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Research Article

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Research on detection system of heat faults based on multi-sensor information fusion

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ABSTRACT

Aiming at the different sampling rates of multiple sensors for the real-time detection system of heat faults in high-voltage equipment in substation, the step by step prediction fusion algorithm based on synchronous sampling data was used to rapidly calibrate the location of thermal faults. And a new method that using infrared thermal imager together with CCD (Charge Coupled Device) camera and wireless sensor networks was proposed to implement heat faults detection. The energy harvesting technique was employed to obtain solar energy, which achieved the independent power supply of sensor nodes. The experimental results in a substation showed that the system proposed in this paper could effectively detect overheating faults of the transformers and could improve the operation reliability of the electrical equipment..

Key words: Multi-sensor information fusion；heat faults；step by step prediction fusion algorithm；infrared thermal imager； wireless sensor network

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INTRODUCTION

With the development of modern power industry into the high voltage and large capacity, high requirement of the power equipment maintenance was required to ensure the safe and efficient operation of electricity production. The thermal effect of electrical equipment was the critical cause of many faults and abnormal phenomenon, therefore, temperature detection of the electrical equipment was a necessary means to ensure the reliable operation of the electrical equipment [1]. At present, the special methods used for measuring heating defects of high-voltage equipment mainly included two categories: the one was using infrared thermal imager for non-contact measurement, and the other was using a variety of wireless detection device for contact measurement [2].

Currently, the method using the infrared temperature measurement technology to detect heat faults has been widely used in power system. Most of which was hand-held infrared devices. In recent years, the infrared and visible light camera have been installed at the cradle head, and acquired automatically and circularly the infrared thermal imager of electric equipment in the substations under the control of monitoring computer [3].While utilizing the infrared thermal imager of fixed position to measure, the accuracy of the measurement was largely influenced by factors such as the background radiation, measure distance, ambient temperature, etc. Furthermore, there were blind areas where infrared thermal imager cannot detect, for instance, resistance of other apparatuses, apparatus located in electric cupboard, etc. The strong electromagnetic fields produced by high voltage interfered with radio wave badly, therefore, it was necessary to choose an appropriate frequency when using the wireless device to monitor the condition of electrical equipment. ZigBee wireless sensor network have many features: low cost, short-time delay, the unlicensed bands, high safety, low power consumption, and the network was the ideal solution to solve the heating problem of real-time and online detection of high-voltage equipment [4].

With the rapid development of power industry, the labor intensity of the maintenance personnel of power equipment has been increasing and the use of a single sensor to detect equipment heating defects cannot guarantee the stable running. The technology of multi-sensor information fusion was adopted to enhance the survival ability of the monitoring system. Simultaneity, the system had better fault correction capability due to the information redundancy between the different sensors. The coverage abilities of time and space could be expanded through the complement and combination of the detection abilities of time and space between different sensors.

STRUCTURE OF THE DETECTIONSYSTEM OF HEAT FAULTS

Installing the infrared thermal imager at the substations scene of the temperature measurement became possible for its price had fallen sharply. The fixed infrared thermal imager cannot inspect the blind area, therefore, a new method that the infrared thermal imager was put together with ZigBee wireless sensor network was put forward to realize the real-time and online detection of the high-voltage equipment. The detection system of heat faults for high-voltage equipment was shown in figure 1.

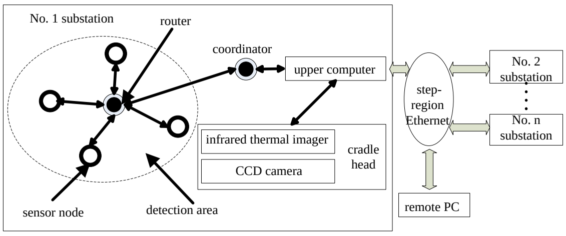

Fig.1 Structure of detection system

In figure 1, the infrared thermal imager was set on the controllable digital cradle head, and was installed at the framework of the equipment according to the actual position of the substation and the effective distance of temperature measuring of infrared thermal imager. The monitoring angle or the exact location of the focus device could be adjusted manually with the monitoring system. The pre-set points could also be checked automatically with the settings of the monitoring platform parameters. While automatically inspecting, all the measured parts of electrical equipment were scanned with infrared thermal imagery to find out the hot abnormal areas. Then, the accurate temperature of the abnormal parts and the key testing equipment were measured and the heat spectrogram was taken.

Imaging parameters of CCD camera was similar to the infrared thermal imager. Controllable cradle head was the positioning device to capture the photos, which was controlled by a principal computer through the RS-485 transmission signal. According to the program instructions, cradle head selected the corresponding anchor point, which not only supported and installed the integrated cameras and thermal imagers, but also could expand vision field of the CCD cameras and infrared thermal imagers. Cradle head could rotate a 330° in the horizontal direction, and could pitch a ±30° in the vertical direction.

ZigBee wireless sensor network in figure 1 was designed based on the IEEE 802.15.4 technical standard and ZigBee network protocols. The sensor node in the figure could measure the heating temperature and send the wireless data. The router could transmit wireless data, and the network coordinator could send the receiving data to the upper computer [6]. The upper computer communicated with the remote computer in real time and realized the remote detection through the special cable of the power system. In order to manage the heat defects of high-voltage equipment in multiple cross-regional substations centrally, the remote PC made a two-way communication with the upper computer of each substation through the Ethernet. Then, the remote fault analysis and database management for the PC from different IP addresses could be realized.

The transformer substation was a powerful source of electromagnetic interference, therefore it would produce some electromagnetic interference under the normal or fault conditions. In this paper, electromagnetic compatibility was one of the key issues when designing the temperature sensor nodes, which was directly contacted with high-voltage equipment. The interferential signal frequency mainly concentrated from 20kHz to 30MHz in the substations, therefore this frequency band was avoided and 2.4GHz frequency was used to transfer the wireless data. In general conditions, the unwanted signal could not interference the sensor node.The sensor nodes designed in this paper, which had been tested by a measuring and testing centers in China, could meet the electromagnetic compatibility requirements of substation intelligent electronic devices [7].

MUTI-SENSOR INFORMATION FUSION AND THE LOCATING OF FAILT POINT

The procedure of multi-sensor information fusion

With the rapid development of power industry, the labor intensity of the power equipment maintenance personnel was increasing and the use of a single defect detection to detect equipment heating defects cannot guarantee the stable running. The technology of multi-sensor information fusion was proposed, which can enhance the survival ability of the monitoring system. At the same time, due to the information redundancy between the different sensors, the system has better fault correction capability. The coverage abilities of time and space can be expanded through the complement and combination of the detection abilities of time and space between different sensors.

Infrared detection technology was a kind of observation technology that used infrared detectors to collect the heat distribution information of equipment under the infrared radiation status, and then converted into visible images. It could realize the observation of temperature distribution in the large area, and temperature measurement at the fixed point of local defects [8]. However, the infrared thermal imager created an image of different temperature distribution, therefore, it could not show the geometrical shapes of the parts at same temperature. When the observed equipment in the complex situations, such as it was blocked by other equipment, or it was set in the electric cabinet, etc., it was hard for observers to determine the location of the heat source through infrared thermal images quickly and accurately [9]. In this system, wireless temperature measurement sensors on the key equipment that could not be able to be observed by the infrared thermal imager were installed, and the infrared thermal imager and CCD optical sensors as well as ZigBee wireless sensor network were applied to the thermal fault detection.The system displayed thermal energy distribution of the measured target through infrared thermal images, and displayed the complete shape and accurate position of measured target in the visual image forms. The thermal fault could be located fast and accurately with the registration of infrared thermal image and visible light image and the fusion of the hot faults information together with the information obtained by the wireless temperature sensors. The procedure of multi-sensor information fusion was shown as figure 2.

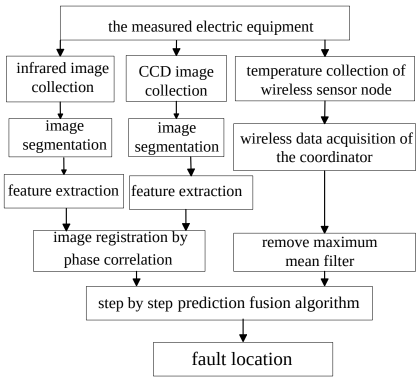

Fig.2 Flow chart of multi-sensor information fusion

The registration of infrared thermal image and visible light image, as well as the accurate locating of the fault points on the infrared image was the hot research fields of the electrical equipment fault detection[10]. This system adopted the Phase Correlation Algorithm [11] for image registration. Assume that the image $f_1(x,y)$ could produce the image $f_2(x,y)$ with the translation of the $x(k) \in R^{n\times 1}$,i.e.

$$f_2(x,y) = f_1(x-d_x, y-d_y) \tag{1}$$

And the corresponding Fourier transform was shown as the equation of (2):

$$F_2(u,v) = F_1(u,v)\exp(-j2\pi(d_x u + d_y v)) \tag{2}$$

The power spectrum in the frequency field was shown as the equation of (3):

$$\frac{F_2(u,v)F_1^*(u,v)}{\left|F_2(u,v)F_1^*(u,v)\right|} = \exp(-j2\pi(d_x u + d_y v)) \tag{3}$$

Where, the symbol "*" represented phase conjugation. Impulse function of $\delta(x-d_x, y-d_y)$ could be obtained by the inverse transformation of power spectrum. There were obvious peaks in the position offset and we could get the translation of the two images. Experiments showed that if the speed of this method was faster, it would have a better reliability and a higher accuracy.

The step by step prediction fusion algorithm
Multi-sensor information fusion system could be divided into two categories: synchronous and asynchronous sensor system. Traditional fusion algorithm usually was based on which all kinds of test data were measured and arrived at the same time, so called measure of synchronization. The data of the multi-sensor fusion must be on the condition that the different sensors were observed at the same time and on the same entity. In this paper, the research objective was a dynamic system of multiple sensors that had the different sampling rates. By using a step by step prediction fusion algorithm [12], the data of infrared sensors and CCD sensors could be fused with the data of wireless RF sensors to locate heat defects points of the electric equipment rapidly.

We set multi-sensor dynamic system as shown in the equations of (4) and (5):

$$x(k+1) = \phi(k)x(k) + w(k) \tag{4}$$

$$z_i(k) = H_i(k)x(k) + v_i(k), i = 1,2,\ldots,N \tag{5}$$

In the equation of (4), the integer of k was a discrete time variable, and $k \geq 0$; $x(k) \in R^{n\times 1}$ was the state vector; $\phi(k) \in R^{n\times n}$ was the system matrix; $w(k) \in R^{n\times 1}$ was the system process noise, which was zero mean and white noise sequence, and

$$E\{w(k)w^T(j)\} = Q(k)\delta_{kj}, k, j \geq 0 \tag{6}$$

And in the equation of (6), $Q(k)$ was nonnegative definite matrix.

After registering the infrared and visible light image, we fused the average filtering data of radio frequency sensors. Therefore, the step by step fusion filtering algorithm had two sensors with different sampling rates to observe characteristics of the target. In the equation of (5), $z_i(k) \in R^{P_i\times 1}$ was the value of $x(k)$ observed by the i sensor; $H_i(k) \in R^{P_i\times n}$ was measuring matrix; $v_i(k) \in R^{P_i\times 1}$ was a zero mean white noise sequence, and

$$E\{v_i(k)v_j^T(l)\} = R_i(k)\delta_{ij}\delta_{kl}, i, j = 1,2,\ldots,N; k, l \geq 0 \tag{7}$$

And in the equation of (7), $R_i(k)$ was positive definite matrix. Assume that $x(0),\ w(k),$ and $v_i(i=1,2)$ were independent of each other.

$$z_1^k(i) = [z_i^T(1), z_i^T(2),\ldots, z_i^T(k)]^T \tag{8}$$

$$z_1^k = [z_1^T(1), z_1^T(2),\ldots, z_1^T(k)] \tag{9}$$

In the above equations, $z_1^k(i)$ was the gather of measuring sequence set of the sensor i in the time of 1, 2,…,k. z_1^k was the gather of measuring sequence set of the two sensors in the time of 1, 2,…,k.

The essential idea of the step by step filtering was that if the global estimated value $\hat{x}(k|k)$ of $x(k)$ and the corresponding error covariance $P(k|k)$ in the time of k all had been obtained, we could use the local observations in the time of k+1 together with the Kalman filter to estimate the $x(k+1)$ in turn, thus to obtain the global estimated value $\hat{x}(k+1|k+1)$ and the corresponding error covariance $P(k+1|k+1)$.

The results and analysis of the fusion algorithm

Aiming at the wall bushing which was easy to occur current caused heat faults in the substation, the wireless temperature measuring device had been installed at the bushing joint in the No. 2 transformer in a substation to obtain the three-phase bushing contact temperature. And the live video images were acquired by the infrared thermal imager and the CCD camera. After the image registration, the data were fused with the contacting temperature of the three-phase wall bushing obtained by the coordinator. Suppose that the initial state was $x(0) = x_0$, and the initial covariance matrix was $P_0 = E\{[x(0) - x_0][x(0) - x_0]^T\}$. And given that fusion cycle was $T = 60s$, and that infrared and wireless sensor sampling period respectively was T_1, T_2, and $T_1 = 20s$, $T_2 = 10s$, then we could get fusion results of the different time shown in table 1.

From the results, the temperature rise of phase C was obviously higher than the other two phases, therefore suspecting it has defect. After repeated measurement, the temperature was still high. It was found that the casing joint of phase C had oxidation with inspection of the No. 2 transformer bushing. By analysis, we found that the conductive part of wall bushing and the busbar was the terrible oxidation because the wall bushing and the busbar were aluminum conductors and copper conductors without copper aluminum transition in the joint terminal. After dealing with the oxidation and recovering the power, the testing for temperature rising of phase C was normal. The experiment results showed that the step by step prediction fusion algorithm had a good effect on the target state estimation.

Tab.1 Results of data fusion

initial time / t (°C) / category		9:00 environmental temperature 20.4 °C			14:00 environmental temperature 29.3 °C		
wireless temperature measurement data	A	25.2	25.1	25.0	35.1	35.2	35.2
		25.1	25.0	25.1	35.2	35.3	35.2
	B	23.7	23.6	23.7	34.5	34.6	34.6
		23.8	23.8	23.8	34.7	34.7	34.8
	C	37.6	37.6	37.7	49.6	49.7	49.6
		37.7	37.8	37.9	49.6	49.6	49.6
infrared temperature measurement data	A	25.1	25.2	25.1	35.1	35.2	35.2
	B	23.5	23.4	23.5	34.4	34.2	34.4
	C	37.4	37.4	37.5	49.3	49.4	49.3
data fusion results	A	25.1042			35.1833		
	B	23.6083			34.4917		
	C	37.5667			49.4667		

CONCLUSION

The temperature detection of the high-voltage electrical equipment has become a practical problem about the safe operation of the electrical equipment in the power system, which needs to be solved pressingly.

The temperature detection of the high-voltage electrical equipment has become a practical problem about the safe operation of the electrical equipment in the power system, which needs to be solved pressingly. It was crucial significant to enhance the reliability of electrical equipment and to ensure the safety and stable operation of power system. Based on the on-line detection of heat faults of multi-sensor information fusion, it could not only solve the problem that some parts of electrical equipment was unable to be inspected by using on-line infrared thermal imager singly, but also it could be equipped with wireless temperature sensor on the key equipment to locate the thermal fault points quickly. Energy capture technology was used to collect solar energy and provide heat energy for equipment, which had solved the problem of independent power supply of the sensor nodes. The system could be improved during practical application to have greater practical value and realistic significance.

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