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Application of Digital Twin Technology in the Field of Substation Equipment Operation and Maintenance

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SUMMARY

As the most basic unit of the power grid system, the digital development of substation equipment is an important driving force for the power grid digitalization, and it is also one of the main goals of the power grid digitalization. As a digital technology that has developed rapidly in recent years, digital twins reflect the state of physical entities in real time through physical models, monitoring data, and big data throughout the life cycle, so as to realize the prediction, management, and analysis of actual activities. In recent years, digital twin technology has become a hotspot in multi-industry research. The fields involved have gradually expanded from the initial aerospace and manufacturing fields to agriculture, medical care, navigation, automobiles, petroleum, electric power, urban planning and other fields. Up to now, more than 1,000 universities, enterprises and scientific research institutes have carried out digital twin research around the world, and related research results have been published in academic journals. Based on the development status and trend of digital twin technology, this paper puts forward the framework of the digital twin of substation equipment for intelligent operation and maintenance, establishes the equipment life cycle data link, clarifies the data real-time interface design, and also proposes a method for rapid simulation to reflect the equipment characteristics. At the same time, it also summarizes the application scenarios of digital twin technology in the field of substation operation and maintenance, and the technical challenges faced by digital twin technology in the practical process. The research content provides a method reference for the industrial development of digital twin technology in the field of substation equipment.

Focusing on the digital twin of power equipment, the equipment simulation analysis model, online monitoring system, equipment pre-test, overhaul and production data are effectively integrated and connected to form a digital twin system of power equipment. The system can comprehensively collect all the data throughout the life cycle of the equipment and form a complete data system, thereby laying a foundation for the evaluation and diagnosis of the equipment status. In addition, the information model, basic data, business data, real-time data, algorithms, etc. contained in the digital twin can be shared by other systems to form a unified data source, which greatly improves efficiency of data utilization and facilitates maintenance. In general, the architecture of the power equipment operation and maintenance system based on digital twins has the following characteristics: 1) It can well support the collection and integration of various power equipment data. 2) Supporting the continuous improvement of the digital model. 3) The simulation and prediction of different faults can be realized. 4) It is easy to realize the visualization of equipment operating status.

KEYWORDS

Digital twin; GIS; maintenance; rapid simulation; state evaluation

1. Introduction

Digital twin refers to the full use of physical models, sensors, operating history and other data to integrate multi-disciplinary and multi-scale simulation processes [1]. It serves as a mirror of physical products in the virtual space and reflects the entire life cycle process of corresponding physical products. The digital twin model was originally a three-dimensional model proposed by Professor Grieves. In recent years, scholars have continuously enriched and improved the model. At this stage, the most academically recognized one is the five-dimensional digital twin. The model includes five main bodies: physical entities, virtual models, service systems, twin data and connections. The six principles to be followed are: Information physical fusion is the cornerstone; multi-dimensional virtual model the engine; twin data the drive; dynamic real-time interactive connection the artery; service application the purpose and the full-scale physical entity the carrier. In recent years, digital twin technology has gradually been promoted and applied in various industries, including the electrical industry.

The equipment reliability in the power system directly affects the safety and stability of the operation of the power system. For a long time, due to the lack of effective state assessment methods, a large amount of operation, maintenance and overhaul work is required, resulting in unnecessary waste of resources. This paper carries out the research on digital twin modeling technology of substation equipment, proposes a standardized description method of equipment design, production, operation and maintenance data, and builds a 3D digital twin model of GIS equipment to realize the digital specification description of the full life cycle of the equipment. It also conducts research on the rapid simulation technology of the internal overheating state of the equipment to meet the actual needs of remote detection, diagnosis and operation and maintenance services for substation equipment. This paper studies and explores new technologies to realize the intelligent interconnection and intelligent operation and maintenance of power equipment, promote the integration of advanced digital technology and business, and speed up the overall transformation and upgrading of the operation and management of power grid substation equipment.

2. Design of Digital Twin of GIS Equipment

The digital twin of power equipment is shown in Figure 1, and is mainly composed of the device entity, the data exchange interface and the digital twin. The actual equipment information data is obtained from the equipment production, operation and management process, including basic equipment information, production design data, factory test data, operating environment data, online monitoring data and various sensor measurement data. The data exchange interface is a standardized information transmission channel, which can ensure timely and efficient data transmission at all time stages in the entire life cycle of the equipment operation. The digital twin obtains the externally collected data through the data exchange interface, stores the data in a structured manner, establishes a virtual model corresponding to the device, and can receive the simulation analysis request of the external system to drive the simulation system to simulate various operating conditions of the device. It can provide external simulation analysis result and update it in time according to the actual situation. The digital twin and data exchange interface takes the device digital terminal as the carrier, and the device digital terminal can operate independently or rely on the cloud.

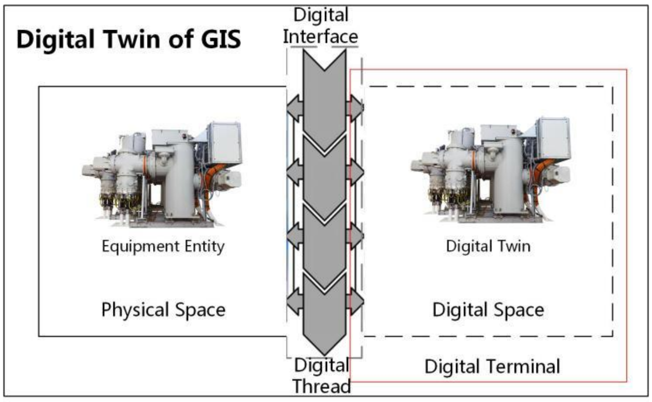

Fig. 1 Digital twin of power equipment

Considering that the application of digital twins of substation equipment in substations has been functionally divided, the digital twin system architecture of substation equipment as shown in Figure 2 is established, which is divided into three layers: Equipment layer, perception layer and application layer.

Equipment layer: It includes the main equipment of production and operation and corresponding digital terminals, realizes the digital information storage of equipment, process information recording and edge operation of digital twins.

Perception layer: It contains various sensing systems, equipped with cameras, robots and drones and other monitoring devices to realize the collection and transmission of equipment information. It is transmitted down to the digital terminal and transmitted up to the application layer.

Application layer: It contains the data storage hub and monitoring management platform to realize the storage, extraction, analysis, display and application of all relevant information.

The device layer digital terminal and the application layer function complement each other. The digital terminal provides functions such as edge computing and on-site rapid analysis for the application cloud, and the application cloud provides backup and computing power and functional supplements for the digital terminal.

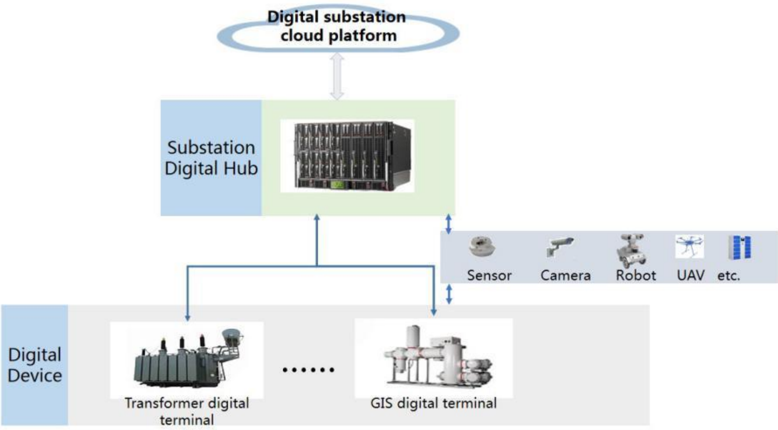

Fig. 2 Digital twin system architecture of substation equipment

Taking the combined electrical equipment as the research object, in order to realize the data twin system of substation equipment supporting intelligent operation and maintenance, it is necessary to complete digital characterization of the equipment life cycle, real-time data interaction, and the integration of state evaluation and simulation technology. According to the different stages of the equipment life cycle, the equipment data is divided into design and production data, manufacturing and installation data, production operation data and maintenance data. Combined with the requirements of equipment operation and maintenance, the interactive data is divided into status data, environmental data, operation data, maintenance data and manual data. The status data reflects the parameter quantity of the equipment status. The environmental data is mainly the ambient temperature and humidity. The operation data includes heat, partial discharge, noise and other parameters that reflect the operating conditions of the equipment. The maintenance data is the data change due to specific conditions during the equipment operation. The manual data is the data generated by manual intervention or correction during the equipment operation. Through the simulation of various typical faults, a database of fault status results is obtained, and field-circuit simulation analysis is performed on the simulation results of each status according to the operating model of the equipment, and the complex 3D simulation analysis of the equipment is converted into a coupled 3D based on the one-dimensional operating model. The simulation model of the simulation results realizes real-time simulation analysis, state evaluation and three-dimensional display of internal characteristics of the complex state of the equipment.

3. Research on Data Transmission and Storage Scheme

3.1. Data Classification

Classified management according to the data types driving the digital twin model of GIS equipment includes:

Display information: Component size information, material information, production information, installation information, and maintenance information are stored in the database display information module. The digital twin model obtains the corresponding component information from the database and operates it in the software through interactive events such as clicking, moving and staying. Appeared on the top.

Rendering effect information: The physical field data (electric field, magnetic field, temperature field and mechanics) representing the state of the device are stored in the database rendering information module in a specific format file, and the digital twin model is rendered to the corresponding part of the visual model by analyzing the data information of the file superior.

Action information: The sensor data and position information data of the switch action are stored in the database action information module. The digital twin model is driven by the switch command to the database to obtain information, and the action is restored to the three-dimensional model.

3.2. Data Storage

The GIS equipment digital twin data storage management is mainly divided into physical model, collection module, data module and display module.

The physical model is determined by the physical attributes of the equipment itself and the objective environment of installation and operation, and is not affected by the external operating environment. It is the basic mapping of physical equipment in the digital space. According to the design drawings of the GIS equipment and the information of the production raw materials, the basic three-dimensional data model of the equipment can be constructed, which can be GIM, BIM, 3DS and other model formats. According to the equipment production process and raw material information, the relevant information is associated with the geometric model to define the physical properties of each component. According to the environmental conditions of the equipment installation and operation, the external constraints of the model and the range of environmental characteristic parameters are set.

The acquisition module is a channel for the digital system to acquire real-time data. The acquisition layer also has the functions of data format unification, data classification, data labeling, and calling model layer data. The acquisition module receives the data of each sensor installed in the equipment, and uniformly converts the data into the same format. The data is labeled according to different sensor types, which are uncontrolled sensor data and controlled sensor data. The uncontrolled sensors collect GIS static data, such as voltage, current, temperature, and mark and sort the corresponding data according to sampling speed. The controlled sensor collects the dynamic data of the GIS during the switching operation, such as the switching speed, the current of the opening and closing coil, and the mechanical characteristics. The acquisition module transmits the sampled data to the data layer in real time according to the tags, and at the same time obtains system information from the substation data system, including switch action instructions, power outage plans, maintenance plans.

The data module stores various data generated during the equipment operation, and manages the data through real-time databases and historical databases, including a rapid simulation module, to realize real-time simulation of the electric field, magnetic field, and temperature field in the GIS. The data module includes a database and a simulation module. The database classifies and stores the data uploaded by the collection module according to equipment information data and GIS action characteristic data. Equipment information data includes equipment operating status data, overhaul and maintenance information, production information, environmental information. GIS action characteristic data mainly includes switch opening and closing speed, opening and closing coil current, mechanical characteristic curve, tripping and reclosing instructions, switching action timing. The database is divided into a real-time database and a historical database. The real-time database is directly connected to the acquisition module. The relevant data is stored and managed according to the First-In-First-Out (FIFO) principle. According to different sampling frequencies, different data spaces are allocated to the data. The real-time database stores the latest data within one month. The historical database data is obtained from the real-time database, and the data in the real-time database beyond the storage period is written into the historical database in units of days. For data with a sampling frequency of device information data higher than one day, it is stored according to the minimum, maximum, and average values of the data collected in one day. For GIS action feature data, all are directly written into the historical database. The simulation module builds rapid simulation models of simulation fields with different parameters through processing methods such as machine learning and simulation model degradation. By receiving data from the real-time database, the boundary conditions are constructed to realize the rapid simulation of the internal characteristics of the equipment based on the sensor data. The results of the simulation module are analyzed and converted, and the corresponding results are stored in the real-time database.

The display module realizes the external functions of the system through the support of the physical model, acquisition module, and data module. The display module realizes the external interaction of the system interface, including model display, data exchange, simulation calculation and state evaluation. The display module uses the equipment structure data of the model module and the status data of the data module to visualize the real-time status of the equipment. The real-time database data is called to meet real-time display requirements; historical database is called to realize historical status query. The display module controls the data module simulation module through instructions. The simulation data of temperature field, magnetic field and force field generates a *.bin file every 1 minute, and parses the *.bin file through Python to obtain the data of the simulation model effect transformation to realize the simulation state display.

4. Rapid Simulation of Digital Twin Model

4.1. Model Reduction Technology

Simulation technology has been widely used in the power industry, and is gradually changing from “single discipline/single physics” to “multidisciplinary system integration/multi-physics coupling”. The development of digital twin technology has brought new opportunities and challenges to simulation.

As a general analysis method, finite element simulation can reach high simulation model accuracy. However, for large-scale models that run three-dimensional transient analysis, this method consumes huge resources and time in calculations. Therefore, reduction technology is particularly important in realizing rapid simulation. Model reduction technology has long been applied in the field of automatic control and circuit systems, and has always been one of the theoretical foundations of ultra-large-scale circuit design automation software. However, it is only in recent years that this theory has been applied to 3D simulation. How to transform a large-scale complex system into a smaller-scale approximate reduced-order system under certain conditions and meet the accuracy and stability of the simulation is the key to rapid simulation.

4.2. Simulation Model Construction

This paper takes the temperature field of GIS equipment as an example to illustrate the realization of rapid simulation.

According to the physical structure of the object under investigation, a three-dimensional model of the object is established. GIS heating faults usually occur at the busbar joints, and build a three-dimensional geometric model as shown in the Figure 3.

Fig. 3 Temperature simulation part

For CFD simulation of the temperature field, the geometry needs to be cleaned and simplified to form a high-quality geometry that satisfies the CFD simulation. Since the GIS equipment is filled with SF6 gas, it is a conjugate heat transfer simulation. It is necessary to extract the geometry of the inner flow channel and share it with the solid geometry, and the geometry is meshed, as shown in Figure 4.

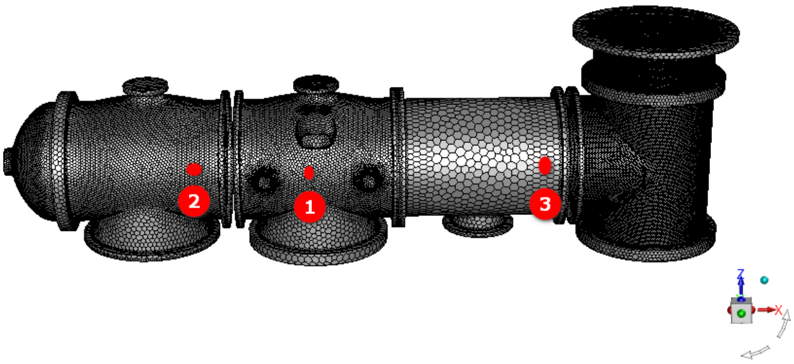

Fig. 4 Simulation Geometry of Temperature Field

For the simulation of the digital twin model of the temperature field, it is generally necessary to know the heat loss of the heating part. However, in the actual operation of GIS, the heat consumption of the heating part cannot be obtained through the sensor, and only the temperature distribution of the shell surface can be measured. Here, we use the inversion method for simulation: The temperature field distribution of the housing under different heating power consumption is simulated, and the corresponding relationship between the heating power consumption and the housing temperature is obtained through the analysis of the simulation results. Then the heat dissipation power of the heat-generating component can be obtained by reverse deduction when the temperature of the casing is known. Then, the temperature field distribution result data under different power consumption is obtained through simulation, and the training data of the model reduction is formed. Through the method of machine learning, a reduced-order model of the temperature field is generated. Finally, the temperature field reduced-order model is code-packaged to form a file that can be run independently and integrated into the digital twin model.

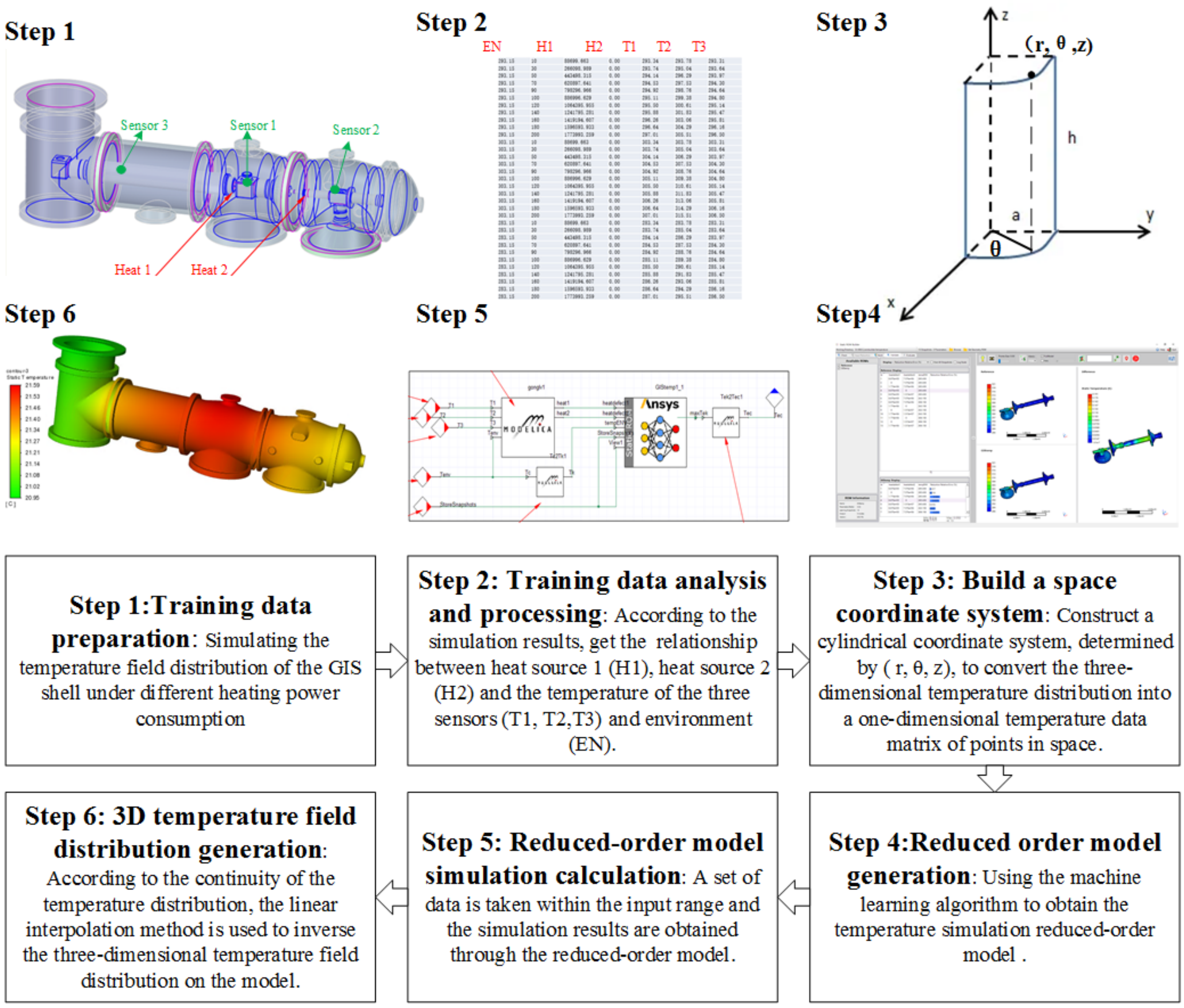

Fig. 5 The Process of Rapaid Simulation of Temperature Field

The red dot in Figure 4 is the position of the temperature sensor, and the temperature data of the corresponding point is obtained. There are two electrical connections inside the model, which are two heat sources. The process of rapaid simulation of temperature field are shown in Figure 5. The heat source and ambient temperature are set as input variables, and the temperature values of the three temperature sensors are set as output values. Multiple sets of operating conditions are run in the finite element simulation software, in which the range of volumetric power and external ambient temperature cover the maximum and minimum values of the actual situation. The relationship between heat source 1 and heat source 2 and the temperature of the three sensors is studied, and different heat source values are set to simulate multiple sets of data. Through mathematical analysis of the simulation results, the relationship matrix between heat source 1 and heat source 2 and the temperature of the sensor is obtained. Taking the conductor centerline as the axis to construct a cylindrical coordinate system, and characteristic points on the conductor, shell, insulator surface and inside the air cell module, and the points are determined by (x, r, θ). According to the position of the point and the results of the above simulation analysis, the temperature value, the temperature change gradient and the change direction (x, y, z) at the point are determined, and the temperature field distribution can be approximated by the temperature data of all points. Taking the characteristic points as the intermediate connection, the reduced-order correspondence between the three-dimensional temperature field and the one-dimensional data set M= (X, Y, Z) is established.

GIS equipment temperature reduction data preparation: The sampling points of training data are generated by DOE method, and the Central Composite Design (CCD) method is sampled. There are three variables, two heating elements and ambient temperature. Multiple simulation calculations are performed in the 3D simulation software to obtain the training data set, and save the results in a certain format and file structure. Among them, Points.bin provides node coordinates, Settings.json provides simulation condition information, and Doe.csv stores sampling point information. The training data adopts the static rom machine learning method to learn and train the three-dimensional simulation result data, and finally generate a temperature reduction model.

A set of data is taken within the input range and the simulation results are obtained through the reduced-order model. The output result file is binary in .bin format, which contains the coordinate information (x, r, θ) of each feature point and the corresponding temperature information (x, y ,z). The output result is assigned to the established three-dimensional model. According to the continuity of the temperature distribution, the linear interpolation method is used to inverse the three-dimensional temperature field distribution on the model, as shown in Figure 6.

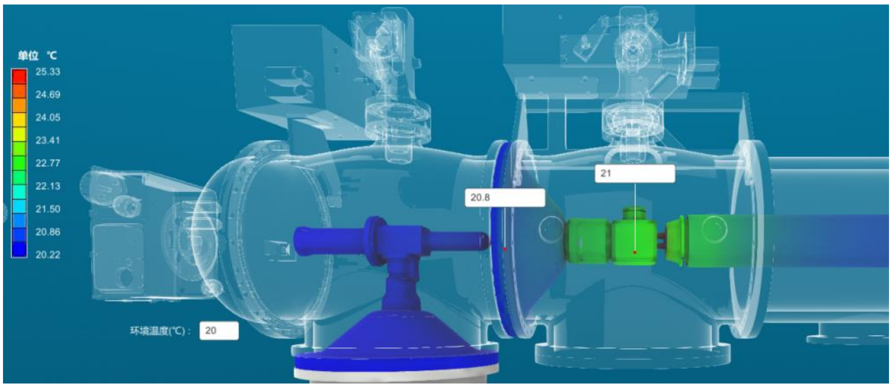

Fig. 6 Inversion of Temperature Simulation Results on Digital Twin

4.3. Simulation Accuracy Verification

The accuracy verification of the digital twin of the GIS equipment temperature is mainly compared with the calculated value of the 3D simulation. A set of data within the input range is taken and the inverted three-dimensional temperature field distribution is obtained through rapid simulation. The three-dimensional temperature field distribution is obtained through finite element simulation, and the error of the two temperature field distributions is obtained by comparing the two simulation results. The maximum and average values of the error distribution are compared with the set error range. If the error exceeds the set range, the set of data are added to the machine learning training set to retrain for a new reduced-order model, and perform verification again until the verification error is within the range.

5. State Assessment Based on Digital Twin

According to the cause and manifestation of GIS equipment operation failure, the health evaluation of GIS equipment is divided into insulation state evaluation, conduction state evaluation, operation state evaluation and control state evaluation.

Taking the conductivity evaluation as an example, conductivity evaluation and inspection objects are the conductors and gas chambers of GIS equipment to determine the normal value range and allowable fluctuation range of various direct parameters under normal operating conditions, such as conductor voltage, current, air pressure, gas composition, and partial discharge volume.

Parameter evaluation: Obtaining real-time data of each direct parameter through the equipment digital twin model. If any direct parameter exceeds the allowable fluctuation range of the normal value, the evaluation result will be output. The GIS conductor status is abnormal, which means that the equipment needs to be repaired and maintained as soon as possible. If it is within the range, the simulation evaluation is input.

Simulation evaluation: The real-time conductor voltage, current, and gas chamber temperature are input as boundary conditions into the GIS digital twin model for simulation analysis, and the temperature field distribution on the conductor and between the conductor and the gas chamber is calculated. At the same time, the normal value is input as the boundary condition, and the temperature field distribution on the conductor and between the conductor and the gas chamber is also calculated. Comparing the temperature field distribution results of the two calculations, if one of the maximum value and the average value of the temperature field distribution exceeds the allowable range, the GIS conductivity state is output. Note that although the GIS is operating normally from the parameter measurement, the temperature distribution inside the GIS is abnormal. At this time, it is necessary to formulate a pre-test maintenance plan for the equipment according to the management requirements. If it is within the range, then the historical data evaluation is input.

Historical data evaluation: The real-time conductor voltage, current, and air chamber housing temperature are used as data sets, and the voltage, current, and air chamber housing temperature corresponding to historical faults and defects are converted to values under the same operating conditions for comparative analysis. If half of these data exceed the historical data or if the largest one exceeds 1.5 times of the historical data, the output of the GIS conduction state concern means that more attention needs to be paid to monitoring the conduction state of the equipment. Otherwise, the output GIS conduction state is normal.

6. Summary

With the development of digital technology, the digitalization of the power grid is an inevitable trend of development, which puts forward higher requirements for the management and evaluation of the full life cycle of substation equipment. The digital twin can solve the problem of disconnection between the operation and maintenance of substation equipment and production design at this stage. By establishing a digital twin model of the equipment, a digital model asset library of substation equipment is formed, and the digital delivery of substation equipment is realized. The digital twin gathers equipment-related data, performs real-time analysis of the equipment status in the digital space, solves the problem of information islands in different online monitoring systems at this stage, and improves the efficiency of data utilization. Through the digital twin, the internal characteristics and operation mechanism of the equipment can be directly reflected, which is of great significance for equipment operators to deeply understand the equipment operation status. This paper studies the data modelling method, and applies the “digital twin” to the field of management, operation and maintenance of substation equipment, and proposes the application prospects and possible technical routes of the digital twin technology in the field of substation technology. It also points out the challenges faced by the digital twin technology in its application and provides a development direction for the digitization of electrical equipment.

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