

Review

Thermographic Measurements in Electrical Power Engineering—Open 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 to different standards and how operators should react when detecting a specific anomaly. 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 seem to be too general and do not cover all practical situations, even though, in many countries, thermal imaging diagnostics of overhead lines or overhead outdoor and indoor power stations have been used for years based on industry standards or good practices. The article aims are 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



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1. Introduction

Wherever any cause generates heat, thermal imaging measurements become an indispensable diagnostic tool [1–3]. Thermal imaging can be an 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 [4,5]. To assess, for example, the type of damage in electrical installation based on 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, considering the characteristics of the individual fields of application and the ability to perform examinations and interpret the results correctly [6,7].

In general, the thermal imaging measurements in power engineering, among others, used for testing indoor or outdoor installations and equipment are listed below [8]:

- The detection of thermal bridges in the insulation of electric furnaces, and overheating points due to damage to the insulation of chamber furnaces, continuous furnaces, melting furnaces, dryers, boilers, and pipelines;
- The testing of internal combustion engines and turbines;
- Wind turbine integrity testing;
- Tests on electroenergetics elements to determine heat distribution and assess the components' cooling conditions [1,2];

- The surveillance of the operation and the detection of overheating points on rotating machinery and equipment, bearings, gears, shafts, couplings, drive belts, chains, conveyors, compressors, and pumps [3];
- The detection of overheating points in electrical equipment and installations, such as fuses, contacts, switchgear and circuit breakers, busways and distribution panels, stationary batteries and chargers, emergency and Diesel generators [9], UPS, overhead and cable lines, substations, transformers, thyristors, motors, insulators, and electrical circuits [10–12];
- Testing photovoltaic panels and installations [13]. Electrical devices designed for the power industry are intended for power transmission. Generally, being loaded with rated power and occasional short-term overloads do not significantly affect their technical condition. However, excessive power will cause the device to overheat, shortening its life cycle and performance. An uncontrolled increase in temperature results in damage to devices, often resulting in significant costs and an unplanned interruption in energy supply. In many cases, fires even occur, affecting not only the device itself but also buildings or neighboring facilities. The effects of a seemingly minor damage can be huge. When 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;
 - The detection of load asymmetry;
 - The 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 are not fully exhaustive. The fault reason can be:

- Surface and internal cracks and material inhomogeneities;
- Insulation deterioration and aging [12];
- Weak mechanical connection;
- Partial short circuits;
- Induced eddy current;
- Cooling system failure;
- The wear of electric brushes;
- Semiconductor failure (photovoltaic panels) [13].

Some of the factors are independent of the device itself and related to the conditions of heat exchange. These factors can be external pollution, excessive ambient temperature, the obstruction of ventilation inlets, the presence of other hot objects, etc. It is not possible to include a full description of possible applications within the limited framework of this article. Some of these examples, particularly those related to electrical power engineering, are discussed in more detail 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] and, above all, cannot replace general and specific rules of conduct with electrical devices. Generally, the thermographic inspection only delivers information about possible malfunctions but does not protect against them. It should be applied in combination with operational and technical documentation of tested installations to prevent failures, fires, and losses [15].

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 as collected by the authors during the inspection of selected objects of high-voltage stations or lines. The places with increased temperature are caused by weak connections—Figure 1a,b,d—or leaking effects—Figure 1c. One of the most commonly used measurements is that of connectors on the 110, 220, and 400 kV transmission lines.

The subjects of the tests are the cable clamps on the 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 line wire connection. The use of a helicopter to fly around the line makes it possible to inspect a significant length of the electric line at one time and obtain results in a relatively short time.

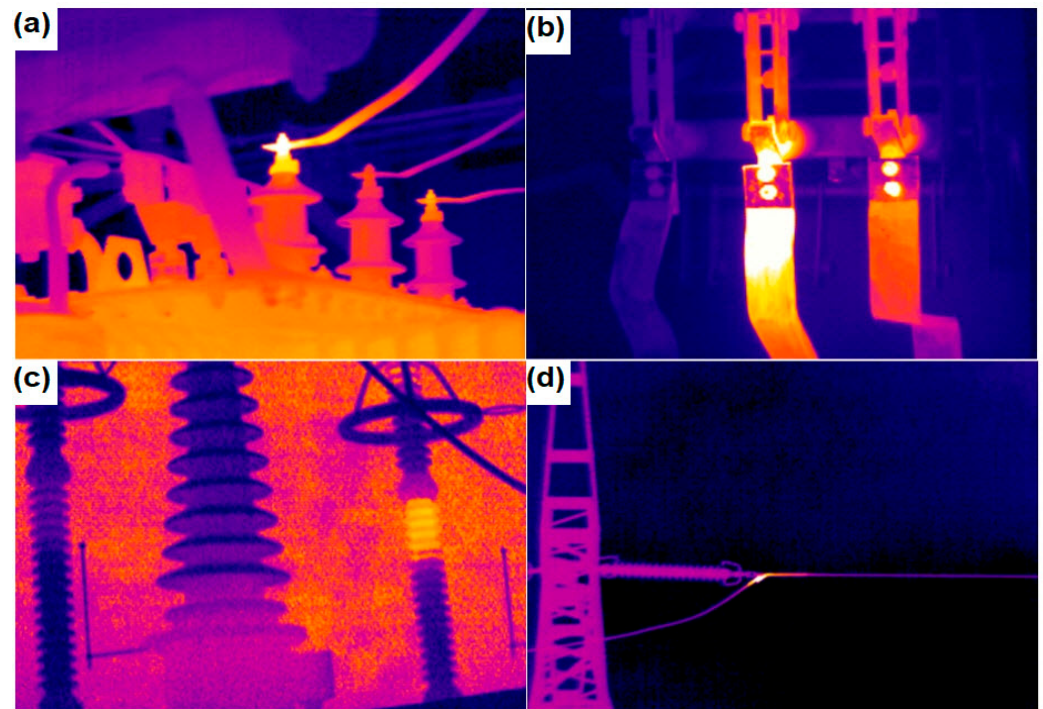


Figure 1. Overheated screw connection clamps on: (a) transformer insulator, (b) knife switch; (c) location of insulation weakening point; and (d) overheating of a cable clamp on the pole.

When applying InfraRed Thermography (IRT) to the condition monitoring and diagnostics, it is strongly recommended that the severity assessment criteria be established [16]. In practice, no singular severity assessment criterion is universally applicable to the variety of situations that need to be considered. These criteria can be general categories that identify temperature levels versus levels of criticality or applied to specific components. The first approach is checking whether the measured temperature is lower or not than the absolute temperature limit given in the technical documentation for the tested element. It should be noted that the temperature of line components is very much influenced by atmospheric conditions changing the heat transmission between the object and surroundings.

For example, Figure 2 shows the effect of wind on the temperature difference between the clamp and the electrical conductor. It can be seen that the wind velocity has a significant effect on the temperature difference for the same current load. It is extremely visible and significant for heavy loads. 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 is rainfall or snowfall. Therefore, conclusions based on the temperature reading without considering other factors may lead to incorrect assessments and decisions. Furthermore, there are also other relevant factors related to the drawback of thermography like the influence of the emissivity of the surface of the tested object that can be polluted on temperature readings, the reflected radiation of other objects, a small difference between the object and ambient temperatures, the air transparency decreased by fog, some contaminating types of gases or smoke, pollution, and weather conditions if an inspection is carried out outdoors. Their influence on the temperature error was deeply analyzed, for example, in the book [1]. Before starting the inspection, the minimum requirements of the IR camera should be confirmed. They are at

least the following: spectral range, temperature range, operating ambient air temperature range, thermal sensitivity NETD, geometric resolution, absolute error of measurement, and adjustable parameters like emissivity, reflected temperature, adjustable focus, temperature level, and span, as listed in the standard [13] dedicated to testing photovoltaic systems. It seems that this standard is a unique example of a professionally and carefully prepared guideline for inspection practice and, in the authors' opinion, could be adapted to electrical power equipment and systems. Furthermore, typical mistakes must be avoided as the imprecise focus—in many low-cost IR cameras, the focus is fixed and can result in an image being unsharp, an incorrect emissivity setting as an object parameter, and the IFOV being too small (the object is too small or too far); therefore, temperatures can be overstated or understated [14]. It is illustrated in Figure 3. For example, this problem is common in the aerial thermographic inspection of photovoltaic plants [17]. The drone being equipped with an IR camera is still moving; therefore, first, the camera must be fast enough to avoid image blurring. Second, to obtain reliable measurements, the IR system must comply with the requirements of the inspection equipment as stated in [13] again. To be sure, the IFOV should be evaluated on information about the distance to the object, camera geometrical resolution, and optics angle. After that, the IFOV must be compared with the minimal object dimension, and good practice applied as given below and recalled here as a reminder because it is often neglected by camera users. Due to a phenomenon called optical dispersion, radiation from a very small area will not give one detector element enough energy for the correct value. The commonly used practice is making sure that the hot area where the spot value requested is at least 3×3 pixels. Just multiply your theoretical spot size ratio called the IFOV by three, which gives you a spot size ratio of 3×3 pixels instead of 1×1 . This number is going to be more accurate.

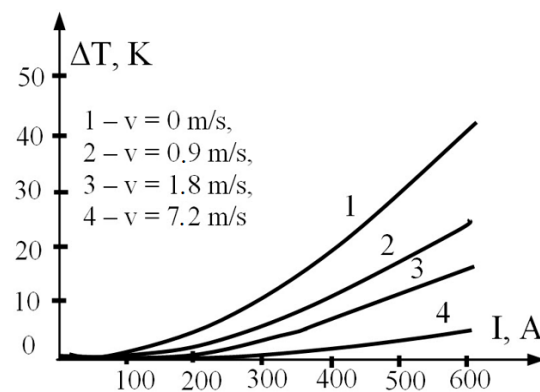


Figure 2. Dependence of the temperature difference ΔT between the wire and the clamp on the current flow at different wind speeds v , m/s [18].

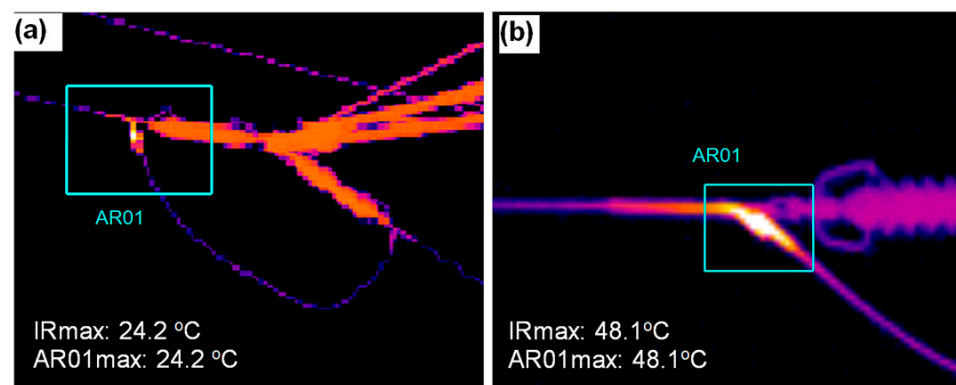


Figure 3. The effect of IFOV value on the temperature indication: (a) distance too far, and (b) correct result.

Thermal imaging measurements are most often used to determine the condition of an electrical wire after many years of use, when, due to aging effects, it becomes covered with an 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 the absolute maximum permissible temperature criterion [16] due to the high uncertainty of such a measurement. Even if an inspection is performed in optimal conditions and mistakes are avoided, the IR camera accuracy is about 2 °C.

In paper [19], the ambient, rated, and maximal temperatures for different materials used to build the electrical components such as PVC, polyethylene, silicone rubber, connectors and terminations (copper, copper alloy, or aluminum), fuses, coils, and relays are given and discussed. 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 measurements with historical data taken for the same environmental and operational conditions. Generally, these temperature difference 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, a statistical analysis can be used to set operational limits for trending and predicting temperature performance [16].

We will discuss some approaches taken from published papers and standards. The 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 [18]. Based on these criteria, it can be determined whether there is a need for immediate replacement or repair (IMM), or whether it can be carried out later, for example, during the 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 a high temperature can be accepted as being normal for high currents. For a correct assessment, a percentage of the nominal current load, the wind speed, and being registered by IR camera temperature rise must be considered. As discussed previously due to the effect of the object cooling by wind, the lower temperature differences are indications for a technical review and maintenance for higher wind speeds. For example, for a measured temperature rise of $\Delta T = 20$ K at 40% of a rated load, if the load is twice as high—80%, the temperature rise will be four 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 [18].

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

Abbreviations: IMM—immediately, and UR—urgently.

2.1. Low-Voltage Installations

Slightly different recommendations and criteria presented in Tables 2 and 3 are given in the work [20]. The study assumes that the load remains constant for at least 45 min before measurements are taken, and, for the meanwhile in work [21], 15 min is suggested as being enough to obtain a steady state and constant temperatures. The German VDE standard [22] requires 15–30 min for low voltage and 15–60 min for high voltage on installations up to

20 kV. You can see there exist at a least few proposals on it and, therefore, this issue needs further analysis and discussion.

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 [20].

Fault Class	ΔT_n , K	Recommendations
1	>30	IMM
2	5–30	UR
3	<5	O

Abbreviations: IMM—immediately, UR—urgently, and O—observe.

In addition, the measurements should be carried out at the time of the highest possible current load. The measurements cannot be performed if a tested element is conducting a negligible current, i.e., under 20% of the nominal load according to the authors [21].

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

- For a symmetrical three-phase load, a temperature difference between clamps on three neighboring phases $\Delta T > 3$ K;
- The clamp and ambient temperature difference $T - T_o > 35$ K;
- The clamp temperature $T > 70$ °C.

In many situations, the condition on the nominal load is not met. Furthermore, the temperature rise is affected by the condition of heat transfer to the surroundings. These factors are considered in work [20] 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.

Method 1. Table 2 is used in three-phase systems for the 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 according to the formula:

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

where:

$k = 1.6 \div 2.0$ —the exponent depending on heat transfer conditions, i.e., weather conditions: $>k = 1.6$ —good, $k = 1.8$ —fairly good, and $k = 2.0$ —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 —the clamp and ambient temperature for the current load I , K;

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

The permissible values of ΔT_n are specified in Table 2.

In another paper [23], the linear formula has been obtained for the temperature of the hot spot as a function of the current. It allows us to evaluate the temperature that would be reached if the nominal current circulated through the circuit. The drawback of this is that heat conditions are not considered as they previously were.

2.2. High-Voltage Installations

In this case, a distinction is made between two types of clamps: shielded and uncovered. The values for a permissible temperature rise are given for them in Table 3. What can be surprising in contrast to the low-voltage installations other fault classes are defined in [20]. Instead of 3 classes, only two are proposed—the last class “observe” is removed. This is justified by more difficult conditions for technical inspections and, finally, higher costs, and even fully confirmed by the experience of the authors of this manuscript conducting this kind of inspection 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 [20].

Fault Class	Shielded Connection		Exposed Connection	
	ΔT_n , K	Recommendations	ΔT_n , K	Recommendations
1	>3	UR	>20	UR
2	1–3	NSSI	<20	NSSI

Abbreviations: UR—urgently, and NSSI—during the next scheduled service inspection.

Example

Let us consider the measurement situation shown in Figure 4. The middle phase, as its temperature is much higher than the right-side reference phase, will be tested. 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 2, the result obtained indicates that repairs should be carried out immediately ‘TMM’.

- 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 2, 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.

For low- and high-voltage installations, certain deviations from the values of permissible temperature increases ΔT_n indicated in Tables 1–3 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, and weather conditions), and the financial consequences of failure or shutdown for maintenance. As stated in the introduction, the main purpose of this article is to encourage discussion to develop 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 [24], Table 4, seem to be insufficient and do not cover real-life situations. The most questionable one seems to be deciding on a criterion with low temperature levels as 1–3 K presented in Tables 3 and 4. The measurements of such low differences are difficult and have a high uncertainty due to the limited accuracy of the IR camera, compared to the reference object working in the same ambient conditions and load. The key issue, as mentioned in the standard itself are the 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 [24].

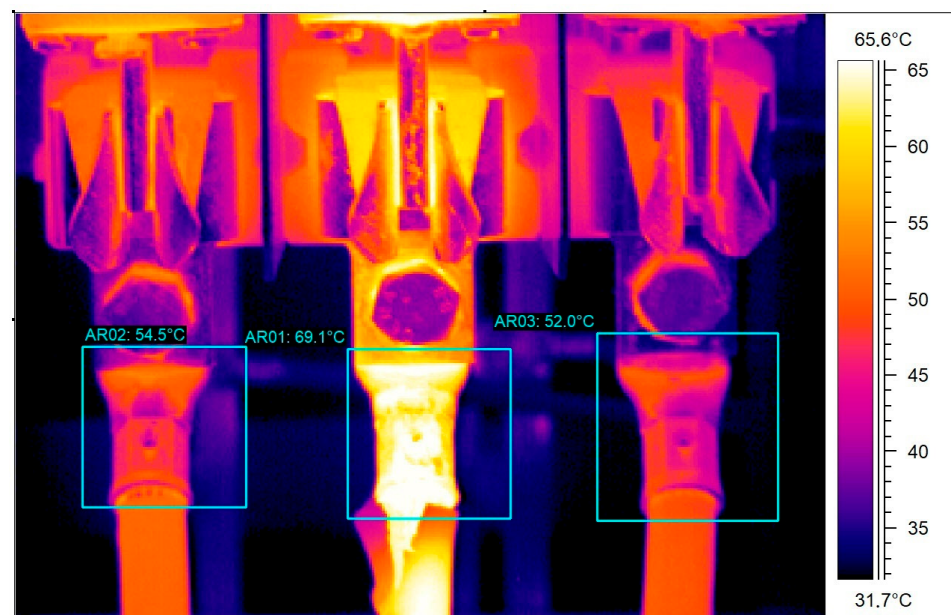


Figure 4. Thermogram showing mid-phase superheating of indoor switchboard area.

Table 4. Suggested actions suggested by the American National Standards Institute based on temperature rise [24].

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 more different interpretation of the anomalies obtained from thermal imaging measurements is presented in the works [22,25]—see Table 5. These recommendations are obligatory, for example, only in selected countries like Germany, and the open question is how they correspond to others presented in the above tables. Are they more realistic, being better suited to practical cases? Relying on the first class reported as $0 < \Delta T < 10$ K as a criterion for recommended action is more resistant and protects against a false indication for maintenance, with unjustified and costly shutdowns and repairs.

Table 5. Interpretation of the anomalies obtained from thermal imaging measurements according to the works [22,25].

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

3. Future Directions

The existing well-accepted standards are very general and are not enough to support the need for an examination of the components of electrical power systems. For example, the standard [26] describes mainly the standard terms. The documents [27,28] provide general principles for infrared thermographic testing in the field of industrial non-destructive testing. The standards [29,30] focus on the instrument's features and properties. The following items are specified: objective lens, detector, image processor, display, thermal stimulation source, and accessories. The procedure for examining electrical equipment with infrared thermography is also very general and not fully related to high-voltage power engineering, unfortunately. A more constructive discussion and arrangements are needed to set a valuable standard. It is worth noting that the lack of such global standardization and the existence of too many standards or even drafts like in Poland [31] is very inconvenient when results from thermal imaging measurements in specific countries must be transferred and interpreted in another one.

A good standard should be precise and cover the goals and interests of the various involved entities including the associations and standardization committees, installation operators, workers, end users, and even insurance agencies. This is clearly illustrated in the work [32] showing the insurer's point of view which tries to assess the financial risks of fire or malfunction. The insurance company disseminated its recommendation that is not fully consistent with other standards. There is even a discrepancy in vocabulary, and new aspects were pointed out as the extent of the damage and cost. For example, the following list is provided as an example for informational purposes in assessing the severity and possible actions. Four categories are mentioned:

- "Critical"—failure of this component will have a crucial impact on operations;
- "Severe"—failure is not expected to go beyond the tested component and would have a small impact on operations or the facility but repair costs could be significant;
- "Alert"—failure is routine and repairs can be made easily and at a reasonable cost; cost is limited to labor and a few minor parts;
- "Advisory"—helpful information based on engineering judgment.

Unfortunately, in document [32], no temperature rise is proposed or specified for the easy classification to one of the above-mentioned categories, and other legal standards in a given country must support this guideline.

Another open issue that defies attempts at standardization is data pre- and processing techniques for obtaining reliable and repetitive results. As stated in [8], with the increase

in manpower cost and the expansion of the system scale, automation, and intelligence are the inevitable trends of the development of the IRT of power equipment. The problem is related to sophisticated techniques such as deep-learning methods [33,34] and relatively simple techniques used for image pre-treatment, image segmentation, target identification, temperature information extraction, fault identification, and diagnosis [9]. This is caused by the influence of chosen techniques and their parameters on the results.

4. Conclusions

The conclusion on future work is as follows—it is necessary to continue research on finding a solution that is included in international standards and fully acceptable by the 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 power engineering, remembering the basic principle that the decision on repairing belongs to the owner or manager of the installation or facility.

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