months
4	$\Delta T > 70\text{ K}$	Immediate eliminate of a weak point

3. Future Directions

Existing well accepted standards are very general and are not enough supporting the needs of examination of components of electrical power systems. For example the standard [24] describe mainly the standard terms. The documents [25,26] provide general principles for infrared thermographic testing in the field of industrial non-destructive testing. The standards [27,28] are focused on features and properties of experimental instruments. The following items are specified: objective lens, detector, image processor, display, thermal stimulation source, accessories. The procedure for examining electrical equipment with infrared thermography is also very general and not relating to high voltage power engineering, unfortunately. More constructive discussion and arrangements are needed to set a valuable standard. It is worth noting that the lack of such standardization of existence too many standards is very inconvenient when interpreting results obtained from thermal imaging measurements. This is clearly illustrated in the work [29] showing this problem from the insurance company’s point of view. Another issue that defies attempts at standardization is data pre- and processing data techniques for obtaining reliable and repetitive results. As stated in [9] with the increase of manpower cost and the expansion of system scale, automation and intelligence are the inevitable trend of the development of IRT of power equipment. The problem are related not only with sophisticated techniques as deep learning methods [30,31] but relatively simple techniques used for image pre-treatment, image segmentation, target identification, temperature information extraction, fault identification and diagnosis [9]. This is caused by influence of chosen techniques and their parameters on the final results.

4. Conclusions

The conclusion on future work is as follows – we have to continue research on finding solution being included in international standards and fully acceptable by industry. Today, there are at least several standards in force presenting different approaches to the assessment of anomalies in which different temperature thresholds are used. Because trying to generalize, if not impossible, at least seems to be very difficult. A rational solution seems to be the preparation of standards dedicated to specific types of facilities or devices in the area of power engineering because we have to remember the basic principle that decision on repairing belongs to the owner or manager of installation or facility.

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