The Journal of CPRI,
Vol. 13, No. 1, March 2017 pp. 7-12

An active infrared thermography method for nondestructive testing of porcelain post insulators

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In recent years, accidents of porcelain post insulators fracture due to their internal defects often occur, which severely endanger the security and stability of the power system. The traditional ultrasonic testing method requires power off, and the effect and efficiency are barely satisfactory. In this study, a novel approach based on active infrared thermography is proposed to test and evaluate the state of porcelain post insulators. More specifically, an external source of energy is employed to heat the specimen being detected and the thermal front propagates through the object. Due to different thermal properties between defective and sound area, the thermal contrast evolution on the surface of the object can be monitored by a thermographic camera. The recorded data are analyzed by image processing technology to yield information about defect size and depth. The validity of the proposed testing method is proved by a series of experiments performed on specimens containing defects of different sizes at different depths. It is concluded that the active infrared thermography testing method is attractive owing to its quick, contactless, full-field imaging and quantitative defect estimation capabilities.

Keywords: *Porcelain post insulator, nondestructive testing, pulsed infrared thermography, surface crack defect, infrared thermal image, logarithmic temperature-time plot, peak second-order differential time.*

1.0 INTRODUCTION

With the fantastic spur both in economy and in industry, reliable power supply is playing an increasingly important part in modern society. Under this background, monitoring and diagnostics of electrical equipment in power grid has been the research hotspot in electrical engineering. High voltage porcelain post insulator, which is used to provide mechanical support and electrical insulation for a variety of electrical facilities, is one of the most important equipment in transformer and convertor station in the process of power transmission and transformation [1]. When deteriorated in field operation, porcelain post insulator will crack, which poses a severe danger to the proper state of electric power system. Figure 1 shows a typical visual inspection of porcelain post insulator. Previous research has shown that defects in porcelain post insulator could be produced during manufacturing, mishandling during operation, incorrect installation, weathering and inappropriate maintenance [2]. The existence of structural defects could cause stress concentration and then the defects further expanded until porcelain post insulator fractured.

FIG.1. A TYPICAL VISUAL INSPECTION OF FRACTURED PORCELAIN POST INSULATOR

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In the current study, ultrasonic testing method is mainly adopted to detect the defects of porcelain post insulator. The testing results of ultrasonic testing depend on consistent degree of calibration between blocks and the tested objects [3]. Hence, the validity and convenience of ultrasonic testing method are limited. This work presents an active infrared thermography method for detection of defective porcelain post insulators.

The principle of active infrared thermal imaging technique for Nondestructive Testing is simple. The flow of heat transferring through the solid is influenced by internal defects such as degumming, voids and inclusions. In pulsed thermal imaging technique, flashlight lamp is employed to stimulate the specimen under detection, and a thermographic camera is used to inspect the temperature changes over time. The cooling stage of each point on the sample surface will be recorded and analyzed. Then a thermogram of the subsurface structure will be created by a dedicated computer system. Sometimes a simple active infrared thermography NDT system, for instance heat gun plus thermographic camera, can detect large, near-surface defects without data processing and analysis. However, for those deeper and subtler flaws, pulsed thermal imaging technique can be used for repeatable and quantifiable inspection with additional sensitivity. Moreover, the employment of thermographic signal reconstruction technique can improves the sensitivity of detection even further.

2.0 THEORETICAL BACKGROUND

With the purpose of better illustration of the proposed method, a brief theoretical background is presented. In this section, the main pulsed infrared thermography techniques employed in this work are introduced.

2.1 Heat Transfer Theory

In heat transfer theory, the heat transferring through a given cross-section per unit time is proportional to the temperature change rate perpendicularly and the cross-sectional area, which is expressed as the law of Fourier [3]:

$$q = -\lambda \cdot \nabla T = -\lambda \cdot \frac{dT}{dr} \qquad ...(1)$$

According to Equation (1), the direction of heat transfer is opposite to the direction of temperature rise. Hence, the law of Fourier also can be expressed as:

$$q_n = -\lambda \cdot \frac{dT}{dn} \qquad ...(2)$$

The heat rate through the surface area is:

$$Q = \int_A q_n \cdot dA \qquad ...(3)$$

The thermal conductivity is a function of the temperature and the surface area can be a more or less complicated function of the spacial coordinates, therefore the solution of the integral can be very complicated or even impossible. For many technical applications the thermal conductivity can be taken as constant with a mean value. In bodies with simple geometrical shapes, Equation (3) can be solved [4].

2.2 Infrared Thermography Technique

A black body can be approximated by a hollow volume with adiabatic, isothermal inner walls and a small opening through which radiation enters and leaves. The spectral specific intensity of the black radiation $i_{\lambda,s}$ is given by Planck's radiation law.

$$i_{\lambda,s} = \frac{C_1}{\lambda^5 \cdot (e^{C_2/(\lambda \cdot T)} - 1)} \qquad ...(4)$$

The consonants C_1 and C_2 are given as:

$$C_1 = 2 \cdot \pi \cdot c^2 \cdot h = 3.7418 \times 10^{-16}\,\mathrm{W \cdot m^2} \qquad ...(5)$$

$$C_2 = c \cdot h / k = 1.438 \times 10^{-2}\,\mathrm{K \cdot m} \qquad ...(6)$$

Both constants do not include empiric terms but only physical constants. They are the light velocity *c*, the Planck constant h, the Boltzmann constant k. The values of these physical constants are:

$$c = 299792458 \text{m / s} \quad ...(7)$$

$$h = 6.6260755 \times 10^{-34} \text{J} \cdot \text{s} \quad ...(8)$$

$$k = 1.380641 \times 10^{-23} \text{J / K} \quad ...(9)$$

All objects can emit a certain amount of black body radiation according to their temperature. Generally, the higher the temperature of the object, the more infrared radiation it emits as blackbody radiation. The infrared radiation can be detected by a thermographic camera in a manner similar to the way visible light is detected by a normal camera. It even works in total darkness because ambient light levels are not important. This allows it to be used for non-destructive testing in complicated field environments [3-4].

3.0 METHODOLOGY

In pulsed infrared thermography, an external heat source is required to cause a difference in temperature between defective and nondefective regions in the samples under inspection [5-6]. The sample surface is stimulated by a flashlight pulse from photographic flash lamps. As time goes on, the thermal wave will transfer through the sample, and the temperature of nondefective areas will then drop uniformly over time. On the contrary, internal defects, such as porosity, delamination, inclusions, etc., can be thought of as resistances to heat flow that produce abnormal temperature patterns at the surface. The temperature changes can be inspected with a thermographic camera and recorded for later analysis. The recorded data are analyzed by images sequence processing technology to yield information for the recognition quantification of internal defects. The principle of active infrared thermography method for NDT of porcelain post insulator is shown as Figure 2.

The facilities used in the nondestructive testing experiments is shown as Figure 3, which is composed of three parts – IR camera, heat source, and base station. The thermographic NDT system is a fully-integrated hardware and software system that enables to identify, analyze and measure physical properties of materials using Pulsed Thermography. The pulse width of flashlight for heating the sample is 2 ms, and the energy is 9600 J. The sample frequency is 112 Hz, and the acquisition time is 11 s.

1. Infrared camera; 2. Thermal excitation source; 3. Controlling and processing system; 4. Porcelain post insulator for testing

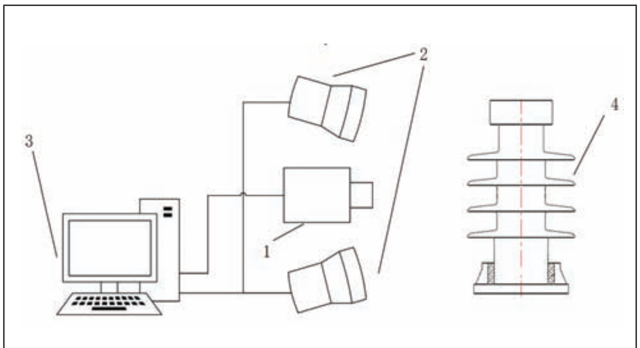

FIG. 2. PRINCIPLE OF ACTIVE INFRARED THERMOGRAPHY METHOD FOR NONDESTRUCTIVE TESTING OF PORCELAIN POST INSULATOR

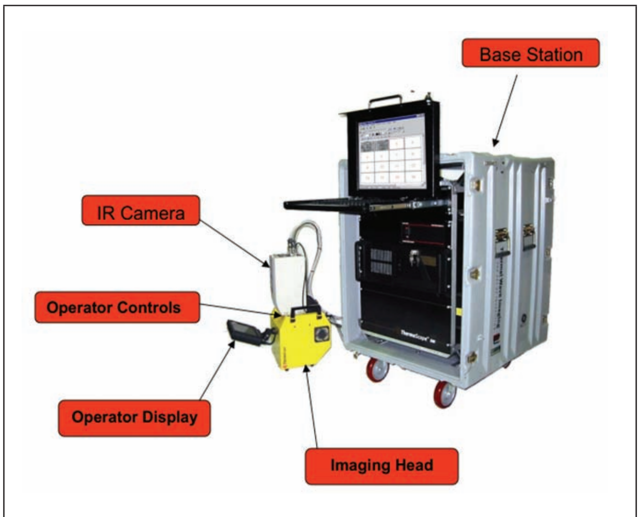

FIG. 3. EXPERIMENTAL PLATFORM FOR NDT OF PORCELAIN POST INSULATOR

4.0 RESULTS AND DISCUSSION

4.1 Samples

In order to reflect the actual situation as much as possible, finite element simulation analysis based on fracture mechanics was conducted before NDT experiments. The calculation results show that surface defects are more dangerous than internal defects. According to the field accident investigation, it is the porcelain cylinder rather than the sheds that fractures when porcelain post insulator breaks. On the basis of above analysis, the testing samples were produced in association with Dalian Insulator Group Co., Ltd. The testing sample is a porcelain cylinder without sheds, which is made of the same material of porcelain post insulator. The porcelain cylinder is 800 mm in length and 120 mm in diameter, which is shown in Figure 4. The diameter of the sample is the same as that of 110 kV porcelain post insulator. In facture mechanics, all kinds of defects can be treated as cracks. On the surface of the porcelain cylinder, several crack defects of different sizes were machined, as shown in Figure 5.

FIG. 4. TESTING SAMPLE

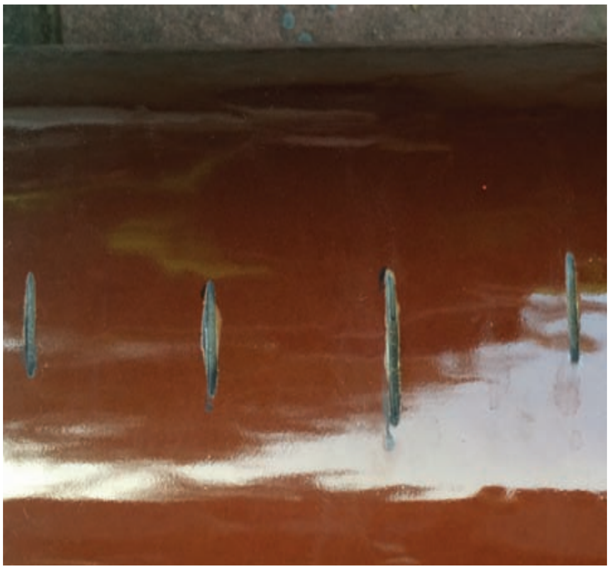

FIG. 5. ARTIFICIAL SURFACE DEFECTS

4.2 Thermal Infrared Images

After heated by flashlight pulse, the surface temperature of porcelain cylinder rises in the first stage, and then decrease. This temperature change can be recorded by infrared camera, and then displayed in the form of thermal images sequence, which contains a large amount of information about defects. Due to good conducting property, the defects of porcelain post insulator will how up early in the thermal images sequence. So the acquisition time was set up to 11 s, and this active thermography technique is a time-saving and efficient nondestructive testing method. In order to obtain sufficiently accurate data, the sample frequency was set up to 112 Hz, which means 112 frames of thermal image can be output every second. So the active thermography technique can generate extremely large data, and many data analysis method can be adopted to yield information about defects.

Figure 6 shows the 10th and the 40th frame of thermal images sequence. In Figure 6, all 4 surface crack defects of different sizes can be clearly observed. The 10th frame has a higher resolution than the 40th frame, which conforms that porcelain post insulator has good conducting property. In actual situation, the defects are generally smaller, and then the raw thermal image may not be able to reflect the information about defects. In that case, several data and image processing method can be used to enhance signal-to-noise ratio and identify the small defects better. Differential operation is one of the common methods. The 10th and 40th frame of first-order differential thermal images sequence are presented as Figure 7, in which the defects identification is significantly enhanced.

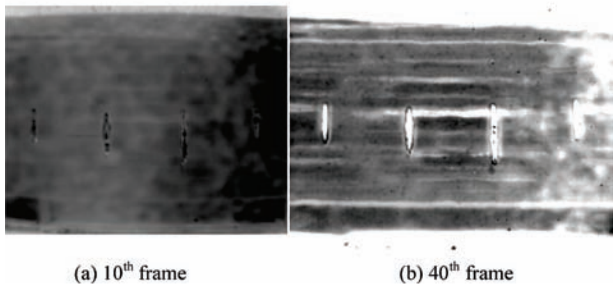

FIG. 6. THERMAL IMAGES

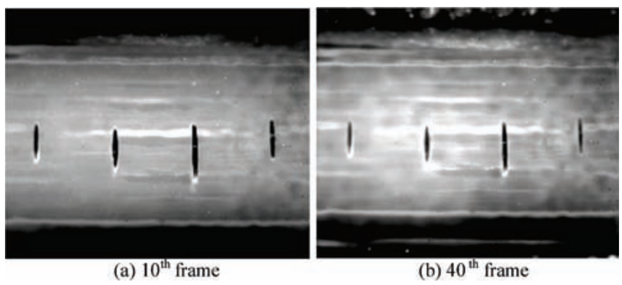

FIG. 7. FIRST-ORDER DIFFERENTIAL THERMAL IMAGES

4.3 Logarithmic Temperature-Time Plot

According to calculation results based on heat transfer theory, the temperature of nondefective area on the surface of sample is expressed as follows.

$$T_{sound}(t) = T_0 + \frac{q}{\sqrt{\pi \rho C \lambda t}} \quad ...(10)$$

Where T_0 is original surface temperature of sample, ρ is density, C is specific heat, λ is thermal conductivity.

Perform logarithmic operations on both sides of Equation (10), logarithmic temperature-time equation can be obtained as below :

$$\ln(T) = \ln\left(\frac{q}{\sqrt{\pi \rho C \lambda}}\right) - \frac{1}{2}\ln(t) \quad ...(11)$$

Logarithmic temperature-time plot of porcelain cylinder sample is shown as Figure 8. According to Equation (11), logarithmic temperature-time plot of nondefective area of sample is approximately a line that goes downward with slope -1/2 [7]. It can be observed that all 4 plots of defect deviate from the line whose slope is -1/2 at a certain moment. The deviation suggests that the pixel is a defect.

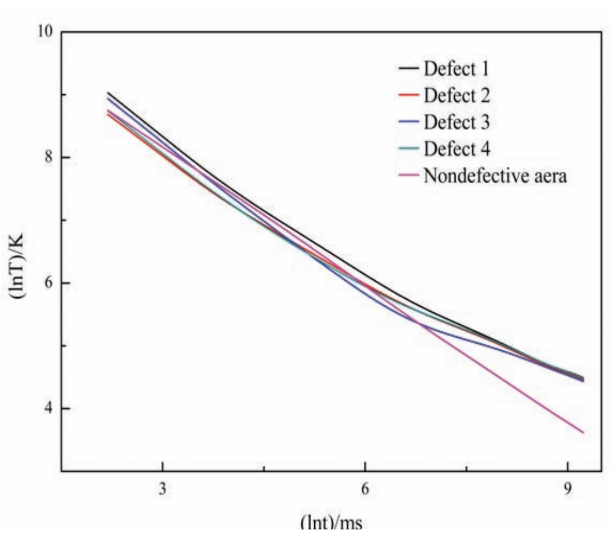

FIG. 8. LOGARITHMIC TEMPERATURE-TIME PLOT

4.4 Quantitative Analysis of Defects Depth

According to calculation results based on fracture mechanics, the depth of defects is one of the most important factors for porcelain post insulator crack accident. So quantitative analysis of defects depth should be one indispensable step of nondestructive testing for porcelain post insulator. In this part, defects depth was calculated based on peak second-order differential time (PSDT) [8].

The first-order differential of logarithmic temperature-time equation is expressed as follows.

$$\frac{d(\ln T)}{d(\ln t)} = \frac{t}{T} \cdot \frac{dT}{dt} \quad ...(12)$$

Perform differential operations on both sides of Equation (12), second-order differential of logarithmic temperature-time equation can be obtained as below.

$$\frac{d^2(\ln T)}{d(\ln t)^2} = \frac{t}{T} \cdot \frac{dT}{dt} - \frac{t^2}{T^2} \cdot \left(\frac{dT}{dt}\right)^2 + \frac{t^2}{T} \cdot \frac{d^2 T}{dt^2} \quad ...(13)$$

When the second-order differential of logarithmic temperature-time plot reaches the maximum value, the corresponding moment is peak second-order differential time, as shown in Equation (14).

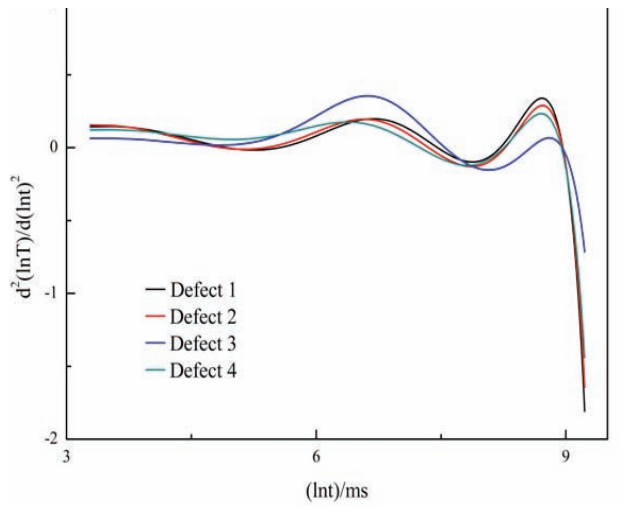

FIG. 9. SECOND-ORDER DIFFERENTIAL LOGARITHMIC TEMPERATURE-TIME PLOT

$$t_{PSDT} = \frac{h^2}{\pi \alpha} \quad ...(14)$$

Where h is the depth of defect, and α is heat diffusivity. Hence, peak second-order differential time is proportional to square of defects depth, and the defects depth can be calculated according to Equation (14).

As shown in Fig. 9, t_{PSDT} = 6.078s, t_{PSDT} = 6.122s, t_{PSDT} = 6.631s, t_{PSDT} = 6.024s. The defects depth of porcelain cylinder was calculated as follows.

$$h_1 = 2.269\text{mm},\ h_2 = 2.277\text{mm},$$
$$h_3 = 2.372\text{mm},\ h_4 = 2.258\text{mm}. \quad ...(15)$$

5.0 CONCLUSIONS

This paper proposed an active thermography method for nondestructive testing of porcelain post insulators. By porcelain cylinder surface crack defects detection experiments, three conclusions can be drawn as follows.

- Pulsed infrared thermography technique can be used for nondestructive testing of porcelain post insulator.
- Both thermal images and logarithmic temperature-time plot can be used for detecting defects of porcelain post insulator.
- The defects depth of porcelain post insulator can be calculated based on PSDT method.

ACKNOWLEDGEMENT

The authors would like to greatly appreciate the financial help from Project Supported by National Natural Science Foundation of China (51377093) and Project Supported by Shenzhen Basic Research Project (JCYJ20150331151536445).

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