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Application of Thermal Imagery Technology for Fault Detection of Large Electrical Equipment and Microelectronic components

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Abstract

With the increasing integration level and power of electrical equipment, their working conditions are becoming increasingly harsh, leading to a higher risk of failure and a growing demand for reliable nondestructive testing (NDT) methods. Thermal imagery, as one of the fully developed method of visualized temperature detection, realizes non-contact error detection by recording infrared radiation from the surface of objects. This paper examines the application of thermal imaging technology for fault detection in large electrical equipment and microelectronic components. The study reviews the fundamental principles and key parameters of thermal imaging, then compares its use across the two scales. For large equipment, thermal imaging effectively handles complex structures and high-voltage environments, offering large-area coverage and non-contact real-time monitoring, though environmental factors may affect accuracy. For microelectronic components, despite limitations in resolution and penetration, thermal imaging provides valuable visualized thermal distribution data for packaging failure analysis. Overall, thermal imaging proves to be an effective and adaptive NDT method, with future improvements in detector performance expected to further enhance its capabilities.

Keywords

thermal imagery technology, fault detection, large electrical equipment, microelectronic components

1. Introduction

Electronic components are the foundational unit that constitutes various types of electrical equipment. Its reliability will straightforwardly affect the security and service life of the whole system. However, along with the enhancing integration degree and increasing power, the working environment of electronic components are getting more severe, leading to a higher risk of malfunction. Once device breakdown happened, in minor cases, the equipment may shut down; in severe cases, it may cause safety accidents. Therefore, regular non-destructive detection is essential. Among all non-destructive testing methods, infrared thermal imaging technology is widely applied because of its advantages such as non-contact, real-time and visual presentation of temperature distribution. Device faults will cause abnormal partial temperature (hotter or colder), thermal imaging technology visualize this shift in temperature into image through capturing objects’ surface infrared radiation, supporting inspector to locate specific fault point precisely and efficiently.

The core theme explored in the article is that the application of thermal imagery in NDT of large electrical equipment and tiny electronic components, including their applicable scene, advantages and limitations. The first part introduces the basic principles and key parameters of thermal imaging technology. The second part analyzes its application and advantages and disadvantages in the detection of large electrical equipment. And the third part discusses its application and advantages and disadvantages in the detection of micro electronic components. Finally, draw a conclusion and look forward to future development. Hoping that the analysis in this article can provide certain value for researchers in related fields when choosing detection methods and equipment.

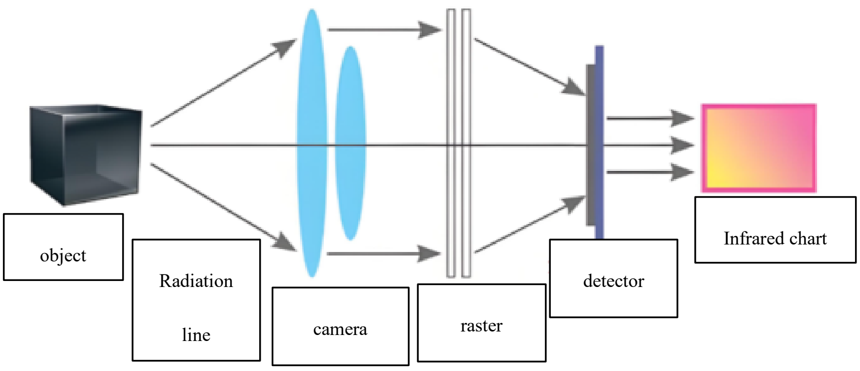
2. About Thermal Imagery

The initialization of thermal imagery can be chase back to 19 century. During 1800, when researching solar spectrum, scientists discovered that waves with lower frequency compare to red light was able to heat the thermometer up, which proofed the existence of infrared red radiation. After that, infrared red radiation detector was developed and further improved. Until 1943, the machine which could visualize the infrared radiation that was received was invented, realizing thermal imagery for the first time [1]. Since then, the precision and detection range for thermal imaging technology was regularly enhanced [2]. The size of thermal imaging devices was also reduced as well as the devices was getting popularized to the public.

2.1 Basic Theories of Thermal Imagery

The basic theories about thermal imaging detection is that every object radiates infrared red energy. As a result, if there is any damage to electrical devices, the thermal and electrical conductivity of damaging area will be affected, leading to abnormal thermal distribution on its surface. Then, thermal imaging technology visualize the broken part through detecting these minor temperature changes. Within the image the thermal imagery provides, different colors symbolize different temperature. Therefore workers can recognize the damaging part straightforwardly as malfunction spots often have a color which starkly contrast with other parts. Normally, in order to locate those breaking parts accurately, the thermal imagery machine will act in white glow mode, which means that as the temperature rises, the color on the image tends to white; and in contrast, parts with lower temperature will have a darker color [2,3].

Figure 1: Schematic diagram of the principle of infrared thermal imaging [4]



2.2 Different Parameters

1) Infrared red resolution is the number of pixels that are contained in the thermal imaging detector, usually presenting through the product of horizontal pixel number and the vertical pixel number. The higher the resolution is, the sharper the image will be, thereby the smallest unit that a thermal imaging detector can recognize is tinier [3].

2) Thermal sensitivity is represented by the smallest temperature difference that the machine can detect. The smaller this number is, the stronger the machine sensory ability is, strengthening the capacity for thermal imagery machine to record shift in thermal energy [3].

3) Detection range is the temperature range where the machine is able to determine the temperature precisely. When this number increase, more various devices and situations will be easily coped by the machine [3].

4) Frame frequency determines the amount of image that a machine can detect per unit time (unit: HZ or frame per second) [3].

5)Spectral response means the range of infrared red radiation wavelength that can be recognized by the machine [3].

3. Application of Thermal Imagery Technology for Fault Detection of Large Electrical Equipment and the Analysis of Advantages and Disadvantages

3.1 The Application of Thermal Imaging Technology in the Fault Detection of Large Electrical Equipment

Large electrical devices typically operate at a rated voltage above 1 kV. They are the devices which were responsible for generation, transmission, transformation and distribution links of the power system, including power transformer, primary cut-out, disconnector, power cable and capacitor bank. These devices are structurally complex, and operate continuously under high-voltage conditions. Once they are broken, it is highly likely to cause large-scale power outages [5,6]. During their working process, there are mainly three types of hardware failure that can be checked through thermal imaging technology.

1) Current-induced thermal damage

The first one is electric current-induced thermal damage, which includes poor contact of connecting parts, wire breakage worn out of switch contacts, etc. These kinds of failures lead to an increase in loop resistance, which produce excessively heat, presenting as local hot spot in thermal images. Because that the temperature of these parts is significantly higher than other parts, therefore it’s straightforward to recognize [3,7].

2) Voltage-induced thermal damagea. The second failure is voltage-induced thermal damage, which contains insulating medium deterioration, abnormal voltage distribution, oil shortage faults, etc. These kinds of defects produce heat due to increased dielectric loss or deterioration of heat dissipation conditions. But comparatively, the increase in temperature is smaller, and it is presented as overall slight temperature rise or local hot zones within the thermal image. Thereby, high sensitivity thermal imaging technology is required for this situation [5].

3) Thermal damage caused by electromagnetic effects

The third type is thermal damage caused by electromagnetic effect, including the transformer core is grounded at multiple points, generates heat due to eddy current losses, etc. These defects produce thermal energy due to the leakage flux and eddy current loss increase. Normally, in the thermal image, these places are shown as local hot spot, and the loss points need to be analyzed in combination with the equipment structure [3,7].

3.2 The Advantages and Disadvantages of Thermal Imaging Technology in the Detection of Faults in Large Electrical Equipment

Using thermal imagery technology in large devices error detection is efficient and secure, especially for current-induced heating type faults. However, the limitations of thermal imagery’s surface-level detection and its susceptibility to environmental interference require operators to consider the device’s structure and operational states when doing failure detection, enhancing the accuracy rate of fault diagnosis [6].

Table 1: The advantages and disadvantages of thermal imaging technology in the fault detection of large electrical equipment

Aspects	Advantage	Disadvantage
Detection method	Non-contact detection: not required to touch electrical devices, making it suitable for high-voltage and hazardous environment while protecting staff.	Surface detection limitations: can only detect the temperature distribution on the surface of the equipment and is difficult to directly locate the precise position of internal faults.

Aspects	Advantage	Disadvantage
Detection efficiency	Large area rapid imaging: can simultaneously monitor the whole thermal distribution of large electrical devices. A thermal image covers multiple detection points, offering greater efficiency than single-point thermometers.	Thermal conduction interference: after the heat generated by internal faults reached the surface, it might be diminished or diffused, leading to misjudgment.
Operation state	Online real-time monitoring: it can continuously monitor the running equipment for 24 hours, avoiding production halt losses.	Environmental interference: outdoor equipment tends to be affected by environmental conditions like sunlight, wind, rain and snow, leading to temperature measurement errors.
Error recognition	Visual and intuitive presentation: convert temperature data into images, making hot areas clearly visible and facilitating the locating process of suspected fault locations.	Lack of internal structure information: heat map cannot provide detailed geometric structures inside the equipment. For complex or early minor faults, other methods may need to be combined with thermal imagining for further verification.
Range of application	Adaptable to complex structures: for confined spaces that are difficult for traditional methods to access, thermal imaging can be utilized for long distance detection.	Emissivity impact: the surface emissivity of different materials varies. If it is not set correctly, it can cause temperature measurement data

4. The Application and Advantages and Disadvantages Analysis of Thermal Imagery in the Fault Detection of Microelectronic Components

4.1 Utilization of Thermal Imagery on Minor Electrical Components' Error Detection

Microelectronic components refer to miniaturized electronic devices or systems with dimensions at the micrometer level that are manufactured using microelectronics process technology. They feature tiny size, high integration, low power consumption and high reliability. And they are the foundation for electronic devices to achieve miniaturization and high performance [5,6]. Commonly seen electronic components include:

1) Chip component: such as surface mount resistors, capacitors and inductors of size 0402(1.0mm × 0.5mm) or 0201(0.6mm × 0.3mm). They are widely used in the main-board of smart phone and ipad.

2) Discrete semiconductor devices: Small-signal transistors, diodes, usually used for magnifying signals, switch control and rectifying circuit.

3) Integrated circuit chip: Central processing unit, memory, power management chip. It integrates millions to billions of transistors internally, forming the core of a complex electronic system.

4) MEMS (Micro-Electro-Mechanical Systems):Accelerometer, gyroscope, pressure sensor. They integrate mechanical structures and electronic circuits onto micrometer-scale chips, and are applyed in fields like smart phones and electric vehicles.

5) Packaging modules: Rf front-end modules and power supply modules. These modules encapsulate multiple chips and passive components on a micro-substrate to achieve specific functions.

In the perspective of thermal imaging, the error detection is mainly divided into three types.

1) Welding Interface Damage

The first type is welding interface type damage, which includes false soldering, bridging, fatigue cracking of solder joints and voids. False soldering increases the resistance and the temperature increase at local hot spots is very small. Bridging forms short-circuit channel which leads to significant hot spot and increasing temperature. Fatigue cracking hinders heat conduction and presents an abnormal temperature distribution. Voids hinders heat dissipation, forming local hear accumulation and increasing temperature [8].

2) Component Body Damage

The second type is that the component body class is damaged, including chip leakage, resistance drift, capacitor short circuit/leakage. Chip leakage forms tiny hot spots. An increase in resistance will raise the temperature. And capacitor short circuit will produce severe thermal energy.

3) Packaging Interconnection Damage [8].

The third type is that packaging interconnection class is damaged, such as delamination and bond line breakage. Delamination forms air gap which causes heat accumulation, bond line breakage eliminates the current in corresponding areas, presenting as local cold zone [9].

4.2 The Advantages and Disadvantages of Thermal Imaging Technology in the Fault Detection of Microelectronic Components

Thermal imagery enables non-contact, high-resolution detection of microscopic damages on tiny components that traditional methods cannot capture. However, its spatial resolution is limited by infrared wavelengths, and the extremely small temperature changes caused by faults are easily covered by environmental interference. Additionally, opaque packaging materials may block thermal signals. Thus, operators must consider material properties and environmental conditions to enhance detection accuracy, and may need to combine thermal imaging with other techniques for comprehensive result.

Table 2: The advantages and disadvantages of thermal imaging technology in the fault detection of microelectronic components

aspects	advantage	disadvantage
Detection method	Non-contact and non-destructive, which eliminates physical interference and avoids unnecessary errors.	Uses infrared waves with wavelengths much longer than visible light, so spatial resolution cannot reach the level of optical microscopy and cannot be the top-tier NDT technique.
Detection efficiency	High-resolution detectors enable precise detection of tiny damages at the millimeter or even micrometer scale on miniature components.	The temperature changes caused by faults in miniature electrical devices are extremely small, making detection difficult and requiring high-sensitivity settings.
Operation state	Enables visualization of thermal distribution, allowing researchers to directly identify heat accumulation locations and surrounding heat dissipation patterns for accurate analysis.	Operation becomes complex with high sensitivity settings, requiring skilled personnel and incurring significant costs.
Error recognition	Visualized thermal imaging helps directly locate abnormal hot spots and identify fault areas accurately.	Environmental temperature variations during detection introduce interference, making the measurement process more difficult and affecting error recognition accuracy.
Range of application	Suitable for detecting miniature components where traditional methods (e.g., single-point temperature measurement) fail to capture overall temperature distribution.	Limited penetration of thermal waves through opaque materials that encase mini components, which may block temperature monitoring and reduce applicability.

5. Conclusion

5.1 Summary of Findings

This study compares thermal imaging applications in large electrical equipment and microelectronic components. For large equipment, thermal imaging benefits in wide-area, non-contact monitoring of abnormal hot spots, but surface-only detection and environmental interference will restrict its accuracy. For micro components, it provides valuable thermal distribution visualization for packaging failure analysis, but limited penetration and weak thermal signals from minor faults remain major challenges.

5.2 Future Directions

Admittedly, thermal imagery is a reliable technology that can be assigned in electrical devices' nondestructive testing. Its capacity of adapting multiple environments and its high level precision have rendered this product to be notable within the competitive market. However, limited detection resolution and weak penetration ability also indicate that this technology is not perfect.

Along with the infrared detector's development, higher resolution and sensitivity will be achieved, thereby thermal imagery's practicability will also be improved, intensifying its value in use

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Conflicts of Interest

The authors declare no conflict of interest.

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