ASM Sc. J., 19, 2024

https://doi.org/10.32802/asmscj.2023.549

Condition Assessment of Electrical Power Devices using Infrared Thermography: A Review

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Departures from the stable operation of electrical equipment usually appear as changes in parameters such as vibrations, pressure, temperature, power, and flow. Excessive changes in these parameters will indicate significant damage, leading to total or partial breakdown of equipment. This paper reviews the use of infrared thermography (IRT) for the operating condition temperature monitoring of electrical equipment. Infrared thermography is a contactless method that is based on thermal radiation principles and used for determining the temperature distribution on the surface of objects by measuring the intensity of radiation emitted by the object. The basic principles underlying IRT are presented in this review, showing its pros and cons, the various IRT methods, processes involved in IRT image acquisition, intelligent techniques for IR image analysis, and factors that affect the accuracy of results, including technical, environmental, and procedural factors. Also presented is an overview of common applications of IRT condition monitoring to solar energy, medicine, civil infrastructure, and aerospace equipment. Common faults in electrical equipment, including those in transformers, circuit breakers, feeder pillars and arrestors, are discussed with illustrations from recent research studies. These studies have demonstrated the effectiveness of IRT in the predictive maintenance of electrical installations. Hence, the replication of the techniques reviewed in this work is recommended so as to reduce current costs incurred in maintaining and replacing damaged equipment, and the associated time losses.

Keywords: infrared thermography; condition monitoring; electric power equipment; equipment maintenance

I. PRINCIPLES OF CONDITION ASSESSMENT

Condition monitoring refers to techniques or processes undertaken to monitor the operating characteristics of equipment in such a way that changes and trends of the monitored characteristics can be used to estimate the equipment's health and to predict the need for maintenance prior to the onset of serious deterioration or breakdown (Han & Song, 2003). It enables the detection of problems before major malfunctions occur in a machine or component, which may lead to financial loss, environmental pollution, injury or loss of human life (Bagavathiappan *et al.*, 2013). Condition monitoring is carried out to reduce or prevent unplanned breakdowns and maximise the availability of equipment.

For condition monitoring assessments, the common parameters are vibration, pressure, flow, displacement, power and temperature (Thorsen & Dalva, 1998), and sudden or unexpected changes in these parameters indicate significant changes in the condition of equipment. The reliable use of temperature as a condition indicator is limited by two factors: (i) it has a slow response to early damage, and (ii) temperatures inside a machine are sensitive to ambient temperature fluctuations (Kalliomäki, 1983). To

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minimise these, the temperature sensors used for condition monitoring should be as small as possible, and temperature differences, rather than a single temperature, should be measured to eliminate the influence of ambient temperatures.

Condition monitoring procedures may be carried out according to two basic methods of maintenance: preventive maintenance and predictive maintenance. In the preventive maintenance of electrical components, quantities which either prevent or assist the development of failure are monitored based on historical data of working capacity, previous data of component failures, and mean time to failure (MTTF) component performance. An example is the measurement of oil flow in recirculating oil lubrication, where a drop-out will cause failure of bearings. On the other hand, predictive maintenance involves frequently collecting data such as the efficiency or heat distribution in an electrical equipment, analysing the data obtained in order to determine the level of failure. In predictive maintenance, initial failures cannot be prevented, but faults in electrical equipment can be detected in early stages and thus, serious damage can be prevented. An example is the monitoring of a bearing failure due to ageing (Kalliomäki, 1983; Ullah *et al.*, 2017).

Condition assessment methods were grouped under traditional diagnostic methods and non-traditional diagnostic methods in an alternative classification by Wang *et al.* (2002), which is specific to power transformers. Traditional diagnostic methods include: oil testing, power factor testing, winding resistance test, winding turns ratio test and infrared thermography, while non-traditional diagnostic methods include: recovery voltage measurement, winding insulation oil testing, internal temperature measurement, tap changer monitoring, etc. Besides IRT, other maintenance techniques presently used in condition monitoring of electrical equipment include x-ray tomography, frequency response analysis, spectroscopy, vibration analysis (Khan *et al.*, 2016), and, recently, electromagnetic interference (Timperley & Vallejo, 2017).

II. THERMOGRAPHIC DIAGNOSTICS

A. The Electromagnetic Spectrum

The electromagnetic spectrum is shown in Fig. 1 and consists of the full range of the electromagnetic spectrum — gamma rays, x-rays, ultra-violet waves, visible light, infrared, microwave and radio waves, listed in the order of increasing wavelengths. The different properties of the various types of electromagnetic radiation are due to differences in their wavelengths, and the corresponding differences in their energies. The amount of energy possessed by an electromagnetic radiation is given by

$$E = hc / \lambda \tag{1}$$

where E is energy in kJ/mol, λ is wavelength in m, c is speed of light (3.00 x 10^8 m/s), and h is Planck's constant (3.99 x 10^{-13} kJ.s.mol^{-1}). The frequency, υ (Hz), of an electromagnetic wave is related to its wavelength via

$$\lambda \nu = c \tag{2}$$

Generally, electromagnetic radiations of longer wavelengths have corresponding lower frequencies and lower energies. Consequently, gamma rays which have the shortest wavelength in the electromagnetic spectrum, have the highest frequency and energy.

The designation *infrared* means "below red", and is because among the colours of visible light, the red colour has the longest wavelength and precedes infrared radiation. Infrared radiation has wavelengths between 750 nm and 1 mm, which are longer than the wavelengths of visible light, but shorter than those of microwaves. All objects with a temperature above the absolute zero emit infrared energy, which is invisible to the human eye.

B. Basic Thermographic Principles

The thermal radiation emitted by an object depends on its temperature, which in turn depends on the thermal radiation received by the object and internal phenomena occuring within it. These cause the atoms and molecules within the object to vibrate more or less vigorously, and these vibrations are sensed as its temperature (Garrido *et al.*, 2018a).

Thermal radiation theory introduces the concept of the blackbody, which is defined as an imaginary object which absorbs all incident radiations and emits a constant spectrum. Its wavelength-specific emitting power per unit area and per unit solid angle, L_λ (Wm$^2\mu$m^{-1}sr^{-1}), at a temperature T (in Kelvin), is given by the Planck's law as (Khan *et al.*, 2016):

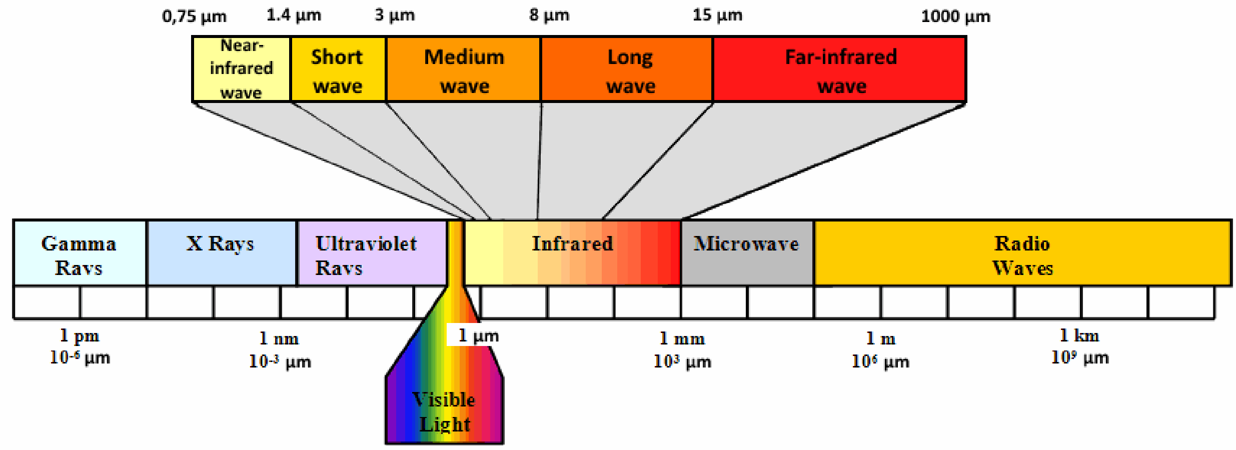

Figure 1. The electromagnetic spectrum (Protherm, 2013)

$$L_\lambda = \frac{C_1}{\lambda^2\left[\exp\frac{C2}{\lambda T} - 1\right]} \tag{3}$$

where C_1 and C_2 are the first and second radiation constants, respectively.

Integrating Planck's law (Eqn. (3)) over all frequencies, the Stefan-Boltzmann's law is obtained, which states that the total energy emission rate, $\dot{Q}$, from a surface of area, A, is proportional to the fourth power of its absolute temperature, i.e.,

$$\frac{\dot{Q}}{A} = \varepsilon\sigma T^4 \tag{4}$$

where σ is the Stefan-Boltzmann's constant (σ = 5.676 × 10^{-8} Wm^{-2}K^{-4}) and ε is the emissivity of the emitting surface.

The wavelength of the peak of the emission spectrum is also related to the absolute temperature of the emitting surface by Wien's displacement law, which states that the blackbody radiation curve for different temperatures will peak at different wavelengths that are inversely proportional to the temperature. As shown in Fig. 2, as a direct consequence of Planck radiation law, there is a shift of the peak at different temperatures, which shows the spectral brightness of a blackbody as a function of wavelength at any given temperature. Wien's law is expressed mathematically as

$$\lambda_{max} T = 2897.7 \text{ µmK} \tag{5}$$

Thus, when the infrared radiation of a certain wavelength emitted by a body is detected by an infrared detector, the temperature of the body can be obtained by re-arranging Eqn. (4) to make T the subject of the formular (Bagavathiappan *et al.*, 2013).

Infrared thermography is a contactless method that is based on the foregoing principles, used for determining the temperature distribution on the surface of objects by measuring the intensity of radiation emitted by the object. This technique uses infrared imaging to measure the infrared energy emitted by the object (Glavaš *et al.*, 2016). It is suited for assessing the operational conditions of electrical installations because most electrical installation components either get hotter or cooler before failure. A number of advantages are associated with the use of IRT, including (De Potter, 2017):

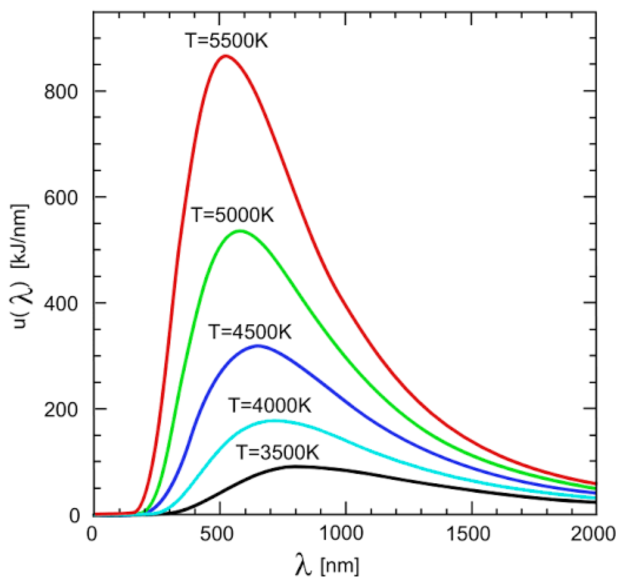

Figure 2. Wien displacement law (Bruice, 2013)

- It is a non-contact and non-destructive test method.
- Measurements are taken in areas inaccessible for other methods.
- Tests can be performed during normal operation of electrical installations.
- The results are available in real-time.
- Visual pictures can be captured over large areas.
- It can detect deteriorating components prior to failure.

However, the use of IRT is limited by the:

- difficulties associated with interpreting images accurately;
- difficulties inherent in obtaining accurate temperature measurements;
- inability to measure internal temperatures of devices; and
- cost and delicate nature of IR cameras.

C. Infrared Thermography Methods

Infrared thermography procedures can be broadly classified into two major categories, namely passive thermography and active thermography. In passive thermography, the temperature of the object under investigation is recorded without exposing it to any external heat stimulation; the object itself acts as a source of heat. This means that the observed temperature patterns are solely due to existing temperature distributions within the object. This method is called passive since the existing temperature distribution of the object scene is analysed. Alternatively, active thermography requires the object under investigation to be subjected to external heat stimulation. In active thermography, the object under investigation is heated by an artificial heat source in order to investigate heating or cooling processes in the object during or after the thermal excitation.

Depending on the nature of the heat stimulation, active thermography can be further subdivided into pulsed thermography, lock-in thermography, pulsed phase thermography, etc (Bagavathiappan *et al.*, 2013). In pulsed thermography, a heat pulse of short duration is used as the heat simulation and the thermal excitation is monitored. The short pulses are applied with duration ranging from a few milliseconds for high-conductivity materials to a few seconds for low-conductivity materials. Due to the brief duration of heating, the temperature increments above the initial component temperature are just a few degrees, thus preventing any thermally induced damage to the component. Lock-in thermography has its heat simulation in the form of a sinusoidal heat wave being supplied to an object under investigation. Thus, the heat flux applied is modulated at a given frequency. Pulsed phase thermography is a combination of pulse thermography and lock-in thermography.

Two fundamental passive thermographic diagnostics methods were identified by (Fidali, 2015): the absolute method and the relative method. The absolute method is employed, for example, in the case of a single thermographic examination of an object for which previous inspections have not been conducted and for which there are no running objects of similar design. Because electrical devices are not always operated at rated load during absolute thermographic inspections, the need arises for the maximum allowable temperature, $Tmaxcorr$, of the equipment being monitored to be corrected with respect to the measured load current, Im, (A), rated load current, Iz, (A), rated temperature rise (from standard), Tzw, and measured ambient temperature, Tom. This is achieved by using Eq. 6 (Fidali, 2015):

$$T_{maxcorr} = \left(\frac{I_m}{I_z}\right)^2 T_{zw} + T_{om} \tag{6}$$

The relative method of passive IR thermography is used to assess the conditions of devices by comparing the results of thermographic observations with reference data. The relative method is further sub-grouped into comparative *qualitative* thermography and comparative *quantitative* thermography (Fidali, 2015). In comparative qualitative thermography visual analyses of shapes, sizes of temperature profiles, etc., are used for condition assessment of the equipment by visually comparing features in the temperature distribution fields of two or more objects of the same design, or thermograms of the same object acquired at different times. Alternatively, in comparative quantitative thermography, the difference in the temperatures of the observed object and a reference value is used as the diagnostic symptom. The reference value could be the temperature of a similar object operating under the same condition, the ambient temperature, or the temperature of the same object at another moment of time.

Table 1. Maintenance testing specifications for electrical equipment (Mechkov, 2017).

Priority	Δ*T* between similar components under similar load	Δ*T* over ambient temperature	Recommended action
4	1°C to 3°C	1°C to 10°C	Possible deficiency, warrants investigation
3	4°C to 15°C	11°C to 20°C	Indicates probable deficiency, repair as time permits
2	—	21°C to 40°C	Monitor until corrective measures can be accomplished
1	> 15°C	> 40°C	Major discrepancy, repair immediately

A number of criteria are applied when assessing the working condition of electrical equipment with IRT. Four classes of thermal deficiencies in electrical equipment have been identified by the International Electrical Testing Association (NETA) standard and these are presented in Table 1 (Mechkov, 2017). The table is used for analysing thermographic results in order to determine priority levels and recommend further actions based on the criterion of temperature difference between a measured component and the temperature of ambient air or a similar component under similar loading.

Barash *et al.* (1973) employed both quantitative and qualitative thermography approaches for predicting the occurrence of breast cancer. The presence of malignant tumour was detected as a rise in temperature in one breast in comparison to the other. The four features of the thermogram used for analysis were the vein pattern, vein temperature, background temperature and areolar temperature. The results were quantified on a scale of 1 to 4. Scale 1, being normal and 4 being maximum abnormal. Using a colour technique, a value was assigned depending on the difference between the temperature of one breast compared to that of the corresponding anatomical area on the contralateral side. Qualitative infrared thermography has also been applied to buildings, being used to detect and characterise their possible thermal pathologies, and also characterise the properties of their composing materials (Garrido *et al.*, 2018a). A program was developed for fault detection at Tomsk Polytechnic University (Grinzato *et al.* 1998) to calculate the thermal signals of defects, using the temperature difference between the defective and sound zones. It was also applied to diagnose plaster-brick delamination, insulation deficiency, moistened locations etc.

The quantitative thermography approach was applied by López-Pérez and Antonino-Daviu (2017) for detecting faults in a group of twenty industrial induction motors (lubricating pump motor, blower motor, and fan motor) in a petrochemical plant. Abnormal temperature values were detected, which had different origins — twelve were due to mechanical problems, six due to electrical faults, five had thermal faults, while one was due to environmental factors. The study of Mechkov (2017) also applied a quantitative thermography technique for transformer maintenance. The study was carried on several transformer stations of a utility company. The results were analysed using temperature difference between similar components and temperature difference over ambient air as shown in Table 1. The results and analysis of the infrared images indicated that abnormal hotspots were mostly detected between nut and rod at the low voltage bushings of transformer phases.

D. Image Acquisition in Infrared Thermography

Whereas thermal radiation from hot objects can only be seen in the visible spectrum at temperatures above ~ 525°C, an infrared camera can detect infrared energy well before it becomes visible to the human eye. Infrared cameras (also referred to as thermal imagers) are non-contact devices that detect infrared energy and convert them into electronic signals that are then processed to produce two-dimensional visual images. They create pictures of heat rather than light (Kad, 2013).

Infrared detectors are broadly classified into two categories: photon detectors and thermal detectors. Photon IR detectors absorb radiation which interacts with electrons within the detector to produce electrical output signals due to changes in electronic energy distribution. Photon detectors are wavelength-dependent and have highly efficient signal-to-noise performance. They have very fast response but need cryogenic cooling. Alternatively, a thermal IR detector absorbs radiation which changes its temperature. The resultant change in its physical properties leads to the generation of electrical output. The detector element is suspended on legs, which are connected to a heat sink. Unlike photon detectors, thermal detectors are generally wavelength-independent. The signals produced depend only on the IR radiant power (or its rate of change) but not upon its spectral content (Rogalski, 2002).

Thermal IR detectors are of three basic kinds: bolometer, thermocouple and pyroelectric sensors. Bolometers are thermal sensors which use temperature-dependent resistors attached to the IR absorbing plate to sense temperature signals (Wood, 2001). A microbolometer is a specific type of bolometer used as detectors in infrared cameras. Thermographic cameras are similar to digital cameras, with one key difference. Unlike charge-coupled device sensors used in digital cameras, thermal cameras use microbolometer arrays. The main distinguishing feature of a bolometer when compared with other IR sensors is that it uses an electrical resistance change to detect increase of temperature (Wang *et al.*, 2004).

Figure 3 shows the processes involved in the capture of thermograms using an IR camera. The IR camera captures the thermal profile (also called thermogram) of an object, which consists of a thermal picture and a temperature scale. The different colours on the temperature scale represent the different temperature spots on the equipment (Huda & Taib, 2013b). The temperature scales may range from black (coolest) through red to white (hottest).

Thermographic cameras can also be grouped according to their use of cooled thermal detectors and uncooled detectors. Cooled cameras (including those which use photon detectors) are contained in a vacuum-sealed case and cryogenically cooled, whereas uncooled cameras use a sensor that operates at ambient temperature. The thermal sensitivity of uncooled cameras is about 0.05°C compared to 0.01°C for the cooled ones. Hence, the cooled cameras produces superior image quality, though they are more bulky and expensive compared to uncooled ones (Bagavathiappan *et al.*, 2013).

E. Analysis of IR Thermograms

As just described, the thermal images acquired in most IRT inspections of electrical components and machinery, are analysed qualitatively. This is fast and does not warrant rigorous evaluation but relies on perceptual intuition to decide on whether equipment is in order or not. Thus, the

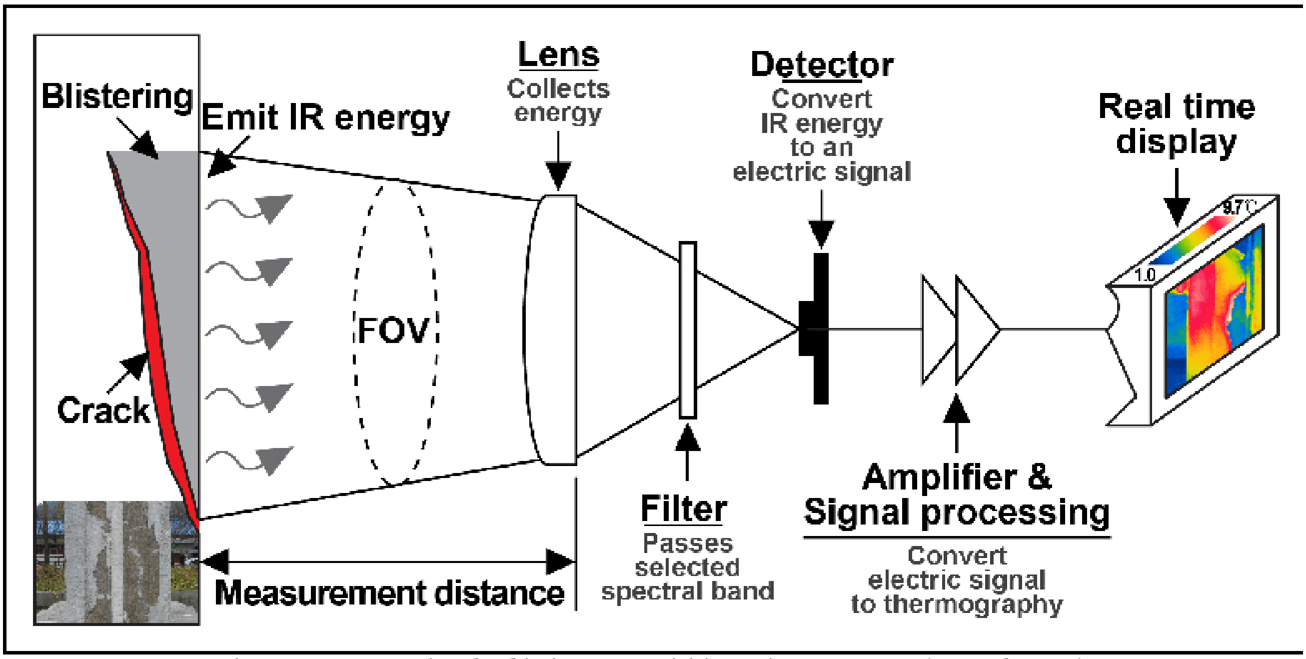

Figure 3. Processes involved in image acquisition using IR camera (Jo *et al.*, 2013)

condition of electrical equipment are manually classified on the basis of the presence of abnormal hot spots or large temperature differences in different parts of infrared images (Zou & Huang, 2015).

Computational image processing is an alternative means of analysing the thermal images obtained in IRT. These images are first converted into greyscale images, which retain the intensity information of the image. Faulty regions in the equipment appear brighter than the normal repeated regions in the greyscale images (Fang, 2023). Further analysis of infrared images generally consists of three steps. The first step is to identify the region of interest (ROI) in the IR image (Zou & Huang, 2015). This key step can be performed in any of two ways: either by using binary image segmentation techniques or by manual segmentation.

In the next step, descriptive information, such as the statistical features of the regions, which are distinctive enough to be classified, are extracted. These features includes the first-order histogram features (such as mean, variance, standard deviation, skewness, kurtosis, energy and entropy), the grey-level co-occurrence matrix features (such as energy, contrast, entropy and homogeneity) and the differences between hot and reference regions.

The final step is a classification step in which the extracted information is analysed to decide whether the IR image reveals a possible fault or not. Artificial neural networks (ANN) are the tools of choice for this step. ANN is a branch of computational intelligence with which the relationships between datasets of actual inputs and datasets of actual outputs of a system can be determined. Learning approaches are used in which the input data are trained to create fitting networks of datasets which give the predicted outputs. A number of ANN techniques are available for IR image data analysis (Ullah *et al.*, 2020), including convolutional neural networks (Choudhary *et al.*, 2021; Wang *et al.*, 2021; Yongbo *et al.*, 2020; Han *et al.*, 2023).

Ten electric power substations were monitored in the study of Ullah *et al.* (2017), from which 150 IR images of different electrical equipment were obtained. The basic MLP ANN approach was used for analysing the images to identify defects in the equipment; 79.78% accuracy was achieved. With the addition of a novel graph cut-out technique, the accuracy of the classification improved to 84%.

III. FACTORS AFFECTING THE ACCURACY OF IRT RESULTS

The accuracy of IRT measurements could be affected by a number of factors which are categorised as procedural, technical or environmental conditions. Procedural factors are those factors relating to the methodology of the infrared measurements. They generally concern the thermographer himself, and such factors are minimised by employing qualified personnel. Technical factors are factors relating to the particular method used for performing the IRT, such as emissivity of the object under investigation, camera-to-object distance, load current variation, and the camera specifications. Environmental factors are those factors that show the dependence of IRT measurements on atmospheric conditions. Environmental factors, which include ambient air temperature, humidity, precipitation (snow, rain, fog, etc.), wind and solar irradiation must be considered during IR inspections. For example, an increase in ambient air temperature leads to a higher measured temperature of objects under investigation, whereas humidity, rain or snow reduces the measured temperature values. Environmental factors are especially important when undertaking outdoor inspections, thus, IRT monitoring of large civil structures are performed after sunset to avoid the effects of direct solar radiations and to obtain an appreciable temperature difference between the defect and defect-free regions (Bagavathiappan *et al.*, 2013; Jadin & Taib, 2012).

Emissivity is also an important technical factor to be considered in order to correctly determine the temperature of an object with IRT. Emissivity is the ratio of thermal radiation from the surface to radiation from the black body at the same temperature. To illustrate, supposing two materials with different emissivity values are heated to the same temperature, the material with a lower emissivity will appear duller and at a lower temperature both to the eye and to the thermal imager than that of higher emissivity. The recommended emissivity setting for electrical installation inspection is 0.9, according to the Infrared Training Centre (ICT) (Glavaš *et al.*, 2016). Thermograms are thus interpreted on the basis of the apparent temperature, using the analysis of surfaces with greater emissivity and avoiding the shiny metal parts.

The following solutions have been proposed to increase the accuracy of IRT results (Huda & Taib, 2013a; Garrido *et al.*, 2018a; De Potter, 2017):

- While capturing the image, the thermal imager orientation should be directly facing the target electrical equipment.
- The lens of the IR camera should not be focused on the object with perpendicular direction in order to avoid the measurement of self-reflection of the lens on the surface under study.
- The installation to be inspected must be in service, if possible under full load.
- Since thermographic cameras cannot see through solid materials, covers or doors of cabinets should be opened during inspection.
- Visual images should be taken alongside thermal images.
- An appropriate electrical component to thermal camera distance should be maintained. This distance depends on the imager type in use for the IR inspection. Huda and Taib (2013a), using a Fluke Ti25 IR imager, set the distance at 1 m, while Ullah *et al.* (2017), who used a FLIR T630 imager, set the distance between 5 to 8 m.

IV. APPLICATIONS OF INFRARED THERMOGRAPHY

As highlighted in the preceding discussions, infrared thermography (IRT) is well suited for the condition assessment of electrical connections and electrical installations. Other applications of IRT includes condition monitoring in nuclear, aerospace, food, medicine, wood and paper industries. Table 2 shows a collection of research studies in which IRT was applied and the key findings obtained.

Table 2. Applications of IRT methods showing key findings

Work [Ref.]	Study Objectives	Methodology	Key findings
Animal Management Applications			
Hurnik *et al.* (1984)	Utilisation of thermal infrared scanning as a technique in the early detection of illness.	Daily data collection and analysis of thermal infrared images of the gluteal region from a constant distance of 2.5 m directly behind the cow using a thermovision unit.	IRT can be applied for the early detection of health disorders in dairy cattle. Also, 37^{o} C isotherm on the gluteal region is the healthy cow's body surface temperature, this temperature increase substantially if the animal became ill.
Loughmiller *et al.* (2005)	Evaluation of changes in mean body surface temperature (MBST) measured with infrared thermography associated with growth performance in healthy pigs subjected to changes in feed intake or dietary nutrient profile.	Feed was prepared. Next, images were taken at a distance of 2 m perpendicular to the side of each pig while it was standing. Then, collected digital images were analysed.	IRT can be used to detect differences among individual pigs in mean body surface temperature associated with feed intake, growth rate and dietary energy content in more variable environmental conditions than those used with calorimetry.
Schaefer *et al.* (2004)	Investigation of the capability of infrared thermography as an early detection method for	Simultaneous comparison of infrared characteristics in both infected and control animals was conducted over	IRT can be used in developing an early prediction index for infection in calves as temperature of facial scans increased by 1.5°C to over 4°C ($P < 0.01$) several days to 1

	identifying animals with a systemic infection.	approximately 15 days.	week before clinical scores or serum concentrations of acute phase protein indicated illness in the infected calves.
Medicine Applications			
Kargel (2005)	Investigation of local heating effects of the ear-skull region that handheld mobile phones can cause in humans.	First quantification of thermal effects due to normal commercial mobile phones. Next, relative comparisons of overall exposure from different mobile phones, and then, identification of those phones that cause the smallest local heating and interaction with the human body.	Different commercially available handheld mobile phones can cause very different thermal effects under identical experimental conditions.
Brånemark *et al.* (1967)	Investigation of infrared thermography in the treatment of diabetes.	A group of young diabetics with or without vascular complications were studied using IRT.	Thermal abnormalities exits in the hands, feet, toes and fingers of diabetics.
Morgan *et al.* (1995)	Investigation of a group of dry eye patients and a group of age- and sex-matched normal using an advanced infrared detection system.	Patients with dry eyes and a control group were selected. Next, infrared radiation emitted by the eye was measured with a 6T62 Thermo Tracer detection apparatus. Images are then analysed.	Assessment showed that the mean ocular surface temperature (32.38 ± 0.69^{o}C) was greater in the dry eye group than with the control group (31.94 ± 0.54^{o}C). Also, there was a greater variation of temperatures across the ocular surface in the dry eye group than in the control group.
Civil Structure Applications			
Garrido *et al.* (2018b)	Presentation of a procedure for the automation of thermographic building inspections with the focus on thermal bridges.	First a thermal image rectification process is applied. Next, designing criteria are established, then optimal interval for thermal transmittance is determined.	Accuracy of detecting thermal bridges in buildings is increased by 15% when compared with existing methodologies, considering the false positives and negatives obtained in each methodology.
Iordache & Iordache (2017)	Determination of the infiltration rate when the main warehouse is exposed at a 50 Pa pressure difference, n50Pa (1/h).	Using assessment of the permeability law (the airflow at different pressure differences) of the building and by means of power law interpolation in determining the airflow at 50 Pa pressure	Indoor air infiltrations in a deep-freeze warehouse can be visualised by means of the infrared thermography. The measured value of air change rate at 50 Pa, was found n50 = 0.08 (1/h).

		difference.	
Różański & Ziopaja (2018)	Analysis of the applicability of infrared thermography as a diagnostic tool to support the inspections of the structure and equipment elements of bridges.	Two tests were performed, namely: in-situ and laboratory tests.	IRT can be used for routine bridge inspections, though having substantial limitations.
Fox *et al.* (2016)	Qualitative comparison of pass-by thermography and walk-through thermography.	Two methodologies were used: walk-through methodology and work-past methodology.	Inspections were much faster using walk-past thermography, on the other hand, more defects were detected using walk-through thermography for building inspections.
Lerma *et al.* (2018)	Discussion concerning the opportunities and constraints of using active IRT to detect air leakage points.	A qualitative and quantitative approach was used in analysis of thermal images.	Combining active IRT with pressure differences is an effective methodology for detecting air infiltrations.
Solar Energy Applications			
Gerber *et al.* (2015)	Demonstration that the consistent modelling of EL and dark lock-in thermography (DLIT) images using a SPICE-based model can obtain properties of solar modules.	First, thermography and EL analysis of CIGS modules and a-Si:H solar modules. Next, simulation of EL and power images. Then, lock-in thermography and differential electroluminescence analysis are performed.	Demonstration that properties of solar modules like the spatial voltage distribution, the resistances of the front and back contact, and the shunt resistance of local defects can be obtained using LIT and electroluminescence (EL) measurements.
Djordjevic *et al.* (2014)	Examination of a number of problematic modules and identification of several common defects that have appeared on installations around Western Australia.	First step is visual observation of solar modules. Next, electrical measurements were performed to test the module output, infrared photographs of the solar module were then taken and analysed.	New defects, specific to Western Australia were not found. Common defects included: discolouration, cracking, snail tracks, antireflection coating damage, soiling, bus-bar oxidation and corrosion, hotspots and strings etc.
Simon & Meyer (2010)	Location of hot-spot areas in different samples of solar cells using IRT.	c-Si solar cells were subjected to hot-spot checking while in the dark using IRT.	There is a direct correlation between areas of high impurity contaminants and hot-spot heating in different samples of mc-Si solar cells, which can be easily identified using IRT.
Ancuta &	Analysis of visible and	Analysis were made using the	IR analysis can be performed for fault

Cepisca (2011)	invisible defects for the PV array using non-destructive techniques.	temperature factor for PV panels for different environmental conditions.	analysis of photovoltaic (PV) panels, also the best IR thermographic testing images resulted during sunny days with low relative humidity.
Hu *et al.* (2014)	Presentation of a low-cost and efficient temperature distribution analysis for identifying PV module mismatch faults.	Six PV panels are arranged into two strings, their surface temperatures are recorded by a thermal camera under different conditions.	A thermography-based temperature distribution analysis to analyse three different fault categories (cell, module and string levels) developed in photovoltaic systems.
Veldman *et al.* (2011)	Comparison of non-destructive test methods for testing back-contact modules such as: lock-in thermography, electroluminescence, X-ray scanning, and ultrasonic inspection.	Dark lock-in thermography (DLIT) and electroluminescence (EL) and X-ray and ultrasonic inspection were used.	X-ray inspection is relative expensive and ultrasonic inspection is time-consuming. On the other hand, DLIT is fast, accurate and economical. EL imaging is complementary to DLIT.
Hoppe *et al.* (2010)	Investigation of efficient polymer solar modules sealed under glass with high lateral and thermal resolution.	Organic photovoltaic modules was prepared then dark lock-in thermography (DLIT) was used in obtaining images.	DLIT is an efficient tool for investigating parasitic energy dissipation in organic solar cells and solar modules produced via integrated series connection.
Breitenstein *et al.* (2003)	Demonstration showing that lock-in thermography not only permits one to locate shunts, but also allows one to measure their current quantitatively.	Quantitative analysis of the spatial distribution of the dark forward current density of solar cells.	The investigation of a typical multicrystalline solar cell shows that the shunts are predominantly responsible for deterioration of the low-light-level performance of the cell.
Kaplani (2012)	Analysis of aging defects appearing in 18–22-year-old PV modules, identified by means of IR thermography and digital image processing.	Both digital images and IR images are obtained from cells exhibiting different degrees and forms of optical degradation and then analysed.	IRT identified temperature degradation effects in bus bars, contact solder bonds, blisters, and hotspots.
Buerhop *et al.* (2012)	Demonstration of reliability of detecting modules with reduced power output using IR-imaging.	Modules were captured by an IR-camera, further they are characterised in detail by means of IR-thermography, EL-imaging and IV-characteristics.	Quality check of photovoltaic (PV) plants under certain operating conditions can be performed by employing infrared-imaging.

Goutam *et al.* (2014)	Analysis of IR images in order to find the locations of maximum and average cell surface temperature.	A thermal IR camera was used to observe the spatial distribution of cell surface temperature. Additionally, four K-type contact thermocouples (accuracy ± 2° C) were also used to record the cell surface temperature at specific locations.	During continuous charge and discharge up to 100A, the temperature distribution was more uniform compared to the distribution during micropulse cycling. Maximum temperature was observed near the positive tab of the cell during micropulse cycling.
Moropoulou *et al.* (2007)	Investigation of a building integrated photovoltaic system at the School of Chemical Engineering of the National Technical University of Athens.	In-situ measurements were performed during September-October between 10:00-17:00.	Thermographic analysis for on-site monitoring of building integrated photovoltaic systems is quite effective.
Aerospace Applications			
Ibarra-Castanedo *et al.* (2007)	Demonstration of the capabilities of pulse thermography (PT) for qualitative and quantitative analysis of aerospace materials.	Three effective processing techniques were used: differentiated absolute contrast (DAC), thermographic signal reconstruction (TSR), and pulsed phase thermography (PPT).	A combination of DAC, TSR and PPT increases the accuracy of pulse thermography.
Meola *et al.* (2006)	Investigation of lock-in thermography (LT) for non-destructive evaluation of aerospace materials and structures.	Five kinds of specimens were selected, and lock-in thermography was performed on them.	LT is useful for both non-destructive evaluation and temperature monitoring.
Zhao *et al.* (2017)	Demonstration of the effectiveness of LT in inspecting intimate contact disbonds in titanium alloy honeycomb sandwich structure.	The specimen and experiment are set up, and then lock-in thermography is carried out.	Lock-in thermography (LT) is suitable for the inspection of the skin-to-core disbonds in titanium alloy honeycomb structure.
Duan *et al.* (2013)	Quantitative evaluation of the capability and reliability of optical LT and PT on the aluminium foam material.	Quantitative evaluation using optical thermographic techniques.	Lock-in thermography (LIT) and pulse thermography (PT) is useful for non-destructive evaluation of aluminium foam material, especially in cases where X-ray tomography may not be available.

V. IRT DETECTION OF THERMAL ANOMALIES IN ELECTRICAL EQUIPMENT

Faults in electrical equipment manifest as deviations in voltages and currents from their normal operating values. If this equipment is operated at power ratings above their specifications, the excess power is transformed into heat, causing elevated temperatures within the device. Even in the absence of excess power supply, faults in electrical installations cause internal temperatures to rise to abnormal levels since the thermal energy generated by an electrical component is directly proportional to the square of the current passing through it. Faults in electrical equipment are commonly caused by increased resistances, increased loads, induced heating and harmonics (Jadin & Taib, 2012). Table 3 provides a collection of studies on IR evaluation of faults in electrical equipment.

Table 3. Applications of IRT methods to fault finding in electrical equipment showing key findings.

Work [Ref.]	Study Objectives	Methodology	Key findings
Electrical Applications			
Huda & Taib (2013b)	Investigation of IRT as a predictive/preventive maintenance program to identify thermal defects in electrical equipment.	Multilayered perceptron network, statistical features and discriminant analysis classifiers were used to characterise the thermal status of hotspots.	Using discriminant analysis for monitoring of equipment thermal conditions produced a better performance accuracy of 82.40% when compared with a neutral network.
Mechkov (2017)	Presentation of an overview classification of thermal abnormalities, results and their analysis.	Relative temperature criterion (ΔT criterion) by NETA was adopted for classification of thermal abnormalities.	Hotspots in transformers are likely results of loosely tightened joints.
Ullah *et al.* 2017	Investigation of the application of IRT for predictive maintenance to identify the presence of a defect and non-defect in electrical power substations of 110 kV.	Multi-layered perceptron was used (MLP) in the classification of thermal conditions of components of power substation.	The performance of MLP shows initial accuracy of 79.78%. Augmenting the MLP with graph cut increased accuracy to 84%.
Glavaš *et al.* 2016	Perform energy audit of electrical installations.	Several relative temperature criterion (ΔT criterion) were adopted for assessing the state of electrical equipment.	Thermography is very effective for energy audit and maintenance of electrical installations.
Huda & Taib (2013a)	Performance evaluation of three sets of features namely first-order histogram-based features, GLCM features and component-based intensity.	Three sets of features were extracted by image analysis, which were used as input data for the neural networks.	Component-based intensity features performs better compared to first-order histogram based statistical and grey-level co-occurrence matrix as input data for the neural networks.
Kim *et al.* (2021)	Evaluate the use of IRT image-	ANN object detection	The faster R-CNN approach was

	based fault detection approach for electrical facilities.	algorithms were trained using 16,843 IRT images from power distribution facilities obtained with a thermal camera.	more accurate (63.9% mean average precision) than the YOLOv3 algorithm (49.4%).
Wang *et al.* (2021)	IR detection of thermal defects in substation equipment using convolutional neural network.	CNN model for features extraction and the support vector machine for classification.	The proposed method had a superior accuracy of 99.5%, above the accuracies of existing methods.
Zarco-Periñán *et al.* (2021)	Development of model to determine electric equipment condition at high currents from extrapolations of IRT results obtained at sub-critical current conditions.	Linear extrapolation of temperature and current change values obtained from experiments on thermally aged circuit of connected electrical components.	Accuracy of developed linear approximation model between temperature and current was validated by field experiments.
Cai *et al.* (2020)	Determination of temperature characteristics of ZnO arrestors.	Voltage-current measurements and IR image acquisition under different temperature and current impact conditions.	Relationship between temperature and arrestor non-linear coefficients was obtained and validated.

Descriptions of the faults that occur in common electrical equipment are provided in the following sections with illustrative IR thermal images obtained by monitoring electrical equipment at the University of Nigeria.

A. Transformers

Heat is normally generated in transformers due to hysteresis losses, eddy current losses and dielectric losses resulting in temperature rises within transformer cores and windings. The temperature rises are regulated by cooling with either air or oil, and temperature rises above ambient of 65°C for oil-cooled transformers and 150°C for air-cooled transformers, are typical during normal operation. Inefficient cooling could result from loose or dirty connections, unbalanced loads, overloading, low oil levels at the cooling fins, etc., can cause transformer temperatures to exceed these normal operating conditions. These elevated temperatures tend to appear in the primary and secondary bushing connections, cooling fins, and internal bushing connections of transformers. Among other traditional diagnosis methods, temperature changes in a transformer can be easily monitored using IRT. Figure 4 shows normal and images of a transformer next to a thermal image that reveals regions of low and elevated temperatures.

Figure 4. Normal and thermal images of a transformer

B. Circuit Breakers

A circuit breaker senses the heat produced by current and automatically opens the circuit to protect electrical equipment from damage whenever abnormalities in temperature are detected. Faults in circuit breakers could result from overloaded circuits, power surges, short circuits, and ground faults. These faults could be easily detected by monitoring temperature changes via IRT. The thermogram of a circuit breaker shown in Fig. 5 clearly reveals in bright colours, the components at elevated temperatures.

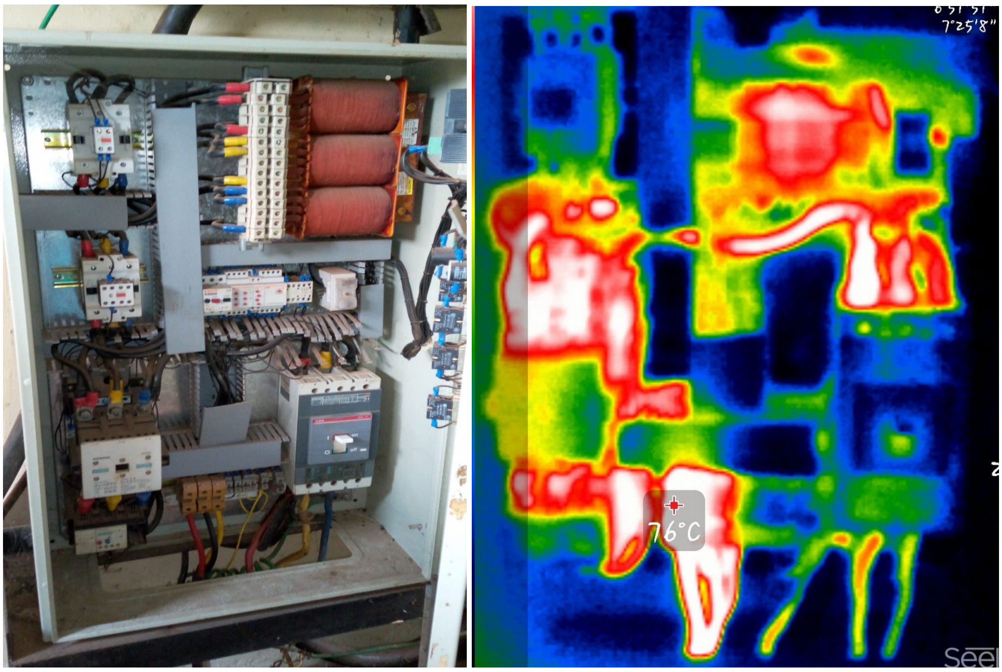

Figure 5. Normal and thermal images of a circuit breaker

C. Feeder Pillars

Feeder pillars are the first set of protection devices at the secondary side of transformers from which power is distributed. As shown in Fig. 6, a typical feeder pillar comprises an enclosure, bus-bars, incoming units, outgoing units and fuses. These fuses permit the flow of current in normal operation, but short circuit to cut power to electrical appliances as a safety measure, to protect the systems against overloading and overheating conditions. Overheating in feeder pillars could occur at the fuse clips, resulting from faulty (loose or dirty) connections of the incoming and outgoing unit cables (Sun *et al.*, 2016). IRT is a fast and effective means of monitoring the thermal condition of feeder pillars.

D. Surge and Lighting Arrestors

These devices divert lightening charges to the ground, and thus protect equipment from damage due to lightening strikes. Most arrestors employ a metal oxide varistor (MOV), which is a semiconductor sensitive to voltage. At normal voltages the arrestor acts as an insulator, while at the higher voltages encountered in lightening strikes, it acts as a conductor, directing the lighting charges to the ground (Jadin & Taib, 2012). A normal image of an arrestor is shown in Figure 7 along with IR images of an arrestor before and after being subjected to a 50 Hz 18 kV current (Lisowska-Lis, 2019). Faults developed in the operation of arrestors leads to generation of centralised heating, which can be quickly detected using IRT.

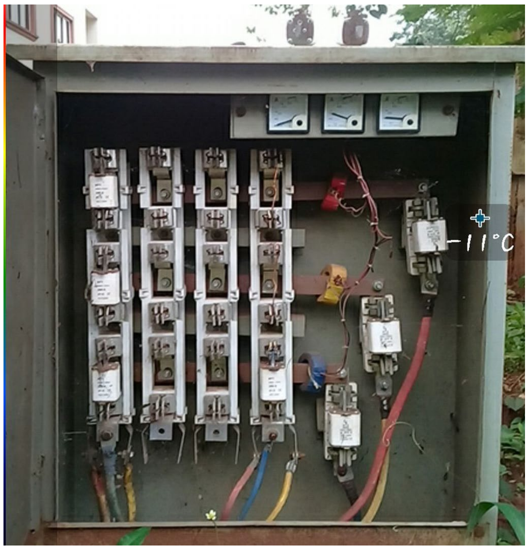

Figure 6. A feeder pillar

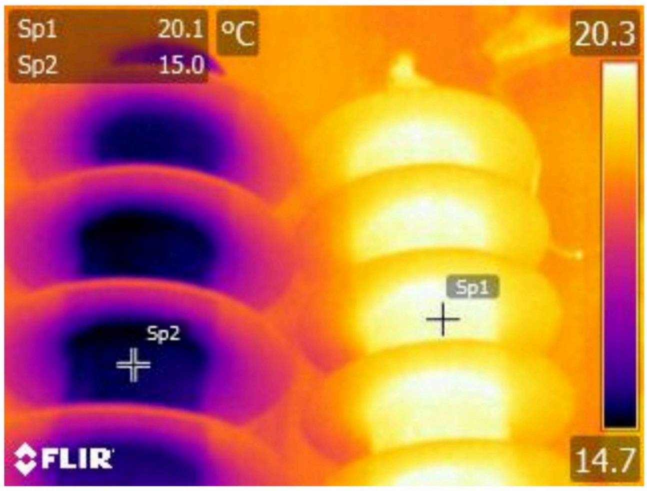

Figure 7. Normal (Power Quality World, 2011) and thermal images of an arrestor (Lisowska-Lis, 2019)

VI. CONCLUSION

Opportunities clearly exist for further applications of infrared thermography as a condition monitoring technique for electrical devices. Presently, the run to failure approach is the most widespread in maintenance activities, in which only corrective maintenance of facilities is carried out. This paper has illustrated instances in which IR thermography has been effectively applied in the predictive maintenance of electrical installations. The widespread replication of these will aid in reducing the high costs of maintenance and equipment replacement and reduce time losses associated with current methods.

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