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Review

A Review of Infrared Thermography for Condition-Based Monitoring in Electrical Energy: Applications and Recommendations

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Abstract: Condition-based monitoring (CBM) has emerged as a critical instrument for lowering the cost of unplanned operations while also improving the efficacy, execution, and dependability of tools. Thermal abnormalities can be thoroughly examined using thermography for condition monitoring. Thanks to the advent of high-resolution infrared cameras, researchers are paying more attention to thermography as a non-contact approach for monitoring the temperature rise of objects and as a technique in great experiments to analyze processes thermally. It also allows for the early identification of weaknesses and failures in equipment while it is in use, decreasing system downtime, catastrophic failure, and maintenance expenses. In many applications, the usage of IRT as a condition monitoring approach has steadily increased during the previous three decades. Infrared cameras are steadily finding use in research and development, in addition to their routine use in condition monitoring and preventative maintenance. This study focuses on infrared crucial thermographic theoretical stages, experimental methodologies, relative and absolute temperature requirements, and infrared essential thermographic theoretical processes for electrical and electronics energy applications. Furthermore, this article addresses the major concerns and obstacles and makes some specific recommendations for future development. With developments in artificial intelligence, particularly computer fiction, depending on the present deep learning algorithm, IRT can boost CBM analysis.

Keywords: condition-based monitoring; diagnosis; fault detection; infrared thermography; non-destructive

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1. Introduction

Condition-based maintenance (CBM) is described as the process of seeing and documenting significant changes in tool variables, including machine noises, temperature, and soil conditions that might indicate a future failure. Maintenance or other preventative measures can be arranged to resolve the issue(s) before it develops into more catastrophic shortcomings [1] by continuously monitoring equipment status and noting any abnormalities that would ordinarily limit an asset's lifespan. Figure 1 shows how CBM differs from prognosis and diagnosis, even though recognizing defects is an essential aspect of all three. The definitions listed below are all viable options.

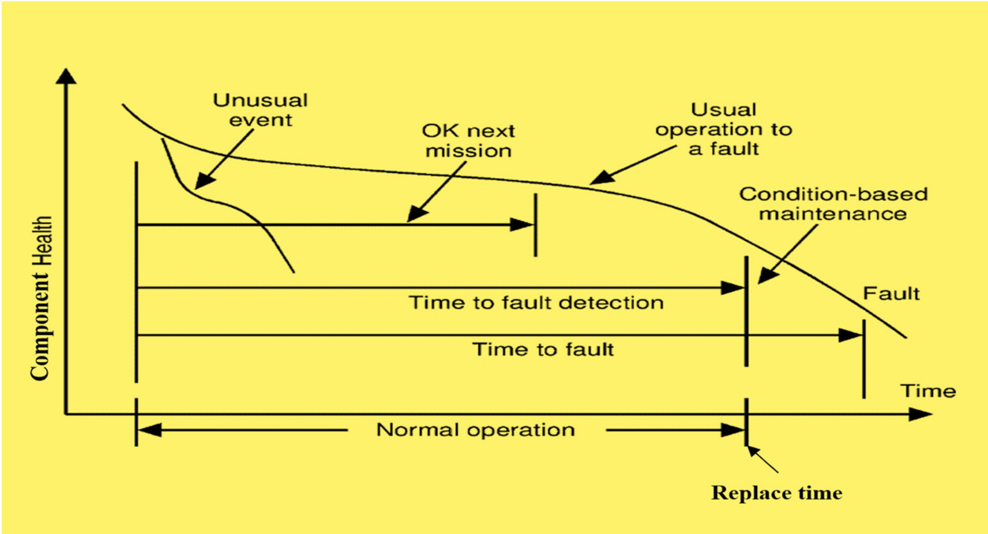

Figure 1. Fault prognosis, diagnosis, and CBM scheme [2].

Figure 1 [2] shows the fault prediction, diagnosis, and CBM systems. The fault incidence is to blame for the rise in health levels. The prediction issue may be divided into two types. The first form of forecast may only have a limited time horizon—is the component fit to fly the next mission? The second kind is to estimate how much time we have before a certain issue occurs, and hence how much time we have until we should replace it. Diagnosis analyses the fundamental cause of a malfunction after it has happened; prognosis evaluates a component's present health state. CBM evaluates the status of an element in real-time so that it may take appropriate action if it wanders away from its healthy state [3]. It forecasts the component's health at some point in the future.

Because it provides adequate infrared images of a device component with no physical attachments (non-intrusive), needs little arrangement, and provides data in a short period, IRT is an advanced system in CBM to evaluate anomalous thermal behavior in machinery [4]. IRT has played a significant role in predictive and preventive maintenance programs, particularly for electronic components, because of its benefits of being non-contact, independent of electromagnetic interference, secure, and able to give a comprehensive assessment scope [5–7]. By monitoring the quantity of infrared radiation emitted by the device, IRT is often utilized to assess the thermophysical properties of electrical items (temperature). Although the electrical equipment inspection technique is relatively simple, there are a few factors to consider, such as environmental influences and the state of the equipment, which will generally influence the study's outcomes, particularly outdoor inspections, such as in power distribution systems. The IRT device, the electrical equipment to be checked, and data interpretation skills are hurdles for a skilled electrical system thermographer [8]. According to [9], bearing (41%) and winding (37%) failures account for most induction motor faults. Because it may cause an increase in motor surface temperature, the inter-turn issue is the more serious of the two. This may result in a complete loss of phase and lethal short circuits in the worst-case situation. Any three-phase induction motor must be linked to a three-phase alternating current (ac) power source of rated voltage and load for optimal operation. Even if one of the three-phase supply cables is unplugged once these three-phase motors are started, they will continue to operate. Single phasing is the loss of electricity via one of these phase supplies. Special protective relays that can identify and isolate the linked loads may detect single phasing. Overcurrent and negative phase sequence relays are used in smaller motors. Protection against single phasing is standard on motor protection relays for bigger motors [10]. Furthermore, a short circuit relay protects against excessive currents or currents that exceed the equipment's permitted current rating, and it works fast. The gadget trips and breaks the circuit as soon as an overcurrent is detected [11]. On the other hand, the cooling system's failure might be to blame for the induction motor's temperature increase. Infrared thermography can be used to identify this condition, although there is relatively little literature on the subject [12,13].

The theoretical phases of thermography and thermal imaging were mainly explored in Section 2 of this article, which concentrated on thermal radiation's underlying concepts and functioning. The evaluation criteria for infrared thermography in condition monitoring are divided into two sections: relative temperature criteria and absolute temperature criteria, introduced in Section 3. Section 4 thoroughly presents the state-of-the-art Algorithms and Methods of IRT. IRT has been effectively used in Section 5 for various condition monitoring applications, including electrical and electronic motor equipment inspection. Despite the ongoing study, several existing and future concerns and challenges connected to the IRT in CBM must be addressed. Sections 5 and 6 explain the results and suggestions, respectively.

2. Theoretical on Thermography and Thermal Imaging

The cornerstone for IRT is the physical phenomenon that anybody with a temperature over absolute zero (−273.15 °C) emits electromagnetic radiation. The strength and spectrum composition of emitted radiation from a body is inextricably linked to its surface. Calculating the radiation intensity of an object may be used to determine its temperature in a non-contact method [14]. Figures 2 and 3 demonstrate the electromagnetic spectrum and emissive power distribution as a function of wavelength, respectively.

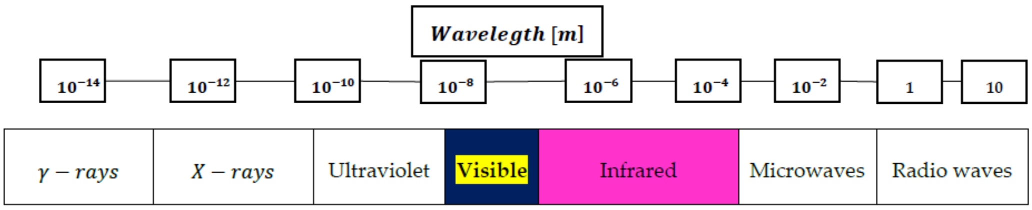

Figure 2. This Electromagnetic spectrum [15].

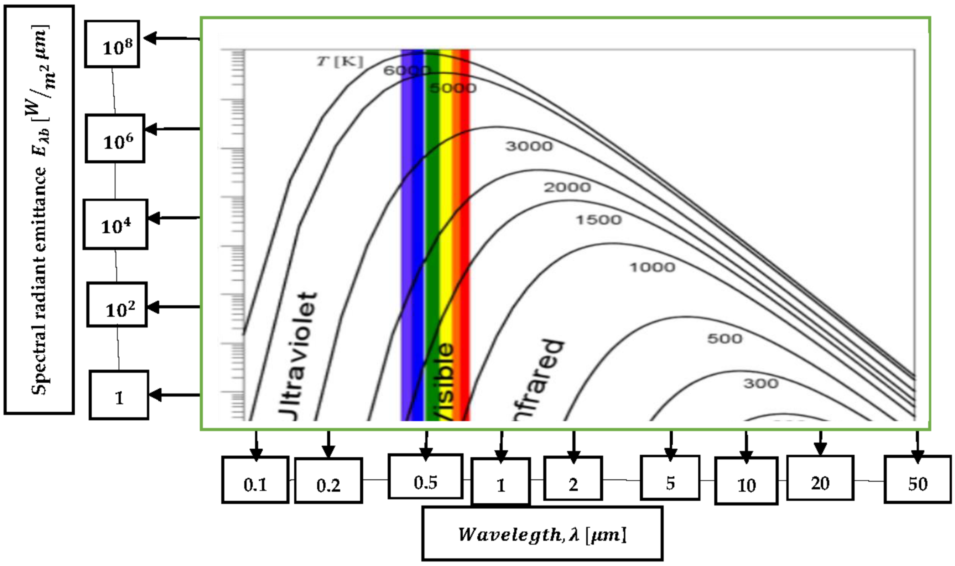

Figure 3. Distribution of emissive power with wavelength [16].

Amongst the most significant benefits of IRT-based condition monitoring is the minimal amount of equipment needed. The equipment includes a thermal camera, a tripod or camera platform, and video output devices to show the gathered infrared thermal pictures for such applications. Infrared cameras have progressed through three generations since their inception [17]. Zhang et al. [18] and Wan [19] go into considerable detail about the creation and basic concepts of various infrared sensors. The first cameras employed a single element sensor and two scanning mirrors to create pictures. They were apprehensive about the possibility of whiteout (i.e., saturation owing to high intensity). The second-generation cameras used two scanning mirrors, a significant linear array or a tiny 2-D array as detectors, and a time delay integration system for picture improvement. The lack of mirrors in third-generation cameras and the use of large focal plane array (FPA) sensors and on-chip image processing leads to higher system dependability and sensitivity [17]. The two kinds of thermal detectors are cooled and uncooled. Modern solid-state advancements have cleared the road for developing novel sensors that are more precise and have better resolutions. Uncooled cameras have a thermal sensitivity of about 0.05 degrees Celsius (°C), while cooled cameras have a thermal sensitivity of 0.01 °C [20]. These cameras provide excellent spatial and temperature solutions, compactness, and mobility to mention a few benefits. Furthermore, these cameras are lighter, use silicon wafer technology, and are less costly than cooled infrared cameras [21,22]. As a result, current IRT technology will aid electrical utilities for CBM analysis since all advancements will provide accurate data analysis using recent AI algorithms in computer vision.

A standard experimental setup for IRT-based condition monitoring research can be seen in Figure 4. The produced thermal pictures are exhibited on a computer, enabling the specific temperature of the object to be calculated without touching it. The obtained thermal pictures are often pseudo-color-coded, making interpretation more straightforward and faster. The source snapshot and a typical infrared thermal picture of a structural element are shown in [20].

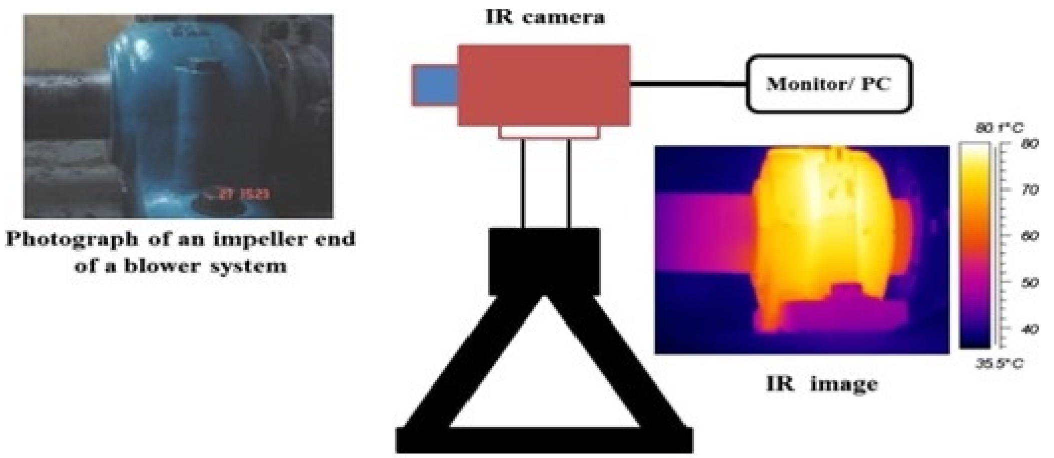

Figure 4. Schematic of a typical experimental setup for IRT.

Before selecting an infrared camera, many factors must be examined since the ability to create a clear and accurate thermal picture is highly dependent on these performance criteria [23]. A few key factors are covered further down.

2.1. Spectral Range

The spectral range is the region of the infrared spectrum where the infrared camera will work. The thermal radiation that an item generates gets more concentrated in shorter wavelength bands as its temperature increases. For observing objects at ambient temperature, a long-wavelength band (7.5–14 µm) is preferable. This is due to two factors: first, bodies at room temperature emit mainly at these wavelengths; second, measurements taken at some of these wavelength ranges are unaffected by solar radiation (accurate for outdoor measurements) since solar radiation is primarily in the relatively short wavelength bands. The use of short wave (2–5 m) technology is recommended [8].

2.2. Spatial Resolution

Temperature resolution refers to the minor temperature fluctuation seen by the infrared camera in view. Object temperature, ambient room temperature, object to camera distance, filters, and other experimental factors all affect temperature resolution. Noise equivalent temperature difference (NETD), minimal resolvable temperature difference (MRTD), and minimum detectable temperature difference (MDTD) are the most often utilized temperature resolution criteria. NETD readings for Stirling cycle cooled cameras at room temperature are usually smaller than 0.025 Kelvin (K) [20].

2.3. Spatial Resolution Laser Pointer and Interchangeable Lens

To see where the camera's lens is aimed and prevent coming into close contact with hot regions, laser pointers may be utilized. You may change lenses based on your requirements using interchangeable lenses. Flexibility with external equipment and measuring equipment, as well as speedy data transfer through cable, Wi-Fi, and Bluetooth, and the inclusion of text and voice feedback, are all benefits [24]. The thermal camera has become a more helpful instrument.

2.4. Temperature Range

The temperature range specifies the temperature values that an infrared camera can detect at the highest and lowest levels. Temperatures typically range from 20 degrees Celsius (°C) to 500 °C. Different filters may be used to extend the content up to 1700 °C [20].

2.5. Frame Rate

The number of frames acquired every second by an infrared camera is the frame rate. Higher frame rate cameras are often preferred for monitoring motion information or dynamic events like the propagation of heat fronts. The standard frame rate is 50 Hertz (Hz) [20].

2.6. Accuracy

The precision with which the thermal camera measures the temperature is reflected in its accuracy. The advanced thermal camera is accurate to within 1 percent (%) [25].

3. Experimental Methodologies

It is advised that severity criteria be established when employing infrared thermography for condition monitoring in electrical equipment. There are two types of severity criteria: generic categories that specify temperature levels, and particular sorts of equipment or components. With the collection of data, severity criteria evolve. Based on the equipment's design, operation, installation, maintenance characteristics, criticality, and failure causes, it is essential to create severe standards for each kind of material. The relevance of the device or component to the overall strategy, protection, and so on are all considerations that go into setting severity criteria for specific devices or components. Thermographers use temperature increases to detect temperature intensity or structural faults in essential equipment, mechanical parts, bearings, electrical supply, and more [26,27].

- Relative temperature criteria: A collection of safety requirements depending on the temperature increases separated into groups is referred to as "relative temperature criteria". We can have advisory, intermediate, severe, and critical kinds in electrical machines. You may have a rule that says if a machine's temperature climbs 10 degrees over a baseline temperature, it is considered advisory. It is deemed to be critical when a device's temperature rises beyond 104 degrees above a connection or baseline temperature.
- Absolute temperature criteria: To determine the maximum permissible temperature, a thermographer may utilize material or design parameters obtained from previously published data. When the emphasis of the monitoring is on the machine's material, material criteria are employed, whereas design criteria are utilized when the attention is on the machine's design. Despite the fact that the criteria are segregated into these two groups, the material element is often included in the method, making it an adequate criterion for monitoring dependability. The component material with the

lowest temperature specification should be utilized as "alert criteria" if you are using material criteria to assess the heating of many surrounding components.

- Profile Assessment Criteria: A profile assessment procedure is used to examine temperature differences and trends over any surface. To do a profile evaluation in thermography, you must first establish the absolute and differential temperatures by performing a severity assessment. The state of the machine or component will be classified into two parts: "as new" and "failed." According to Hitchcock, temperature profile, historical trends, regional variations, absolute temperatures, and the region of anomalies are all essential aspects of a profile investigation.

3.1. Classifying of Thermographic Techniques

There are two types of experimental approaches to thermographic methods: active and passive.

3.1.1. Active Thermography

When the temperature difference is difficult to see and external stimulation is exposed on the surfaces of the objects, active thermography, also known as adaptive, non-equilibrium, and non-steady-state thermography, is often utilized [28]. Active thermography needs an external heat source to activate the materials under test. A heat gun, hot water jets, hot air jets, or a hot water bag might be used as the initial heat source. Optical heat sources include high-power cinematographic lamps, quartz line IR lamps, high-power photography flash, and laser beams [29].

3.1.2. Passive Thermography

The item's temperature under inquiry is recorded without any external heat stimulation since the material alone functions as a source of heat in passive thermography. It is feasible to assess the condition of structural components, such as rotor blades, from the earth's surface without halting their operations using passive thermography. Periodic pressures during blade rotation generate heat, and defective locations may be diagnosed using accurate heat flow dynamics [30]. In mechanical testing, passive thermography may also be utilized to detect the degradation and thermomechanical behavior of the composite [31].

3.2. Image Acquisition for Thermographic Images

The following thermal images were taken using a thermal infrared camera from the main switchboards of numerous buildings. An FPA detector with a pixel size of (160 × 120), spectral coverage of 7.5 millimeters (mm)–14 mm, and thermal sensitivity of 0.1 at 30 °C was used in this camera. In the 368 images, there are 500 hot components, each with its own priority level. Each piece of equipment has one or more hot ingredients as well as a reference or standard feature. The thermal imager was directed firmly at the target electrical equipment to acquire a precise measurement while collecting the imaging. The distance between the infrared camera and the target electrical equipment was 0.5–1.0 m. As recommended for essential electrical equipment, the emissivity was tuned to 0.95 [32]. The ambient temperature of the equipment was about 30–33 °C throughout the inspection. Manual condition classification of electrical equipment is performed in this research using a qualitative classification approach known as the ΔT (temperature difference) criterion [33]. The ΔT criterion is determined by calculating the temperature difference between the hotspot and the reference site. The temperature of a malfunctioning component that is higher than the reference location is known as the hotspot temperature, where the reference location is the same kind, load, or repetitive component of the equipment with the lowest temperature. According to the priority level, the circumstances are categorized into two classes, normal and faulty, which are shown in Table 1 with their accompanying suggested measures.

Table 1. ΔT values and necessary steps regarding component thermal condition.

Thermal Condition	Priority Level	ΔT (°C)	Recommended Actions
Overheated	I	$\Delta T \geq 15$	Significant disparity; must correct it immediately
	II	$5 < \Delta T < 15$	Repair as soon as possible if there is a potential defect
Normal	III	$\Delta T \leq 15$	Overheating of a minor kind demands further study

Figure 5 shows a thermal picture of equipment in the following states: (a) overheated (priority 1), (b) overheated (priority 2), and (c) standard. Area B is hotter than regions A and C, as shown in Figure 5a. Figure 5b depicts A as being overheated in comparison to B and C, while Figure 5c illustrates B and C as being overheated in contrast to A. Consequently, the reference components in Figure 5a–c are, respectively, areas A, B, and C. An automated solution is necessary since the existing approach relies significantly on human segmentation of key regions for CBM analysis on electrical equipment using classic image processing methods [34]. Figure 5 shows how high-resolution thermal imaging expert information may be utilized as prior knowledge in AI modeling to measure the ΔT (temperature difference), which is among the most crucial metrics in the CBM analysis of electrical instruments.

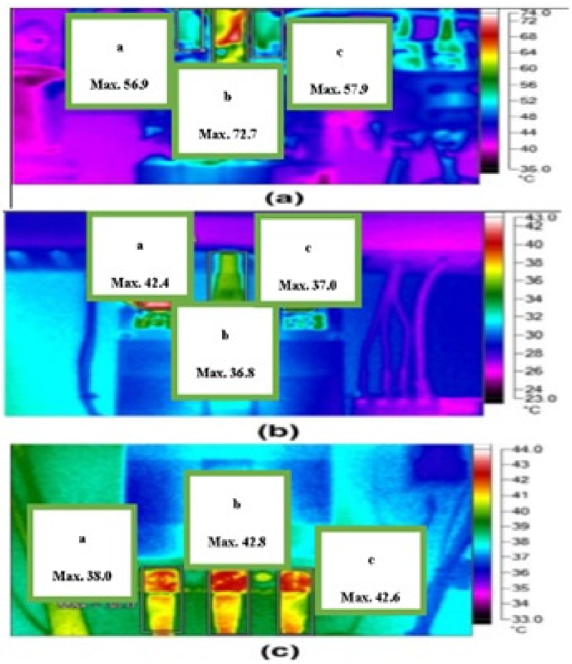

Figure 5. Thermal images. (**a**) overheated, (**b**) overheated, and (**c**) standard.

3.3. Image Processing and Feature Extraction

The thermal picture is turned into a greyscale image at the image processing step, which contains the image's intensity information. The malfunctioning zone in the greyscale picture is brighter than the typical recurring region in the equipment. The thresholding approach is widely used to identify faults in thermal images [35,36]. Manual thresholding takes a long time and requires more human effort to notice a defect. To identify flaws in electrical equipment, a modified maximum entropy-based Kapur thresholding approach was developed [37]. On the other hand, the suggested method can only deliver the crucial feature with specific user-defined threshold values. Three sets of characteristics are taken from the areas of interest once the target regions have been detected. Figure 6 displays multiple thermal grey pictures and their associated images after thresholding.

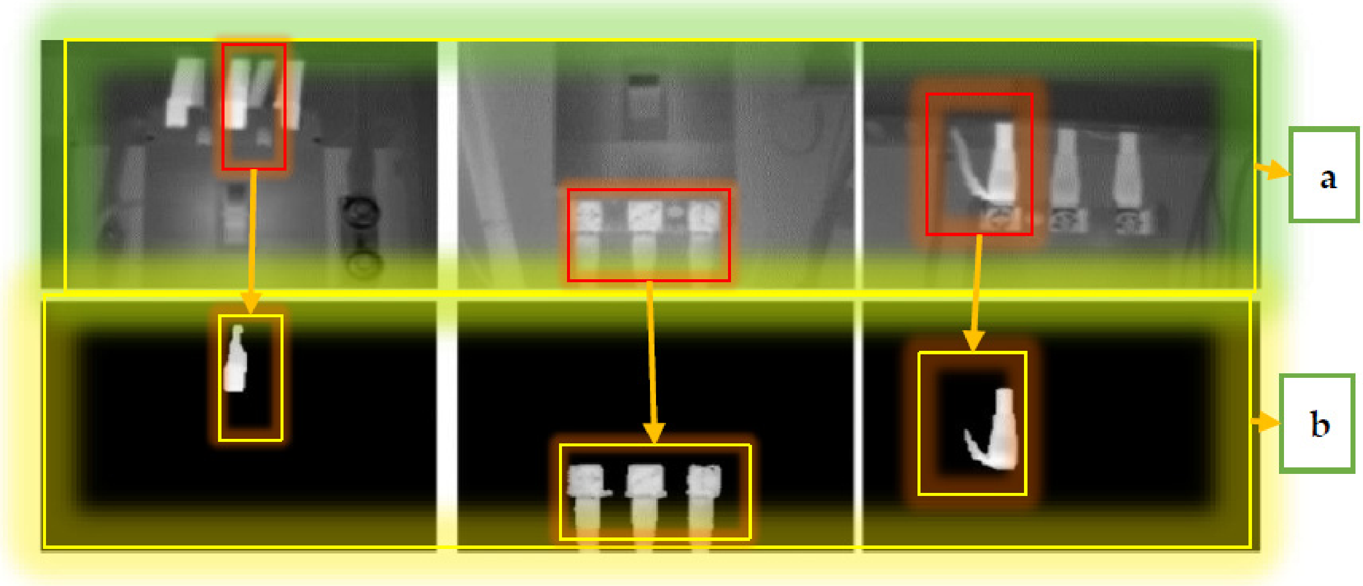

Figure 6. Some thermal grey images and their corresponding pictures after image processing: (**a**) gray scale image, (**b**) segmented image [34].

3.4. IRTs Typical Condition Monitoring for Electrical Equipment

The temperature comparison between hot and reference regions is used for manual component condition monitoring [34]. Qualitative ΔT factor analysis is the name given to this procedure. Once the thermal images have been acquired, and a color map has been evaluated, the hotspot and reference areas are visually identified. The hotspot allows complicated components to reach their maximum temperature. However, the reference region supports the lowest temperature of the same sort, load, or recurring element in the equipment. The ΔT factor, utilized as decision-making criteria for the overheated component's state, is calculated using the ratio between the hotspot and reference spot temperatures. The ΔT factor may be calculated just with RGB data. The International Electrical Testing Association (NETA) [8], the American Society for Testing and Materials (ASTM): E 1934-99a [38], the National Fire Protection Association (NFPA), the military standard: MIL-STD2194 [39], and the Allen-Bradley motor control center standard [39] are just a few of the most commonly used standards. Because of its simplicity and low emissivity impact, it is often employed in electrical thermography. The most significant disadvantage of this method is that it will not function in a three-phase system since all phases would overheat simultaneously. The flowchart of an IRT evaluation of a three-phase electrical system [40] is shown in Figure 7.

The following are the infrared thermographic examination methods exhibited in Figure 7:

- Temperature trends are compared between stages. The temperature is uniform with a balanced load and under typical operating circumstances.
- For each phase, the conductor route is traced. There are no hot patches or temperature gradients on the conductor.
- If the metal enclosure blocks the current-carrying elements of the switchgear and electrical junction during scanning, the camera will show the heat pattern generated by the sheet metal. Between stages, the picture is compared to the internal components and the heat pattern. The heat pattern associated with load currents is linked to switchgear trended data.

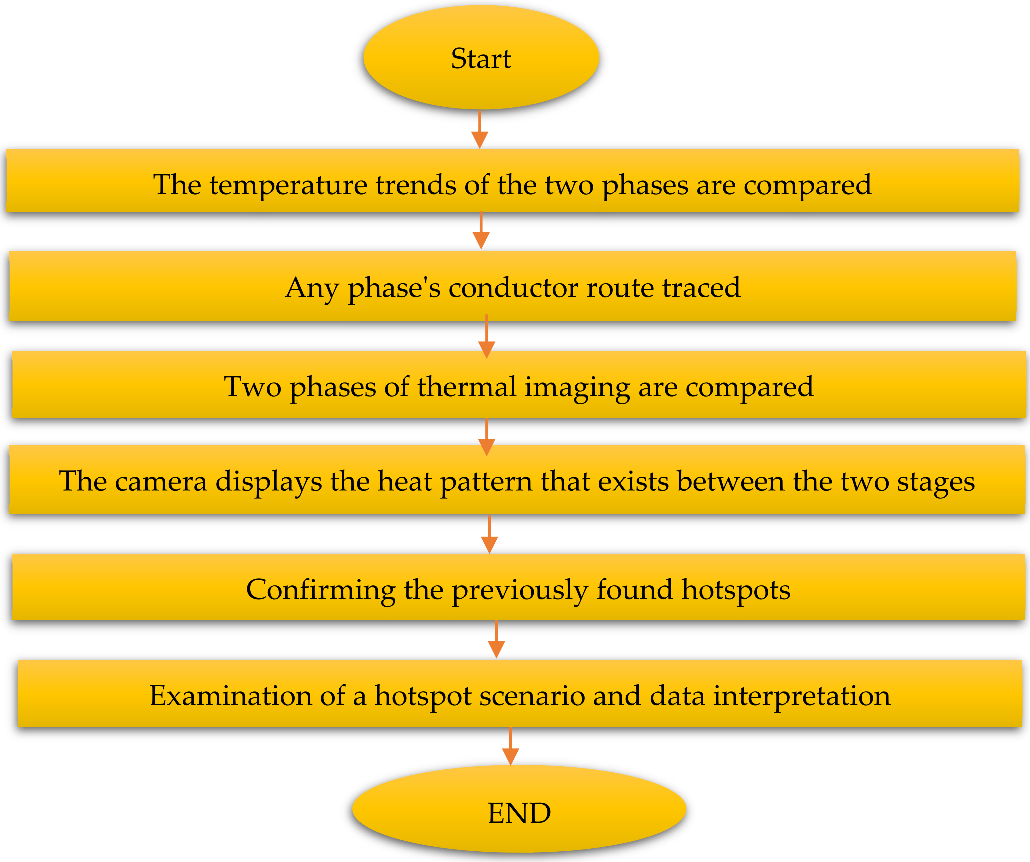

Figure 7. Infrared thermographic examination flowchart [41].

4. The State-of-the-Art Algorithms and Methods

Statistical characteristics are retrieved using the K-means algorithm, and a support vector machine (SVM) is used as a classifier in our method. A coarse-to-fine parameter optimization strategy is used to improve the classification performance of SVM.

4.1. K-Means Algorithm

K-means [42], sometimes known as K-average, is a clustering technique. The representative point of each cluster subset is the mean of all data in that cluster. The main concept behind the K-means method is to partition a dataset into distinct categories via an iterative process, with the goal of optimizing the criteria function for assessing clustering performance. Distance (e.g., Euclidean distance, Manhattan distance, or Minkowski distance), error sum of squares, or cluster mean are all regularly used criteria functions.

An infrared picture without a temperature scale is first transformed into a greyscale image, which contains the image's intensity information. In a greyscale picture, the problematic areas in equipment seem brighter than the usual parts [34]. The K-means algorithm is then used to cluster this greyscale picture into k sections. The lowest, mean, median, and maximum grey values, as well as the area (total number of pixels) in each cluster, are all easily determined.

Figure 8 depicts the flow chart for extracting statistical characteristics using the K-means algorithm. The following is a description of the procedure:

- Convert a thermal picture to a greyscale image and set up cluster centers for each of the k groups.
- All points in the picture should be clustered into k groups based on their minimal distance.
- Calculate each cluster's mean value and use it as the new cluster center.
- Steps (2) and (3) should be repeated until the cluster centers do not change.

- Each picture is divided into k areas, with grey values ranging from tiny to big being colored differently.
- Obtain the minimum, mean, median, and maximum grey value and area information for each cluster, and then the temperature information for each cluster.

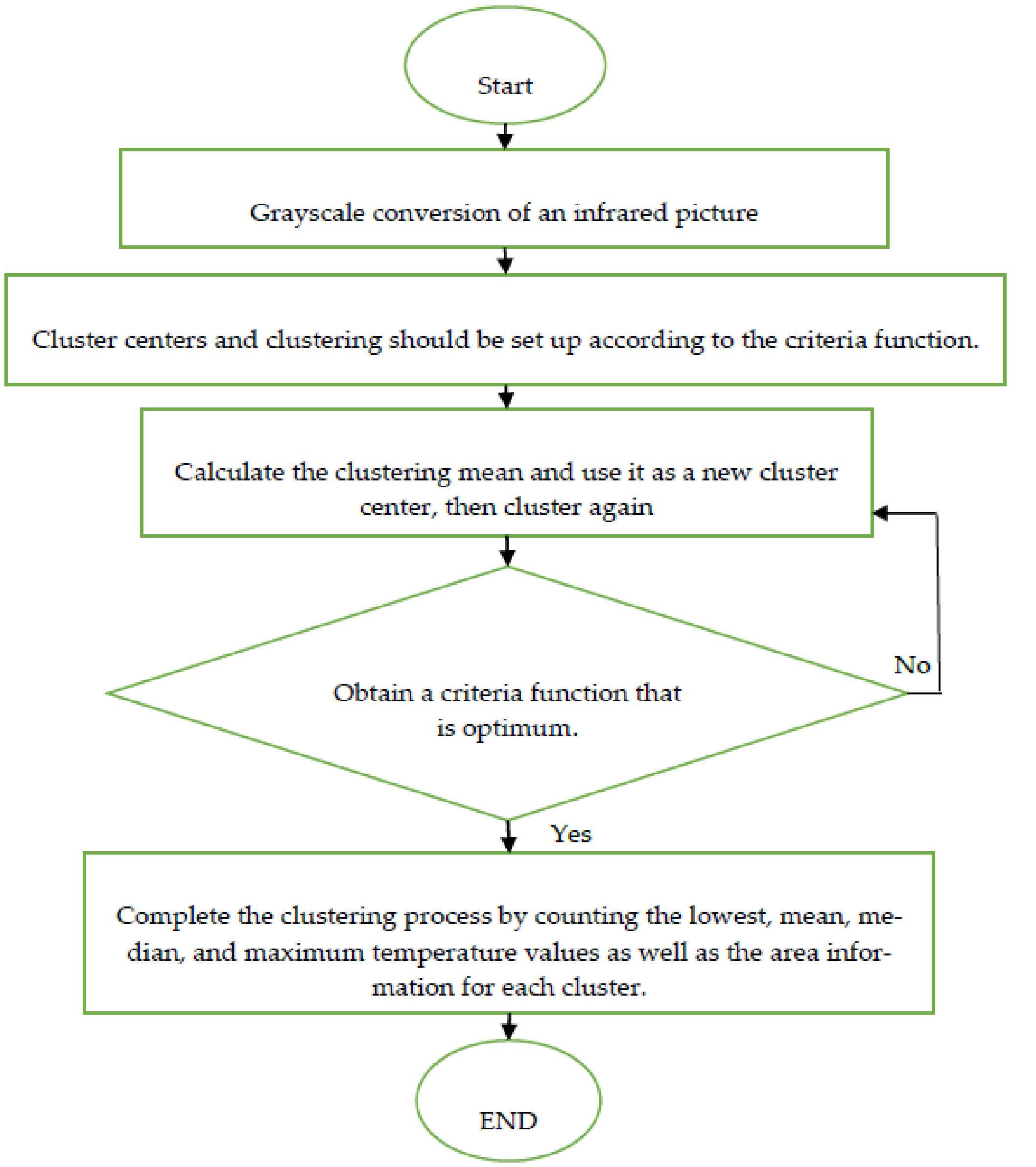

Figure 8. Flowchart of the K-means method for extracting statistical characteristics.

4.2. SVM Parameter Optimization

The support vector machine (SVM) is used as a classifier, which is a learning system that estimates decision surfaces directly rather than modeling a probability distribution across training data using a hypothesis space of linear function in a high dimensional feature space, and the Gauss function is usually used as the radial basis function (RBF) kernel. SVM is extensively used because it has several appealing qualities, including good overfitting avoidance, the capacity to handle vast feature spaces, and data condensing [43]. The choice of punishment parameter C and kernel function g has an impact on SVM classification performance [44]. Gradient descent, simulated annealing, ant colony optimization, genetic optimization, particle swarm optimization, and more SVM parameter optimization techniques are available [45].

A parameter optimization strategy from coarse to fine is described to enhance the classification performance of SVM. To begin, the punishment parameter C's and the kernel function g's scope and step length are both initialized. The most accurate parameters are then discovered by exploring the mesh parameter grid using cross-validation. Finally, by doing a chaotic search of logistic sequences around the parameters acquired in the first step, the global approximation optimum parameters are produced. The parameters obtained in the preceding two processes are used to train and test individually, with the best result being utilized as the final result. Our technique has the benefit of being able to rapidly determine global approximate optimum values.

The stages in the SVM parameter optimization process are described in Figure 9.

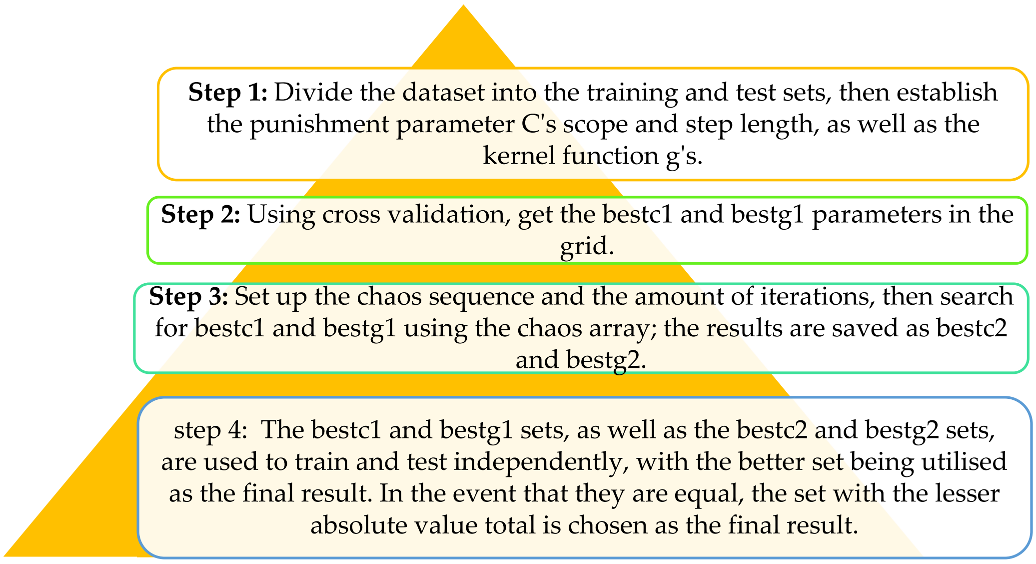

Figure 9. SVM parameter optimization process.

5. IRT Applications in Condition Monitoring for Electrical Energy

Component failure is mainly caused by excessive heat and resistance. Figure 10 shows how infrared cameras monitor this heat, which may be employed in several applications. An infrared camera detects the IR energy of an object, converts it to temperature, and displays the temperature distribution for structural health monitoring and non-destructive examination [46]. Thermography is a valuable diagnostic technique in the electrical sector that is crucial to assessing problems across various assets such as switchboards, transformers, cables, and other electrical components with electrical defects and high resistance connections. Non-contact temperature monitoring systems have grown in popularity as online condition monitoring technology has become an unavoidable aspect of today's maintenance plan. As online condition monitoring technology has become an inevitable part of maintenance strategies in today's scenario, with loss of insulation materials (e.g., refractory) in high or low-temperature process equipment, damage to rotating equipment, electrical and cooling issues that are not visible to the naked eye, non-contact type monitoring strategies have become more popular. Non-contact temperature monitoring systems have grown in popularity as online condition monitoring technology has become an unavoidable aspect of today's maintenance plan. Infrared thermography [47] is a non-contact method of obtaining a precise, reproducible surface temperature profile. The applications for which infrared thermography may be used are shown in Figure 11.

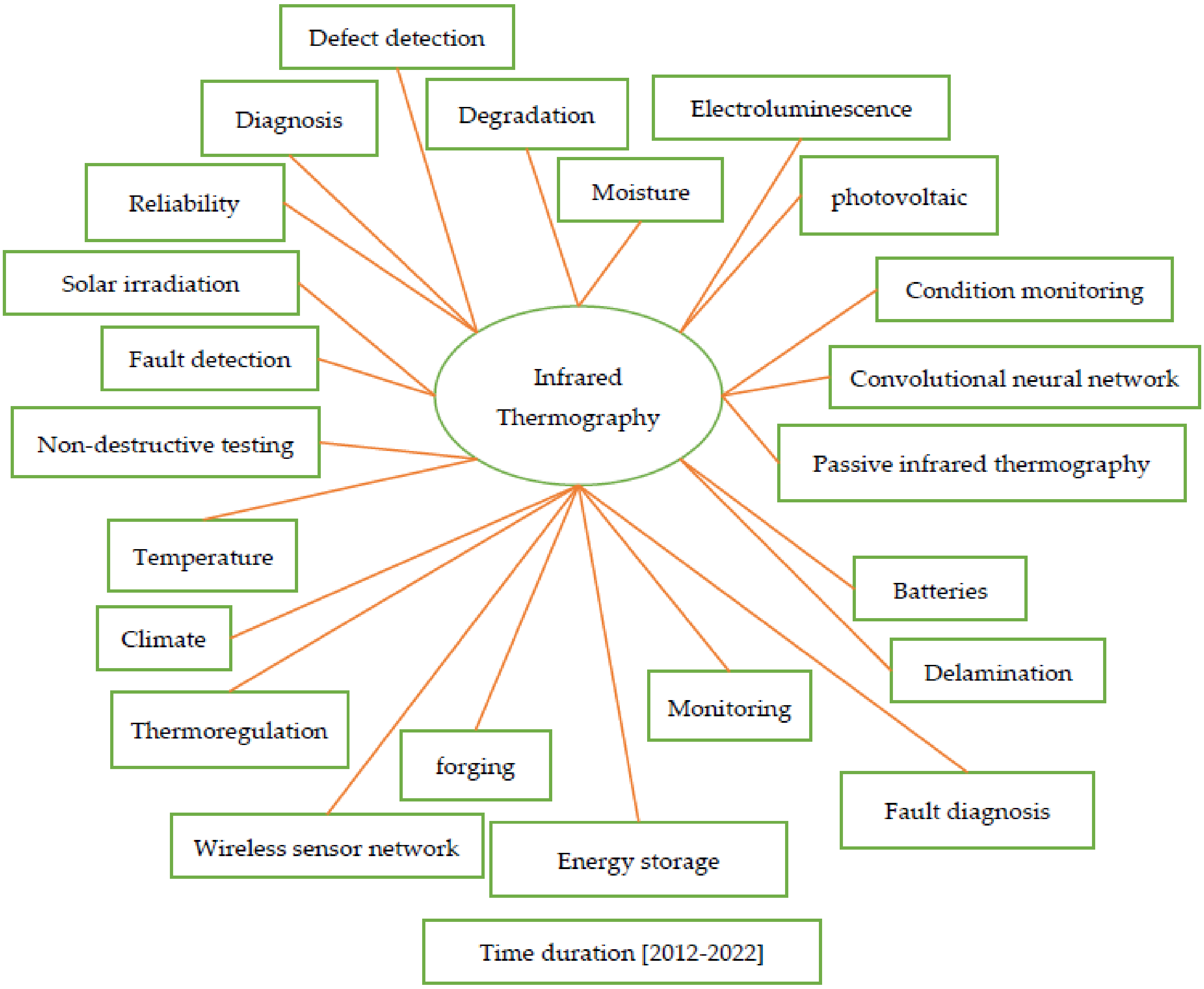

Figure 10. Keyword co-occurrence map in the context of IRT [48].

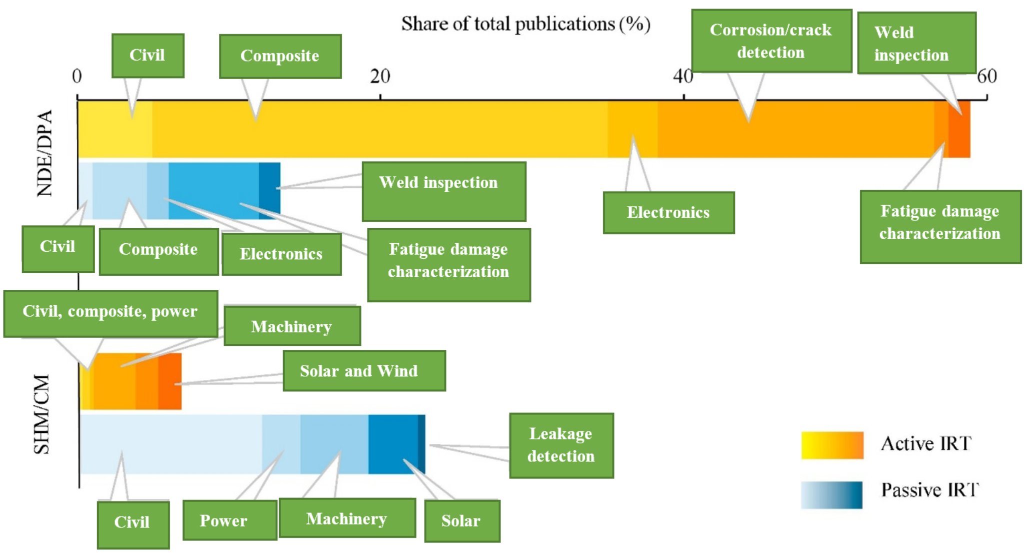

Figure 11. Different methods and applications of IRT [49]. (SHM: Structural Health Monitoring, CM: Condition Monitoring. NDE: Non-Destructive Examination, DPA: Destructive Physical Analysis).

5.1. Results in the Electrical and Electronics Applications

According to numerous assessments, IRT thermography is widely employed in the electrical and electronics engineering field [8,39,50]. Many of the applications in this field are connected to industry, but they also include tertiary sectors, transportation, and power plants, to name a few. The maintenance of electrical systems is an essential application of IRT. Experts have used the IRT camera for years to inspect panel boards, bus bars, electric cables, and other critical elements of these installations like transformers, power meters, or capacitor banks for reactive power compensation [39,51–57], where experts use the IRT camera to observe the correct operation of the equipment based on established limits. For electrical and electronic applications in condition monitoring, Bellow identified numerous criteria, examples, and methodologies.

5.2. Hotspot Detection

The easiest approach to find the hotspot inside the IRT picture is to use segmentation. The authors of [58] compare many picture segmentation approaches and discuss their advantages and disadvantages. Because of its straightforward implementation, the thresholding approach has become a popular picture segmentation technique. The grey-level histogram separates the target object from the background at a defined threshold. The automatic threshold technique of the T. Otsu method is widely used in many applications. Capacitors, transformers, and other electronic components have been utilized to identify flaws using the Infrared Thermal Anomaly Detection Algorithm (ITADA). ITADA is based on Otsu's statistical threshold selection technique and detects flaws in capacitors, transformers, and other electronic components using grey-level histograms. Support vector machines (SVMs), used to segment color images, have a promising future. In [59], it is shown how to segment stochastic photos using random walker segmentation based on partial differential equations (PDE). Additionally, ref. [60] describes the use of thermographic image processing to identify faults in lightning arresters. To perform fault categorization, it utilized a collection of neuro-fuzzy networks. The neuron-fuzzy classifier is used to detect faults. It is also possible to use edge-based segmentation algorithms such as the Robert, Sobel, Prewitt, and Canny operators [61]. This approach identifies the moment when grey level intensity levels abruptly shift. Color picture segmentation may be done using spectrum analysis. However, previous information about the object's hues is difficult to come by. The topic of picture segmentation has seen a lot of research [59,61–65]. However, only a handful have been examined in terms of employing thermal image processing to monitor electrical equipment state [5,33,60,66–70]. Consequently, in the context of electrical equipment condition monitoring, this work focuses on picture segmentation methods for thermographic pictures obtained by IR cameras. The condition of the spinning gear is monitored using various signal processing techniques [71,72], e.g., the implementation of an unsupervised online detection using artificial neural networks (ANNs) has been described in [73]. Yazici et al. [74] have reported an adaptive, statistical time-frequency method for the detection of bearing faults. In [75], a fuzzy fault detector using Concordia patterns was used to detect stator unbalance and open-circuit faults. Broken bar faults can also be detected by time- and frequency-domain analysis of induced voltages in search coils placed internally around stator tooth tip and yoke and externally on the motor frame. Stator fault detection using external signal injection is discussed in [76]. Power transformers' fault detection methods and techniques are also discussed in several articles, e.g., frequency-response analysis (FRA) addressed in [72] is a powerful diagnostic method in detecting winding deformation, core, and clamping structure for power transformers, the multiple linear regression model is proposed in [77], for the early detection of transformers with accelerated oil aging, the vibroacoustic method (first noticed in aviation technology) will be applicable, transformers with a rated power of several tens of MVA [78], and a numerical procedure has been developed using the wavelet transform for processing and analysis of vibration signatures produced by the operation of tap changers [79,80]. In certain circumstances, non-contact thermographic image measurement may be beneficial.

As a result, the current project tries to address these issues. The majority of scholars in this field [59,60,62,66,69,81] have used grayscale for processing. It has been discovered that the Sobel operator performs better for thermal pictures based on several image criteria. Following that, the Otsu approach is used on the identical photos, yielding good results. Figure 12 depicts hot zone identification using grayscale pictures and image processing techniques: (a) RGB image, (b) grayscale image, (c) Prewitt, (d) Roberts, (e) Sobel, (f) Otsu. On the other hand, the offered approaches locate the interest area without classifying the intensity of the equipment's condition, necessitating human determination of crucial parameters, most notably the method's threshold value.

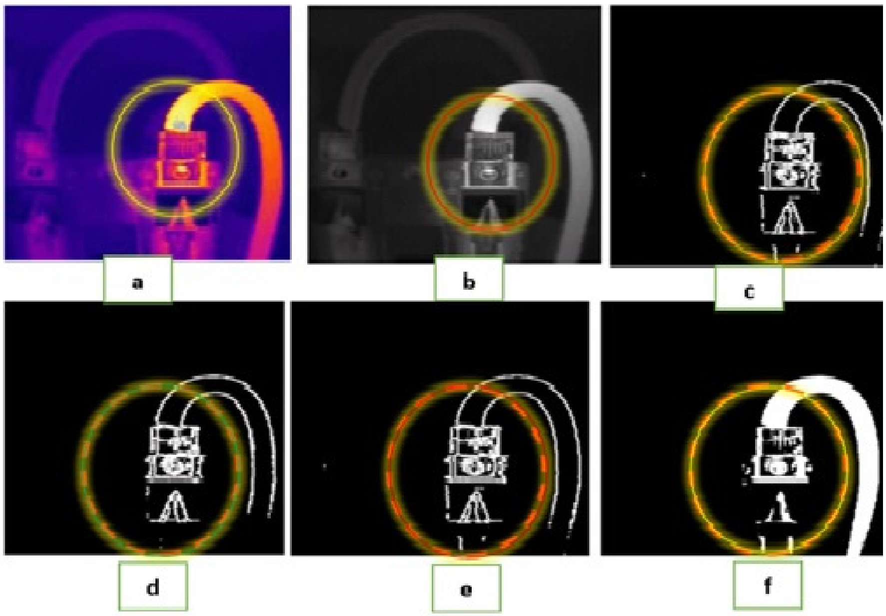

Figure 12. Identification of a hotspot area picture in grayscale: (**a**) RGB image, (**b**) grayscale image, (**c**) using Prewitt, (**d**) using Roberts, (**e**) using Sobel, (**f**) using Otsu [82].

5.3. Improving Inspection Techniques

The quality of measurements has increased as new advances in current IRT equipment have been made. Surface temperature variations of less than 0.1 °C may be resolved by most contemporary IR imagers [83,84]. Despite the advantages of modern IRT camera designs coupled with powerful image processing and display systems, there are still various considerations to consider while performing an inspection, even if temperatures can be reliably detected. This is crucial particularly for outside assessments conducted in substations, underground, and aerial distribution [7]. Procedural, technical, and environmental/ambient variables are the main elements that influence the accuracy of IRT measurements [83,85]. If certified or competent personnel are used, it may reduce the procedural component. The essential technical features are the emissivity of the equipment under examination, load current variation, the distance of the item under inspection, and IRT camera characteristics [83,85,86]. Results may be misconstrued or inaccurate if all these aspects are ignored. Table 2 highlights all the environmental consequences that must be considered when doing an IRT examination [6,83,85–87]. Before beginning, any IRT examination should complete preliminary research. In this case, most thermographers will need some data from the target site. It is sometimes required to investigate the history of the target place and the electrical power equipment. To acquire the most essential and most precise measurement, you need to use a suitable and appropriate tool. IRT devices' long-wave (usually 8–14 m) sensing is ideal for prolonged outside inspections, particularly during bright seasons. This is because thermal detectors in this wave range are more sensitive to ambient temperature objects and have robust smoke transmission [6,88]. Tables 2 and 3 outline all of the criteria for the inspection tools and the target equipment, respectively.

Table 2. Consideration of environmental factors during the inspection.

The Aspect of the Environment	The Impact on the IRT Measurement
Ambient air temperature	When the ambient temperature rises, so does the temperature of the machinery. The IR system becomes less reliable at very hot or shallow temperatures. According to the temperature increase of 0–9, 10–20, 21–49, and >50 °C, the authors classified the severity of the flaw-induced overheating into four types: attention, moderate, severe, and critical [39].
Precipitation/humidity (snow, rain, fog, etc.)	The temperature may drop drastically, causing the data to be misinterpreted. The only moderately heated equipment may be cooled below the abnormal temperature.
Wind or other convection	Wind velocities may drastically cool a high resistance fitting from speeds as minimal as 1–5 miles per hour (mph). The temperature differential between the equipment and the ambient space may be decreased to a few degrees above the ambient space at speeds greater than 5 mph.
Sun or solar radiation	Minor temperature swings will be hidden by the device's sun heating, mainly if it absorbs much solar light (such as old conductors).

Table 3. The characteristics of factors related to the target equipment and the inspection tool.

Tools and Equipment	Characteristic
Electrical Loads	The proper load on the wires must be negotiated with the customer before the inspection. - The load on the line should be at least 40% of the nominal load during the recording. - Approximately 75% of the load is optimum. - When the load is more than 90%, the lines get very hot, making precise identification of overheated spots impossible [86].
Equipment Emissivity	The emissivity of most conductors is between 0.1 and 0.3. While emissivity values as high as 0.97 may be found in greasy, dark, hot, and aging conductors, visual evaluation in the field from a distance is frequently difficult [83,86]. Moreover, there are several non-contact and nondestructive inspection tools that have already been introduced such as the Laser Ultrasound Inspection system, Study of Flip Chip Solder Joint Cracks [89], Laser-SQUID Microscopy, monitoring and Analysis of Large Scale Integration (LSI) -Chip-Defects [90], laser line photoluminescence imaging for outdoor inspections [91,92], Ultrasonic Suspension for force measurement [93], and laser ultrasonic signals from particles suspensions [94].
Thermal Gradient	High-resistance heat is typically generated at the surface on the inside. Thermal gradients exist between the apparatus's hottest point and the surface under investigation [87].
IRT Device (camera)	The observed waveband and the spatial and measurement resolution are all elements to consider [87]. It is also essential to consider the sensitivity and signal processing speed [83].
Distance andAngle	As the distance between them widens, the IRT picture's resolution drops. An acute angle image has less information than one shot at a straight angle.

5.4. Methods of Measurement and Analysis

Electrical equipment's thermal condition may be measured in two ways. The first is known as quantitative, and it involves taking the equipment's precise temperature. The second form is qualitative, which measures a hotspot's relative temperature to other equipment areas under comparable circumstances. Electrical components' evaluation often employs qualitative analysis [35,95]. IRT inspection is governed by the International Electrical Testing Association (NETA), the American Society for Testing and Materials (ASTM)—E 1934, and the National Fire Protection Association (NFPA)—NFPA 70-B. The application of methods allows for a quick, reliable, and comprehensive assessment of the severity of observed issues. The NETA standard is often used in the testing process for electronic components, employing the delta T criterion as indicated in Table 4 to establish the degree of severity. Temperature increases over a predefined reference, such as ambient air temperature, a comparable component under similar circumstances, or the maximum allowable temperature, determine these delta Ts. Rather than using current standards, some thermographers create their testing specification tables from their own experiences. The severity level rating is often based on the highest temperatures for both qualitative and quantitative data. As shown in Figure 13a, the maximum temperature values may be estimated using any commercial infrared image analysis tool by choosing an area or specifying a spot on the components or equipment. As shown in Figure 13b, a single line temperature profile can depict the temperature changes throughout all stages. In general, automated area of interest selection may improve the human selection process.

Table 4. NETA and MIL-STD2194 standards for IRT-based electrical equipment inspection features [8,48,96].

Standards	Temperature Difference (ΔT) (°C)		Actions to Be Taken
	Under Equivalent Stress, between Comparable Components	ΔT over Ambient Temperature (°C)	
NETA	1–3	1–10	A potential shortage needs further examination.
	4–15	11–20	Indicates a potential flaw that has to be fixed as soon as feasible.
	-	22–40	Continuously monitor until a solution can be found.
	>15	>40	There is a significant imbalance that must be addressed once and for all.
MIL-STD2194	10–20	-	Despite the remote possibility of component failure, corrective steps must be conducted at the next scheduled routine maintenance period.
	24–40	-	Failure of a component is likely unless it is repaired.
	40–70	-	Component failure is almost inevitable unless something is done.
	>70	-	A component is on the verge of failing.
Introspection Institute Standard for Electrical Components	1–10	-	During the following maintenance period, corrective action should be conducted.
	>10–20	-	Corrective actions are necessary when time allows.
	>20–40	-	Immediate corrective action is essential.
	>40	-	Immediate corrective action is required.

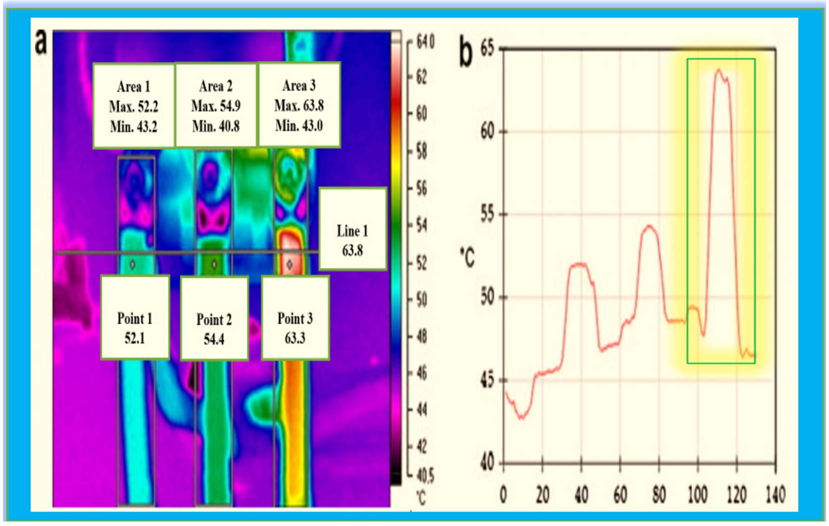

Figure 13. (**a**) Techniques for extracting temperature values and (**b**) the temperature profile across Line 1 [8].

5.5. Application to Motors

Induction motors with three phases are the most used prime movers in numerous industrial applications. Thermography for motor condition monitoring and problem diagnostics is necessary and may be justified economically [97]. The stator, rotor, and bearings are the main components of an induction motor (IM). IMs will fail if any of these components or their subcomponents are damaged. The stator, bearing, rotor, and other mechanical flaws are the most common IM faults, although the wide categorization of IM faults is presented in Figure 14.

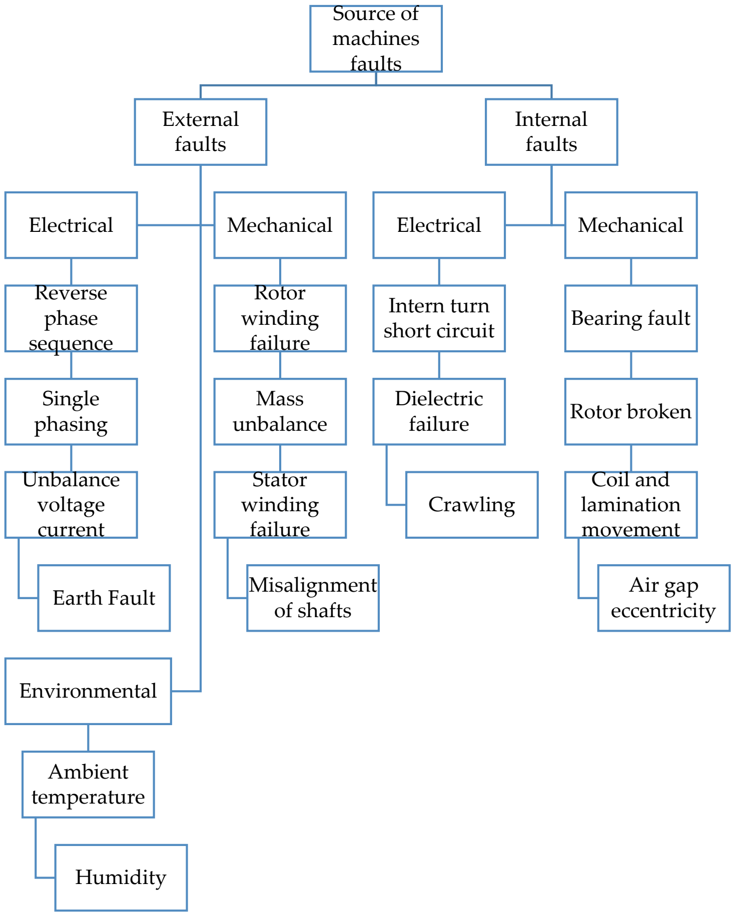

Figure 14. Classification of faults in induction motors [98].

Although IMs are quite constant in their functioning, their failure limits the smooth operation of IMs, which costs the industries a lot of money. The Electric Power Research Institute (EPRI) and the Institution of Electrical and Electronics Engineers conducted statistical analyses of IM failures, as shown in Figure 15 (IEEE). In Figure 15, a bar chart depicts a comparison of several problems that often occur in rotating machinery. Bearing, stator, rotor, and other defects are the different types of faults. The percentage frequency of their occurrence is clearly shown in the bar chart. According to [9], the majority of induction motor defects (41%) and winding (37%) are connected, as indicated in Figure 15's bar chart. The inter-turn defect is the more dangerous of the two since it may cause a rise in motor surface temperature. Due to a short circuit, this might result in a full loss of phase and potentially deadly accidents. However, a failure of the cooling system might cause a temperature increase in an induction motor [12,13].

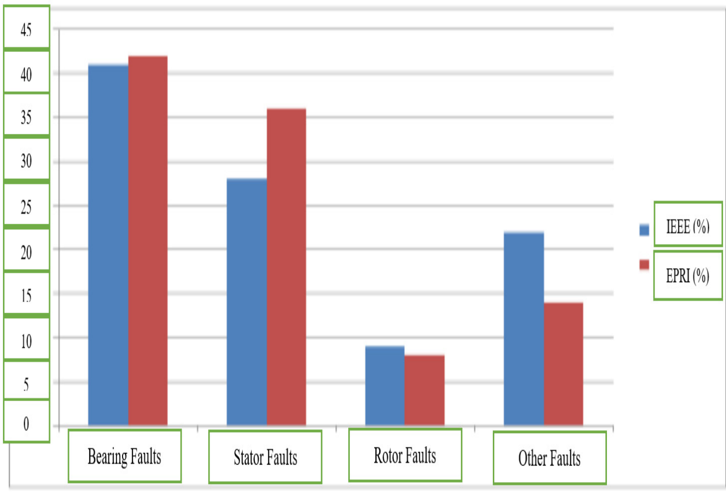

Figure 15. Study of induction motor faults by IEEE and EPRI [98].

5.5.1. Failure of Cooling System

The discrepancy between the input electrical power P_i and the output mechanical power P_0 is referred to as P_{loss}(1). These losses are dissipated in the form of heat. This heat is evacuated into the environment through convection and radiation processes. Heat is dispersed into the surroundings in a self-cool motor by forced convection P_{fconv} radiation P_{rad}, as defined in (2) [68]. The collection of debris, obstruction of air passages, damage or loose fans, and poor clearance during installation are all major causes of cooling system failure [97]. When the cooling system fails, forced convection is disrupted, causing the motor surface temperature to rise. A thermographic examination can identify this temperature increase. The International Electrical Testing Association (NETA) suggested a standard for thermographic testing of electrical systems, as illustrated in Table 4. This is used to determine the severity of a malfunction and the degree of maintenance priority for electrical systems and spinning machinery. Early identification of cooling system failure may be aided by recreating this defect in the laboratory and measuring the temperature of the motor at the target area of interest in line with NETA standards. Figures 16 and 17 depict a healthy cooling system and a cooling system failure, respectively, using thermography [97].

$$P_{loss} = P_i - P_0 \tag{1}$$

$$P_{loss} = P_{fconv} + P_{rad} \tag{2}$$

The regions Al and A2 in Figures 16 and 17 indicate the surface temperature of the motor stator and fan cowing, respectively. The maximum surface temperature of the motor stator and the cooling section are represented by TA1 and TA2. All these tests were carried out at a constant temperature of 27 °C (Ta).

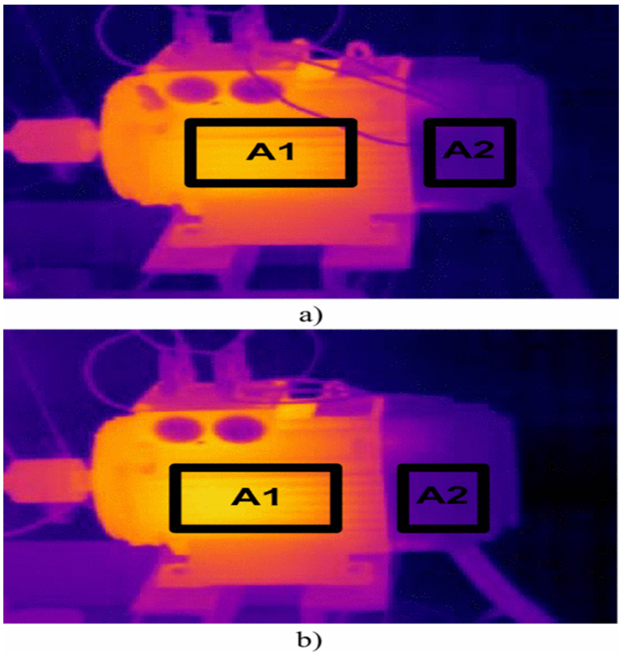

Figure 16. Thermal image of healthy motor at (**a**) no load and (**b**) at 50% load condition [97]. Region A1 is motor stator and region A2 is fan cowing.

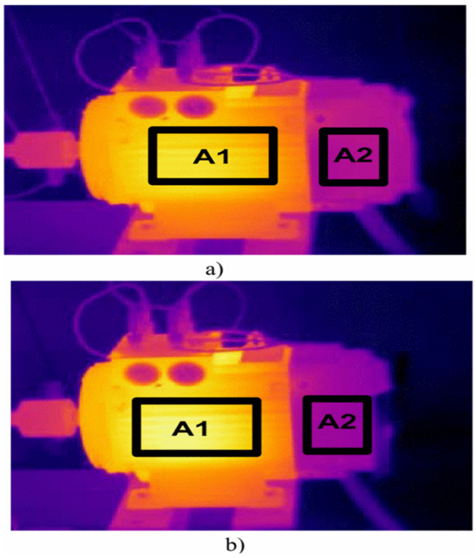

Figure 17. Thermal images of faulty motor at (**a**) no load and (**b**) 50% load condition [97]. Region A1 is motor stator and region A2 is fan cowing.

5.5.2. Bearing Faults

Bearings are one of the most important components of rotating equipment, and they are used in a wide range of technical applications such as turbines, heavy machinery, rolling mills, and ships. Bearings, being the principal component of a rotating machine, provide a number of tasks, including decreasing friction between relative moving components and providing support for the spinning shaft [99]. According to IEEE and EPRI, 41 percent and 42 percent of bearing faults occur during operation, respectively, as illustrated in Figure 15. For the CM of bearings in IMs, acoustic emission and vibration signal analysis were compared [100]. Figure 18 depicts an autonomous bearing problem detection framework that uses thermal imaging to identify four distinct bearing states in an induction motor.

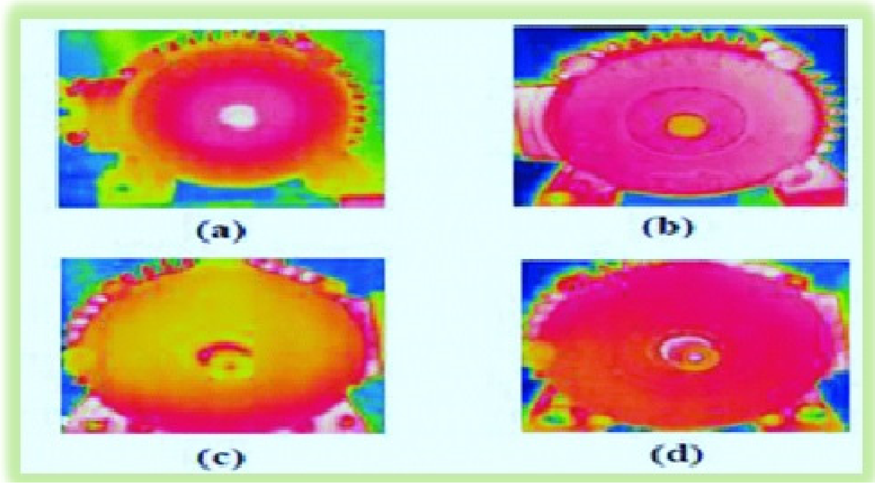

Figure 18. Thermal picture of four bearing states (**a**) No lubrication (**b**) Inner race defect (**c**) Outer race defect (**d**) Healthy. In an electrical laboratory at NITTTR, Chandigarh, thermal pictures of an induction motor were captured using a FLIR E-60 (thermal camera). During the experiment, the camera was placed 2 feet away from the induction motor. Under laboratory circumstances, thermal pictures of an induction motor were recorded. Thermal photos of the four bearing states in the three-phase squirrel-cage induction motor were captured: outer race, inner race, lake of lubrication problems, and healthy. Each condition included 24 thermal photographs [101].

5.5.3. Stator Fault

One of the most well-known issues in IMs is stator winding failure [102]. If an IM isn't working properly, it might slow down production or even shut down the facility, which can lead to an increase in the frequency of accidents. Early defect identification lowers production time lost, increases operator safety, and decreases maintenance costs [103]. Stator windings, stator frames, and winding laminations are some of the most prevalent stator problems, although stator windings are the most common. Thermal, mechanical, electrical, and environmental stressors all contribute to stator winding breakdown [104]. Thermal stress is one of the most important factors in the breakdown of insulation. According to IEEE and EPRI, stator winding faults occur 28 percent of the time and 36 percent of the time, respectively, as illustrated in Figure 15. An infrared investigation of winding asymmetry is shown in Figure 19.

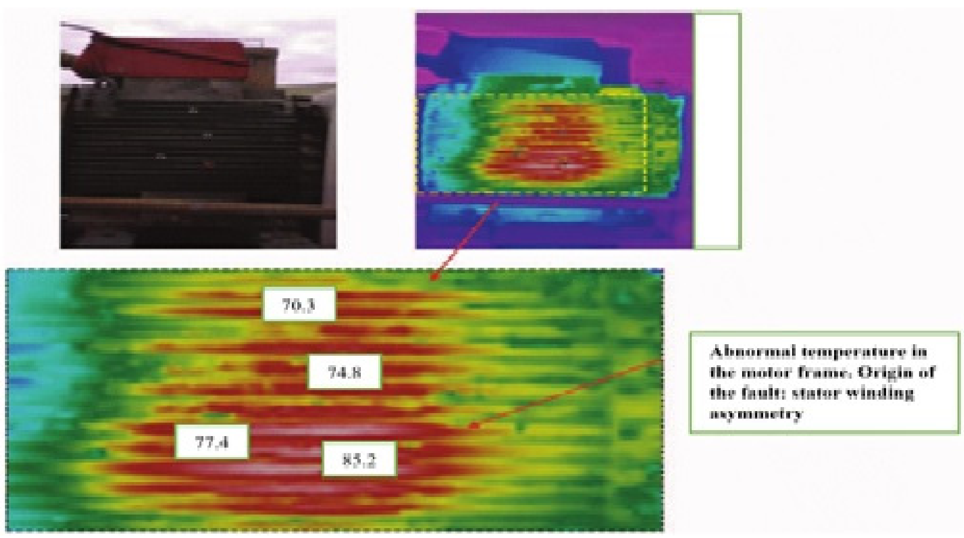

Figure 19. Infrared investigation of asymmetry in motor windings [105]. Figure 5 illustrates this. The infrared examination of the motor revealed high heating in the motor frame (85.2 °C on the surface

and, most likely, over 100 °C within). During the examination, no cooling irregularities were discovered. The bearings were re-lubricated and repaired at a workshop as a preliminary step, but no temperature decrease was noted. After that, the motor terminal box was examined, and just a little temperature differential was discovered between the connections. An ohmmeter was used to test the winding resistance of each phase, and the findings were rather fascinating; there was a large winding asymmetry across phases, resulting in a Max Delta R value of about 9%. Internal high resistance connections, broken twists, or internal shorts might all be the cause of this. This might be the source of the unusual heat dissipation. Finally, rewinding the motor was advised.

5.5.4. Eccentricity Fault

The situation is known as air-gap eccentricity when the distance between the rotor and the stator in the airgap is not uniform. The two types of eccentricity defects are static and dynamic eccentricity, as illustrated in Figure 20. The condition of static eccentricity occurs when the offset between the center of the shaft and the center of the stator is constant, while dynamic eccentricity occurs when the offset between the center of the shaft and the center of the stator is changeable. As indicated in Figure 20, Rr is the rotor's radius and Rs is the stator's radius. Methods such as FFT, wavelet, and Hilbert transform have been utilized to extract signals for the detection of eccentricity defects in IMs [106].

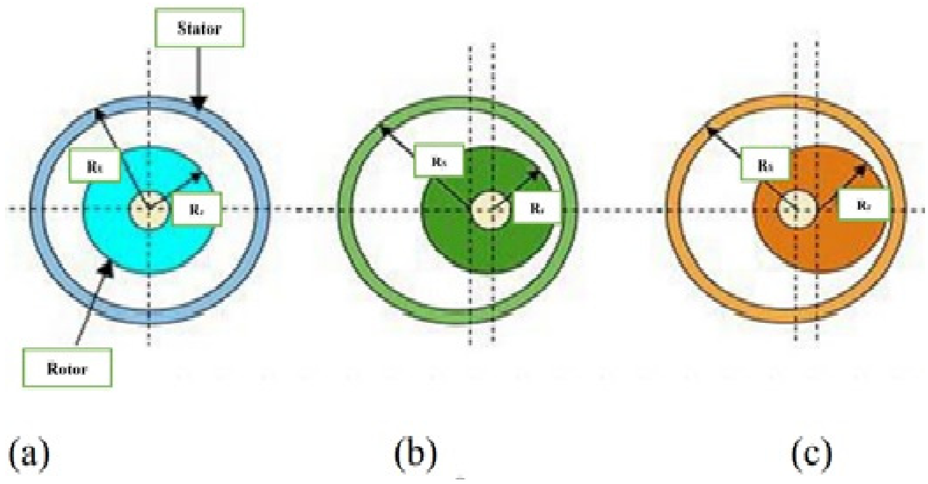

Figure 20. Cross-section of induction motor (**a**) normal (**b**) static eccentricity (**c**) dynamic eccentricity [106].

5.6. Including and Excluding Criteria

There are some criteria that are assigned to select the manuscripts from the specific Scopus database. In Table 5, The criteria for exclusion and inclusion of the manuscript for the selected 76 papers in the condition monitoring of thermography in Electrical, Electronics, and electrical motors application is as given below:

Table 5. The research between the years 2002 and 2022 on Condition monitoring of thermography towards Electrical, electronics, and rotating equipment.

Ref. No.	Authors	DOI Number	Keywords	Monitor	Publisher	Year	Country of Origin	Total Citation
[107]	Sangeeetha M.S et al.	10.1007/978-981-16-2422-3_14	Improved active contour modeling; Multilevel thresholding; Segmentation	Electrical equipment	Springer	2022	India	0
[108]	Li W. et al.	10.1016/j.microrel.2021.114409	Electric inverters; Electric losses; Parameter estimation; Insulated gate bipolar transistor inverter	IGBT inverter	Elsevier	2021	China	0
[109]	Vakrilov N.V. et al.	10.1109/ET52713.2021.9579707	infrared thermography; thermal analysis; thermal monitoring	Electrical machines	IEEE	2021	Bulgaria	0
[110]	Phuc P.N. et al.	10.1109/TEC.2021.3060478	induction motor; rotor temperature estimation; validation; virtual sensing	Induction Machines	IEEE	2021	Belgium	0
[111]	Leppänen J. et. al	10.1016/j.microrel.2021.114207	Device technologies; Electrical breakdown; High-humidity environment; Power semiconductor module	Semiconductor diodes	Elsevier	2021	Finland	0
[112]	Das A.K. et al.	10.1109/JSEN.2021.3079570	Convolutional neural network; metal oxide surge arrester; pollution severity classification; transfer learning	Surge Arrester	IEEE	2021	India	0
[113]	Nit Hamirpur et al.	10.1109/ICCES51350.2021.9489095	Hotspot detection; Induction motor; Infrared thermography (IRT); Remaining life; Thermal efficiency	Three phase induction motor	IEEE	2021	India	0
[114]	Xia C. et al.	10.1049/hve2.12023	Electric fault currents; Electric power transmission networks; Failure analysis; Image enhancement	Power equipment	John Wiley and Sons Inc.	2021	China	4
[115]	Choudhary A. at el.	10.1016/j.measurement.2021.109196	Deep learning; Fault detection; Infrared thermography; Machine learning	Rotating machine	Elsevier	2021	India	11
[116]	Hassan M.U. et al.	10.1049/gtd2.12106	Cable sheathing; Degradation; Distribution functions; Insulation; Nondestructive examination	Aerial bundled cables	John Wiley and Sons Inc.	2021	Pakistan	0
[117]	Susinni G. et al.	10.3390/electronics10060683	Condition monitoring; Junction temperature; Power device; Power electronics; Reliability	Semiconductor devices	MDPI	2021	Italy	4
[118]	Kumar P.S. et al.	10.1109/JSEN.2020.3029041	Condition monitoring; hall effect sensors; induction motor; infra-red sensors; inter-turn winding fault	Stator End-Winding	IEEE	2021	Singapore	2
[119]	Vidhya R. et al.	10.1109/ICEES51510.2021.9383639	Condition Monitoring; Image Processing; Wavelets	Transformer breather	IEEE	2021	India	1
[120]	Shao H. et al.	10.1109/TIM.2021.3111977	Fault diagnosis; infrared thermal images; rotor-bearing system; two-stage parameter transfer	Rotor-Bearing	IEEE	2021	China	0
[121]	Ziuzev, A.M. et.al	10.18799/24131830/2021/1/3002	AC electric motors; Compressor station; Stator winding insulation; Thermal circuits with lumped parameters; Thermal insulation resource; Thermodynamic model	AC electric motors	Tomsk Polytechnic University, Publishing House	2021	Russia	0

Table 5. *Cont.*

Ref. No.	Authors	DOI Number	Keywords	Monitor	Publisher	Year	Country of Origin	Total Citation
[122]	Najafi M. et al.	10.1109/ICSPIS51611.2020.9349599	Condition Monitoring; Image Processing; Infrared Thermography; Interpretable Machine Learning	Electrical Equipment	IEEE	2020	Iran	0
[123]	Alshorman O. et al.	10.1109/ICDABI51230.2020.9325635	Fault diagnosis and detection; gearboxes; image; rotating machinery; sensors; wind turbines	Rotating Machinery	IEEE	2020	Saudi Arabia	3
[124]	Redon P. et al.	10.1109/IECON43393.2020.9254639	Deep learning; fault diagnosis; image processing; induction motors; infrared thermography	Induction motors	IEEE	2020	Spain	2
[125]	Sahu M. et al.	10.1109/GUCON48875.2020.9231138	Aging Acceleration Factor; Hotspot Temperature; Per Unit Life; Transformer Preventive maintenance	Transformer	IEEE	2020	India	0
[126]	Xu X. et al.	10.1109/ICHVE49031.2020.9280056	Cable accessories; Faster RCNN; infrared image processing; Mean-Shift; smart condition diagnosis	Cable Accessories	IEEE	2020	China	1
[127]	Shahriari Nasab P. et al.	10.1109/TEC.2020.2974789	Computational Fluid Dynamics; Coupled magneto-thermal model; Switched Reluctance motor; temperature signature	Reluctance Motor	IEEE	2020	Iran	2
[128]	Wang B. et al.	10.1109/TIM.2020.2965635	Fault diagnosis; infrared detection; instance segmentation; insulator images; substation automation; temperature fitting	Insulator	IEEE	2020	China	27
[129]	Ni Z. et al.	10.1109/TPEL.2019.2962503	Accelerated lifetime test (ALT); active thermal control; ageing indicator; condition monitoring; failure mode	Power converters	IEEE	2020	United States	27
[130]	Singh R.P. et al.	10.1109/ICESC48915.2020.9155858	Condition Monitoring; Dissolved Gas Analysis; Thermography; Transformers	Transformers	IEEE	2020	India	0
[131]	Zhang P. et al.	10.1109/JSAC.2020.2968974	Bearing rotating elements; temperature sensor; thermal monitoring	Bearing Rotating Elements	IEEE	2020	China	4
[132]	Al-Musawi A.K. et al.	10.1016/j.infrared.2019.103140	Bearing faults; Edge detection; Image segmentation; Induction motor; Thermal condition monitoring	Three-phase induction motor	Elsevier	2020	Iraq	13
[133]	Nasiri A. et al.	10.1016/j.applthermaleng.2019.114410	Convolutional neural network; Cooling radiator; Deep learning; Fault detection; Thermal image analysis	Radiator	Elsevier	2019	Iran	14
[134]	Phuc P.N. et al.	10.3390/en13010037	Induction motor; Lumped-parameter thermal network; Model fitting; Transient thermal modelling	Induction machine	Energies	2019	Belgium	6
[135]	Chen J. et al.	10.13334/j.0258-8013.pcsee.190362	High-voltage power electronics; Junction temperature application; Junction temperature physical meaning	High Voltage Power Electronics	Chinese Society for Electrical Engineering	2019	China	5

Table 5. *Cont.*

Ref. No.	Authors	DOI Number	Keywords	Monitor	Publisher	Year	Country of Origin	Total Citation
[136]	Olanrewaju O. et al.	10.1109/PEE.2019.8923270	infrared thermography; power modules; steady state; temperature distribution; thermal maps; transient	Power Module Prototype	IEEE	2019	United Kingdom	0
[137]	Novizon et al.	10.1088/1757-899X/602/1/012007	Metal oxide surge arresters; Surge arresters; Temperature profiles; Thermal images; Thermal parameters	Surge arrester	IOPscience	2019	Indonesia	0
[138]	Dragomir A. et al.	10.1109/UPEC.2019.8893616	Infrared monitoring; thermal fault; thermographic report	Electrical Equipment	IEEE	2019	Romania	1
[139]	Zhang Q. et al.	10.1109/ICEMS.2019.8922346	Junction temperature; MOSFET; online condition monitoring; SiC devices	MOSFET On-line Based on On-state Resistance	IEEE	2019	China	5
[140]	Doolgindachbaporn A. et al.	10.1109/EIC43217.2019.9046583	Condition monitoring; time series decomposition; transformer thermal model; winding temperature indicator	Cooling Faults in Power Transformers	IEEE	2019	United Kingdom	0
[101]	Choudhary A. et al.	10.1109/GUCON.2018.8674889	Condition Monitoring; Preventive Maintenance; Thermal Camera; Thermal Imaging	Induction motor	IEEE	2018	India	8
[141]	Dragomir A. et al.	10.1109/ATEE.2019.8725019	Condition monitoring; infrared; thermal stress; thermography	Electrical Equipment	IEEE	2018	Romania	1
[142]	Andrade A.F. et al.	10.1109/ICHVE.2018.8642094	Electrical systems; Housing temperature; Radiation heat; Surge arresters; Thermal behaviors; ZnO surge arresters	ZnO Surge Arrester	IEEE	2018	Brazil	1
[143]	Hu Y. et al.	10.1109/ACCESS.2019.2918029	Base-plate solder; health condition monitoring; multi-chip IGBT module; Wind power converters	Multi-Chip IGBT Module	IEEE	2019	China	11
[144]	Wei K. et al.	0.1109/ACCESS.2019.2909928	Bond wires; Condition monitor; IGBT; Solder fatigue	IGBT Modules	IEEE	2019	China	8
[145]	Lee S.Y. et al.	10.1007/978-981-13-6447-1_68	Electrical fault detection; Infrared thermography; Intelligent fault diagnosis; Thermal imaging	Electrical fault diagnosis	Springer	2018	Malaysia	3
[146]	Sangeetha M.S. et al.	10.1109/ICOEI.2018.8553948	Condition monitoring; distance; electrical equipment; emissivity; Thermographs	Electrical Equipment	IEEE	2018	India	2
[147]	Krishnan S.R. et al.	10.1002/smll.201803192	Epidermal electronics; hydration; NFC; thermal sensing; wireless electronics	Epidermal electronics	Wiley-VCH Verlag	2018	United States	43
[148]	Mariprasath T. et al.	10.1016/j.infrared.2018.02.009	Condition monitoring technique; Hotspot temperature; Power quality; Thermal imager; Transformer	Transformer	Elsevier	2018	India	25
[149]	Choi U.-M. et al.	10.1109/TPEL.2017.2690500	Failure mechanism; insulated gate bipolar transistor (IGBT); power cycling (PC) test; power device module; reliability	Power Device Modules	IEEE	2018	Denmark	86

Table 5. *Cont.*

Ref. No.	Authors	DOI Number	Keywords	Monitor	Publisher	Year	Country of Origin	Total Citation
[150]	Resendiz-Ochoa E. et al.	10.1109/ACCESS.2018.2883988	Condition monitoring; failure analysis; image segmentation; Induction motor; infrared imaging; thermal analysis	Induction Motor Failure	IEEE	2018	Mexico	10
[151]	Lopez-Perez D. et al.	10.1109/IECON.2017.8216652	Fault diagnosis; induction motors; infrared thermography; isotherm; predictive maintenance	Industrial electric motors	IEEE	2017	Spain	3
[152]	Liu Z. et al.	10.1109/SDPC.2017.35	Convolution neural network; Fault diagnosis; Infrared (IR) imaging; Rotating machinery	Rotating machinery	IEEE	2017	China	7
[153]	Dragomir A.	10.1109/SIELMEN.2017.8123307	HV busbar systems; Infrared thermography; Thermal stresses	Electrical equipment	IEEE	2017	Romania	4
[154]	Resendiz-Ochoa E.	10.1109/DEMPED.2017.8062412	Condition monitoring; fault diagnosis; image segmentation; induction motors; infrared imaging	Induction motors	IEEE	2017	Mexico	17
[155]	Mechkov E. et al.	10.1109/ELMA.2017.7955462	Evaluation criteria; infrared thermography; maintenance; transformers	Transformer's maintenance	IEEE	2017	Bulgaria	5
[156]	Munoz-Ornelas O. et al.	10.1109/IECON.2016.7793682	Condition monitoring; Induction motors; Infrared imaging; Predictive maintenance; Thermal analysis	Induction motors	IEEE	2016	Mexico	9
[99]	Ramirez-Nunez J.A. et al.	10.1109/IECON.2016.7793158	Fault detection; Image processing; Infrared image sensors; Infrared imaging; Monitoring; Predictive maintenance	Industrial machinery	IEEE	2016	Mexico	10
[157]	Dragomir A. et al.	10.1109/ICEPE.2016.7781319	Dust thickness; infrared monitoring device; thermal stresses	Electrical equipment	IEEE	2016	Romania	50
[158]	Khan Q. et al.	10.1109/ICEEOT.2016.7755208	Condition Monitoring; Infrared Thermography; Motor; Preventive maintenance; Transformer	Electrical equipment	IEEE	2016	India	10
[97]	Singh G. et al.	10.1109/ICPES.2016.7584040	Condition monitoring; Failure of cooling system; Fault diagnosis; Induction motor; Infrared thermography	Induction motor	IEEE	2016	India	9
[159]	Singh G. et al.	10.1016/j.infrared.2016.06.010	Condition monitoring; Fault diagnosis; Induction motor; Inter turn fault; Thermography	Induction motors inter turn	Elsevier	2016	India	65
[82]	Dutta T. et al.	10.1109/CMI.2016.7413761	Edge detection; color model; image segmentation; thermal monitoring	Electrical equipment	IEEE	2016	India	22
[160]	Zou H. et al.	10.1016/j.infrared.2015.08.019	Feature extraction; Infrared thermography; Intelligent fault diagnosis; Parameter optimization; Support vector machine	Electrical equipment	Elsevier	2015	China	50

Table 5. *Cont.*

Ref. No.	Authors	DOI Number	Keywords	Monitor	Publisher	Year	Country of Origin	Total Citation
[161]	Janssens O. et al.	10.1016/j.infrared.2015.09.004	Condition monitoring; Fault diagnosis; Image processing; Infrared imaging; Machine learning; Rotating machinery	Rotating machinery	Elsevier	2015	Belgium	76
[162]	Perpiñà X. et al.	10.1109/TPEL.2014.2346543	Light-emitting diodes (LEDs); solid-state lighting (SSL); thermal modeling; thermal parameters extraction	LED lamps	IEEE	2015	Spain	16
[163]	Taheri-Garavand A. et al.	10.1016/j.applthermaleng.2015.05.038	Artificial neural network; Condition monitoring; Cooling radiator; Discrete wavelet transform;	Cooling radiator	Elsevier	2015	Iran	50
[164]	Zou H. et al.	10.1109/ChiCC.2015.7260642	Feature extraction; Infrared image; Intelligent fault diagnosis; Parameter optimization; Support vector machine	Electrical equipment	IEEE	2015	China	14
[165]	Dragomir A. et al.	10.1109/ICEPE.2014.6969915	Diagnosis; infrared thermography; monitoring; thermal stresses	Electrical equipment	IEEE	2014	Romania	9
[166]	Garcia-Ramirez A.G. et al.	10.1109/ICELMACH.2014.6960449	Induction motors; Infrared imaging; Temperature; Thermal analysis	Induction motor	IEEE	2014	Mexico	24
[167]	Karvelis P. et al.	10.1109/IECON.2014.7049001	Fault diagnosis; image segmentation; Induction motor; object matching	Induction motor	IEEE	2014	Greece	26
[168]	Li K. et al.	10.1109/TPEL.2013.2288334	Eddy current pulsed thermography (ECPT); insulated gate bipolar transistor (IGBT); nondestructive evaluation	IGBT modules	IEEE	2014	United Kingdom	125
[169]	Chen H. et al.	10.1109/TDMR.2013.2292547	Circuit topology; monitoring; MOSFET switches; prognostics and health management; thermal management	Power MOSFETs	IEEE	2014	China	124
[34]	Huda A.S.N. et al.	10.1016/j.infrared.2013.04.012	Condition monitoring; Electrical equipment; Features; Infrared thermography; Multilayered perceptron network	Electrical equipment	Elsevier	2013	Malaysia	47
[170]	Huda A.S.N. et al.	10.1016/j.applthermaleng.2013.07.028	Discriminant analysis; Electrical equipment; Infrared thermography; Preventive/predictive maintenance	Electrical equipment	Elsevier	2013	Malaysia	105
[171]	Jadin M.S. et al.	10.1109/SIECPC.2013.6550790	Condition monitoring; image classification; Infrared image; object recognition; reliability	Electrical installations	IEEE	2013	Malaysia	12
[172]	Cui H. et al.	10.1109/ICEIEC.2013.6835498	Fault diagnosis; image processing; Infrared thermography; neural network	Power equipment	IEEE	2013	China	17
[69]	Eftekhari M. et al.	10.1016/j.infrared.2013.10.001	Condition monitoring; Feature extraction; Induction motor; Infrared thermal image; Inter-turn short circuit fault	Inter-turn fault in induction motor	Elsevier	2013	Iran	35
[33]	Jadin M.S. et al.	-	Electrical equipment; Image preprocessing; Image processing; Infrared thermogram; Thermal anomalies	Electrical equipment	Academia	2011	Malaysia	15

Table 5. *Cont.*

Ref. No.	Authors	DOI Number	Keywords	Monitor	Publisher	Year	Country of Origin	Total Citation
[173]	Manana M. et al.	10.1016/j.applthermaleng.2010.11.023	DC motors; Electric machines; Fault diagnosis; Infrared imaging	Field winding fault	Elsevier	2011	Spain	36
[174]	Younus A.Md. et al.	10.1109/PHM.2010.5414573	Infrared thermography; Machine condition monitoring; Machine fault diagnosis; Mechanical systems	Machine fault	IEEE	2010	South Korea	12
[175]	Feng J.Q. et al.	10.1109/ICPST.2002.1067880	Condition monitoring; genetic algorithms; Power transformers	Power transformer	IEEE	2002	United Kingdom	9

6. Conclusions and Recommendations

IRT has shown to be a successful condition monitoring and fault diagnosis tool for noncontact and non-invasive real-time temperature monitoring of targets throughout the years. IRT is especially useful for preventative maintenance programs and online monitoring of electrical equipment since it delivers accurate and trustworthy data. To minimize misunderstandings or improper analysis of IRT data, modifications and changes to the algorithm and analysis techniques should be explored. Recent developments in the IRT inspection of electrical equipment demonstrate that an intelligent system is in high demand. IRT is a safe imaging technique aside from its superior temperature sensitivity, spatial resolution, and noncontact nature. The improved IRT inspection tools may aid CBM analysis by transferring data to a new and powerful AI for computer vision, which will provide utility companies with helpful information.

Recent advancements in IRT technology are noted as possible future work prospects leading to scientific CBM analysis. Existing IRT technologies have the potential to become well-known and competitive fault diagnosis CBM approaches for electrical equipment in the following years. Aside from the previously reported observations and conclusions, which are trustworthy and efficient for qualitative and qualitative diagnostics, quantifying the influence of each thermal fault pattern on the performance of various applications is an unavoidable issue [176]. When combined with AI as a decision-making tool, the thermal fault pattern with high resolution from IRT might be a game-changer for CBM analysis. However, present and near-future research problems include knowing "when" each defect arises and "how" it propagates during field operations, even after it has been identified. Resolving such knowledge gaps is critical in pursuing [177] from a variety of viewpoints. Furthermore, the goal of recent developments, ongoing studies, and future research challenges is to standardize IRT readings in the field as part of issue diagnostics and preventive maintenance strategies. In response to these directives and concerns, utility industries will pursue future IRT-based fault detection systems using thermography in electrical diagnostic and predictive maintenance. In general, the goal is to build a broad application in the electrical utility business that is commercially successful. As a result, the IRT with AI modeling will almost certainly face the following challenges:

- NFPA 70E, Standard for Electrical Safety Requirements for Employee Workplaces, 1995, is one of the numerous publications in the 70 series released by the National Fire Protection Association (NFPA). One of the essential improvements in thermographers' work habits is conducting electrical checks. It has to do with avoiding an electrical arc flash, which may be very dangerous or even deadly at low levels of 400 V. Additionally, thermographers who are not electricians may be ignorant of the risks of working near active components. NFPA 70E defines limitations and advises personal protective equipment (PPE) to reduce the severity of accidents. Another alternative is to utilize an Infrared Inspection Window, which separates environments with different pressures or temperatures while still allowing IR radiation to pass through.
- Continuous thermal imaging provides additional advantages over periodic thermal examination, particularly in electrical equipment reliability. Continuous thermal monitoring is a benefit since defects may occur at any moment. Furthermore, it is not operator-dependent, and it is not reliant on frequent inspection, particularly under large loads. In addition, real-time monitoring may trigger signals or alerts if abnormalities arise unexpectedly, allowing necessary action to be performed simultaneously. Furthermore, integration with existing Supervisory Control and Data Acquisition (SCADA) systems would allow for real-time remote monitoring without the need for a separate system or report, which is conceivable but not practicable with regular thermal inspections.
- Thermocouples, infrared (IR) cameras, and fiber Bragg gratings have all been used to measure high temperatures (FBGs). Most thermocouples and infrared cameras monitor temperature on the cutting tool's rake and flank faces. They are not appropriate for

temperature readings because of the difficulties of placement between the flank face and the workpiece surface. Furthermore, FBGs are contact sensors, which have the drawback of being fragile and difficult to mount near the measurement site. Only a few solutions give a reasonable solution for temperature readings on the workpiece surface, but integrated sensors in the cutting tool are difficult to install. A two-color fiber-optic pyrometer might be used to circumvent these limitations. To circumvent the emissivity dependency of temperature, it exploits the ratio of optical powers at two spectral bands to construct a self-referencing mechanism. Using optical fibers, you can see isolated regions with a spatial resolution limited only by the numerical aperture and fiber diameters.

- Due to the increased need for preventative maintenance in electrical power equipment, more reliable and resilient intelligent solutions, such as the automated segmentation algorithm to determine the region's interest in detecting the hotspots of electrical equipment, are urgently required. The majority of existing systems employ manual segmentation based on standard image processing methods. These methods' output will likely capture the artificial hotspot in the region of interest, enabling CBM analysis to detect the temperature difference. Due to the various properties of the equipment, the created intelligent systems could only be employed for special electrical equipment up until now. As a result, a clever, smart system model must be devised and built to address the picture quality issue. Noises will usually impact the collected picture when inspections are done outside. As a result, complex image processing methods and new algorithms have to be investigated to tackle these issues.

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