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Yiying Zhu, Ruiqian Su, Junyue Wu, Qian Lv, Huapeng Shan

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Multiple fault diagnosis method for regional power grid based on DTS simulation system

Yiying Zhu* and Ruiqian Su

Guangzhou Power Supply Bureau of
Guangdong Power Grid Co., Ltd,
Guangzhou, 510630, China

Email: zhuyiying2023@163.com

Email: 87833656@qq.com

*Corresponding author

Junyue Wu, Qian Lv and Huapeng Shan

Dongfang Electronics Corporation,
Yantai, 264000, China

Email: wujunyue@dongfang-china.com

Email: 1031742138@qq.com

Email: 416126568@qq.com

Abstract: In order to solve the problems of high false alarm rate and long diagnostic time in existing power grid fault diagnosis methods, this paper studies a regional power grid multiple fault diagnosis method based on DTS simulation system. Firstly, use the DTS simulation system to obtain regional power grid status data. Then, effectively classify multiple faults in the power grid. Finally, based on the collected regional power grid status data and fault classification results, an ELM model is used to diagnose multiple faults in the regional power grid. According to the test results of fault diagnosis effectiveness, the false alarm rate of the proposed method has never exceeded 20%, and the average diagnostic time is 7.34 seconds, which is always less than 10 seconds. This indicates that the proposed method has high accuracy, fast efficiency, and good diagnostic effect in diagnosing multiple faults in the power grid.

Keywords: DTS simulation system; regional power grid; multiple faults; fault diagnosis; two phase short circuit; three phase short circuit.

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Biographical notes: Yiying Zhu holds a Master's degree in Electrical Engineering from Wuhan University. She is currently the Chief of the Distribution Network Dispatching Department of the System Department of Guangzhou Power Supply Bureau of Guangdong Power Grid Corporation. Her research interests include distribution network simulation training, distribution network self-healing, and distribution network autonomous driving.

Ruiqian Su holds a Master's degree in Control Engineering, School of Automation, Guangdong University of Technology. He is currently the Chief of the Distribution Network Dispatching Department of the System Department of Guangzhou Power Supply Bureau of Guangdong Power Grid Corporation. His research interests include DTS simulation of distribution network faults, programmed operation of distribution network, self-healing of distribution network, and automatic driving of distribution network.

JunYue Wu is currently employed at the Technology Center of Dongfang Electronics Co., Ltd., where he has been involved in the operation and management of power automation system products as well as research and development management. Currently serving as the Deputy Director of the Guangzhou Research and Development Center, he is primarily responsible for research on dispatching automation operation and integration technology of distribution and power information systems.

Qian Lv received her Master's degree in Computer Science and Technology from China University of Petroleum (East China) in 2015. She is currently working in research and development at Dongfang Electronics Co., Ltd. She is proficient in programming languages such as C++, C #, QT, and is familiar with databases such as Oracle, Jincang, and Dameng. Her position level is Deputy Chief Engineer.

HuaPeng Shan is currently employed at the Technology Center of Dongfang Electronics Co., Ltd., where he has been involved in the operation and management of power automation system products as well as research and development management. Currently serving as the Technical Director of the Guangzhou Research and Development Center, he is primarily responsible for research on dispatching automation operation and integration technology of distribution and power information systems.

1 Introduction

Electricity is the fundamental energy of modern society, driving the production activities and service provision of various industries, promoting the development of industrial manufacturing, commercial operations, transportation, and information communication (Wei et al., 20223). However, when faults or accidents occur in the power grid, it may lead to power outages, which can have a huge impact on production, commerce, and daily life (Yang et al., 2023). Especially in the event of a regional power grid failure, it may involve multiple power supply areas, substations, and transmission lines, with a wide range and complex equipment, resulting in a longer repair time and requiring more human and material resources for maintenance and fault recovery. Therefore, ensuring the safe operation of the power system and grid is the primary task of governments at all levels, energy management departments, and power enterprises (Wu and Lu, 2023). In order to ensure the safe operation of the power system and power grid, relevant institutions and enterprises will take a series of measures, including regular maintenance and repair, establishment of fault diagnosis and early warning systems, equipment updates and renovations, safety training and standardisation. In addition, safe operation also requires coordination and cooperation with other critical infrastructure (such as communication, transportation, etc.) to respond to the challenges of emergencies and

natural disasters (Yao et al., 2021). Therefore, quickly and accurately diagnosing power system faults and taking timely measures to repair them are crucial for maintaining the reliability and continuous power supply of the power grid.

Wang et al. (2020) propose to use the power grid simulation calculation data management platform PSDB to simulate faults in ultra-high voltage AC/DC hybrid power grids. This is mainly achieved by integrating the offline model with the smart grid dispatch control system D5000, and designing a reverse model for large-scale AC/DC hybrid power grid faults. The method in Zou et al. (2023) use particle swarm optimisation and generalised regression neural network algorithm to establish a PSOGRNN diagnostic module for adjacent areas, and uses D-S evidence theory to effectively diagnose power grid faults in each area. The method in Shao et al. (2022) input short-circuit device data related to associated protection within the subnet, constructs a neural network diagnostic module for judgment, improves the accuracy of the fault diagnosis module through the performance index of generalised error entropy, increases the connections between different levels of the sub neural network, and provides real-time feedback on the fault diagnosis results. Qu et al. (2020) introduce a "non" logical relationship model into probabilistic Petri nets, divides faults into three types based on fault alarm information, and establishes corresponding diagnostic models. Wu et al. (2022) propose an improved differential evolution algorithm based on the basic characteristics of differential evolution algorithm, and analyses the fault diagnosis of electrical quantities in the power grid according to the algorithm characteristics and operational rules. However, the diagnostic results of the above methods in practical applications have certain errors compared to the actual results, which can easily lead to false alarms. The accuracy of diagnosis still needs to be improved.

Therefore, this article studies a multi fault diagnosis method for regional power grids based on the DTS simulation system. The Dispatcher Training Simulator (DTS) can simulate the scheduling and operation of the power grid under different fault conditions, and connect with on-site equipment through sensors and actuators to effectively obtain status data of the regional power grid. This method can simulate various practical situations and provide rich data support for fault diagnosis. The specific research route is as follows:

- 1 *Data acquisition stage*: Use DTS simulation system to obtain status data of the regional power grid. The DTS simulation system conducts power dispatch work in a simulation environment, and then performs corresponding processing and operations based on different power grid faults. It can be connected to on-site devices through sensors and actuators to collect status data of the power grid.
- 2 *Multiple fault classification stages*: Effective classification of power grid fault types can improve the efficiency of fault diagnosis when multiple faults occur in the regional power grid, help accelerate the recovery time of the power system, and reduce the economic losses caused by power grid faults.
- 3 *Fault diagnosis stage*: Based on the collected regional power grid status data and fault classification results, ELM (Extreme Learning Machine) model is used for fault diagnosis. Obtain the state data of the regional power grid from the DTS simulation system for normalisation processing. Based on the normalised data, calculate the changes in three-phase current and use the changes in three-phase current as input to the model. Train and learn the ELM model, and use the classification results of

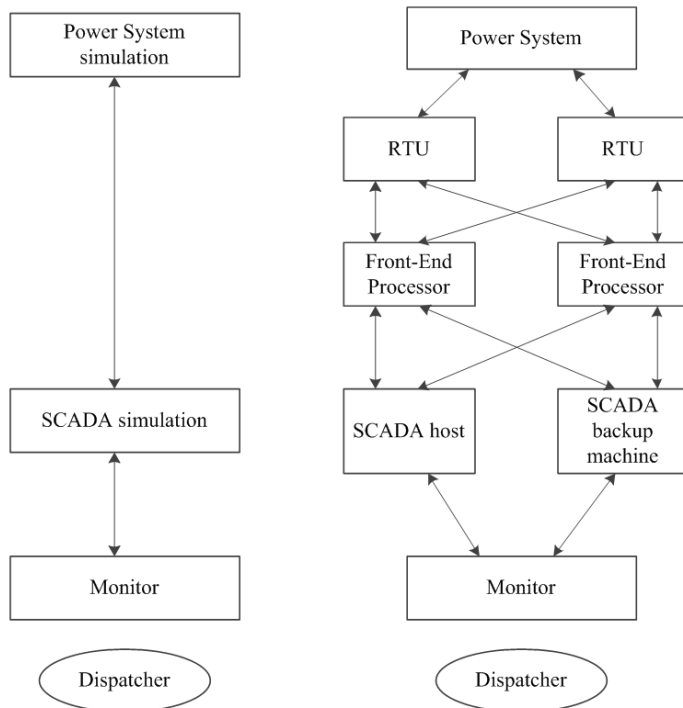
power grid faults as the goal of ELM network learning. Establish a fault diagnosis model through training and learning. Using a trained fault diagnosis model, classify and identify multiple fault data of the regional power grid, and the output result is the multiple fault data of the regional power grid.

2 Design of multiple fault diagnosis method for 2-region power grid

2.1 Acquisition of regional power grid state data based on DTS simulation system

DTS simulation system is a computer digital simulation system used to train power grid dispatchers, which can simulate various operational situations in modern power grid operations and perform real-time calculations on the scheduling operations of power grid operators. The overall structure of the DTS simulation system is shown in Figure 1.

Figure 1 Overall structure of DTS simulation system



In the application process of DTS simulation system, it is necessary to set up a simulated power system and control centre environment. The personnel conducting scheduling operations need to conduct power scheduling work in the simulated simulation environment, and then carry out corresponding processing and operations according to different power grid faults. The main foundation of a DTS simulation system is the control centre, which is a virtual control centre built on real hardware. In the control centre, it includes network analysis module (NA), automatic generation control module

(AGC), data acquisition and monitoring module (SCADA), and other related modules. Through the composition of these modules, the components form a scenario that can truly restore the power system of the power grid. They can be connected to on-site devices through sensors and actuators to collect status data of the power grid, such as voltage, current, power, etc. At the same time, they can also execute control commands, such as switch operations, transformer switching, etc. The RTU transmits the collected data and executed commands to the planting centre through a communication network, providing real-time power system status monitoring and control for operators (Qu et al., 2020; Wu et al., 2022).

Based on this, this article obtains the state data of the regional power grid based on the DTS simulation system. Provide a foundation for multiple fault diagnosis in subsequent regional power grids.

2.2 *Classification of multiple faults in the power grid*

Multiple faults in the power grid refer to the simultaneous or continuous occurrence of multiple equipment or component failures in the power system. These faults may hinder or restrict the flow of electricity between multiple parts of the power grid, thereby having a significant impact on the operation and reliability of the power system (Jiang et al., 2023). The cascading effect of multiple faults in the power grid refers to the fact that one local failure can trigger other local failures, leading to cascading reactions and further expanding the scope and extent of the fault. This situation can cause power grid interruptions, resulting in power outages and production interruptions for users (Cheng et al., 2021). In addition, multiple faults can also cause power quality issues, such as unstable voltage, abnormal frequency, and increased harmonics, which seriously affect the normal operation of user equipment. The complexity of multiple faults in the power grid also increases the difficulty of its recovery (Li et al., 2020). The increase in time and resource investment has put forward higher requirements for the restoration of the power system. Multiple faults in the power grid have a significant impact on the operation and power supply reliability of the power system (Liu and Wang, 2020). Therefore, corresponding measures need to be taken to address multiple faults in order to improve the ability of the power grid to cope with multiple faults.

Based on the DTS simulation system mentioned above, obtain the state data of the regional power grid. Determine the chain relationship between each fault based on the collected fault data and analysis of the fault causes. Based on the analysis results of chain effects, develop specific standards for fault classification. Finally, a comprehensive analysis of the classification results is conducted to further optimise the operation and fault management strategies of the power system (Wei et al., 2022; Hu et al., 2019). The specific fault classification is shown in Table 1.

Effective classification of power grid fault types can improve the efficiency of fault diagnosis when multiple faults occur in the regional power grid. By comprehensively considering the situation where multiple equipment or components in the power grid fail simultaneously or continuously, it breaks the limitations of traditional single fault diagnosis and more comprehensively reflects the actual operating status of the power grid. And the concept of cascading effects was clearly introduced in the classification, which means that one local failure will cause other local failures, making the classification more practical and warning.

Table 1 Classification of multiple faults in the power grid

<i>Fault classification</i>	<i>Fault category</i>	<i>Fault type</i>
Once fault	Main transformer fault	Internal, external, and external dead zones
	Line fault	Single phase grounding, two-phase grounding, triple grounding, phase to phase short circuit, three-phase short circuit, two-phase disconnection, line CT dead zone
	Bus fault	Single phase grounding, two-phase grounding, triple grounding, interphase short circuit, three-phase short circuit, bus tie dead zone
	Generator failure	Emergency shutdown, emergency output reduction, load rejection, internal, external, loss of excitation
	Load fault	Grounding, phase to phase, load jump
	PC and CT fault	Once fault
	Capacitance and reactance faults	Grounding, phase to phase
	Switch fault	Rejection, misoperation, reclosing settings, and synchronisation settings
Secondary fault	Automatic protection device	Rejection, misoperation, PT disconnection, CT disconnection
	PC and CT fault	Secondary fault
Human operation error	Misoperation	Load closing switch, load pulling switch, live grounding switch, ground wire closing switch, charging no-load line or transformer with switch, line forced transmission, switch closing at permanent fault point

2.3 Multiple fault diagnosis of regional power grid based on ELM

Based on the collected regional power grid status data and fault classification results, an ELM model is used to diagnose multiple faults in the regional power grid. The state data of regional power grids includes various indicators, such as power, voltage, current, etc., which usually have different measurement units. Normalisation processing can unify these indicators to the same magnitude and range, eliminate dimensional differences, and facilitate data comparison and analysis. Obtain regional power grid data through normalisation processing method. The calculation formula for normalisation processing is as follows:

$$X = \frac{x' - x_{\min}}{x_{\max} - x_{\min}} \quad (1)$$

In the formula, x' represents the amplitude of zero sequence voltage within the set period, $x_{\min}$ represents the minimum value in historical power grid data, and $x_{\max}$ represents the maximum value in historical power grid data (Ni et al., 2020; Yang and Gao, 2022; Wang et al., 2019).

Based on the normalised regional power grid data X , the three-phase current change value y can be calculated using the following formula:

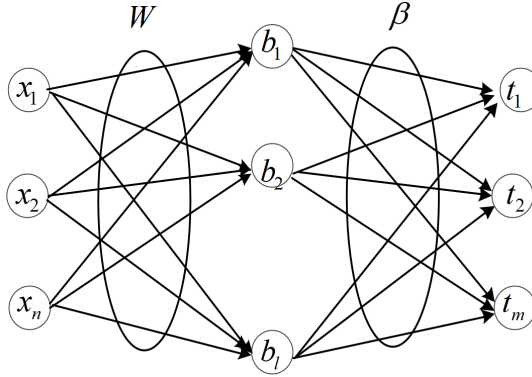
$$\Delta I_{\varphi} = \frac{I_{\varphi(j)} - I_{\varphi(e)}}{XI_{\varphi(e)}} \quad (2)$$

$$y = \begin{cases} 0 & \Delta I < 0 \\ \Delta I_{\varphi} & 0 < \Delta I_{\varphi} < 1 \\ 1 & \Delta I > 1 \end{cases} \quad (3)$$

In the formula, φ represents any one of the ABC three-phase; ΔI_{φ} represents the phase φ current; $I_{\varphi(j)}$ and $I_{\varphi(e)}$ represent the maximum current value of the φ phase in the cycle after and before the fault, respectively.

By taking the three-phase current variation value as input and combining it with the model of Extreme Learning Machine (ELM), a fault diagnosis model can be established through training and learning. ELM has a high training and learning speed, and compared to traditional neural network algorithms, ELM can significantly reduce training time. And ELM does not require iterative algorithms during the training process, but directly solves the optimal weight matrix. This can avoid the problem of local optimal solutions in traditional neural network algorithms and has better generalisation ability. The ELM structure diagram is shown in Figure 2 (Chen et al., 2019; Lu et al., 2022; Jin et al., 2019).

Figure 2 ELM structure diagram



Assuming there are N training samples (X_i, T_i) , where $1 \leq i \leq N$, $X_i = [x_{i1}, x_{i2}, \dots, x_{in}]^T \in R^n$ is the input vector of the i -th data sample, $T_i = [t_{i1}, t_{i2}, \dots, t_{im}]^T \in R^m$ is the output vector of the i -th data sample, n and m are the dimensions of the input vector and output vector, respectively. If the number of hidden layer nodes is l , the ELM network can be represented as:

$$\sum_{f=1}^l \beta_f g(W_f X_i + b_f) = Q_i \quad (4)$$

In the formula, $g(x)$ represents the activation function, $W_f = [w_{f1}, w_{f2}, \dots, w_{fn}]^T$ represents the input weight value, b_f represents the threshold of the f hidden layer neuron,

$\beta_f = [\beta_{f1}, \beta_{f2}, \dots, \beta_{fm}]^T$ represents the output weight value and $Q_i = [O_{i1}, O_{i2}, \dots, O_{im}]^T$ represents the output vector of the i -th training sample.

Taking the classification results of power grid faults as the goal of ELM network learning, the expression is:

$$\sum_{i=1}^N \|Q_i - T_i\| = 0 \quad (5)$$

It is necessary to find a suitable set of β_f , W_f , and b_f , and randomly generate input weights and hidden layer neuron thresholds without the need for iterative weight adjustment, in order to accelerate training speed. Enable:

$$H\beta = Y \quad (6)$$

Among them, $H = \begin{matrix} f(W_1X_1 + b_1) & \cdots & f(W_lX_1 + b_l) \\ \vdots & \square & \vdots \\ f(W_1X_N + b_1) & \cdots & f(W_lX_N + b_l) \end{matrix}$, l is the number of neurons in the

hidden layer.

In theory, when there are enough hidden layer neurons, suitable β_f , W_f , and b_f can be determined, so that the output vector Y_i of ELM approaches the sample output vector T_i with zero error. In fact, when the number of neurons in the hidden layer does not exceed the number of samples N , the error can approach any ε , that is:

$$\sum_{i=1}^N \|Y_i - T_i\| < \varepsilon \quad (7)$$

Usually, ELM randomly sets β_f , W_f , and b_f , and remains unchanged during initialisation, and sets the ideal output value $Y=T$, which is:

$$H\beta = T \quad (8)$$

In the formula, T is the label output matrix, and on this basis, β is fitted using the least squares method, that is:

$$\beta^* = H^+T \quad (9)$$

In the formula, β^* is the β obtained through least squares fitting, and H^+ is the generalised inverse matrix of H , $H^+ = H^T(HH^T)^{-1}$.

Then obtain the final output matrix β , which is:

$$\min_{\beta} \|H^+\beta^* - T\| \quad (10)$$

The output result is the data of multiple faults in the regional power grid, and based on the above process, the diagnosis of multiple faults in the regional power grid is achieved.

3 Experimental plan

In order to verify the effectiveness of the DTS simulation system in diagnosing multiple faults in regional power grids, this paper uses the D5000 system and PSOGRNN diagnostic module to conduct comparative testing while conducting simulation diagnosis,

in order to verify the practicality of the proposed method. Collect all operating data of the power grid in Region A in the past 3 years, and after manual screening, retain the data of 180 power grid faults that occurred in the past 3 years as the sample data for testing.

3.1 Experimental data

This article takes the case of multiple power grid faults that have occurred in region A as a reference, collects historical fault data, and copies the current power grid fault situation into the simulation environment of this article. According to the hardware requirements of the DTS simulation system, the computers used in this experiment are all Windows systems with versions of Windows 7 and Windows 8. The environmental settings are shown in Table 2.

Table 2 Environmental Settings

<i>Project</i>	<i>Parameter</i>
PC system	Windows 7/Windows 8
Debugger	FormulaTranslation
Development environment	Compag Visual Fortran 6.5
Development platform	C/C++/MicrosoftVisual Stdio
Server	EMS/DTS
Language model	CIM/E
Dial-up Networking	PPP protocol
Programming techniques	Java
Basic network communication	TCP/IP protocol
Document	HTML
Information publishing server	MS II S5.0
Browser communication	Java Applet
Broadcast	UDP

3.2 Experimental plan

- 1 *Building a DTS simulation system:* Firstly, it is necessary to build a DTS simulation system suitable for simulating multiple fault environments in the power grid. The system should have functions such as simulating power grid operation, fault occurrence, and fault diagnosis.
- 2 *Set initial parameters:*
 - Power grid structure: Taking a 110 kV line in Area A as the research object, including SD station, 110 kV S1 line 1035 line, # 2 main transformer, busbar 1004 line, 1006 line, and 110 kV S2 line 1022 line, among other components.
 - Equipment parameters: Set according to the actual equipment parameters of the power grid, including the rated voltage, current, impedance, etc. of transformers, switches, lines, etc., as shown in Table 3.

Table 3 Equipment parameter settings

Equipment type	Equipment number	Rated voltage (kV)	Rated current (A)	Impedance (Ω)	Capacity (MVA)
transformer	T1	110	1,000	0.01	10
switch	S1	110	-	-	-
switch	S2	110	-	-	-
line	L1	110	-	0.015	-
line	L2	110	-	0.018	-

- *Fault type:*
 - 1 a single-phase permanent grounding fault occurred in phase A of 110 kV S1 line 1035 line
 - 2 110 kV S1 line 1035 line experiences refusal to move or overstepping
 - 3 the 110 kV S2 line 1022 line at SD station experienced AB two-phase short circuit and ABC three-phase short circuit faults.
 - *Fault location:* 1035 line phase A, SD station 110 kV S2 line 1022 line head end.
 - *Fault duration:* 5 seconds.
- 4 *Simulate fault occurrence:* Input the settings of multiple faults in the power grid of the above lines into the DTS simulation system, simulate the environment of multiple faults in the power grid, and diagnose the faults.
 - 5 *Analyse diagnostic results:* Conduct a detailed analysis of the diagnostic results to verify the accuracy and efficiency of the methods used.

3.3 Design of performance indicators

In this test of fault diagnosis effectiveness, the false alarm rate and fault diagnosis time were selected as the test indicators. Compare the diagnostic effects of three different diagnostic methods on multiple faults in the A region power grid in the past three years. The lower the false alarm rate of fault diagnosis, the higher the diagnostic accuracy of this method, which is expressed as:

$$FPF = \frac{p}{N} \quad (11)$$

In the formula, p represents the number of false positives, and N represents the total number of non-faulty samples.

The shorter the fault diagnosis time, the higher the diagnostic efficiency of this method. When both indicators are higher than the other two methods, it indicates that this method has a good diagnostic effect on multiple faults in the power grid.

3.4 Testing and analysis of performance indicators

3.4.1 Calculation results of line current

Obtain the current value of AB two-phase short circuit fault point to ground through the DTS simulation system. The details are shown in Table 4.

Table 4 Current to ground at AB two phase short circuit fault point (kA)

Line	Positive sequence current	Negative sequence current	Zero-sequence current	A-phase current	B-phase current	C-phase current
S2 line	0.555	0.556	0.000	0.961	0.962	0.002
1022 line	$\angle -1.50$	$\angle 0.45$	$\angle -1.82$	$\angle -0.98$	$\angle 2.17$	$\angle -2.13$

According to the data in Table 4, the relationship between two-phase short-circuit current and each phase sequence current is analysed. The current calculation formula obtained from AB two-phase short-circuit is:

$$\left| I_{fa}^{(2)} \right| \approx \left| I_{fb}^{(2)} \right| \approx 0.961 \text{ kA}, \left| I_{fc}^{(2)} \right| = 0.002 \text{ kA} \quad (12)$$

In the formula, $I^{(2)}$ represents negative sequence current, fa represents the faulty phase A, and fb represents the faulty phase B.

The calculation formula for the relationship between two-phase short-circuit current and three-phase short-circuit current is as follows:

$$\begin{cases} \left| \frac{I_f^{(2)}}{I_f^{(3)}} \right| \approx \frac{0.961}{1.094} \approx \frac{\sqrt{3}}{2} \\ I_f^{(2)} = \frac{\sqrt{3}}{2} I_f^{(3)} \end{cases} \quad (13)$$

Through equation (7), it can be concluded that when the positive sequence impedance is equal to the negative sequence impedance, the two-phase short-circuit current value is $\frac{\sqrt{3}}{2}$ times the three-phase short-circuit current value.

Obtain the current value of ABC three-phase short circuit fault point to ground. The details are shown in Table 5.

Table 5 ABC three-phase short circuit fault point to ground current (kA)

Line	Positive sequence current	Negative sequence current	Zero-sequence current	A-phase current	B-phase current	C-phase current
S2 line	1.094	0.000	0.000	1.094	1.094	1.094
1022 line	$\angle -1.39$	$\angle 0.38$	$\angle 2.54$	$\angle -1.39$	$\angle 2.80$	$\angle 0.71$

Based on the data in Table 5, analyse the relationship between the three-phase short-circuit current and the phase sequence currents. In Table 5, the positive sequence current and negative sequence current in the three-phase short-circuit current are:

$$|I_f^{(1)}| = 1.094kA, |I_f^{(2)}| = |I_f^{(3)}| = 0 \quad (14)$$

Therefore, it can be known that when a symmetrical short circuit occurs in the ABC three-phase, the current value of the three-phase short circuit size is:

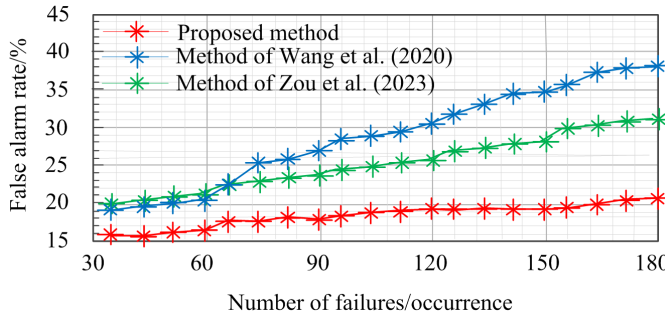
$$|I_{fa}^{(3)}| = |I_{fb}^{(3)}| = |I_{fc}^{(3)}| = |I_f^{(1)}| = 1.094kA \quad (15)$$

At this point, the current calculation of a 110 kV line in the A region power grid has been achieved through the DTS simulation system.

3.4.2 Comparison results of false alarm rates in fault diagnosis

To verify the effectiveness of the method proposed in this paper, a fault diagnosis false alarm rate test was conducted using the fault diagnosis method proposed in this paper, in conjunction with the fault diagnosis methods in Wang et al. (2020) and Zou et al. (2023), to diagnose 180 power grid faults that have occurred in the A region power grid in the past three years. The comparison results of false alarm rates for fault diagnosis are shown in Figure 2.

Figure 2 Comparison of false alarm rates for fault diagnosis using different methods



From Figure 2, it can be seen that as the amount of fault data in the power grid increases, all three different methods have improved false alarm rates for fault diagnosis. Among them, the false alarm rate of the method in Wang et al. (2020) increased from 19% to 38%, the false alarm rate of the method in Zou et al. (2023) increased from 20% to 31%, while the false alarm rate of the DTS simulation system proposed in this paper increased from 16% to 20%, which never exceeded 20%, far lower than the two methods compared. This article proposes a DTS simulation system with a low false alarm rate for fault diagnosis and a high accuracy for diagnosing multiple faults in the power grid.

3.4.3 Comparison results of fault diagnosis time consumption

To further verify the practicality of the method proposed in this article, ten sets of events with three or more faults occurring simultaneously were randomly selected from 180 power grid fault data for testing, and the diagnostic time of different methods for these ten sets of faults was statistically analysed. The specific comparison results are shown in Table 6.

From Table 6, it can be seen that the diagnostic time of the method in Wang et al. (2020) ranges from 12.70 seconds to 16.75 seconds, with an average diagnostic time of 14.34 seconds. The diagnostic time of the method in Zou et al. (2023) ranges from 15.70 s to 18 s, with an average diagnostic time of 16.85 s. In this article proposed method, the diagnostic time of the DTS simulation system is between 5.90 s and 9.65 s, with an average diagnostic time of 7.34s, which is always below 10 s, and much lower than the two methods compared. The diagnostic time of the DTS simulation system proposed in this article is relatively short, and it has high efficiency in diagnosing multiple faults in the power grid, with good diagnostic results.

Table 6 Comparison of Fault Diagnosis Time for Different Methods

<i>Fault group</i>	<i>Fault type</i>	<i>Fault diagnosis time/s</i>		
		<i>Proposed method</i>	<i>Wang et al. (2020) method</i>	<i>Zou et al. (2023) method</i>
1	Grounding, two-phase grounding, once fault	6.45	12.70	16.70
2	Load rejection, internal, loss of excitation	7.55	13.65	17.80
3	Phase to phase short circuit, emergency output reduction, load jump	8.15	14.35	18.00
4	Three-phase short circuit, load closing switch, grounding, bus tie dead zone	9.65	15.70	17.75
5	Reclosing settings, synchronisation settings, live grounding switch	7.35	16.75	16.70
6	Emergency output reduction, three-phase short circuit, interphase short circuit	6.85	13.00	15.70
7	Emergency shutdown, external, ground wire closing switch	7.00	18.45	16.35
8	PT disconnection, line CT dead zone, interphase short circuit	8.50	12.75	17.25
9	Three-phase short circuit, triple grounding, ground wire closing switch	5.90	13.05	16.20
10	Load closing switch, grounding, riple grounding	6.00	12.95	16.05
	Average value	7.34	14.34	16.85

4 Conclusions

This article studies a multi fault diagnosis method for regional power grids based on DTS simulation system. The DTS simulation system can simulate the scheduling and operation of power grids under different fault conditions, and connect with on-site equipment through sensors and actuators to effectively obtain status data of regional power grids.

This method can simulate various practical situations and provide rich data support for fault diagnosis. This method effectively divides multiple faults in the power grid by using DTS simulation system to obtain regional power grid status data, and uses ELM model for fault diagnosis. Through experimental verification, the false alarm rate of the proposed method has never exceeded 20%, and the average diagnostic time is 7.34 seconds, which is always less than ten seconds. This indicates that the proposed method has high accuracy and diagnostic efficiency in the diagnosis of multiple faults in the power grid.

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