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Interactive Design and Application of Virtual Training System for Smart Substation Combining Configuration Algorithm and Digital Twin Technology

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ABSTRACT
Power system simulation training is one of the important means to improve the quality of operators and ensure the safe and effective operation of power systems. Research based on digital twin technology, combined with configuration algorithms to give the substation integration diagram model generation method, developed a smart substation virtual training system. The intelligent monitoring is studied, the digital twin-based substation output voltage anomaly detection method is designed using the tracking differentiator method, and finally the simulation test of the intelligent substation virtual training system is carried out. The analysis shows that the voltage anomaly detection method in this paper is highly accurate and can extract the voltage anomaly waveform, and the offset rate of its collected signal is significantly lower than that of the comparison method (11.58%~14.84%), which is only 0.54%. The training test of fast distance protection, differential protection and zero sequence protection verifies the feasibility and effectiveness of the virtual training system in practical application. The platform can effectively promote the reform of applied electric power practice courses and provide a backbone for the training of new power system talents.

Keywords: digital twin, grouping algorithm, graph model generation, tracking differentiator method, anomaly detection, substation virtual training system

1. Introduction

With the proposal of the national energy development strategy, smart substation becomes a key link in the construction of smart grid. In the actual construction, the newly built or renovated or expanded smart substations need to carry out comprehensive acceptance tests before they can be put into operation, which puts forward high requirements for the commissioning, operation and

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maintenance capabilities of the acceptance personnel [1-3]. In view of this, intelligent substation operation and maintenance training system came into being, which can effectively improve the business level of intelligent substation acceptance personnel [4].

As an epoch-making technology product, virtual reality effectively associates the real scene with the virtual scene, and realizes the logical determination and simulation of the three-dimensional scene through sensing equipment [5]. For the intelligent substation operation and maintenance training work, the immersive interactive scene created by virtual reality technology, through the construction of the internal data model, real-time mapping of all the scenes associated with the substation equipment and substation operation mode, so that the staff in the virtual scene operation, in a timely manner, to understand the importance of the work tasks [6-10]. Especially for some large-scale equipment, virtual disassembly can be completed through virtualization operations, so that personnel really understand the principles of the equipment operation process, which contributes to the enhancement of professional competence [11-13]. In addition, the training scenarios built by virtual reality technology can realize integrated and collaborative training, supporting multi-scene and multi-point training and processing [14-17]. Even if a risk arises, the scenario can be reproduced through data simulation for the next operation and judgment [18-19]. The independence of this process can make the staff timely clear to the operation of a series of problems during the operation, comprehensively improve the professional ability of the staff, reduce the cost of enterprise loss.

At present, the developed substation training simulation system has played a better role in the training of substation operation specialties. Literature [20] proposes an intelligent substation protection equipment on-site inspection virtual system, which realizes the enhanced display of equipment information in the real space and virtual space, effectively improves the quality and efficiency of staff inspection, and has important application value. Literature [21] embedded the serious game exploration mode into the intelligent substation virtual training system, and the staff can perform operation tasks and skill training in this virtual scene to achieve the result of safety training. Literature [22] shows that 3D interaction technology can quickly generate 3D simulation scenes based on 2D scene graphs and present virtual scenes of substation simulation systems with realistic effects, which reflect great practical value in simulation training. Literature [23] developed a training environment for distribution line maintenance based on virtual reality technology, which avoids the security threat of training complex tasks in real scenarios, and helps power line operators achieve good training results as a learning medium. Literature [24] used 3ds MAX and Unity3D software to establish a virtual 3D model of a substation, which effectively meets the training needs of substations by introducing station roaming, fault simulation and other functions that help substation staff to conduct systematic training. Literature [25] established a virtual reality-based substation practice simulation system, which achieved a high operating frame rate through 3D scene establishment and model optimization, and provided sufficient immersion and realism for the substation training program. Literature [26] designed and realized a substation virtual reality training platform with data storage and client communication functions, and introduced multi-user technology to improve the traditional system does not support multiple users to train at the same time, to provide assistance and support for the training of substation enterprises. Literature [27] describes the application of three-dimensional simulation virtual technology in the training of high and low voltage trip operation of the power system, which is conducive to ensuring the correctness of the switch operation ticket, and reducing the risk of equipment failure and personnel casualties. Although the substation virtual training system can effectively reduce the training risk and improve the quality and efficiency of training, in the face of the secondary circuit faults and abnormalities that occur in the actual operation process, it is often not possible to accurately locate the fault point, which seriously affects the quality of operation and maintenance work and the elimination time of the intelligent substation.

The proposal of digital twin technology can effectively enhance the human-computer interaction function of substation models and provide real-time and intelligent services. Literature [28] points out that digital twin is an empowering technology with interactivity and visualization, and its application in the power system communication system can realize remote monitoring and control, and in the field of power operator training and education can effectively enhance the interactive experience. Literature [29] shows that the application of online digital twin technology can enable users to simultaneously control virtual and real power equipment and view the status of the equipment in real time, which provides powerful technical support for the establishment of power communication training and education systems. In addition, the related configuration algorithm is of great significance for improving the quality of relay protection automatic device equipment and secondary circuit operation and maintenance of intelligent stations, and for ensuring the safe and reliable operation of the system. Literature [30] proposes breadth priority search algorithm and depth search fault inference algorithm for intelligent substation secondary virtual device operation and maintenance for visualization display and fault monitoring and diagnosis, which strengthens the intuitive connection between devices. Literature [31] established a fault localization method for substation secondary system based on diagnostic model and fuzzy fault tree theory, which can be intelligently deduced according to the substation configuration information so as to determine the faulty equipment, and provides technical support for the fault diagnosis of the secondary system of intelligent substation. Therefore, the combination of configuration algorithm and digital twin technology to build the virtual training system of intelligent substation can significantly enhance the operation and maintenance personnel for the secondary circuit cognition and analysis and processing ability, which is of great significance for the simulation training of intelligent substation.

The article introduces digital twin technology and configuration algorithm into the construction of intelligent substation virtual training system, designs the integrated generation method of substation diagram model based on graphic configuration software, establishes the optimization objective function of the integrated generation of substation diagram model, and solves the optimization objective function by using particle swarm algorithm to generate the substation diagram model. For the abnormal output voltage monitoring of the substation, digital twin technology and tracking differentiator are used to complete the identification of abnormal output voltage, and the change of sinusoidal axis of symmetry offset rate with the voltage applied and the detection results of abnormal voltage waveforms are analyzed through experiments to demonstrate the performance of the proposed voltage abnormality detection method. Finally, the virtual training system of intelligent substation is simulated and analyzed, and fast distance protection test, differential protection test and zero sequence protection test are carried out for a certain section of the line, so as to analyze and verify the practical application effect of the virtual training system of intelligent substation based on digital twin technology.

2. Virtual training system for intelligent substations

The characteristics of power system operation determine that personnel training cannot be carried out through the direct operation of actual equipment, thus it is of great practical significance to utilize power system simulation training to improve the technical level of operators and ensure the safe, economic and high-quality operation of the power system. This paper combines digital twin technology and configuration algorithms to design an intelligent substation virtual training system.

Digital twin substation is based on the information technology system and grid information model of digital identification, automation perception, networked connectivity, inclusive computing, intelligent control, and platform service, recreating a digital substation in digital space that matches and corresponds to the physical grid, holographically simulating, dynamically monitoring, real-time diagnosis, and accurately predicting the state of the grid's physical entities in the real world, and promoting the digitalization and virtualization of the grid's entire elements, real-time state of the grid, and real-time state of the grid's entire elements. It can promote the digitization and virtualization of all elements of the power grid, the real-time visualization of all states, the synergistic and intelligent operation and management of the power grid, and realize the synergistic interaction and parallel operation of the physical power grid and the digital power grid.

2.1. Modeling of the virtual training system

2.1.1. Training system components. Intelligent substation virtual training system is mainly composed of power system simulation, monitoring system simulation, outdoor equipment simulation and secondary screen cabinet simulation platform. Power system simulation simulates the physical behavior of primary and secondary equipment of the power system. Monitoring system simulation simulates the human-machine interface function of substation automation system background. Outdoor equipment simulation uses multimedia and VR technology to simulate the operation of outdoor primary equipment and its ancillary equipment and various abnormal states, which can be used for equipment inspection or on-site operation training. The secondary screen cabinet simulation simulates the protection screen, control screen, signaling screen, DC screen, AC screen, etc. The simulation can be used for the training of equipment patrol or local operation.

According to the substation voltage level stratification, in accordance with the “busbar for the latitude, unit for the longitude, the circuit breaker as a reference, according to the electrical wiring order” principle to build three-dimensional virtual substation simulation system. Including substation system equipment modeling and substation system scene modeling. In order to optimize the development process, 3DS MAX object-oriented modeling tools are used to establish: switch, knife gate and ground knife and other primary equipment on-site simulation equipment models, mutual inductors, surge arresters, institutional boxes, operating boxes, convergence control cabinets and other auxiliary equipment models, control room, geographic environment, such as substation environment model.

2.1.2. Substation diagram model generation. When the substation diagram model is drawn, there are problems such as low quality factor of the diagram model and long generation time of the diagram model. Therefore, the research combines the technology of configuration algorithm to propose a virtual substation diagram model integrated generation method. Generally, the configuration software is regarded as an “application generator” in the software field, and the operator combines the functional modules in the way of building blocks according to the needs of actual specific control tasks and application objects.

Based on the graphic properties of the graphic configuration software, the graphic module is automatically drawn, and the substation diagram model is constructed by combining the outer model and inner model. The outer model describes the substation graphics by using the inlet and outlet lines and boxes, and usually only displays the inlet and outlet lines of two voltage levels, which are the upper level and the local level. The inner model, i.e., the single line diagram of primary main equipment connection in the substation.

The line wiring algorithm based on the outer model of the substation and the layout algorithm of the inner model of the substation are obtained from the above analysis. When there are more intersections, even shorter lines will have an impact on the generation of the substation diagram model for larger complex networks. Therefore, it is necessary to construct an objective function for solving the discrimination of the model, graphic file, and downward calibration log sent from the receiving station side, and then shorten the automatic generation time of the diagram model.

1) Multi-constraint objective function construction. Taking the principle of generating the substation diagram model with the least number of crossing points, the shortest line, the least number of crossing lines and the uniform distribution of substations as the principle, the Manhattan distance of

the line and the number of crossing points of the line are combined to establish the objective function. Among them, the objective function of the substation is:

$$S_j(i,p,k,m_j,n_j)=S[S_0(j),S_o(i)D(p),V(k),x_j,y_j] \tag{1}$$

i is the partition number, p is the territorial number, k is the grade number corresponding to the voltage, m_j is the number of strips obtained by the substation in the distribution process, n_j is the corresponding sequence of the block assigned to the substation in the m_jth clause, is the serial number corresponding to the substation, S_p is the identification code corresponding to the substation, S_D is the control partition attribute, D is the attribute of the territorial company, V is the highest voltage level attribute, x_j is the abscissa corresponding to the upper left corner of the substation drawing in the drawing, y_j is the corresponding ordinate of the upper left corner of the substation drawing in the drawing.

The objective function of the line is:

$$L_e(q)=L_e[L_p(q),V(k),S_{p1}(j),S_{p2}(r),x_{1j},x_{2r},C()] \tag{2}$$

q is the serial number corresponding to the line, L_p is the identification code corresponding to the line, V is the line voltage level attribute, S_{b1},S_{b2} is the starting and ending substation identification code of the line corresponding to the substation serial number j,r, x_{ij},x_{ij},x_{ij} is the internal transverse coordinates of the two endpoints in the modeled graph within the substation, and $C()$ is the corresponding single-line diagram of the line system.

Schematic description of the substation arrangement using the arrangement of printed circuit boards and circuit elements: the length H_g of the rectangular outer model of the substation is fixed and uniform, and the arrangement of the model inside the substation affects the width of the outer model of the substation. The width is regularized, i.e. the unit length W_g is determined and the corresponding width of the substation j is replaced by a multiple N_j of the unit length, so that the outer model of the substation can be described by an electronic component with a $H_s\times N_j$ rectangular base.

There are N_{uyer} parallel component slots in the plane of the printed board, all of which contain slots corresponding to the n $H_g\times 1$ rectangular bases next to each other, into which the electronic components present in the model outside the substation can be inserted. The sides of the printed board are usually flanked by vertical alignment corridors, and corresponding horizontal alignment corridors of widths W_b and $H_b\times n$ are usually present in the upper part of all the component slots, whose main function is to connect the wiring of the electronic components of the model outside the substation.

Let W_0 be the corresponding width of the drawing and H_0 be the corresponding height of the drawing, and the relationship between the two is calculated as:

$$H_0=\frac{W_0}{\alpha} \tag{3}$$

α is the aspect ratio corresponding to the drawing.

Let N_{uyer} be the number of strips present in the substation, which can be calculated by equation (4):

$$N_{\text{hyer}} = C_{\text{e}}\left(\sum_{j=1}^{n_s} N_j W_s\right) \tag{4}$$

$C_e()$ is the smallest integer greater than x, and n_s is the number of substations.

n is the number of grids present in each layer, which is calculated by the formula:

$$n = C_{\text{e}}\left(\frac{\sum_{j=1}^{n_s} N_j}{N_{\text{layer}}}\right) \tag{5}$$

2) Objective function solving based on particle swarm algorithm. The particle swarm algorithm searches for the optimal arrangement of the substation map model, and the location of the substation is represented by the minimum number p_j corresponding to the grid where the substation is located, and the relationship between p_j and (x_j, y_j) can be described by equations (6) and (7):

$$x_j = [R_c(\frac{p_j}{n}) - 1]W_g + W_b \tag{6}$$

$$y_j = (H_b + H_g)F(\frac{p_j - 1}{n}) + H_b \tag{7}$$

R_e is the remainder of the calculation, and $F()$ is the maximum integer that returns less than the set floating-point number.

The optimal solution problem is used to replace the integrated generation problem of the substation map model, and the optimization objective function P_{best} is established by integrating the weights corresponding to the total line length and the total number of intersections of the substation map model, which can be expressed as follows:

$$P_{best} = \varepsilon N_{cross} + L \tag{8}$$

ε is the weight factor, N_{cross} is the number of intersections after wiring optimization, and L is the total Manhattan length of the line.

Let the total number of particles in the particle swarm be q and the dimension of the solution space be D. To initialize the particles, each particle is first given a certain position and velocity, and its position and velocity are updated as follows:

$$\begin{cases} v_{md}^{(k+1)} = wv_{md}^{k} + c_1 r_1 (p_{md}^{best} - X_{md}^{k}) + c_2 r_2 (p_d^{best} - X_{md}^{k}) \\ \qquad m = 1, 2, \cdots, q; d = 1, 2, \cdots, D \end{cases} \tag{9}$$

$v_{nd}^{(k+1)}$ is the d-dimensional component of the velocity of particle m after the $k+1$rd iteration, w is the inertia weight, v_{md}^{k} is the d-dimensional component of the velocity of particle m after the kth iteration, c_1, c_2 is the learning factor, r_1, r_2 is a random number uniformly distributed between 0 and 1, p_{md}^{best} is the d-dimensional component of the individual historical optimal position of the mth particle at the moment of t, and p_d^{best} is the d-dimensional component of the historical optimal position of all the particles that have ever been reached. X_{nal}^{k} is the d-dimensional component of the position of particle m after the kth iteration

The corresponding position X_{nd}^{k+1} of particle m in the solution space is updated using equation (10):

$$X_{md}^{k+1} = X_{md}^{k} + v_{md}^{k+1} \tag{10}$$

In order to ensure the effective output of substation map-model integration, it is required that all particles can reach the optimal position. Therefore, a threshold is set, and the iteration is stopped when the target value reaches the set threshold, and the optimal arrangement of the substation is output to obtain the optimal position of each device in the substation. The optimal position is denoted as:

$$p_d^{best}(t) = \left[p_{d1}^{best}(t), p_{d2}^{best}(t), p_{d3}^{best}(t) \right] \tag{11}$$

$p_{dl}^{best}(t), p_{d2}^{best}(t), p_{d3}^{best}(t)$ respectively, is the optimal position of the substation equipment in the x, y, z direction in the 3D coordinate system at the t moment.

As a result, the output of the substation map-model integration scheme is realized.

2.2. Interactive Function Design

Intelligent substation virtual training system can simulate the training of substation system inspection, reversing and fault protection and other operations. The inspection module can simulate the routine inspection of substation equipment, and if the equipment has abnormal operation status, it will alert the maintenance at the first time. The fault protection module can realistically restore the phenomena generated when the substation fails, and assist in guiding the operator to troubleshoot the fault protection operation. The reverse gate module guides the operator to complete the actual reverse gate operation process in strict accordance with the step-by-step guidelines of the operation ticket, in order to protect personal and system safety.

2.2.1. Inspection module. Substation inspection is a regular inspection of equipment, timely detection of abnormalities, defects, hidden dangers, and timely maintenance to ensure the safe and stable operation of the equipment when abnormalities are found. The intelligent inspection program of the substation virtual training system is shown in Figure 1. Daily prudent and efficient inspection can effectively avoid the occurrence of accidents such as transformer oil leakage, line short-circuit and insulator flashover and reduce the economic loss of the substation. The inspection module combines the floating mode with the ground walking mode, so that students can observe the actual condition of the equipment at different heights and orientations, and recognize the appearance of the substation equipment more comprehensively, thus improving the quality of training.

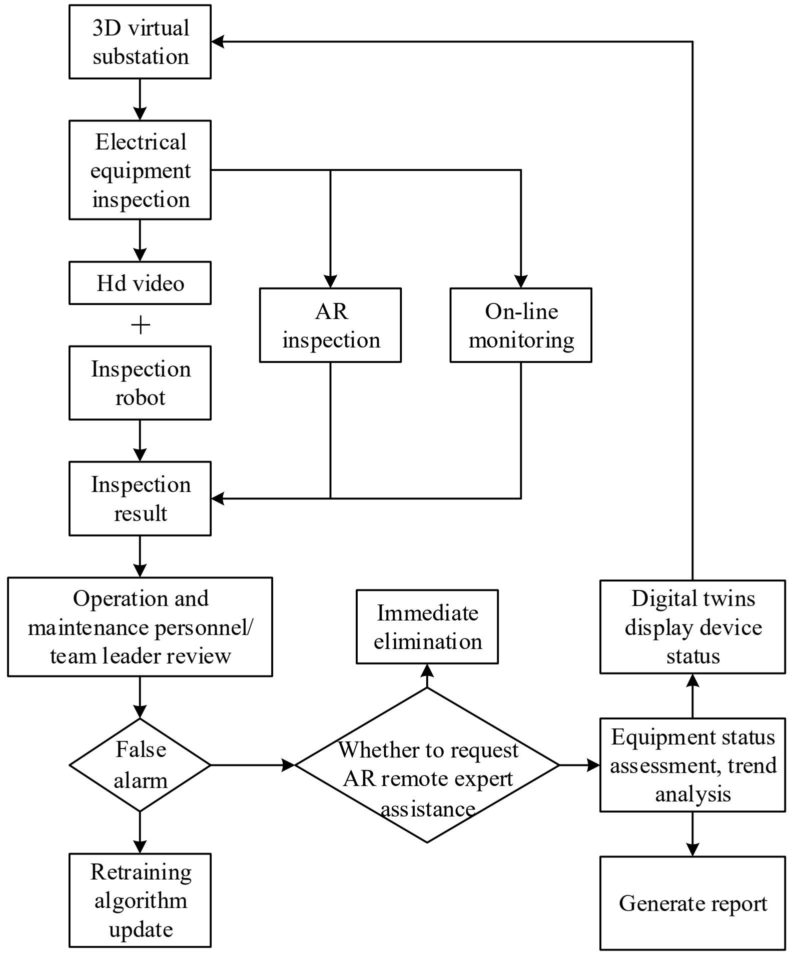

Fig. 1. Intelligent tour scheme for substations virtual training system

2.2.2. Fail-safe modules. Substation fault protection refers to troubleshooting and restoring the normal operation of the platform by invoking the platform differential protection, backup protection and other measures when the power supply process is hindered due to the failure of the substation equipment. The platform fault protection module includes transformer fault protection, busbar fault protection, line fault protection and other functions, of which the transformer fault protection module includes permanent short-circuit between turns of the body, A-phase bushing flashover, lightning arrester A-phase flashover, single-phase short-circuit, two-phase short-circuit, two-phase ground, busbar fault protection includes single-phase permanent ground and single-phase short-circuit, and the line fault protection includes 60% of the line distance single-phase short-circuit, two-phase short-circuit, two-phase ground, three-phase ground. , two-phase grounding, three-phase grounding, three-phase short circuit, single-phase permanent grounding.

2.2.3. Reverse gate module. Reverse gate operation is the operation of switching electrical equipment from blackout to power supply or from power supply to blackout, and its operation must comply with the operation ticket system and guardianship system, and be carried out in strict accordance with the operation process. The reverse gate module of the substation virtual training platform guides students to simulate the state switching of equipment such as circuit breakers and disconnect switches in the substation according to the step-by-step process of the operation ticket, which can avoid electrical failures in the actual physical system due to misoperation, and thus simulate the future operation in the actual physical system at a lower cost.

3. Intelligent monitoring of substations based on digital twins

Intelligent substation virtual training system provides a platform for students to comprehensively master the operation of important power system equipment, fault analysis, etc., in order to meet their engineering practice ability and practical hands-on ability. Substation anomaly monitoring is one of the key links, for this reason, a digital twin based substation output voltage anomaly monitoring system is proposed.

3.1. *Substation monitoring design*

Construct substation voltage visualization monitoring system based on digital twin technology. The substation three-dimensional visualization monitoring system is able to implement real-time monitoring of the equipment status of the substation, the operation information can be detected intuitively by means of the interface display, the operation of the substation equipment can be obtained through the statistics of the two-dimensional charts, and the timely acquisition of the operation data and fault data can be realized, and the administrators can find the equipment problems and solve the alarm conditions in a timely manner through the timely issuance of the alarm notification. Establishment of equipment fault knowledge base and real-time detection of substation output voltage abnormality based on tracking differentiator method.

The 3D visualization monitoring system based on digital twin technology is divided into 2 parts consisting of digital twin monitoring system and digital twin machine room model visualization. And the digital twin monitoring system consists of 2 parts: dynamic loop monitoring and fault diagnosis.

Dynamic loop monitoring is to use oil chromatography to monitor the substation output voltage abnormality, which can monitor the data information of substation voltage change in real time, and can monitor the substation equipment operation and voltage data in real time on the monitoring service platform. The fault diagnosis system analyzes the substation voltage based on the tracking differential to obtain the real-time situation of the voltage, and sends out various warning signals for the abnormal output voltage, and pushes them to the administrator's client in levels and permissions to ensure that the output voltage abnormality is dealt with in a timely manner.

3.2. *Output Voltage Abnormality Detection*

Abnormality detection of output voltage is accomplished by tracking differentiator method on digital twin based substation visualization monitoring system. The singularities and mutation points contained within the output voltage signal of a substation are important information describing the voltage state, which can be quantified as localized eigenvalues of the voltage signal by obtaining its signal time-frequency and frequency-domain information through wavelet decomposition.

The singularity of the output voltage signal can be obtained by the location of the extreme value of the wavelet transform coefficients on the high frequency coefficients of the lower level. Due to the presence of equipment-influenced grid fluctuations in the substation, noise interference with the generation of singularities occurs and large errors can occur. In order to avoid noise interference, noise reduction is applied to the measured voltage signals by means of a linear tracking differentiator with non-destructive and real-time properties to obtain singular values with higher accuracy.

Calculate the output signal $u(y)$ after inertial processing of the voltage signal in the presence of noise interference with Eq:

$$u(y)=\dot{b}(y)+\frac{1}{Y}m(y) \tag{12}$$

where: $b(y)$ represents the signal containing noise, $m(y)$ represents the noise signal, and Y represents the noise multiplier. When the noise multiplier is larger, the differential approximation is lower and the noise interference is less.

The transfer function of the linear tracking differentiator is used to eliminate the noise interference with Eq:

$$\begin{cases} y = \dfrac{1}{\eta_1 - \eta_2}\left(\dfrac{1}{\eta_1 d + 1} - \dfrac{1}{\eta_2 d + 1}\right)\omega \\ \quad = \dfrac{d}{\eta_1 \eta_2 d^2 + (\eta_1 + \eta_2) d + 1}\omega \end{cases} \tag{13}$$

where: η_1, η_2 denotes the inertia time constant and d denotes the variable.

The equivalent state-variable time domain of the discrete linear tracking differentiator transfer function Eq:

$$\begin{cases} x_1(l+1) = x_1(l) + jx_2(l) \\ x_2(l+1) = x_2(l) - \\ j\left\{\dfrac{1}{\eta_1\eta_2}[x_1(l) - b(l)] + \dfrac{\eta_1 + \eta_2}{\eta_1\eta_2} x_2(l)\right\} \end{cases} \tag{14}$$

where: j denotes the integration step, $b(l)$ denotes the input signal, $x_1(l)$ denotes the tracking signal, $b(l)$ denotes the value of the function at the moment l, and $x_2(l)$ denotes the differential signal.

It can be seen that the signal noise suppression effect of the small integral step size is better, but at the same time, as the step size decreases, the more phase information loss of the tracking signal, in order to balance the signal phase loss of the signal denoising process between the relationship between the signal denoising process, the tracking signal is compensated by the discretization of the differential signal ahead of the tracking signal $u(l)$ by the formula:

$$u(l) = \left[x_1(l) + \xi j x_2(l)\right] A \tag{15}$$

where: ξ denotes the corresponding adjustment parameter, and A denotes the amplitude adjustment parameter.

The decomposition and reconstruction of the filtered voltage signal is implemented by the Mallat algorithm, which is expressed as follows:

$$\begin{cases} S_o[u(y)] = u(y) \\ S_k[u(y)] = \sum_l J(2y - l) S_{l-1}[u(y)] \\ F_{k+1}[u(y)] = \sum_l H(2y - l) S_{l-1}[u(y)] \end{cases} \tag{16}$$

$$\begin{cases} S_k[u(y)] = 2\left\{\sum_l j(y - 2l) S_{l-1}[u(y)] + \right. \\ \qquad \left. \sum_l h(y - 2l) F_{l+1}[u(y)]\right\} \end{cases} \tag{17}$$

where: y represents the discrete time series, $u(y)$ represents the input signal, J represents the low-pass filter, S_k represents the wavelet low-frequency coefficients of layer k, l represents the number of decomposition layers, H represents the high-pass filter, and F_k represents the wavelet high-frequency coefficients of layer k.

The anomaly detection of the filtered voltage signal is accomplished by the wavelet transform mode maxima method, and the steps are as follows:

1) Calculate the max and mean of the high frequency coefficients mode of the first layer of the voltage signal.

2) Calculate (max-mean)/mean, set the threshold value, if the result is greater than the threshold value, it is detected as an anomaly.

3) Identify the anomalies of the original voltage signal obtained by reconstruction using the Mallat method by applying the feature extraction amount to complete the anomaly identification.

3.3. Analysis of experimental arguments

In order to verify the effectiveness of this paper's method for online monitoring of substation voltage anomalies, this paper takes a 110kV substation in a power supply area as an experimental object to carry out performance analysis. The digital twin-based substation output voltage anomaly monitoring method is utilized for the experiment.

3.3.1. Offset rate analysis. To test and analyze the data acquisition performance of the method in this paper, in order to show the experimental results intuitively, this paper is based on the variation of the sinusoidal axis of symmetry offset rate with the voltage applied as the experimental index, and compared with the sinusoidal axis of symmetry offset rate of the other monitoring methods, to measure the degree of sinusoidal axis of symmetry deviation of this paper's method in the voltage data acquisition, and the closer the offset rate is to 0, which represents the lower the degree of deviation. The closer the offset rate is to 0, the lower the degree of deviation, and the better the voltage signal acquisition effect is.

A comparison of the acquisition performance of sine wave symmetry offset rate is shown in Figure 2. With the increasing of the applied voltage, the offset rate of different monitoring methods are obviously reduced, and the offset rate of the sampled signal is gradually stabilized after the applied voltage reaches 11kV, which indicates that the signal transmission effect is better at this time. The change of the offset rate of this paper's method after the voltage is applied is more obvious, and its offset rate of the voltage sampling signal of this paper is only 0.54% when the voltage reaches 21kV, while the offset rate of the voltage sampling signal of other traditional monitoring methods also decreases, but the degree of offset is always higher than that of this paper's detection method (11.58%~14.84%), which proves that the voltage of this paper's monitoring method based on the digital twin sampling signal transmission is less distorted, has higher accuracy, and can meet the signal acquisition and transmission requirements of intelligent substation monitoring.

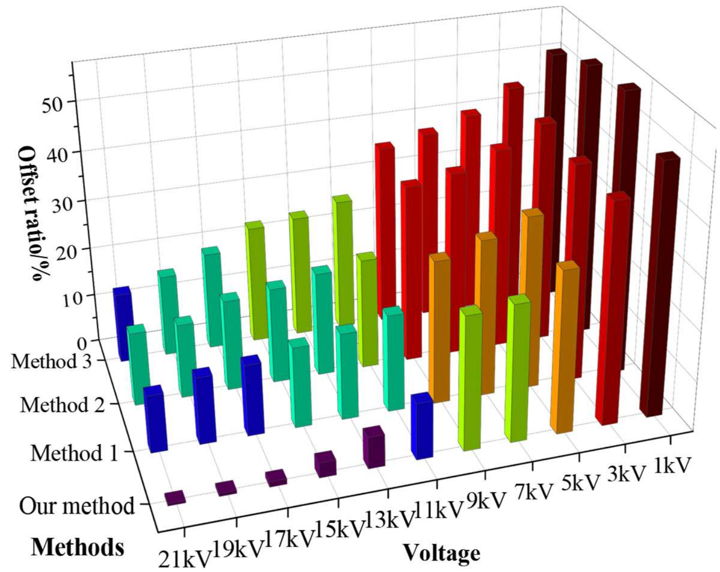

Fig. 2. The acquisition performance of the sine wave symmetry deviation rate

3.3.2. Abnormal waveform detection. With the monitoring data obtained by oscilloscope detection as a reference, compare and analyze the abnormal waveforms of switch closing voltage obtained by the method of this paper, and the abnormal voltage waveform detection is shown in Figure 3. The trend and voltage value of the abnormal voltage waveform obtained by this paper's method and the oscilloscope monitoring are basically the same, which proves that the results obtained by this paper's detection are reliable, and can accurately collect abnormal voltage waveforms to realize the localization of fault parts, so as to provide accurate data support for the diagnosis of voltage faults in the substation.

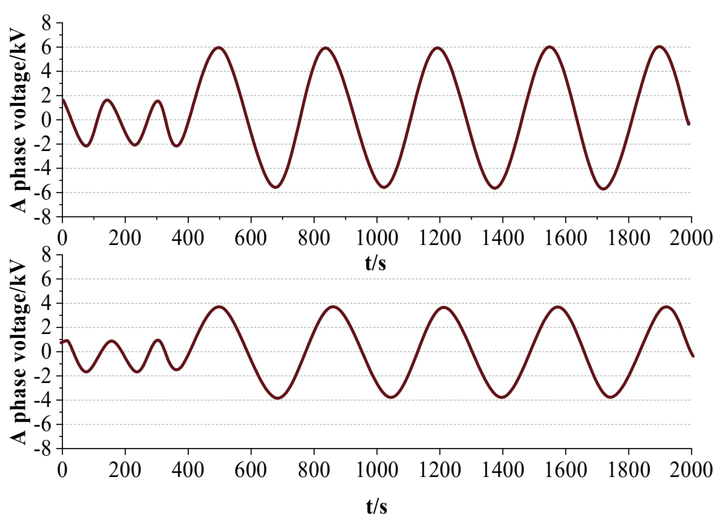

Fig. 3. Abnormal waveform detection of voltage

4. Application of the substation virtual training system

In this chapter, we will test and apply the virtual training system of substation based on digital twin, selecting line protection devices for simulation training and associating the results to virtual reality scenarios to complete the testing of the whole system.

4.1. Introduction to the test experiment

To complete the simulation experiment using the digital twin-based substation virtual training system, the trainer is first required to log in to the instructor client. The trainer constructs a simple network of line protection as shown in Figure 4 in the power grid modeling platform to provide line simulation data for the secondary system. The trainer completes the grid modeling, secondary system protection device modeling, primary system and secondary system information configuration, forms the simulation model and configuration file into a training file, and uploads it to the server through the training network.

Participating trainees log in to the intelligent substation virtual training system, select the training file to download to the local client, and carry out simulation experiments on the platform by adjusting the component parameters, setting system faults and other experiments on the training model in the file, observing the output action signals of the secondary system and the transformation of the node electrical quantities, so as to understand the operation principle of line protection.

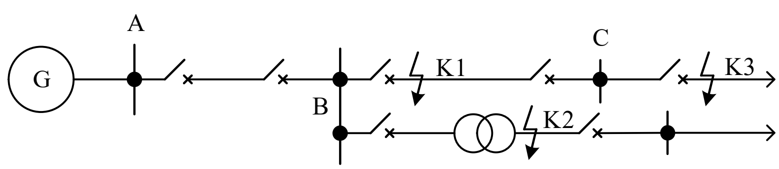

Fig. 4. Line protection simple network

4.2. Practical training simulation test

This section takes line protection as an example, introduces the whole process of training based on digital twin's substation virtual training system, and uses the virtual training system as a signal source to test the function of the protection device model and verify the correctness of the protection device action.

The training instructor wears VR equipment as the first perspective, leading the participating power employees into the virtual substation secondary system protection device terminal control room. The trainer can demonstrate the setting process of the relevant parameters of the protection device for the trainees through the control handle under the virtual reality scenario, such as: the casting and cutting of the protection device, the setting of the action time of the automatic reclosing, the setting of the rated electrical parameters, and the line connection of the protection device.

Use the substation virtual training system as the input signal source of the relay protection device to complete the automatic configuration between the primary system and the secondary system protection device, and set the simulation mode as real-time simulation. Start the virtual reality scene and conduct simulation training in the virtual reality scene.

4.2.1. Fast distance protection test. The training teacher sets a single-phase grounded short-circuit fault occurs in the primary system line at 3s, and the point of fault is the K1 position in Fig. 4, with a duration of 0.3 s. When a fault occurs at the K1 of the line at 3.3 s, the change of voltage and current at the node A is shown in Fig. 5 and Fig. 6. When a single-phase grounded short-circuit fault occurs at K1, the phase A voltage plummets, from 45.21kV to 5.23kV, and the current rises, from 5.32A to 35.29A.

Setting the reclosing time of this experiment to 0.5s, the protection device detects the fault, generates a trip signal at 3s, and attempts the reclosing operation after 0.5s. From the current and voltage waveforms, it can be seen that at this time the fault in the line has been cleared, the line protection device detects the system current and voltage gradually return to normal, meet the reclosing conditions, so the reclosing operation is successful, the system returns to normal operation, and at this time, the line protection device interface indicator to return to normal operation.

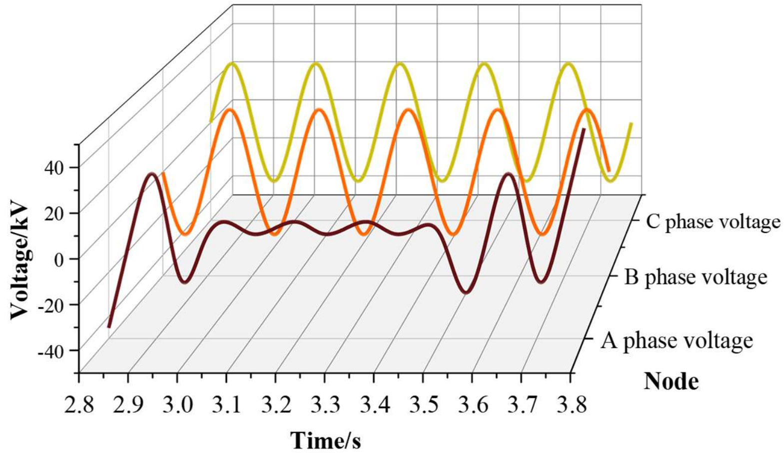

Fig. 5. The change in voltage of node A

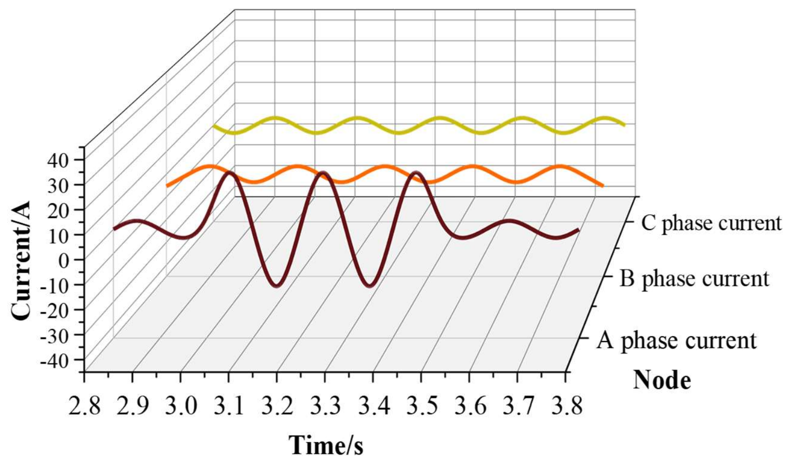

Fig. 6. The change in current of node A

4.2.2. Differential protection testing. Click the reset button on the line protection device in the virtual reality scene to restore the initial parameters of line protection. The trainer re-set the primary system line through the simulation platform client at 3s when a three-phase short-circuit fault occurs, the fault point is at K2 in Figure 4, and the duration is 1 s. The virtual training system of the transformer substation measured the voltage and current changes in the two places near the fault point, B and D, as shown in Figures 7 and 8. A three-phase short-circuit fault occurs in 3s, and the voltages of the two places, B and D, are lowered, and the currents are elevated. Line protection device internal detection of a large unbalanced current flow, start the phase selection element work, determine the fault occurs in the phase for A, B, C three-phase. As the fault still exists in the line after 0.5s, it does not meet the reclosing conditions, so the reclosing fails, and the A, B, C three-phase circuit breakers still maintain the tripping state. The two-dimensional simulation platform at the back end of the system generates an alarm message, records the fault information into the operation log, and plays the alarm sound effect in the virtual scene.

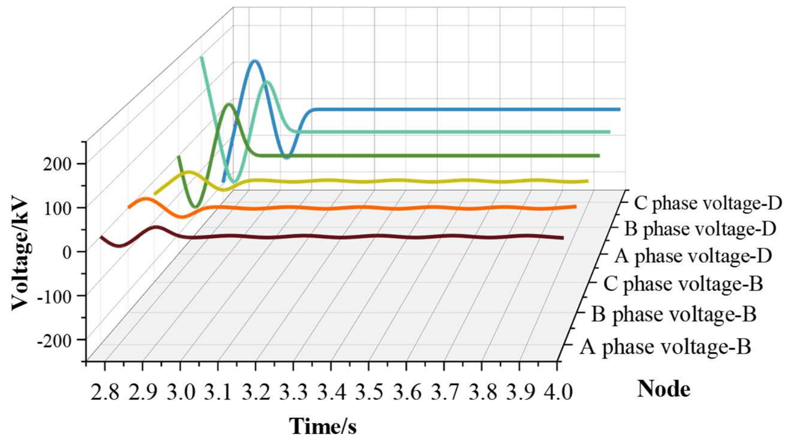

Fig. 7. Voltage variation waveform of node B and D

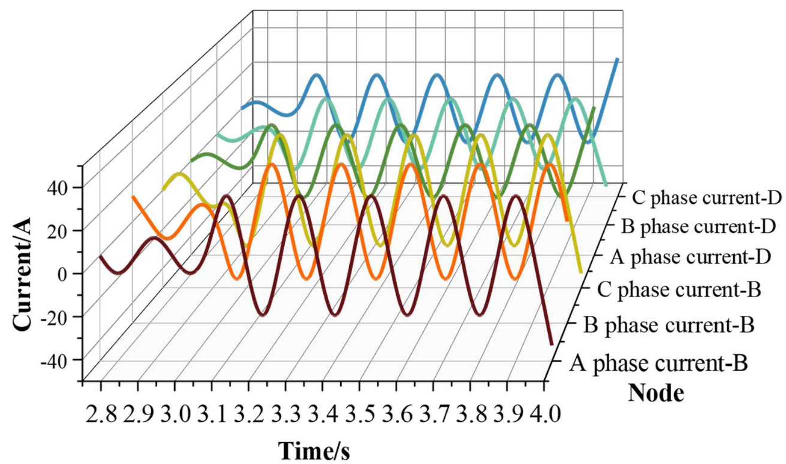

Fig. 8. Current variation waveform of node B and D

4.2.3. Zero sequence protection test. The trainer sets the primary system line to have a two-phase grounded short-circuit fault in 3s, the fault point is K3, sets the fault duration to 0.5s, and sets the zero sequence protection control word on the line protection device to "1". The virtual training system of the substation measures the waveforms of voltage and current changes near node B as shown in Fig. 9 and Fig. 10. 3s later, the A-phase voltage and C-phase voltage of node B are 0, the A-phase current and C-phase current are elevated, and there is no abnormality in the B-phase voltage and current. Starting the phase selecting element, it is judged that the phases where the fault occurs are phase A and phase C, the fault type is two-phase grounded short-circuit fault, and the location where the fault occurs is the zero-sequence protection Ⅱ section of the line protection device. The delay time of zero sequence Ⅱ protection set by the system is 0.5s, so the three-phase tripping signal is generated at 3.5s.

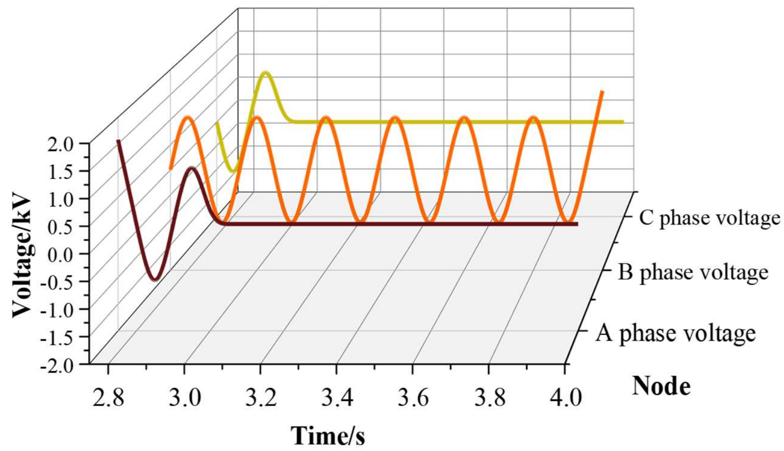

Fig. 9. The change in voltage of node B

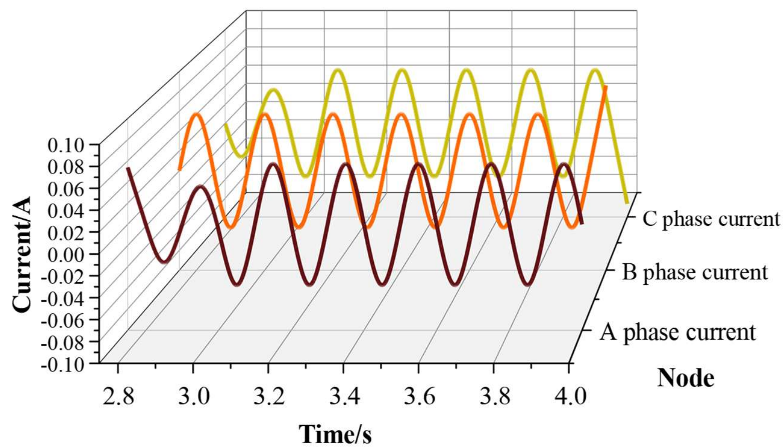

Fig. 10. The change in current of node 10

5. Conclusion

The development of digital twin technology provides new possibilities for the training of electric power talents. This paper combines digital twin technology to design an intelligent substation virtual training system, based on the grouping algorithm technology to propose a diagram-model integration generation method for substation virtual training system. Then the tracking differentiator method is used to build the substation output voltage anomaly detection model, and the experiment finds that with the increase of the applied voltage, the sampling signal offset rate of the voltage anomaly detection model in this paper is reduced to 0.54%, which is lower than that of the comparative method, which is 11.58%~14.84%, and the trend of the monitored voltage anomaly waveform is basically the same as that of the practiced voltage waveform, indicating that the proposed voltage anomaly detection model is capable of accurately carry out intelligent monitoring of substations and extract voltage anomaly features. To analyze the application of the virtual training system of intelligent substation, taking line protection as an example, the participating trainees follow the instructor to complete the training test of fast distance protection, differential protection and zero sequence protection in the virtual training system of intelligent substation. So that the students can participate in the training through the virtual reality scene, learning line protection device in the substation operation process, operation principle and fault handling of the specific manipulation process.

Intelligent substation virtual training system digitally establishes a virtual model of the real substation, superimposes the environment and operation information of the equipment in real time in the same space, realistically restores the system operation state through equipment parameters, operation data, etc., and effectively completes human-computer interaction in the virtual space. The advantages of digital twin technology, such as two-way, continuous, open and so on, make the teaching quality of electric power courses have a qualitative leap.

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