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THE MATHEMATICAL ANALYSIS AND IMPROVEMENT OF MATRIX ALGORITHM FOR FEEDER FAULT LOCATION BASED ON FTU IN THE DISTRIBUTION NETWORK

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ABSTRACT

The mathematical analysis and improvement of matrix algorithm based on FTU has been proposed to solve fault location problem in complex multi-source and multi fault distribution networks of power system. Based on the structural characteristics of the distribution system, a description matrix D is established by assuming the power sources and a positive direction and it derived from the correlation between the positive direction and different power lines. As a function of the fault current direction transmitted by the terminal power supply unit which is our feeder terminal unit (FTU), the fault information vector F is set up. By combining the description matrix D and searching for non-zero elements in the fault information vector, the fault location vector is discovered according to the fault location criteria. During the observation of the elements in the fault location vector, by analyzing we immediately found the location of the defect area. This algorithm can solve problems that cannot be completely solved by other algorithms, such as power terminal failures, ring network failures, and multi-source failures. This method does not require matrix multiplication or normalization. The widespread use of distributed generation (DG) has made the distribution network more complex, and it leads to the failure of the traditional matrix algorithm. Therefore, the matrix algorithm is further improved to adapt the complex characteristics of DG. Considering the accuracy, we avoid random search operations by filtering fault candidate scenarios based on fault confidence and Each algorithm run 100 times in a loop, and the average time taken for a single run is used as a measure of the computational efficiency of the algorithm. The matrix algorithm utilizes the information uploaded by FTU to SCADA to create network description matrix, fault information matrix, which are then used to obtain the fault judgment matrix for fault location and isolation and it proves that the algorithm judgment is effective.

Keywords: Distribution Network, Fault Detection, Matrix Algorithm, Feeder Terminal Unit (FTU)

1. INTRODUCTION

1.1. LITERATURE AND PURPOSE

In the Atmosphere of the power grid, the distribution network serves as a direct connection to power consumers. With the development of economy and the rapid growth of urban power demand, the requirements for power quality and supply reliability are becoming increasingly stringent. In the process of energy

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transmission and distribution, overcurrent faults, such as ground faults, inevitably occur. According to the actual people's living standards in rural and urban areas, the demand for qualified electricity is growing rapidly and it is needed a stable, reliable, and flexible power system. Power line automation in distribution networks is a key technology to improve power reliability. Automatic fault location technology based on FTU is an important component of power line automation in distribution networks Chen et al. (2011).

The development of smart grid puts forward higher and higher requirements for distribution network automation. The application of distribution automation terminal equipment in distribution networks directly determines the automation level of distribution networks. As the core function of distribution automation systems, power line automation directly affects the efficiency of distribution automation implementation due to the speed and reliability of its fault management (power positioning, isolation, and recovery) Li (2016).

The location of distribution network faults is crucial to ensuring power quality and improving the reliability of automated distribution systems Abraham et al. (2004). With the improvement of the automation level of the distribution network, a large number of automation terminal equipment (such as Feeder Terminal Units (FTUs)) are applied to the distribution network. When a fault occurs, the FTU download's fault information, such as the size and direction of the fault current, the fault voltage, and the fault time, as well as the switch status messages that the master station considers to be corresponding by default Leora et al. (2003). Location methods are used to process information and locate fault areas, thereby effectively improving the speed and accuracy of fault location. Currently, there are two methods for evaluating fault location using FTU information: direct algorithm and indirect algorithm. These two algorithms typically use FTU to detect overcurrent to determine if there is a fault in the area, and then use corresponding algorithms to locate the fault.

The fault in distribution network has serious impact on energy supply quality, it also threatens people's normal life and production Ma et al. (2013). Fast and accurate location of the faults in a distribution network is essential for reducing the number and duration of power interruptions and increasing the reliability of the distribution systems. This will lead to consumers satisfaction and will reduce damages due to the interruption Zhou et al.. (2006). The task of fault isolation is to isolate the fault point within the minimum range, that is, start the tripping of the circuit breaker closest to the fault point. If the circuit breaker refuses to operate, the backup protection action of the feeder line will isolate the circuit breaker that refuses to operate Goudarzi et al. (2015).

Proposing effective and fast methods for fault location is a main stage of distribution network automation Guan et al. (2021). Fault location based on the matrix algorithm can quickly and accurately locate faults in the distribution networks. FTUs receive the instructions from the center to control the moving of the loop switch, section switch and the circuit breaker. The matrix algorithm utilizes the information uploaded by FTU to SCADA to create network description matrix, fault information matrix, which are then used to obtain the fault judgment matrix for fault location and isolation. In this way, the occurrence and duration of power interruptions are reduced and the reliability of the distribution systems increased Xu et al.. (2021).

2. TOPOLOGICAL STRUCTURE OF DISTRIBUTION NETWORK

The topological structure of a distribution network is to treat the entire distribution network as a topological structure that combines lines and points based on the connection relationship of distribution components, and then analyze the topological connection of the entire network based on power nodes and switching nodes Ma et al. (2018). The structure of distribution networks is large and complex. It provides the basis for other analysis of distribution networks, such as state estimation, tidal flow calculation, fault location, isolation, power recovery, and grid reconstruction Zhao et al. (2020). Currently, the existing research in this field at domestic and abroad includes incidence table matrix representation, network description matrix representation, node elimination method, tree search representation, discrete processing method and so on. The matrix algorithms usually use network description matrix for this case Zhang et al. (2018). The distribution network with Distributed generation can effectively solve the world's energy problems, improve power quality, and reduce environmental pollution Zhou et al. (2006).

In recent years, the access of distributed generation has complicated the characteristics of distribution network. It has become an important field for fault location in distribution network because it transforms the network from simple single-source network to complex multiple-source network. In the traditional net-based matrix algorithm, by defining a remote terminal unit (RTU) on each column based on the maximum load on the power cord Mei et al. (2008). When a system fault occurs, the RTU on the section switch will detect an overcurrent that exceeds its set value. At this time, the RTU will record the maximum value and occurrence time of the fault current and report it to the SCADA system in the distribution network control center Wei et al. (2002). The SCADA system generates a fault information matrix G and obtains a fault judgment matrix P through the operation of the network description matrix D and the fault information matrix G.

The Figure 1 is showing the Process Flow Chart for Traditional Net-based Matrix Algorithm.

Figure 1

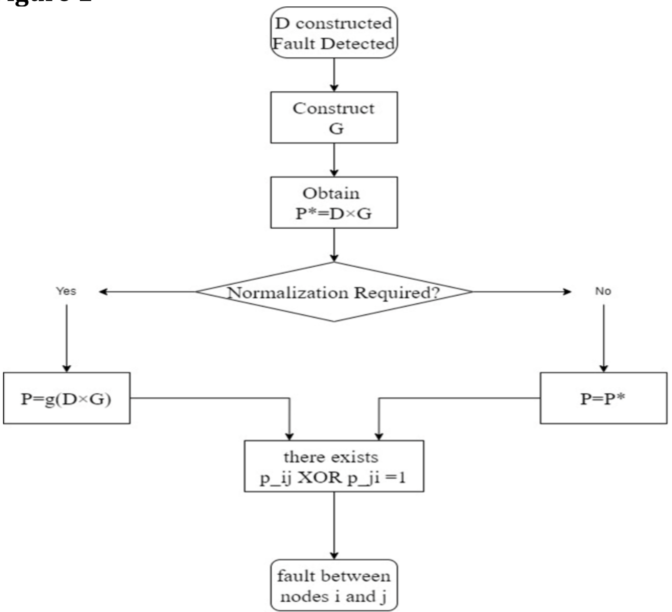

Figure 1 The Process Flow Chart for Traditional Net-based Matrix Algorithm

The traditional matrix algorithm for fault location of distribution network is simple but requires normalization. This method does not consider the direction of power flow. Also, it is only effective in single-source distribution network Mei et al. (2007).

3. MATHEMATICAL ANALYSIS

3.1. ANALYSIS FOR TRADITIONAL NET-BASED MATRIX ALGORITHM

Let's consider the complex network as shown in Figure 2. For generality, the node number are randomly numbered, which has no effect on the fault location. Let's First build the network description matrix D.

Figure 2

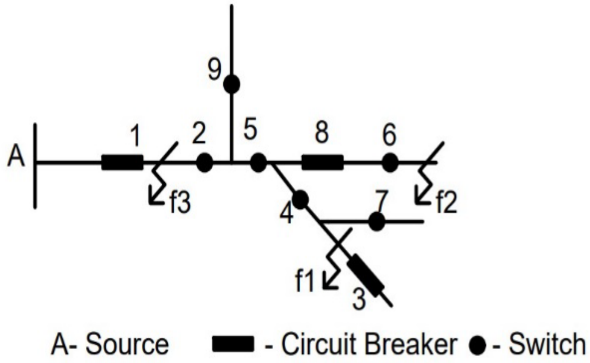

Figure 2 A Complex Single-source Distribution Network

$$D = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{A}$$

We will proceed to analyze fault between node 1 and 2 (f_3). Obtain G and P.

$$G = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{B}$$

$$\mathrm{P} = \mathrm{D} + \mathrm{G} = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{C}$$

condition 1: for the fault between two nodes, when p_{ii} = 1, p_{ij} = 1for all j (j ≠ i), with all p_{jj} = 0, then the fault occurs between node i and j.

From (C), p_{11} = 1, p_{12} = 1 and p_{22} = 0. So, the fault occurs between node 1 and 2.

Now proceed to analyze fault in T-region of node 3, 4 and 7 (f_1). D is the same, obtain G and P.

$$G = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{D}$$

$$\mathrm{P} = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{E}$$

From (E), p_{11} = 1, p_{12} = 1 and p_{22} = 1, no fault between node 1 and 2.

p_{22} = 1, p_{25} = p_{29} = 1 and p_{99} = 0 but p_{55} = 1, so, no fault in T-region of node 2, 5 and 9. p_{55} = 1, p_{54} = p_{58} = 1 and p_{88} = 0 but p_{44} = 1 so, there is no fault in T-region of node 4, 5 and 8.

p_{44} = 1, p_{43} = p_{47} = 1 and p_{33} = p_{77} = 0, so, the fault occurs in the T-region comprised by node 3, 4 and 7.

Now let's consider the analysis of terminal fault after node 6. Obtain its G and P.

$$G = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{F}$$

$$\mathrm{P} = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{G}$$

Condition 2: when $p_{\mathrm{ii}} = 1$, and p_{ij} equals to 0 for all j (j ≠ i), then there is a terminal fault after node i.

From (G), $p_{11} = 1$, $p_{12} = 1$ and $p_{22} = 1$, no fault between node 1 and 2.

$p_{22} = 1$, $p_{25} = p_{29} = 1$ and $p_{99} = 0$ but $p_{55} = 1$, so, no fault in T-region of node 2, 5 and 9. $p_{55} = 1$, $p_{54} = p_{58} = 1$ and $p_{44} = 0$ but $p_{88} = 1$ so, there is no fault in T-region of node 4, 5 and 8.

$p_{88} = 1$, $p_{86} = 1$ and $p_{66} = 1$, so, no fault between node 1 and 2.

Only when $p_{66} = 1$, and all the other elements in i-th are zero, we can say that the fault occurs at the terminal after node 6.

Most natural faults are unique in one region. However, for reliability, we should also consider multiple fault combinations in different areas of the distribution network. It is assumed that defects F1 and F2 occur simultaneously. The fault information matrix G and the fault judgment matrix are obtained in the following manner.

$$G = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{H}$$

$$P = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{I}$$

From (I), p_{11} = 1, p_{12} = 1 and p_{22} = 1, no fault between node 1 and 2.

p_{22} = 1, $p_{25} = p_{29} = 1$ and $p_{99} = 0$ but p_{55} = 1, so, no fault in T-region of node 2, 5 and 9. p_{55} = 1, $p_{54} = p_{58} = 1$ and $p_{44} = p_{88} = 1$ so, there is no fault in T-region of node 4, 5 and 8. p_{88} = 1, $p_{86} = 1$ and p_{66} = 1, so, no fault between node 1 and 2.

p_{44} = 1, $p_{43} = p_{47} = 1$ and $p_{33} = p_{77} = 0$, so, the fault occurs in the T-region comprised by node 3, 4 and 7.

When p_{66} = 1, and all the other non-diagonal elements in 6th row are zero, we can say that the fault occurs at the terminal after node 6.

After analyzing, we can see that the traditional matrix net-shaped algorithm removed the normalization process and so the calculation time is significantly reduced. The fault analysis is based on the FTU information reflected on the diagonal elements of fault judgement matrix. This algorithm is valid whether the distribution network is single-source or multiple-source. It is able to accurately locate fault between nodes, at the terminal of the node and at the T-regions. It can judge a single fault or combination of faults.

If we don't consider the direction of power flow. Also, it is only effective in single-source distribution network. The basic idea is that a distribution network is a variable structure network composed of nodes and switches Zhao (2005). The network infrastructure is described by a network infrastructure matrix. For a network with n nodes, the network infrastructure matrix is a square matrix of n rows and n columns representing the connection relationship between nodes Shi et al. (2014). Based on the characteristics of distribution network structural variants, this method can effectively represent the topology of distribution networks, but it is a matrix-based representation method, and the matrices of distribution networks are very sparse and occupy large storage space Wen et al. (2009).

Let's build the network matrix D and fault information matrix G as follow

$$D = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{N}$$

$$G = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{L}$$

Then obtain Q, from (L), we can see that only one g_{44} is 0, no normalization is required. Therefore,

$$P = Q = \mathrm{D} \times \mathrm{G} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{O}$$

From (O), only $p_{12}\ XOR\ p_{21} = 1$. Thus, we can conclude that the fault occurs between node 1 and 2.

Now we analyze the fault at the terminal between nodes 4 and 3. D is the same, and G is:

$$G = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{P}$$

Obtain Q.

$$Q = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{R}$$

From (N) and (P), $d_{48} = d_{58} = d_{68} = 1$, $g_{88} = 1$ and $g_{55} = g_{44} = 0$, so 8th row and column of P are set to 0. Also, $d_{29} = d_{59} = 1$, $g_{99} = 1$ and $g_{55} = g_{22} = 0$, so 9th row and column of P are set to 0.

$$P=\begin{bmatrix}0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&1&0&0\\0&0&1&0&0&0&1&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&1&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\end{bmatrix} \tag{S}$$

From (S), $p_{34}\ XOR\ p_{43}=1$ and $p_{47}\ XOR\ p_{74}=1$, thus, conclude that the fault either occurs between the 3rd and 4th nodes or the 4th and 7th nodes, which is a T-region.

Now we analyze the fault at the terminal after node 6 (f_2). D is the same, and G is:

$$G=\begin{bmatrix}0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&1&0&0&0&0&0&0\\0&0&0&1&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&1&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&1\end{bmatrix} \tag{Q}$$

$$Q=\mathrm{D}\times G=\begin{bmatrix}0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&1\\0&0&0&1&0&0&1&0&0\\0&0&1&0&0&0&1&0&0\\0&0&0&1&0&0&0&0&1\\0&0&0&0&0&0&0&0&0\\0&0&1&1&0&0&0&0&0\\0&0&0&1&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\end{bmatrix} \tag{U}$$

From (N) and(Q), $d_{34}=d_{54}=d_{74}=d_{84}=1$, $g_{44}=1$ and $g_{55}=g_{88}=0$, so 4th row and column of P are set to 0. Also, $d_{29}=d_{59}=1$, $g_{99}=1$ and $g_{55}=g_{22}=0$, so 9th row and column of P are set to 0.

$$P=\begin{bmatrix}0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&1&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&1&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\end{bmatrix} \tag{V}$$

From (V), there is no element of P that satisfies $p_{ij}\ XOR\ p_{ji}=1$, so this matrix algorithm fails to determine fault location at the terminal of the node.

3.2. ANALYSIS BASED ON THE IMPROVED MATRIX ALGORITHM

With the introduction of distributed generation, the distribution network has changed from a single network to multiple networks Tan (2021). Obtaining distributed generation requires a higher level of fault location in distribution networks. In addition, there are a large number of T-shaped connection segments in the distribution network. When using the conventional matrix algorithm described above to determine the status of communication segment T, two fault location processes may be required; If the results of two locations contradict each other, it can lead to erroneous evaluation of the defect location. Therefore, it is necessary to improve the defect location method of the matrix algorithm so that it can still locate defective segments in the case of single or multiple faults in the DG distribution network.

In this Analysis, we will improve by correcting the shortcoming by enhancing the fault judgement criteria of the traditional one. The access of DG transforms the distribution network into multiple sources Zhang et al. (2019). Therefore, one source is arbitrarily selected as reference power source and the direction the power flow out of that source is defined as the positive direction. Along the positive direction of power flow, regard the circuit breaker, section switch and the loop switch as nodes, we can number them in increasing sequence (random numbering is also acceptable), at the same time number the feeder's location in the network, where the feeder number is the same with the first node number of the feeder. If there is a feeder between node i and j and the positive direction of the power flow is from node i to j, we set d_{ij}= 1, otherwise d_{ij}= 0. Let's have a look on the Figure 3, we assume that A is the unique power source. The number 1 to 12 is the node number and the number L1 to L12 is the feeder number.

Figure 3

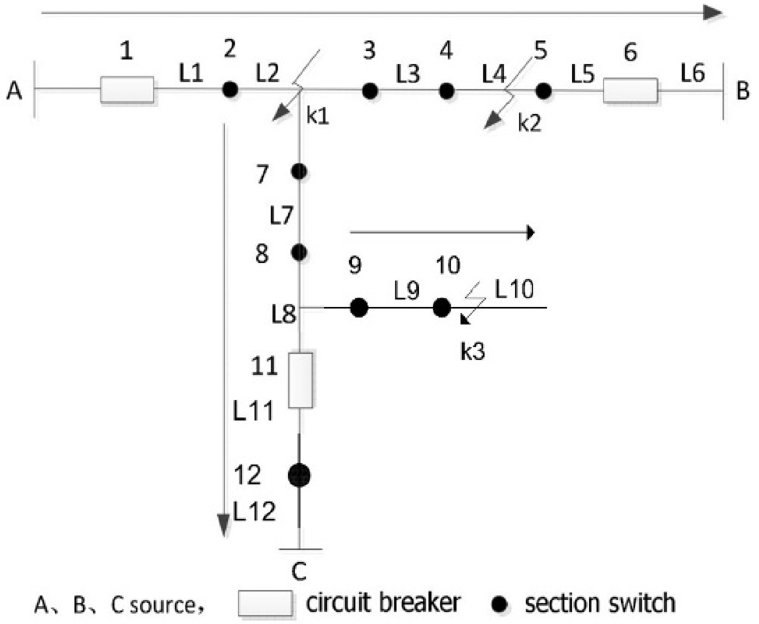

Figure 3 Multiple-source Distribution Network

After numbering all nodes and feeders, the network description matrix D can be constructed from the connections between the nodes and power lines. (D is n×n square matrix for which n is the number of the nodes.) If there is a feeder between node i and node j and the positive direction of the power flow is from node i to node j, we set d_{ij}= 1, otherwise d_{ij}= 0. According to Figure 3, a network describing matrix D is constructed in (J).

$$D = \begin{bmatrix} 0&1&0&0&0&0&0&0&0&0&0&0\\ 0&0&1&0&0&0&1&0&0&0&0&0\\ 0&0&0&1&0&0&0&0&0&0&0&0\\ 0&0&0&0&1&0&0&0&0&0&0&0\\ 0&0&0&0&0&1&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&1&0&0&0&0\\ 0&0&0&0&0&0&0&0&1&0&1&0\\ 0&0&0&0&0&0&0&0&0&1&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&1\\ 0&0&0&0&0&0&0&0&0&0&0&0 \end{bmatrix} \quad \text{(J)}$$

According to the fault information transmitted by FTU to SCADA, a fault information vector can be obtained. The fault information vector F= $\{f_1, f_2, \dots\ f_n\}$, (where n is number of nodes in the network) and the elements in F are defined as follows:

$$f_i = \begin{cases} 1, \text{node i experience positive fault curren} \\ 0, \text{node i experience no fault current} \\ -1, \text{node i experience negative fault curren} \end{cases} \quad \text{(K)}$$

Assuming all faults, k_1, k_2 and k_3 occur: F = [1 1 0 0 -1 − 1 − 1 − 1 1 1 -1 − 1].

We can get the fault judgment matrix P from fault information vector:

$$P = D + diag\ (F) \quad \text{(W)}$$

where diag (F) means the diagonal matrix with diagonal components as vector F. Hence the fault judgement matrix is obtained as follows.

$$P = \begin{bmatrix} 1&1&0&0&0&0&0&0&0&0&0&0\\ 0&1&1&0&0&0&1&0&0&0&0&0\\ 0&0&0&1&0&0&0&0&0&0&0&0\\ 0&0&0&0&1&0&0&0&0&0&0&0\\ 0&0&0&0&-1&1&0&0&0&0&0&0\\ 0&0&0&0&0&-1&0&0&0&0&0&0\\ 0&0&0&0&0&0&-1&1&0&0&0&0\\ 0&0&0&0&0&0&0&-1&1&0&1&0\\ 0&0&0&0&0&0&0&0&1&1&0&0\\ 0&0&0&0&0&0&0&0&0&1&0&0\\ 0&0&0&0&0&0&0&0&0&0&-1&1\\ 0&0&0&0&0&0&0&0&0&0&0&-1 \end{bmatrix} \quad \text{(M)}$$

Fault Judgement Matrix P by Improved Matrix Algorithm

Criterion (1): When a distribution network fault occurs between node i and node j, there are two judgment conditions.

Condition 1): p_{ii} == 1, andp_{ij} == 1for all j (j ≠ i), with all p_{jj} == 0 or -1 (row analysis)

Condition 2): p_{ii} == - 1, and p_{ji} == 1 for all j (j ≠ i), with all p_{jj} == 0 (column analysis)

As soon as one condition is satisfied, it can be judged that there is a fault between node i and node j.

Criterion (2): the judgment condition of terminal fault is: p_{ii} ==1, and p_{ij} equals to 0 (≠ 1) for all j ($j \neq i$).

Now, considering these criteria, it is possible to determine the location of defects based on the defect judgment matrix P represented by (M). The analysis table is shown as follows

Table 1

Table 1 Fault Location Analysis of node

Node No.	**p_{ii} value**	**p_{ij}=1 (for p_{ii} = 1)** **p_{ji}=1 (for p_{ii} = -1)** **($j \neq i$)**	**p_{jj} = 0 or -1(for p_{ii} = 1)** **p_{jj} = 0 (for p_{ii} = -1)**	**Fault Location (Node)**
1.	1	p_{12}=1	p_{22}=1	No fault
2.	1	p_{23}= p_{27} = 1	p_{33} = 0, p_{77}= -1	2-3, 2-7
3.	0			No fault
4.	0			No fault
5.	-1	p_{45} = 1	p_{44} = 0	4-5
6.	-1	p_{56} = 1	p_{55} = -1	No fault
7.	-1			No fault
8.	-1			No fault
9.	1	$p_{9,10}$ =1	$p_{10,10}$ =1	No fault
10.	1	All 0		After 10
11.	-1	$p_{8,11}$ =1	p_{88} =-1	No fault
12.	-1	$p_{11,12}$ =1	$p_{11,11}$ =-1.	No fault

4. RESULT

From Table 1, the fault is obtained as the T-region between nodes 2, 3 and 7 (k_1); the area between node 4 and 5 (k_2); the terminal after node 10 (k_3) and the area between node 8 and 11. The fault detected between node 8 and 11 is clearly a false alarm. To correct that, we made some adjustments to the original fault location analysis principle as follow:

1) Throughout the non-diagonal elements of each row of the fault judgment matrix, judge which nodes jointly form the T regions. In this case, 2, 3, 7 and 8, 9, 11 constitute T regions.
2) Judge whether the uploaded FTU information of the two son nodes in the T regions is the same through the diagonal elements in the fault judgment matrix. In this case, $p_{22} = 1$, $p_{33} = 0$ and p_{77}= -1 (2 as the father node supplied by source A).
3) If the FTU upload information of the two sub nodes in the T regions is different, the equivalent idea is used to correct the FTU upload information

of the two sub nodes to make them the same, that is, to correct the diagonal elements of the corresponding fault judgment matrix. The correction principle is: if the uploaded FTU information of two son nodes is different, as long as one of them is "1", both are corrected to "1"; If there is no "1", as long as there is one "- 1", both are revised to "- 1". In this case, the corrections are made as follows: $p_{33} = \ p_{77}$ = -1.

4) After correcting the fault judgment matrix, use the matrix algorithm fault location criterion to judge whether the T regions is a fault section; After the judgment of the T regions, in order to avoid affecting the positioning results of other sections, the diagonal elements of the fault judgment matrix are restored to the original value.

The followings are respectively the Flow Chart of Improved Matrix Algorithm in Figure 5 by paper Zhang et al. (2019) and the Fault result Table (Single or combination)

Figure 4

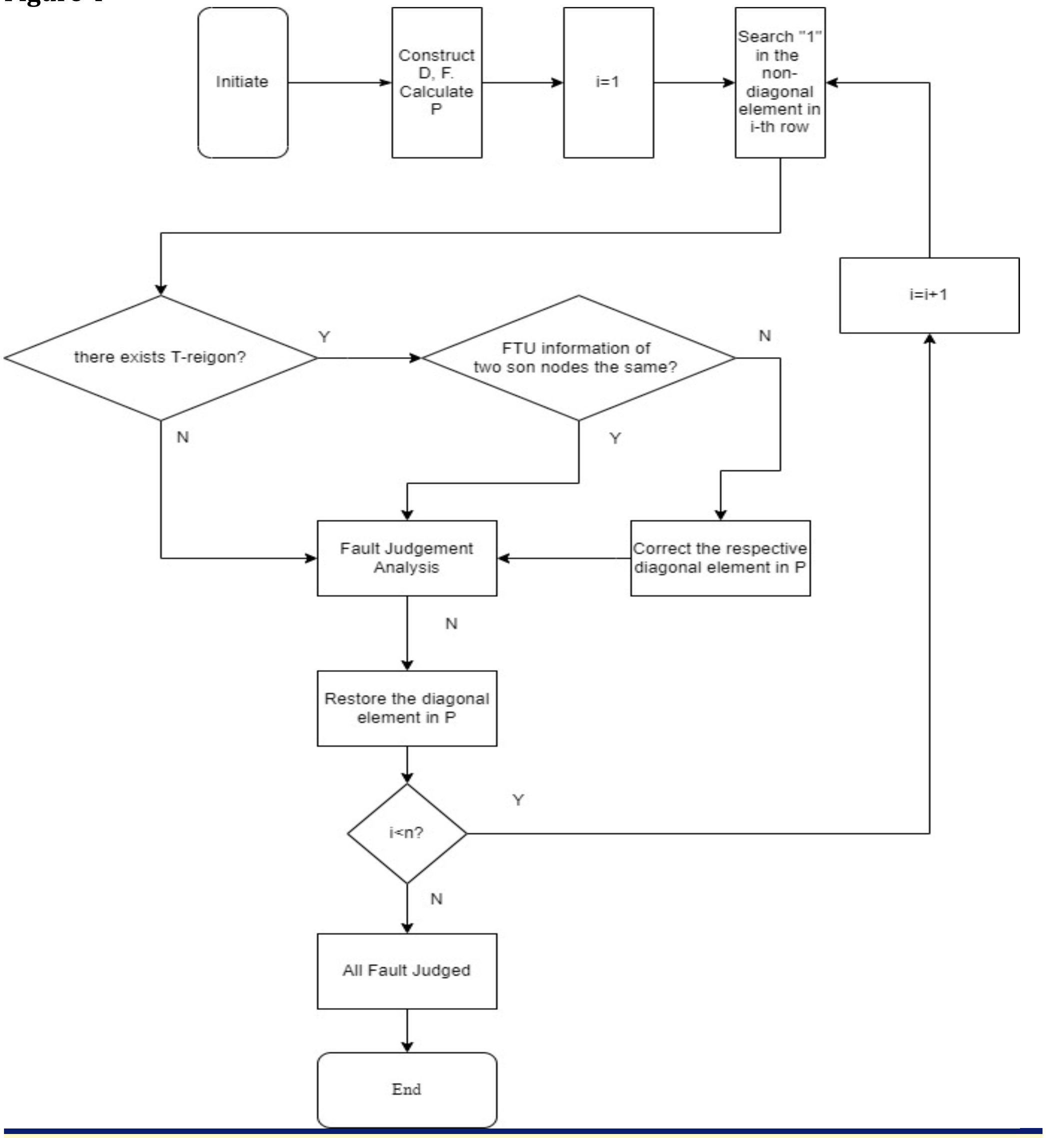

Figure 4 Flow Chart of Improved Matrix Algorithm

Table 2

Table 2 Fault Results

No.	Fault area	Fault Information Vector (F)	Fault Location Analysis	Adjust-ments	Location Results
1.	k1	[1 1 -1 -1 -1 -1 -1 -1 0 0 -1-1]	p_{22} =1, p_{23}= p_{27} =1, p_{33}= p_{77}=-1	p_{99}=-1	L2
2.	k2	[1 1 1 1 -1 -1 -1 -1 0 0 -1 -1]	p_{44} = -1, p_{45} =1, p_{55}=-1	p_{77}=1 p_{99}=-1	L4
3.	k3	[1 1 -1 -1 -1 -1 1 1 1 1-1 -1]	$p_{10,10}$=1 All $p_{i,j}$= 0	$p_{11,11}$=1	L9
4.	k1&k2	[1 1 0 0 -1 -1 -1 -1 0 0 -1-1]	p_{22} =1, p_{23}= p_{27} =1, p_{33}=0, p_{77}=-1. p_{44} = -1, p_{45} =1, p_{55}=-1	p_{33}=-1 p_{99}=-1	L2, L4
5.	k2&k3	[1 1 1 1 -1 -1 1 1 1 1 -1-1]	p_{44} = -1, p_{45} =1 , p_{55}=-1. $p_{10,10}$=1 All $p_{i,j}$= 0	p_{77}=1 $p_{11,11}$=1	L4, L9
6.	k1&k3	[1 1 -1 -1 -1 -1 -1 -1 1 1 -1-1]	p_{22} =1, p_{23}= p_{27} =1, p_{33}=-1 p_{77}=-1. $p_{10,10}$=1 All $p_{i,j}$= 0	$p_{11,11}$=1	L2, L9
7.	k1k2k3	[1 1 0 0 -1 -1 -1 -1 1 1 -1-1]	p_{22} =1, p_{23}= p_{27} =1, p_{33}=-1 p_{77}=-1. p_{44} = -1, p_{45} =1, p_{55}=-1. $p_{10,10}$=1 All $p_{i,j}$= 0	p_{33}=-1 $p_{11,11}$=1	L2, L4, L9

Considering the accuracy, Algorithm 1 and Algorithm 2 have significantly decreased, with some test cases having accuracy below 50%. This indicates that the single-layer model is not suitable for large distribution networks. Algorithm 3 uses intelligent algorithms to locate default segments. As the number of power segments in the distribution network area increases, its accuracy decreases to a certain extent. The accuracy of Algorithm 4 is higher than that of Algorithm 3 because Algorithm 4 uses exhaustive methods to locate defect segments and avoid random search operations. In addition, algorithms 3 and 4 are affected by the T-section cross-section power coupling phenomenon, which incorrectly determines the fault situation of sequence numbers 5, 8, and 10. In this article, we avoid random search operations by filtering fault candidate scenarios based on fault confidence. The figure 6 show that and from (a), we can see the accuracy comparison and from (b) we can see the comparison computational Efficiency Each algorithm run 100 times in a loop, and the average time taken for a single run is used as a measure of the computational efficiency of the algorithm.

Figure 5

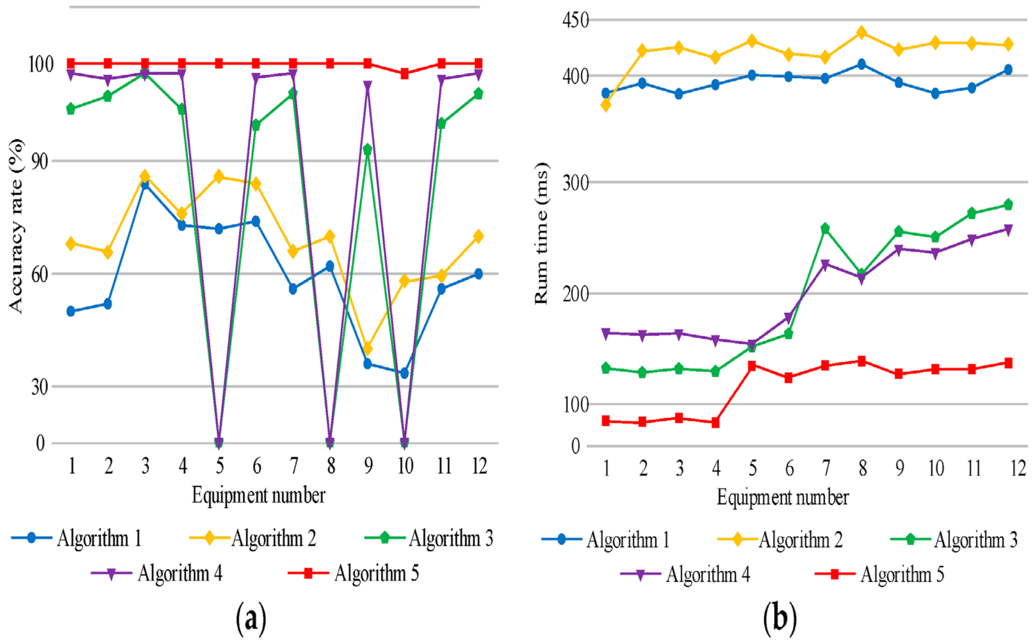

Figure 5 Test result of node Distribution Network

The simulation results show that Algorithm 5 has a computational efficiency of approximately 80ms for a single defect, 130ms for multiple defects, which is 300ms more than the results of Algorithms 1 and 2, and approximately 0.5 times more than the results of Algorithms 3 and 4.

5. CONCLUSION

In this work, we made the analysis and we proposed the improved matrix algorithm based on the existing one. The traditional matrix algorithms can misjudge faults, especially in T-regions. After analyzing, we conclude that the fault judgement matrix needs to be normalized in traditional algorithms and they are also inapplicable to distribution network with DG.

Actually, according to the improved one, the fault judgement matrix no longer needs to be normalized. For network description matrix, it only considers the FTU information of the nodes along the presumed positive direction. In the case of fault analysis of T-regions, further improvements are made to prevent fault misjudgment. When the FTU of two son nodes upload different overcurrent information, adjustment should be made so the information is the same.

This improved algorithm is proven to be effective for whether the distribution network is supplied by single or multiple sources, or there are multiple failures in different areas at the same time, including the T-regions. This fault location algorithm is accurate and time efficient. Because algorithms based on single-layer models require iterative operations in high-dimensional resolution space. Layered models play a more significant role in improving computational efficiency Zhao et al.. (2023). The computational efficiency of Algorithm 3 for single and multiple defects is approximately 132ms and 260ms, respectively, while Algorithm 4 for single and multiple defects is 162ms and 239ms, respectively.

6. FUTURE WORK

The research on fault location in distribution networks based on matrix algorithms is also insufficient. In order to adapt to the development of distribution network automation, matrix algorithms should be more accurate and save time. In the future, with the introduction of various improvement methods, the accuracy of defect localization will be greatly improved, the computational workload will be reduced, and the types of defects that can be solved will increase. From those Mathematical Analysis and Improvement, we will apply these results to the field of industrial technology and further conduct industrial analysis. With the development of communication technology, the location speed can also be greatly accelerated and automation technology has become inseparable from electric power. People rely on electric power to maintain social production and normal life.

CONFLICT OF INTERESTS

None.

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