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Position Identification Method of Isolation Switch for Prosumer Substation Based on Intelligent Image Recognition Technology

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To improve the intelligence and automation for adapting to the development of prosumer substations, this paper proposes an isolation switch opening and closing position discrimination method based on intelligent image recognition technology. The marking point recognition and edge detection method based on the Canny algorithm is developed to identify the open and close position of disconnecting switch. Compared with the traditional auxiliary switch contact, the proposed method can form the "double confirmation" criterion of non-homologous position to realize the open and close position of the disconnecting switch, while providing the auxiliary discrimination support for one-button compatible operation. In addition, the transformation scheme of intelligent recognition and monitoring of the disconnecting switch is designed in the high voltage environment of the substation to enhance the adaptation to the prosumer substation. The field work proves that the designed system has good accuracy and reliability, which can enhance the development of one-button sequence control technology and the implementation and application in the construction site.

Keywords: prosumer substation, intelligent image recognition, isolation switch, position determination, intelligent monitoring

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1 INTRODUCTION

With the popularization of the supporting power grid and the continuous expansion of the construction scale, the increase in the number of substations has greatly increased the workload of operation and inspection (Wang et al., 2019; Wei et al., 2021). Especially the growing penetration of distributed energy resources has made it possible for traditional passive consumers to evolve into active prosumers (Li et al., 2020; Zhang et al., 2022). The prosumer can realize the management of their energy generation, storage, and consumption simultaneously through their electrical infrastructure. Switching operation is an important task for the daily operation and maintenance of substations. High-voltage isolation switch positions often use remote control signals and on-site manual observation to determine whether the opening and closing are in place, which is susceptible to the subjective influence of the observer and has low work efficiency (Chen et al., 2019). Due to the remote location or poor environment and other reasons, manual confirmation cannot be carried out at the remote operation site. At present, some stations use image recognition, pressure sensing and other methods to assist in determining the position of the isolation switch, but the above-mentioned position monitoring methods still have many problems in terms of stability, accuracy and adaptability, such as the equipment installation of pressure sensing, deployment and replacement without power failure, and the wear and oxidize of micro switch contacts (Liu et al., 2018; Cai et al., 2017; Teng et al., 2019). Existing methods for monitoring the opening and closing positions of isolation switches have certain limitations (Cheng and Xiang, 2020). It will be the focus of future research to find new technical methods and means that can improve efficiency and safety to realize the accurate judgment of opening and closing positions.

With the continuous deepening of research on smart grids, one-key sequence control technology based on automation systems has been widely popularized. The key to realize one-key sequence control is to realize accurate discrimination of various high-voltage switch position signals to reduce unnecessary energy consumption (Xiong et al., 2021). The main function is to check the position of the device based on the actual position of the device. In case of special circumstances where the actual position cannot be seen, the indirect method should be used. When at least two different principles or non-homologous indicators change correspondingly at the same time, all determined indicators change (Yu, 2008). Corresponding changes occur at the same time to determine whether the opening and closing are in place, that is, the "double confirmation" of the switch position needs to be realized. At present, the research methods for the identification of the opening and closing positions of the isolation switch mainly include pressure sensor technology, micro switch technology, optical sensing technology, attitude sensor and intelligent image recognition technology (Rodriguez, 2021). Among them, image recognition technology mainly refers to the use of computer vision, pattern recognition and other technologies to extract features from the information in the image area to meet the information and visual needs of users in different scenarios (Zheng et al., 2016).

The principle of the technology based on image intelligent recognition to distinguish the opening or closing position of the isolation switch is to use information processing technology and intelligent recognition algorithm to determine whether the isolation switch is on or off at the opening and closing position of the isolation switch to extract image features (He et al., 2016). Image intelligent recognition schemes are two kinds: one is to set mark points on the key parts of the disconnect switch, and determine the actual coordinates of the mark points through video measurement, so as to judge whether the disconnect switch is in place which is basically suitable for all types of isolation switches, and a video probe can monitor the opening and closing positions of multiple sets of switches and its main advantages are that the original equipment structure is not changed, the installation and maintenance are convenient, the cost is low, and the scope of application is wide. Besides, with the continuous development of machine vision and artificial intelligence technologies, relevant technologies have been widely applied in transportation, safety, UAV (unmanned aerial vehicle), robotics and virtual reality, etc., (Xu et al., 2020). At present, it has been widely used in the "double confirmation" technology of isolation switch opening and closing, and has achieved plentiful good results. However, its disadvantage lies in that the non-integrated design with the device makes the image easily obscured and interfered with, and the lens dust-proof and anti-fouling technology needs to be further improved. In addition, the on-site practical cost of the above-mentioned technology is relatively high, and the installation difficulty is also relatively large. To improve the automation and intelligence level of high voltage isolation switch equipment to reduce its operation cost, including manpower and energy consumption has become an urgent need for the construction and development of future substations.

This paper proposes a method for distinguishing the position of the isolation switch "double confirmation" based on image intelligent recognition technology. The center coordinate of the mark point is calculated by using the technique of scanning the mark point in eight zones, to achieve the accurate judgment of the open and close state of the disconnecting switch. In addition, the development of intelligent identification and detection system of high-voltage isolation switch sub and position pattern are also built. The main contributions are summarized as follows:

1) The reflective marking point on the conductive arm of the isolation switch is design and the coordinates of the marking point is determined based on the gray-scale center of gravity algorithm, aiming to judge the opening and closing status of the isolation switch.
2) The proposed algorithm can output the video signal of the isolation switch to the original video monitoring host of the substation through the image processing host, and automatically determine the opening and closing status of the isolation switch for monitoring.
3) The accuracy of open and closed state judgment and adaptive outdoor environment is greatly improved by considering the active light source lighting and reflective marking points, which can provide the auxiliary discrimination support for one-button compatible operation.

2 DISCRIMINANT ALGORITHM OF ISOLATION SWITCH'S OPENING AND CLOSING POSITION

In this paper, the marking point recognition and calculation method based on intelligent image recognition technology is proposed to identify the open and close position of disconnecting switch, which is a multi-layer perceptron designed based on the visual nerve mechanism. The angle values calculated with the marking point calculation method can be set as the judgment standard of the opening or closing position of the isolation switch. It means if the angle measurement value between the two conductive arms of the isolation switch exceeds set the margin of error, the position signal of the switch opening or closing is incorrect and the position signal is not output, otherwise, sending the position signal.

2.1 Marking Point Recognition

The coding mark point is used to implement the visual measurement work of the isolation switch. According to the positional relationship between the marking point and the coding marking point, the matching and positioning of the marking point can be realized. The design principle of marking points is the appropriate size, easy to paste, and simple graphics, which can accurately reflect the location information for detection and identification. The actual image of the isolation switch should be binarized for discriminating the breaking or closing position. The binarized image is obtained by segmenting a grayscale image by setting an appropriate grayscale threshold, which can reflect the overall and local characteristics of the image. The process of image binarization includes selecting a gray threshold based on the distribution of the image gray value, and dividing the image into background region and target region based on the gray threshold. When the distribution of the internal gray value and background gray value for a specific object is relatively uniform, the threshold method is used to segment the gray image.

Edge detection is to segment the image based on the discontinuity of the amplitude, so as to detect the local characteristics of the image. In this paper, the Canny edge detector algorithm is designed to implement the detection of step edges due to the stronger denoising capability and finer edge handling. The Canny algorithm uses a two-dimensional zero-mean Gaussian function and performs convolution operation on the image matrix to eliminate noise and smooth the image (Kearney et al., 2017). Assume that the position of a pixel point is (x, y), and its gray value (only binary graph is considered here) is $f(x, y)$, the selected Gaussian function is expressed as,

$$h(x, y) = \frac{1}{2\pi\delta^2} e^{\left(-\frac{x^2+y^2}{2\delta^2}\right)} \tag{1}$$

The image after smoothing with the Gaussian filter can be expressed as,

$$F(x, y) = h(x, y) * f(x, y) \tag{2}$$

where $f(x, y)$ is the function of the original image and δ is the distribution parameter of the Gaussian filter.

The grayscale image gradient of smoothed function $F(x, y)$ can be calculated by using the 2*2 operator (Kearney et al., 2017), the first-order derivative in the X and Y directions is expressed as,

$$\begin{cases} G_x(x, y) = [-F(x, y) + F(x, y+1) - F(x+1, y) + F(x+1, y+1)]/2 \\ G_y(x, y) = [F(x, y) - F(x+1, y) + F(x+1, y) - F(x+1, y+1)]/2 \end{cases} \tag{3}$$

Convolving the **Eq. 3** with the original image $f(x, y)$, we can get,

$$\begin{cases} E_x(x, y) = G_x(x, y) * f(x, y) \\ E_y(x, y) = G_y(x, y) * f(x, y) \end{cases} \tag{4}$$

Then the comprehensive gradient amplitude $M(x, y)$ and gradient direction $\gamma(x, y)$ of the pixel point (x, y) can be expressed as,

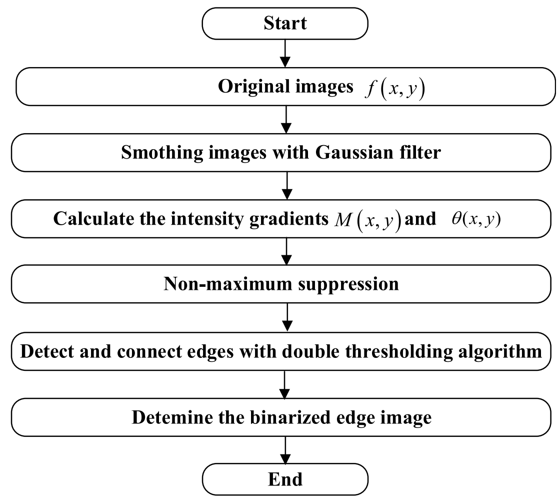

FIGURE 1 | Flow diagram of image contour extraction based on the Canny algorithm.

$$M(x, y) = \sqrt{E_x^2(x, y) + E_y^2(x, y)} \tag{5}$$

$$\gamma(x, y) = \arctan\frac{E_y(x, y)}{E_x(x, y)} \tag{6}$$

The specific steps of contour extraction with the Canny algorithm are shown in **Figure 1**. After edge detection, the eight-neighbor contour scanning algorithm is used to extract the contours of the marker points and obtain the specific information of the contour, and extract the marker points for locating the center.

2.2 Calculating the Center Coordinate of the Marking Point

For the original image function $f(x, y)$, $x = 1, \cdots m$; $y = 1, \cdots n$, thresholding process is expressed as,

$$f(x, y) = \begin{cases} f(x, y), & f(x, y) \geq T \\ 0, & f(x, y) < T \end{cases} \tag{7}$$

where T represents the background threshold. The first-order matrix of the ellipse and circular hole image after binarization can be calculated as,

$$x_0 = \frac{\sum_{x=1}^{m}\sum_{y=1}^{n} F(x, y)x}{\sum_{x=1}^{m}\sum_{y=1}^{n} F(x, y)}, y_0 = \frac{\sum_{x=1}^{m}\sum_{y=1}^{n} F(x, y)y}{\sum_{x=1}^{m}\sum_{y=1}^{n} F(x, y)} \tag{8}$$

The ellipse fitting method is adopted to detect the edge points of the ellipse and conduct the ellipse fitting on the edge points to determine the center of the ellipse. The elliptic image is expressed as,

$$f(A, X) = ax^2 + bxy + cy^2 + dx + ey + f = 0 \tag{9}$$

where $A = [a, b, c, d, e, f]$ and $X = [x^2, xy, y^2, x, y, 1]$. The objective function can be expressed as,

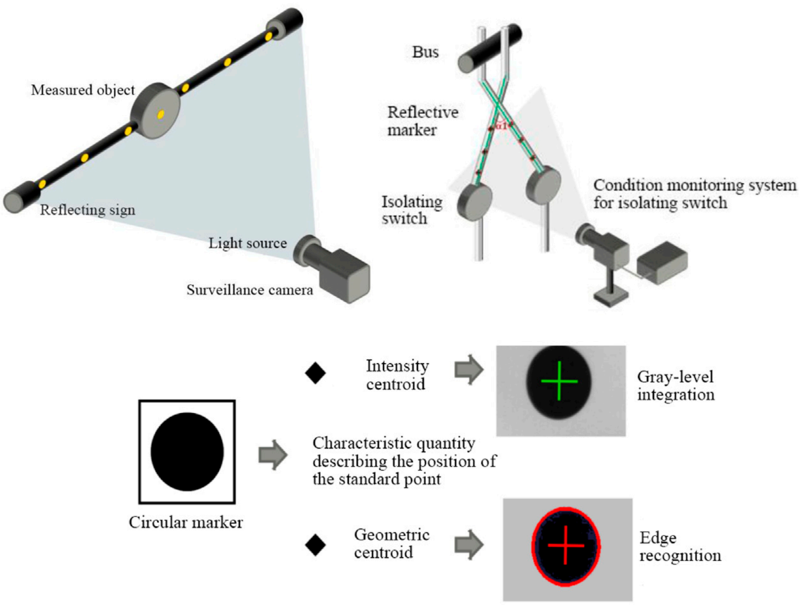

FIGURE 2 | Principles of system design.

TABLE 1 | Continuous exercise process test results.

Image Number	Image Measurement Angle (degrees)	Total Station Angle (degrees)	Error (degrees)
1	20.2578	20.0564	0.2014
2	34.7034	33.4892	1.2142
3	56.0068	55.6248	0.382
4	69.0319	68.7652	0.2667
5	166.8656	166.3416	0.524
6	179.8617	178.9513	0.9104
7 (night)	19.8554	19.5846	0.2708
8 (haze)	179.2845	178.5987	0.6858

$$F(a) = \sum_{i=1}^{N} f(a, x_i)^2 + M\left(|a|^2 - 1\right)^2 \tag{10}$$

where M is the penalty factor. Therefore, the fitting of the ellipse is transformed into a nonlinear least second-order problem, which can be solved based on the Newton-Gauss method. Then the precise center point (X_c, Y_c) can be determined as,

$$X_c = \frac{2cd - be}{b^2 - 4ac}, Y_c = \frac{2ae - bd}{b^2 - 4ac}\left(b^2 - 4ac \neq 0\right) \tag{11}$$

The center point of the obtained ellipse image is the three-dimensional coordinates of the mark point, which is used to calculate the angle between the two conductive arms. We can calibrate the angle values of the opening and closing positions of the isolation switch as the judgment standard and set the acceptable error range. If the angle measurement value between the two conductive arms of the isolation switch is within the error range, the position signal of the switch opening and closing is correct, otherwise, the position signal is not output.

2.3 Discriminant Algorithm of the Opening and Closing Position for the Isolator Switch

With the received image data of the corresponding isolator switch in the open and closed state, the discriminant algorithm of the opening and closing position for the isolator switch can be summarized as follows: the included angle of the corresponding disconnector in the closed state α_c and the included angle in the open state α_o. For the image of the isolation switch in the closed state, identify the marking points on the isolation switch, and calculate the gray-scale center of gravity coordinates of each marking point in the image; aiming at one arm of the isolation switch in the closed state Perform straight-line fitting on the marked points on the isolation switch to obtain slope $k1_c$. For the mark points on the other arm of the isolation switch, perform straight-line fitting to obtain

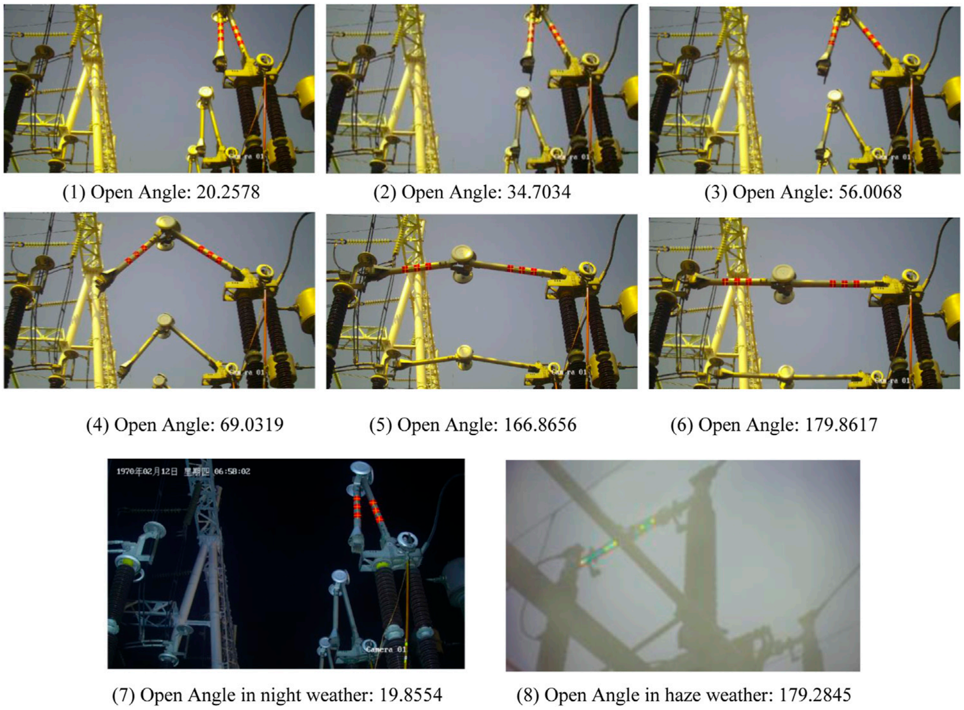

FIGURE 3 | Continuous exercise process test.

slope $k2_c$, calculate the isolation switch in the closed state Angle α_c according to slope $k1_c$ and slope $k2_c$.

$$\begin{cases} \alpha_c = \arctan \dfrac{k2_c - k1_c}{1 + k1_c k2_c} \\ k1_c = (y2_c - y1_c)/(x2_c - x1_c) \\ k2_c = (y4_c - y3_c)/(x4_c - x3_c) \end{cases} \tag{12}$$

where $(x1_c, y1_c)$ is the gray-scale barycentric coordinates of one of the marked points on one arm in the isolation switch image in the closed state, $(x2_c, y2_c)$ is the gray-scale barycentric coordinates of the other marked point on one arm in the isolation switch image in the closed state, $(x3_c, y3_c)$ is the gray barycentric coordinate of one of the marked points on the other arm in the disconnect switch image in the closed state, and $(x4_c, y4_c)$ is the gray barycentric coordinate of another marked point on the other arm in the disconnect switch image in the closed state.

For the image of the isolation switch in the open state, identify the marking points on the isolation switch, and calculate the gray-scale center of gravity coordinates of each marking point in the image, aiming at one arm of the isolation switch in the open state. Perform straight-line fitting on the marked points on the isolation switch to obtain slope $k1_o$, and perform straight-line fitting to the mark points on the other arm of the isolation switch to obtain slope $k2_o$, then calculate the isolation switch in the open state Angle α_o according to slope $k1_o$ and slope $k2_o$:

$$\begin{aligned} \alpha_o &= \arctan((k2_o - k1_o)/(1 + k1_o k2_o)) \\ k1_o &= (y2_o - y1_o)/(x2_o - x1_o) \\ k2_o &= (y4_o - y3_o)/(x4_o - x3_o) \end{aligned} \tag{13}$$

where $(x1_o, y1_o)$ is the gray-scale barycentric coordinates of one of the marked points on one arm in the isolation switch image in the open state, $(x2_o, y2_o)$ is the gray-scale barycentric coordinates of the other marked point on one arm in the isolation switch image in the open state, $(x3_o, y3_o)$ is the gray barycentric coordinate of one of the marked points on the other arm in the disconnect switch image in the open state, and $(x4_o, y4_o)$ is the gray barycentric coordinate of another marked point on the other arm in the disconnect switch image in the open state.

Compare the included angle α of the isolation switch with the included angle α_c of the isolation switch and the included angle α_o of the isolation switch, and determine the state of the isolation switch according to the comparison result. The details are as follows: Compare the included angle α_c of the isolation switch with the included angle α_o of the isolation switch: if the included angle α is within the range of $[\alpha_c - \Delta\alpha, \alpha_c + \Delta\alpha]$, the state of the isolation switch is judged to be the closed state. if the included angle α falls into the range of $[\alpha_o - \Delta\alpha, \alpha_o + \Delta\alpha]$, the isolation switch is judged to be the open state. If the included angle α is not in the range of $[\alpha_c - \Delta\alpha, \alpha_c + \Delta\alpha]$ or $[\alpha_o - \Delta\alpha, \alpha_o + \Delta\alpha]$, the state of the isolation switch is judged to be an abnormal state. where the deviation angle $\Delta\alpha$ is set to 1°.

3 INTELLIGENT IMAGE RECOGNITION AND MONITORING SYSTEM

Reflective marking points are set on the conductive arm of the isolation switch, and the actual coordinates of the marking points are analyzed through the gray-scale center of gravity algorithm. According to the obtained coordinates of the marking points, the relative positions of the moving and static contacts of the isolation switch are determined. The design principle is shown in **Figure 2**.

The specific working principle is as follows. 1) Switch the image information of the mark point on the conductive arm. Reflective marking stickers are used as marking points, which can clearly capture the image information of marking points under the illumination of the active light source in bad weather and low visibility, which can improve the accuracy of the double-confirmation system in bad weather conditions. 2) Transmit the image data to the image processing device arranged on-site for data processing, measure the coordinate points of the calibration mark, calculate the angle between the conductive arms through the coordinate fitting straight line, and calibrate the isolation switch through the straight-line angle value change. The opening and closing process. 3) The processing result (i.e., the position of the isolation switch opening and closing state) is directly transmitted to the substation control zone 1 in a hard-wired manner, and the hard contact signal is sent to the sequence control host, which can avoid the communication from zone 4 to zone 1 can achieve complete physical isolation to ensure network security. The video signal of the knife switch can be output to the video host through the network interface, and the video signal can be watched in real time.

4 ON-SITE TEST

On the isolation switch of the prosumer substation, the continuous exercise process test is implemented in the substation in Hunan province, China. The opening and closing state of the isolation switch test results under the continuous exercise process and night and haze weather conditions are shown in **Table1** and **Figure 3**. The angle calculated from the three-dimensional coordinate point measured by the total station was used as the standard value to verify the validity of the measurement. The continuous movement process of opening and closing verifies that the proposed method can accurately discriminate the opening and closing position of the isolation switch under the night and haze and other bad weather conditions. It is found from the data that the scheme designed in this paper is feasible and can be effectively applied to practical application scenarios, such as the prosumer substation.

5 CONCLUSION

This paper proposes a “dual confirmation” position identification method of the isolation switch based on image intelligent recognition technology. The marking point recognition and edge detection method based on the Canny algorithm is proposed to identify the open and close position of disconnecting switch. The image intelligent identification monitoring system was designed for the construction site of high voltage isolation switch opening and closing position. The practical application effect is verified by in-plant test and field pilot operation, which can objectively and accurately determine the opening and closing position of the disconnecting switch, guaranteeing the accuracy and reliability of the “one-key sequence control” function in smart substations.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

BW: Project design, Methodology, Writing-Original draft preparation. JW: Investigation, Idea, Supervision. PL: Algorithm design. MP: Software, Simulation. CL: Image processing. LW: Date processing, HZ: On-site test, JY: On-site test.

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The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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