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ONLINE MONITORING SYSTEM OF ELECTROMECHANICAL TRANSIENT SIMULATION DATA OF DISTRIBUTION NETWORK BASED ON EDGE COMPUTING

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Abstract. The current distribution network is developing toward the direction of information and intelligent distribution Internet of Things (IoT). In order to explore the online monitoring system for transient electromechanical simulation of distribution networks, this paper is based on the equivalent model of generator sets. Firstly, it describes the relevant theoretical knowledge of edge computing, designs the distribution IoT based on edge computing, and briefly introduces its network architecture. Secondly, based on the discrete-time domain equivalent model of generators, the electromechanical transient simulation distribution network is constructed by introducing the machine network division of the power network. Finally, the Western System Coordinating Council (WSCC)-3 units and 9 nodes are taken as an example, and simulation experiments are conducted under two fault simulation conditions to verify the effectiveness of the simulation model. The results show that under the two fault simulation conditions, the results of equivalent model simulation of generator terminal voltage and relative power angle change are like those of the Power System Analysis Software Package (PSASP). The changing trend of the two is similar and stable. After the PSASP results are stabilized at a value, the simulation results fluctuate extremely up and down the value. For example, under fault condition 1, the changing trend of the relative power angle of the No. 2 generator is first fluctuating and then becomes stable. After violent fluctuation, the relative power angle tends to be stable from about 20s to -12.35°. The result of PSASP software is stable at -12.35°. The transient electromechanical simulation of the generator equivalent model can provide some ideas for the online monitoring system of the distribution network.

Key words: Internet of Things for power distribution, edge computing, transient electromechanical simulation, generator equivalent model, fault simulation

1. Introduction. With the rapid development of China's economy and the extensive application of the 5th Generation Mobile Communication Technology (5G), industrialization has gradually covered all parts of the country. The scale of China's power grid is growing day by day. Its safe and stable economic operation for a huge power network has become an urgent problem in modern power system research [1]. As an effective method to analyze the dynamic stability of a power system, transient electromechanical simulation is widely used in system design, planning, operation, and dispatching [2]. However, as a nonlinear dynamic system with a complex structure, it is particularly difficult to analyze and deal with its operation process and behavior characteristics [3]. Additionally, the scale of data continues to expand, and the efficiency requirements of data processing and computing are also getting higher and higher. Cloud computing can no longer meet these needs, and the edge computing model came into being. Edge computing is used to design distribution networks. Its simulation system has good research significance.

There are many types of research on distribution network simulation systems. Hayes et al. (2020) proposed a co-simulation method of distribution network and local peer-to-peer energy trading platform to solve the problem that the power platform did not fully solve the potential impact of peer-to-peer energy trading and other local power trading mechanisms on the control, operation, and planning of distribution network. The system uses a blockchain-based distributed double auction trading mechanism, and the distribution system simulator is connected to the peer-to-peer energy trading platform. The proposed collaborative simulation method is demonstrated through the case study of typical European suburban distribution network. They found that this method can be used to analyze the impact of point-to-point energy transactions on network operation performance, and moderate point-to-point transactions will not significantly impact network operation performance [4]. Bozorgavari et al. (2020) proposed robust planning of distributed battery energy storage systems from the perspective of distribution system operators to improve network flexibility. The problem is modeled as a nonlinear program. The first-order expansion of the Taylor series on the power flow equation is then used to linearize.

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They used polygons to linearize the circle inequalities and proposed the equivalent linear programming model. In addition, in order to model the uncertain parameters in the proposed problem, including the predicted active and reactive loads, energy and charge-discharge prices, and the output power of renewable resources, a robust optimization framework based on bounded uncertainty is proposed in the next step. Finally, the proposed scheme is applied to the 19-node MV CIGRE benchmark grid through GAMS software to study the capability and efficiency of the model [5]. Liang et al. (2020) proposed a fault line selection method based on adaptive convolutional neural networks (CNNs) for distribution networks by improving the pooling model to shorten diagnosis and fault operation time when a ground fault occurs in a small current system. Experiments show that this method improves the network feature extraction ability. The secondary fault location is identified using the fault location principle at both ends. The fault data obtained from the Simulink simulation is taken as the training set, and an adaptive CNNs model is built based on the TensorFlow framework. The results show that the model has a higher fault identification rate and faster convergence speed. It can be used as an auxiliary hand for distribution network fault diagnosis [6]. These researchers use deep learning algorithms to research and improve the distribution network in terms of point-to-point energy trading platform, distributed battery energy storage system of the distribution system, and fault diagnosis of the current system. However, there are few types of research on online monitoring of transient electromechanical simulation of distribution networks. Therefore, this paper analyzes the electromechanical transient simulation model of the distribution network from the perspective of the generator unit equivalent model.

Based on the equivalent model of generator sets, this paper first introduces the relevant theoretical knowledge of edge computing, designs the distribution IoT based on edge computing, and briefly describes its network architecture. Secondly, according to the practical generator set model, the mathematical model of the synchronous generator set is equivalently transformed. The discrete-time domain equivalent model of the generator set suitable for transient electromechanical simulation is established. At last, based on the discrete-time domain equivalent model of generators, the electromechanical transient simulation distribution network is constructed by creatively introducing the machine network division of the power network. The validity of the simulation model is verified by designing fault simulation experiments.

The design of transient electromechanical simulation for generator set equivalent model can provide a new thinking path for the online monitoring system of the distribution network. This paper is analyzed in four parts. Section 1 is the introduction, which leads to this paper's research purpose and significance by introducing the research background and current research status. Section 2 is materials and methods, and the theoretical basis of this research is briefly described, such as edge computing, distribution Internet of Things (IoT), generator set equivalent model, etc. The electromechanical transient simulation model is built based on the generator equivalent model. Section 3 is the simulation experiment design, through the simulation experiment of the Western System Coordinating Council (WSCC) 3 units and 9 nodes under two fault simulation conditions, compares with the results of the Power System Analysis Software Package (PSASP) software and draws the experimental conclusion. Section 4 is the conclusion, which summarizes the main results and achievements, and points out the shortcomings and prospects for future research.

2. Electromechanical transient simulation based on generator unit equivalent model.

2.1. Distribution IoT architecture based on edge computing. Edge computing is a new method of network edge computing. The concept of "edge" refers to any network resources, computing, and storage in the path between the cloud center and the data source. The European Telecommunications Standardization Association has defined the reference architecture, engineering implementation guidelines, and typical service scenarios of edge computing originating from the 5th Generation of Mobile Communication Technology [7]. Edge computing means that in order to reduce the burden of the cloud computing center on the edge network side near the intelligent terminal device, the computing power of the intelligent device itself and the allocated computing resources are used to process and store a certain amount of data, so as to reduce the burden of the cloud computing center and realize the more efficient and stable operation of the IoT system [8]. Even in a network environment composed of computers and systems delivered by different manufacturers, edge computing technology can realize the interoperability of different operating systems and communication protocols, devices of different manufacturers, and technologies with different principles.

With the continuous development and improvement of computer technology and the technical architecture

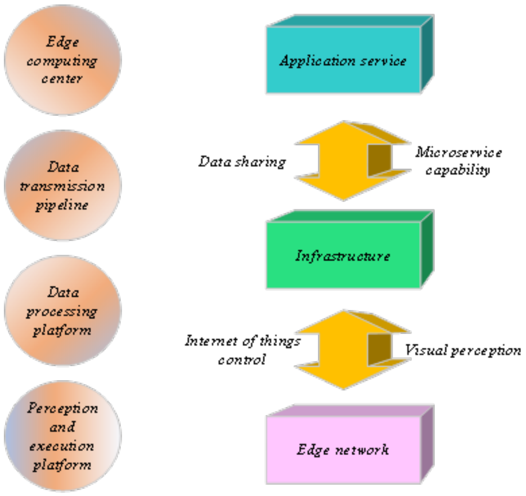


Fig. 2.1: Architecture of power distribution IoT

of the IoT, edge computing, as a technology to reduce the load and burden of cloud computing centers, has increasingly entered the vision of researchers. For the distribution IoT, using edge computing technology, many processing processes can be completed at the ”end” layer through edge servers, intelligent terminals, and other devices, which can greatly improve the efficiency of the system in processing data, receiving user feedback timelier and effectively, and improve the user experience [9]. The breakthrough of edge computing technology is of great significance to the distribution of IoT. Suppose edge computing technology is properly used in the IoT architecture. In that case, many initial data processing processes can be completed at the edge, reducing the burden on the cloud center, improving the overall data processing efficiency of the IoT, and responding to user needs faster. Therefore, using edge computing technology to achieve optimal scheduling and allocation of computing resources in the distribution IoT can complement and cooperate with the cloud computing center to jointly improve the operation efficiency and stability of the distribution network [10].

In 2019, State Grid Corporation of China formally put forward the strategic goal of ”building a comprehensive business ubiquitous power IoT”. It aims to improve the optimal operation level of the power system comprehensively and better meet the social power demand by using advanced technologies such as ”cloud, large, material, mobile, and smart”. The power distribution IoT is an important implementation of the ubiquitous power IoT in the distribution field [11]. Compared with the traditional distribution network, the IoT has the characteristics of the extensive interconnection of terminal devices and edge servers and a comprehensive dynamic and flexible perception of power consumption status. The IoT can realize the real-time intelligent perception of the real-time operation status and digital operation and maintenance of the distribution network, manage all aspects of power equipment, efficiently process the collected information and make rapid intelligent decisions. The power distribution IoT can more efficiently mobilize the active participation of resources from all walks of life, enhance the core competitiveness, and adapt to the demand of power grid enterprises for distributed energy storage and use [12,13]. The architecture of the power distribution IoT is shown in Figure 2.1.

In Figure 2.1, the distribution IoT consists of four parts: edge computing center, data transmission channel, data processing platform, and sensing and execution platform. The cloud computing center is the computing center platform for IoT distribution. Based on the high-performance edge computing platform computer, it uses big data, artificial intelligence, and other technologies to meet the needs of massive, intelligent terminals, edge server devices plug and play, multi-data fusion, and other needs. The cloud computing center provides high-performance computing services, model management, data cloud synchronization, and other functions to the distribution network terminal devices. The data transmission pipeline is used to efficiently transmit a large amount of data in the distribution network, which can be divided into two parts: the remote communication

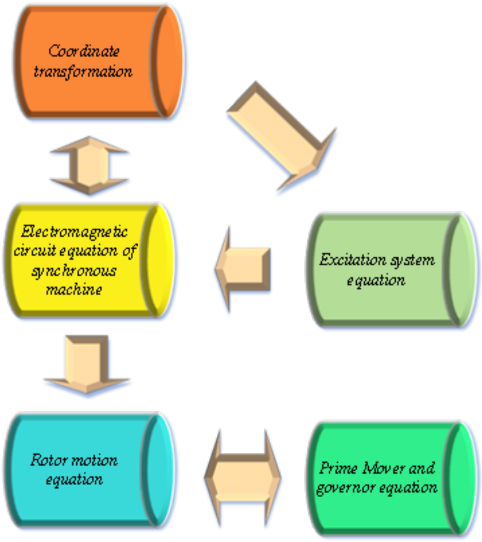


Fig. 2.2: Basic components of the generator set

network and the local communication network. The remote communication network communicates data between the edge computing center and the edge network intelligent terminal. The local communication network provides a data communication channel between the edge network and the edge server. The data processing and the perception platform realize full data collection, perception, and control through data exchange and real-time full duplex interaction with the edge computing center to complete the efficient and stable operation of the entire IoT system. The sensing and execution platform is responsible for providing the overall operation status of the distribution network, application equipment status, and other basic data, executing decision commands, and realizing control functions.

2.2. Time domain equivalent dynamic model of generator set. Because the generator set is a differential equation in the electromechanical transient simulation process of the power system, the interface processing with the network algebraic equation is more complex. Therefore, according to the practical model of the generator set, the mathematical model of the synchronous generator set is transformed, and the discrete-time domain equivalent model of the generator set suitable for transient electromechanical simulation is established. The generator set mainly comprises a synchronous generator, excitation regulation system, prime mover, and speed regulation system. Its typical structure is shown in Figure 2.2 [14].

In Figure 2.2, the excitation system equation affects the synchronous generator magnetic circuit equation. The synchronous generator magnetic circuit equation affects the rotor motion equation and the rotor motion equation. The kinematic equations of the rotor, prime mover, and governor affect each other. The state equation of the generator set is expressed in matrix form as shown in Eq. 2.1-2.3 [15,16].

$$\dot{a}(t') = Qa(t') + P_p a_p(t') + P_G G(t') \tag{2.1}$$

$$b(t') = Wa(t') \tag{2.2}$$

$$a(O') = a(kT) \tag{2.3}$$

In Eq. 2.1-2.3, $0' \leqslant t' \leqslant T$, 0' corresponds to the initial time of the network $T_0 = kT$. Q, P_p, P_G and W are the constant coefficient matrix of the subsystem state equation. a is the internal state vector of the generator

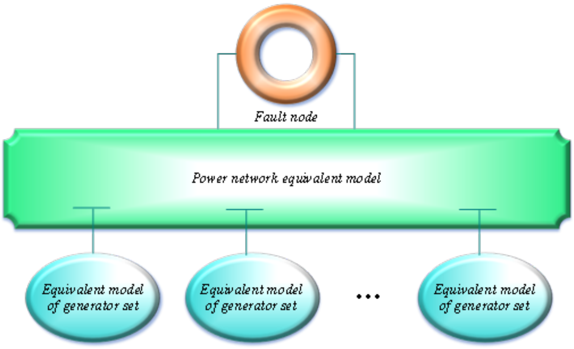


Fig. 2.3: Schematic Diagram of Power Network Division

set subsystem determined by the used model of generator, excitation system, and prime mover. The calculation method is shown in Eq. 2.4.

$$a = [\Delta\varepsilon\omega H_j' H_j" H_i''' \varphi P_m u_R u_q H_g u_g]^T \tag{2.4}$$

a_p is the current parameters I_i and I_j in the i-j coordinate system. The voltage amplitude V_t at the end of the generator and the output active power P_f constitute the input vector of the network side subsystem. The calculation method is shown in Eq. 2.5.

$$a_p = [I_i I_j V_t P_f]^T \tag{2.5}$$

G is the endogenous excitation vector of the generator set subsystem, which includes the reference value of speed ε_0 of prime mover and governor system, the reference value of voltage V_0 of excitation system, and the unit value of synchronous speed ε_p. The calculation method is shown in Eq. 2.6.

$$G = [\varepsilon_0 V_0 \varepsilon_p H_{gi}]^T \tag{2.6}$$

b is the output vector of the generator set subsystem, including the internal generator potential related to the generator stator voltage equation as well as the work angle ω. Its specific form is determined by the generator model adopted and the demand at the grid side. Its calculation method is shown in Eq. 2.7.

$$b = [H_j" H_i" \omega]^T \tag{2.7}$$

2.3. Electromechanical transient simulation program based on generator unit equivalent model.

In the transient electromechanical process of the power system, the differential equation of the generator set and the linear equation on the grid side are usually calculated simultaneously. Then, during the electromechanical transient simulation, the generator set can be separated from the power system. The power network can be divided into interconnections between multiple generator set subsystems and the network [17]. This method of machine network division is conducive to the equivalence of the generator network and simplified calculation, as shown in Figure 2.3 [18].

In Figure 2.3, the fault nodes are separated in the power network for separate processing, which can reduce the amount of simulation calculation. After the fault node is separated and treated separately, the network side equation can be expressed as an equivalent model. The network side equation does not need to be calculated repeatedly in the simulation process. Additionally, the power system is decomposed into multiple generators set subsystems and electrical network subsystems by cutting branch current method. According to the generator equivalent model, the electromechanical transient simulation program is designed, as shown in Figure 2.4.

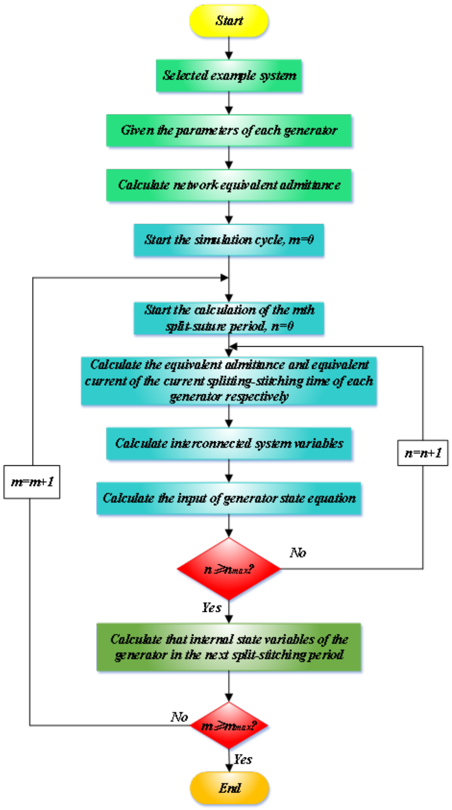


Fig. 2.4: Simulation program based on the equivalent model of generator set

In Figure 2.4, the electromechanical transient simulation calculation process is to calculate the equivalent admittance and current source of the generator unit at the current time according to the generator equivalent model. According to the network's equivalent admittance, the interconnected system variables are calculated. The amount of input at the next moment in the equation of state of the generator set is calculated. Whether the current split-suture period is over is judged. If it is not finished, the program returns to calculate the equivalent admittance and equivalent current source of the generator set the next time, and the calculation is in sequence. If it ends, the program calculates the initial value of the generator set state variable at the next split-suture time. Whether the simulation is over is judged; if not, the program returns to split the network again and continues the calculation.

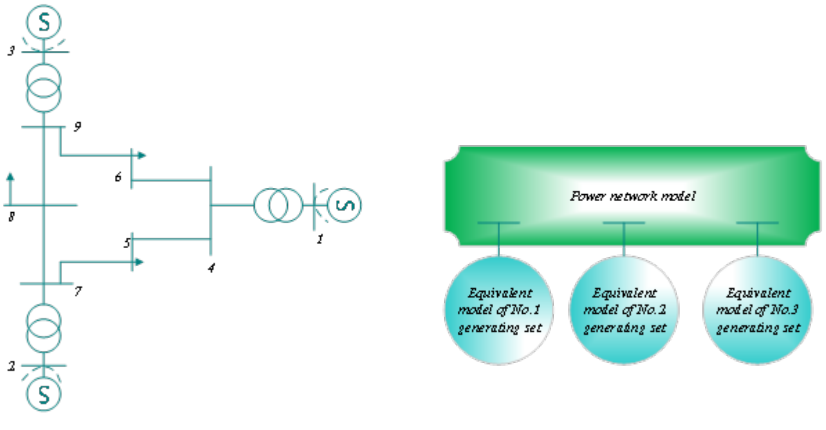
3. Simulation experiment design.

3.1. Simulation experiment environment. The Western System Coordinating Council (WSCC) 3-machine and 9-node are examples of simulation analysis. Its machine network segmentation method and equivalent model are shown in Figure 3.1 [19].

The condition settings of the two faults are as follows: in condition 1, the fault type is set as a three-phase short circuit of No. 2 generator, the fault time is 1s, and the removal time is 1.1s. In condition 2, the fault type is set as 50% of the whole network load removal, the fault time as 1s, and the fault removal time as the simulation end time.

3.2. Simulation experiment analysis under fault condition 1. Under fault simulation condition 1, the generator terminal voltage change is shown in Figure 3.2.

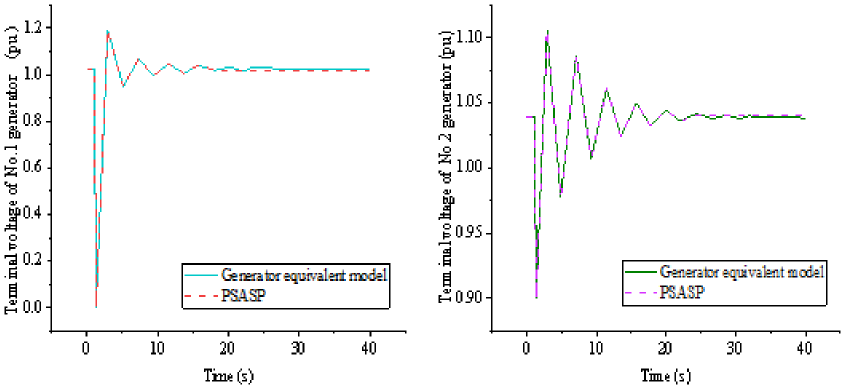
In Figure 3.2, the dotted line results from the PSASP analysis. In Figure 3.2(a), the terminal voltage change of the No. 1 generator through generator equivalent model simulation is very similar to the changing



a

b

Fig. 3.1: Schematic diagram of WSCC3 machine 9-node machine network segmentation method and equivalent results (a is WSCC3 machine 9-node machine network segmentation method. b is WSCC3 machine 9-node generator equivalent model)



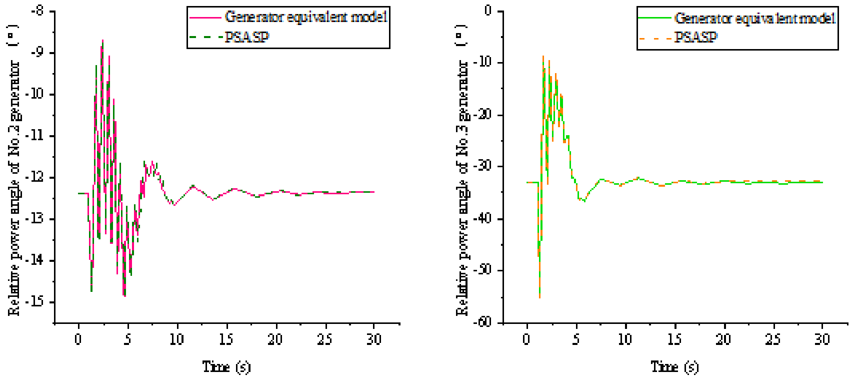
a

b

Fig. 3.2: Voltage change at generator terminal (a is the voltage change at generator terminal 1. b is the voltage change at generator terminal 2)

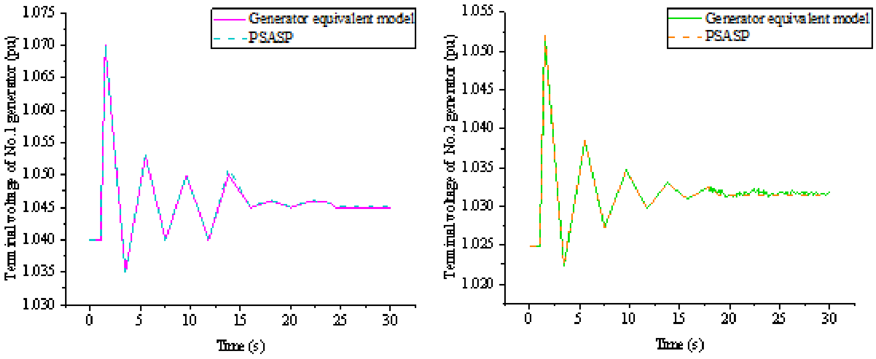
trend of PSASP software results. The terminal voltage change trend is that after fluctuating up and down, it tends to be stable in about 18s. Finally, it is stable at 1.02pu. In Figure 3.2(b), the changing trend of the terminal voltage of the No. 2 generator simulated by the generator equivalent model is very similar to that of PSASP software results. The terminal voltage changes are stable in about 24s after sharp fluctuation. PSASP results are finally stable at 1.04pu. The generator equivalent model simulation results fluctuate up and down at 1.04pu, but the fluctuation value is small. The data shows that the model simulation results are valid. Based on the power angle of the No. 1 generator, the relative power angle of the No. 2 and No. 3 generators is shown in Figure 3.3.

In Figure 3.3(a), the relative power angle change of the No. 2 generator simulated by the generator equivalent model is very similar to the changing trend of PSASP software results. The relative power angle of



a *b*

Fig. 3.3: Relative power angle change of generator (a is the relative power angle change of No. 2 generator; b is the relative power angle change of No. 3 generator)



a *b*

Fig. 4.1: Voltage change at generator terminal (a is the voltage change at generator terminal 1; b is the voltage change at generator terminal 2)

the No. 2 generator fluctuates first and then stabilizes. After severe fluctuations, it tends to be stable from about 20s to about -12.35°. The result of PSASP software is stable at -12.35 °. In Figure 3.3(b), the changing trend of the relative power angle of the No. 3 generator simulated by the generator equivalent model is very similar to that of the PSASP software. The changing trend of the relative power angle of the No. 3 generator is generally upward and stable. After fluctuation, it tends to be stable from about 15s to about -32.8°. The result of PSASP software is stable at -32.8°. The data shows that the simulation result of the generator equivalent model is effective.

4. Simulation experiment analysis under fault condition 2. Under fault simulation condition 2, the generator terminal voltage change is shown in Figure 4.1.

In Figure 4.1(a), the terminal voltage change of the No. 1 generator simulated by the generator equivalent model is like the changing trend of PSASP software results. The terminal voltage change trend is that the terminal voltage tends to be stable at about 25s after sharp fluctuation, and finally, it is stable at 1.045pu. In Figure 4.1(b), the changing trend of the terminal voltage of the No. 2 generator simulated by the generator

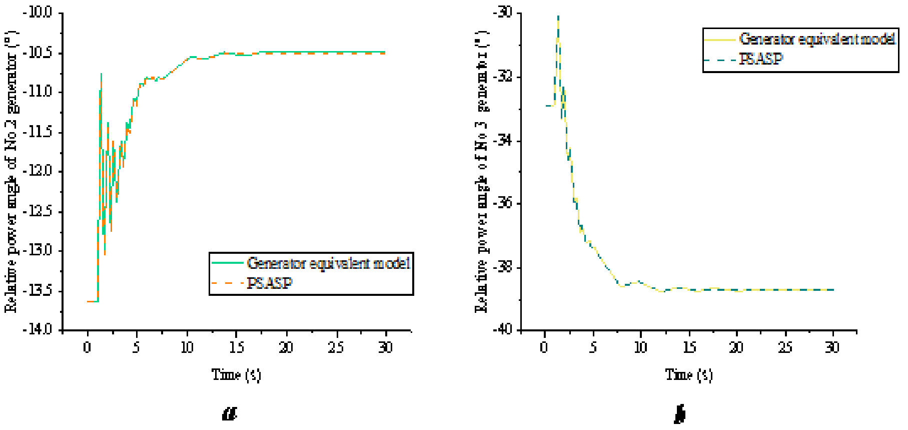


Fig. 4.2: Change of relative power angle of the generator (a is the change of relative power angle of No. 2 generator; b is the change of relative power angle of No. 3 generator)

equivalent model is very similar to that of PSASP software results. The terminal voltage changes are stable in about 18s after sharp fluctuation. PSASP results are finally stable at 1.0315pu. The generator equivalent model simulation results fluctuate up and down at 1.0315pu, but the fluctuation value is small. The data shows that the model simulation results are valid. Based on the power angle of the No. 1 generator, the relative power angle of the No. 2 and No. 3 generators is shown in Figure 4.2.

In Figure 4.2(a), the relative power angle change of the No. 2 generator simulated by the generator equivalent model is very similar to the changing trend of PSASP software results. The changing trend of the relative power angle of the No. 2 generator is rising first and then stable. After severe fluctuations, it tends to be stable from about 10s to about -10.5°. The result of PSASP software is finally stable at -10.5°. In Figure 4.2(b), the changing trend of the relative power angle of the No. 3 generator simulated by the generator equivalent model is very similar to that of the PSASP software. The changing trend of the relative power angle of the No. 3 generator is generally downward and then stable. After fluctuation, it tends to be stable from about 15s to about -38.7°. The result of PSASP software is finally stable at - 38.7 °. It shows that the simulation result of the generator equivalent model is effective.

5. Conclusion. In order to explore the online monitoring system for electromechanical transient simulation data of distribution network, based on the equivalent generator set model, this paper designs the power distribution IoT from the relevant theoretical knowledge of edge computing and introduces the network architecture of power distribution IoT. Secondly, according to the practical generator set model, the mathematical model of the synchronous generator set is equivalently transformed. The discrete-time domain equivalent model of the generator set suitable for transient electromechanical simulation is established. Finally, based on the discrete-time domain equivalent model of the generator, the electromechanical transient simulation system of the distribution network is constructed by introducing the machine network division of the power network. The model's effectiveness is verified by the network segmentation of the WSCC3 machine and nine nodes and the simulation experiment of the equivalent model under two fault simulation conditions.

The following conclusions are found: (1) under the condition that the fault type is set as a three-phase short circuit of No. 2 generator, the fault time is 1s, and the clearing time is 1.1s. The generator terminal voltage change and the generator relative power angle change have little difference between the results of the generator equivalent model simulation and the results of PSASP software. The data shows that the simulation results are valid. (2) Under the condition that the fault type is set to cut off 50% of the whole network load, the fault removal time is 1s. The fault removal time is the simulation end time, and the results of generator terminal voltage change and generator relative power angle change in the generator equivalent model simulation and PSASP software simulation are similar—the data indicating that the simulation results are effective. (3) The changing trend of generator equivalent model simulation and PSASP results is similar and stable. After PSASP results are stabilized at a value, the simulation results fluctuate with a minimum fluctuation above and below the value. However, there are still some deficiencies in this paper. In the process of research and simulation, the nonlinearity of generator equations and constant power load in the network is not considered. In the following research, the electromechanical transient simulation system of the distribution network can be discussed based on the nonlinear equations of generator sets.

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