IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 25 March 2024, accepted 16 April 2024, date of publication 23 April 2024, date of current version 1 May 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3392570

RESEARCH ARTICLE

Multi-Terminal Wireless Differential Protection Method for Offshore Wind Power Collection Lines

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ABSTRACT The development of offshore wind power is a crucial step in China's energy transition and the achievement of carbon peaking and carbon neutrality goals. This paper first introduces a wireless communication technology for independent networking. Its applicability in the field of relay protection is analyzed, and a security encryption scheme for its use in relay protection services is designed. Considering the primary wiring form and protection function configuration of offshore wind power, a multi-terminal wireless differential protection method suitable for offshore wind power collection lines is proposed, achieving synchronization error less than 3° and typical delay of wireless self-organizing network communication less than 12ms. Utilizing multi-terminal data synchronization technology and differential protection algorithms, a scheme for fault isolation and recovery of non-faulty wind turbines is established, thereby achieving minimal range isolation of offshore wind power collection line faults and precise fault section location. The action time of multi-terminal differential protection is less than 40ms. Finally, experimental results confirm that this technology's various metrics satisfy the demands of engineering applications and hold promotional value, offering a reference for the practical application of wireless communication technology in offshore wind power collection line protection services.

INDEX TERMS Offshore wind power, collection line, wireless differential protection, multi-terminal differential protection.

I. INTRODUCTION

China proposes a development goal of achieving carbon peaking by 2030 and carbon neutrality by 2060. The implementation of this "Dual Carbon" goal in the power industry involves constructing a new power system, with new energy sources as the main component. New energy forms, especially wind energy, are anticipated to gradually become the primary energy source in China [1], [2]. China boasts abundant offshore wind energy resources, with the potential for offshore wind energy development reaching up to 500 million kilowatts. Due to their proximity to load centers, offshore wind farms possess a strong absorption capacity. Consequently, the focus of wind power development is progressively shifting towards offshore areas.

Large-scale wind power integration into the power grid provides a large short-circuit current, making the system short-circuit components a dual power supply, which has a significant impact on relay protection [3], [4]. The short-circuit current provided by the fan is affected by the type of unit, wind conditions, and short-circuit type. To avoid large-scale shutdown caused by small faults, the fan needs to have low-voltage ride-through capability, and relay protection should be coordinated with it. The transmission lines and grid connection methods of offshore wind power are different from those of onshore wind power [5], and it is

The associate editor coordinating the review of this manuscript and approving it for publication was Vitor Monteiro.

necessary to study the fault characteristics of offshore wind farms to provide a basis for accurately configuring relay protection. In the configuration and timing of relay protection, the special characteristics of offshore wind power must be considered. The components and lines in the field are treated as double-sided power supply, and the coordination between the protection of each component and the low-voltage ride-through and various protections must be considered to ensure the reliable operation of each protection and avoid large-scale power outages.

At present, there have been some studies on offshore wind farms and wind farm relay protection in the industry. Reference [6] analyzed the current offshore electrical systems and pointed out that the protection of offshore wind farms requires equipment to have higher remote monitoring capabilities, and should strive to achieve fault localization and recovery. It was proposed that special consideration should be given to the protection of box transformers and submarine cables, but no mention was made of time coordination. Reference [7] studied the coordination between grid protection and protection in wind farms, with examples discussing fault situations within the wind farm, but did not propose specific relay protection schemes for offshore wind farms. References [8] and [9] proposed a relay protection configuration and setting method for various components in a wind farm with low-voltage ride-through capability, but only verified and analyzed the protection of the collection line, without analyzing the coordination between various parts of the protection.

The construction of offshore wind farm projects typically involves a series of around 7-10 wind turbines. These turbines are connected to an offshore boosting platform via a 35kV/66kV collection line. However, the relay protection configuration of the collection line is somewhat rudimentary at present, with only protective devices installed at the boosting substation. Section II-B of reference [10] provides a detailed description of the protection configuration for the collection line. The primary focus of the protection function is overcurrent protection, but its selectivity and speed are suboptimal. In the event of a fault at any point along the collection line, all wind turbines in the series will be cut off. This not only broadens the scope of the power outage but also impacts the power generation capacity of the wind turbine. In addition, the collection line lacks a section positioning function, which leads to extended troubleshooting and power generation recovery times. Traditional differential protection uses optical fiber communication, but the harsh marine environment makes it difficult to lay optical fibers in the early stage and maintain them in the later stage. If traditional optical fiber differential protection is used, the construction and maintenance costs will be very high.

To address the issues mentioned above, this paper proposes a multi-terminal differential protection scheme for power collection lines, that integrates the latest wireless communication technology. A differential protection device is installed at the offshore booster station for the collection line, and a collection and execution terminal is placed within each wind turbine tower. These terminals and devices communicate via wireless channels, with the terminal gathering current and voltage data from its corresponding wind turbine and transmitting it to the protection device. In return, it receives and carries out action instructions from the protection device. By optimizing the configuration of measurement points, switches, and other equipment along the power collection line, this multi-terminal differential protection application can precisely locate fault sections. This allows for a minimal fault removal range, ensuring that wind turbines on fault-free line sections remain connected to the grid as much as possible. This can increase their power generation hours and reduce the time required for troubleshooting fault points and restoring power generation of wind turbines in non-fault sections.

The main contributions of this paper can be summarized as:

1) The paper introduces an autonomous wireless communication technology, assesses its applicability in the field of relay protection, and proposes a secure encryption strategy for relay protection services.

2) Considering the wiring structure of offshore wind power and the primary equipment configuration, a scheme for rapid isolation, accurate positioning, and automatic recovery of faults in offshore wind power collection lines is proposed.

3) A scheme for isolating fault points after faults and restoring non-fault section wind turbines is constructed based on the multi-terminal data synchronization and size difference technology of wireless communication, achieving minimum range isolation of power line faults and precise positioning of fault sections.

The rest of this paper is organized as follows. Section II introduces wireless communication technology in self-organizing networks. The configuration scheme for collection line protection is presented in Section III. Section IV proposes the multi-terminal differential algorithm, fault isolation, and the recovery method. Section V presents the data synchronization technique. Section VI shows the experimental results. Finally, Section VII concludes this paper.

II. WIRELESS COMMUNICATION TECHNOLOGY IN SEIF-ORGANIZING NETWORKS

Self-organizing network wireless communication is a multi-hop autonomous system consisting of a group of nodes equipped with wireless transceiver devices. It does not rely on preset infrastructure and offers several unique features such as self-healing networking, rapid deployment, absence of a control center, and strong survivability [10], [11], [12], [13]. Self-organizing wireless communication represents a novel wireless network structure that originated from WLAN and Ad-hoc networks. It provides stable and reliable wireless access services with high bandwidth and low cost. In comparison to conventional mobile and fixed networks, self-organizing networks possess the following distinguishing characteristics: 1) Decentralized Operation. The network operates on an equality basis, ensuring that the failure of any individual node does not impact the overall network operation and this nature contributes to its strong survivability; 2) Self-Organization. The deployment and establishment of the network do not depend on any predetermined infrastructure. Instead, nodes coordinate their activities through layered protocols and distributed algorithms, enabling the rapid and automatic formation of an independent network; 3) Multi-hop routing: When a node needs to communicate with nodes beyond its coverage range, it can be relayed through intermediate nodes with multiple hops, eliminating the need for dedicated routing devices. The self-organized network system employed in this scheme optimizes the LTE frame structure, seamlessly integrating LTE physical layer technology and leveraging channel adaptation techniques in modulation and encoding methods to achieve optimal transmission efficiency. Moreover, the self-organized network system supports a QoS mechanism, enhancing transmission reliability and ensuring the delivery of high-quality wireless services.

A. NETWORKING METHODS AND KEY COMMUNICATION INDICATORS

As depicted in Fig. 1 and Fig. 2, the networking solutions for the wireless self-organizing network primarily comprise star networking and mesh networking.

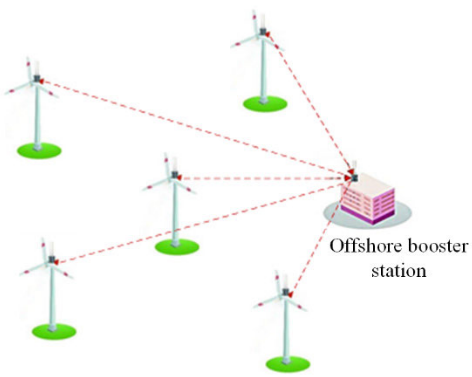

FIGURE 1. Networking solution based on star network topology.

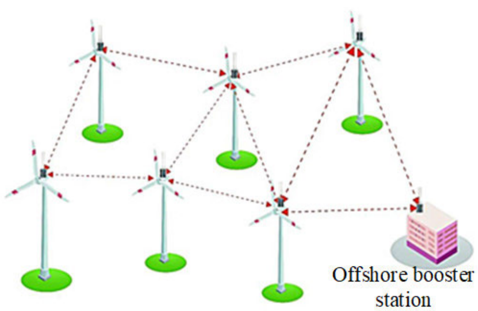

FIGURE 2. Networking solution based on mesh network topology.

To enhance the reliability of wireless self-organizing network communication, the following measures are implemented when applying this technology to relay protection. 1) This technology supports a hybrid automatic retransmission mechanism and adaptive bitstream. Firstly, it facilitates the retransmission of critical information. Secondly, it significantly reduces the error rate, ensuring that the packet loss rate remains below the requirements of relay protection applications; 2) This technology supports frequency hopping strategies based on self-organized channel measurement and evaluation. It allows hopping within and across frequency bands, which is advantageous for avoiding sudden environmental interference. This capability ensures the stability and reliability of differential protection service transmission; 3) This technology utilizes orthogonal multiple access technology to avoid inter-network interference.

The self-organizing network wireless transmission technology supports the transmission of Ethernet frames using a three-layer network protocol. It exhibits the following indicators: 1) Communication bandwidth: The wireless communication interface device provides support for two bandwidth options: 30Mbps and 80Mbps. For differential protection applications, the 30Mbps bandwidth is considered sufficient; 2) Communication delay: In the self-organizing network, the wireless communication exhibits a minimum point-to-point delay of 8ms, with the maximum delay not exceeding 10ms, indicating a high level of stability. if a star network is employed, the delay is slightly higher; 3) Communication distance: Presently, there are various products available with different application scenarios, offering communication distances of 100km, 50km, and 30km. For offshore wind power collection lines, the distance typically does not exceed 10km. Therefore, selecting a communication distance of 30km would be more than sufficient for such applications; 4) Communication frequency band: This technology supports 2.4G and 5.8G unlicensed frequency bands (ISM) open to industry, science, and medicine, as well as custom frequency bands such as 1.4G, 1.8G, etc.

B. NETWORK SECURITY MEASURES

Differential protection is a crucial component of real-time control systems, which must comply with safety protection regulations for power monitoring systems. This section explores the software and hardware aspects to enhance the security of data transmission and ensure its integrity.

In terms of software, a comprehensive three-level security strategy is implemented, incorporating a user-key self-management configuration scheme. The first level is access security, and the system will employ encryption techniques to ensure information security during the access process. The second level is control surface signaling security. New user access and real-time status management of network users need to be completed based on control surface signaling messages, which can prevent illegal user access and control messages from being illegally tampered with. The third level is data plane security. Business data is encrypted to ensure information security. Data encryption supports standard algorithms such as AES128, 3G SNOW, and ZUC.

In terms of hardware, the wireless communication interface device offers support for external hardware methods, such as TF encryption cards, to encrypt the source data. This ensures the safety and reliability of transmitted data. Additionally, the device facilitates the utilization of dedicated encryption chips for system key distribution and management, enabling user access verification confirmation and user data key confirmation to be effectively achieved [14], [15], [16], [17], [18], [19], [20].

When data is transmitted through wireless air ports, the data link layer will choose the configured algorithm and key for private data encryption. The encryption algorithm is implemented using a hardware accelerator, which does not affect the real-time processing ability of the data. After private encryption, data can only be securely transmitted within this network. External detection of relevant data signals, unable to decipher.

Differential protection based on fiber optic communication has been widely used as the main protection in power systems. Wireless differential protection converts the transmission medium from fiber optic to radio waves, and its sensitivity mainly depends on the uncertainty of wireless transmission. In response to this problem, we consider increasing the dynamic adjustment ability of delay jitter and reducing the risk of data synchronization adjustment exceeding the limit caused by frequent delay jitter, while existing transmission delays can meet the basic requirements of differential protection.

III. CONFIGURATION SCHEME FOR COLLECTION LINE PROTECTION BASED ON THE WIRELESS SELF-ORGANIZING NETWORK

A. EXISTING PROTECTION CONFIGURATION

Offshore wind farms usually connect to the grid using AC transmission technology when they are located close to the shore. A transformer is used to increase the output voltage of the wind turbine generator from 690V to 35/66kV, and then a submarine cable sends it to the low-voltage side of the booster station. A booster transformer further raises the voltage and delivers it to the land. The basic connection is shown in Fig. 3 [10].

At present, two common topologies exist for single-string wind turbines in offshore wind power engineering, as illustrated in Fig. 4.

The wind turbine is connected to the step-up transformer at the base of the tower via a frame circuit breaker. A current transformer (CT) is attached to the high-voltage side of the step-up transformer. On the collection line, only CT and voltage transformers (VT) are installed on the offshore step-up substation side, and the line side near the wind turbine is not installed with CT at present. The protection configuration of

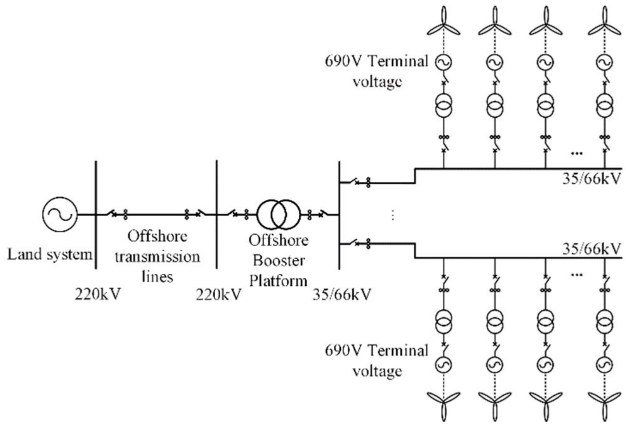

FIGURE 3. Marine wind farm connection diagram.

the collection line is rather simple. Generally, only protection devices that rely on over current principle are installed on the step-up substation end, which has a long fault clearance time and no selectivity. If a fault happens anywhere on the power collection line, all the wind turbines in the string will be disconnected, causing a large power outage and reducing the wind turbines' generation hours.

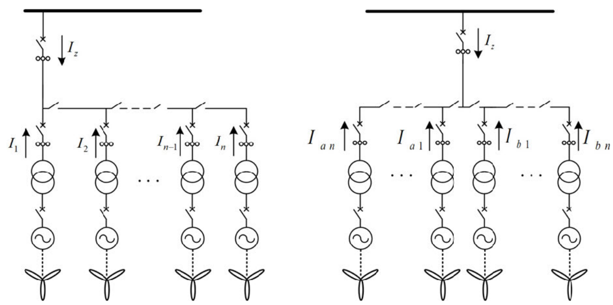

FIGURE 4. Schematic diagram of offshore wind farm collection line.

B. MULTI-TERMINAL DIFFERENTIAL PROTECTION SCHEME BASED ON WIRELESS COMMUNICATION

The popularization of fiber optic communication technology has led to the widespread application of line differential protection in power systems. In recent years, wireless communication has made remarkable progress, enabling data exchange with millisecond delay and ensuring high transmission reliability, meeting the requirements of line differential protection for communication channels. However, implementing fiber optic engineering between offshore wind power platforms and wind turbines is difficult and economically inefficient. The application of the 5G communication method based on public networks faces limitations in offshore environments. To solve the problems of non-selectivity in cutting off the fan and difficulty in fault location in the event of a fault in the power collection line, this paper explores the utilization

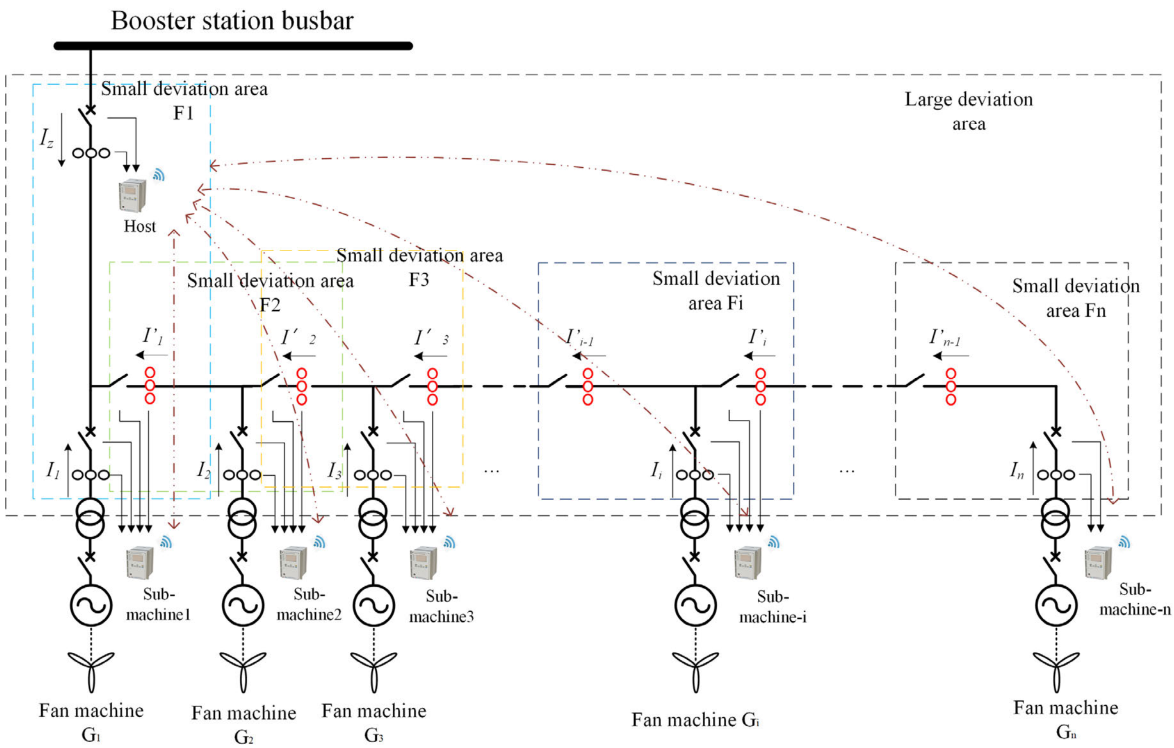

FIGURE 5. Schematic diagram of fault location of offshore wind farm collection line.

of wireless self-organizing communication technology introduced in Section II and proposes a multi-terminal differential protection algorithm based on the wireless self-organizing communication networks. This algorithm aims to achieve fault location, isolation, and recovery, providing effective solutions for the aforementioned issues.

As mentioned above, the wind turbine access point on the power collection line currently lacks CT installation. To precisely locate the exact section where the fault occurs on the power collection line, it is necessary to install CT on the power collection line. After conducting a thorough analysis of cost investment and installation space within the project, it is determined that installing CT is feasible. Fig. 5 illustrates the wiring configuration of the power collection line after the CT is added.

To enhance the operational efficiency of the multi-terminal wireless differential protection system, the network architecture of the multi-terminal wireless differential protection in this scheme adopts a star networking method, and the protection mechanism adopts a primary-secondary topology mode. At the offshore booster station, a differential protection device is configured as the host for the power collection line, while within each fan tower, a collection and execution terminal serves as the differential protection sub-machine. Data exchange between the host and the sub-machine occurs through wireless communication facilitated by a self-organizing network, as depicted in Fig. 5. The protection host is located within the offshore platform switchgear, where it collects local electrical quantities from the power collection line's outlet. It also receives electrical data from the corresponding wind turbine branch sent by each sub-machine through wireless channels. With this information, the protection host performs crucial protection algorithms and logical assessments to accurately identify the fault area. It then sends the appropriate tripping and closing commands to the corresponding sub-machines. The protection sub-machine is locally installed on the fan side, where it gathers the current and switches values of the corresponding branch and accesses point power lines to the fan. The collected data is then transmitted to the protection host through wireless channels. Simultaneously, the protection sub-machine receives and executes the tripping and closing commands issued by the protection host.

This scheme adopts the UDP Ethernet message communication method, encapsulating the optical longitudinal message of the protection device and transmitting it on the wireless channel.

IV. MULTI-TERMINAL DIFFERENTIAL ALGORITHM AND FAULT ISOLATION ALONG WITH RECOVERY METHOD

A. MULTI-TERMINAL DIFFERENTIAL ALGORITHM

As mentioned above, the protection algorithm is computed by the protection host installed in the offshore booster station.

The sub-machines installed on the fan side only perform the tasks of collecting data, data transmission, and command execution. The host receives current sampling data from the outlets of each fan and the collection line. After undergoing synchronous processing, this data is utilized in the differential protection algorithm. The specific data synchronization scheme will be described in Section V. Differential protection comprises two components. The first is the large-area differential algorithm, utilized to judge if a fault exists within the power collection line, facilitating a swift disconnection between the fault and the system. The second component is the small-area differential algorithm, employed to locate the position of the fault section, thereby achieving the isolation of the fault section within the smallest possible range. The division of large and small differential areas is depicted in Fig. 5.

1) LARGE AREA DIFFERENTIAL ALGORITHM

The scope of the large-area differential protection covers the entire collection line. Consequently, the algorithm must incorporate the current at the starting point of the collection line and the current at each wind turbine connected to the collection line. The magnitude of the current at each connection point within the collection line is not pertinent. The fault criteria are shown in (1).

$$\begin{cases} I_d > K \cdot I_r \\ I_d \geq I_{SET} \end{cases} \tag{1}$$

where I_{SET} is the setting value for the differential algorithm's current, which is the minimum operating current. K is the ratio braking coefficient, which can be set as 0.3.

In (1), the differential current can be calculated by:

$$I_d = \left| \dot{I}_z + \sum_{i=1}^{n} \dot{I}_i \right| \tag{2}$$

In (2), the definition of $\dot{I}_z$ and $\dot{I}_i$ is shown in Fig. 5.

The braking current I_r can be written as:

$$I_r = \left|\dot{I}_z\right| + \left| \sum_{i=1}^{n} \dot{I}_i \right| \tag{3}$$

The differential current, once it satisfies (1) following the activation of the protection, indicates that an area fault has occurred within the collection line.

2) SMALL AREA DIFFERENTIAL ALGORITHM

The purpose of the small area differential algorithm is to further determine the fault section after the large area differential algorithm has identified a regional fault in the collection line. This process effectively reduces the scope for fault isolation and investigation. The implementation of the small area differential algorithm requires the integration of current data from each connection point along the collection line, allowing for a step-by-step execution of the differential algorithm.

The ratio braking equation of the small area differential algorithm is as:

$$\begin{cases} I_{ds} > K \cdot I_{rs} \\ I_{ds} \geq I_{SET} \end{cases} \tag{4}$$

where the differential current is calculated by:

$$I_{ds} = \begin{cases} \left|\dot{I}_z + \dot{I}_1 + \dot{I}_1^{'}\right| & i = 1 \\ \left|\dot{I}_z + \dot{I}_1 - \dot{I}_{i-1}^{'}\right| & 2 \leq i \leq n-1 \\ \left|\dot{I}_n - \dot{I}_{n-1}^{'}\right| & i = n \end{cases} \tag{5}$$

In (5), the definition of $\dot{I}_1$ is shown in Fig. 5.

The braking current I_{rs} is:

$$I_{rs} = \begin{cases} \left|\dot{I}_z\right| + \left|\dot{I}_1\right| + \left|\dot{I}_1^{'}\right| & i = 1 \\ \left|\dot{I}_i\right| + \left|\dot{I}_i^{'}\right| + \left|\dot{I}_{i-1}^{'}\right| & 2 \leq i \leq n-1 \\ \left|\dot{I}_n\right| + \left|\dot{I}_{n-1}^{'}\right| & i = n \end{cases} \tag{6}$$

The ratio braking coefficient K is:

$$K = \begin{cases} 0.3 & i \neq n \\ 0.6 & i = n \end{cases} \tag{7}$$

After the protection is activated, any section that satisfies (4) can determine the corresponding fault section.

B. FAULT ISOLATION AND SYSTEM RECOVERY METHODS

To meet the requirements of low voltage ride-through, the fan can remain connected to the grid for a period of time after a system failure. Even if it is isolated from the main network, the fan can still operate for a short time. During this process, the fan's control system will reduce the fault current provided by the fan to below the normal load current. When the fault is cleared, the fan can resume normal operation.

Based on the fan characteristics and the fault section location method of the differential protection, the treatment process can be divided into two steps after a fault occurs in the collection line. The first step is to isolate the fault section, and the second step is to restore power generation in the fault-free area. Fault isolation and system recovery require the design of a new logic, which involves the coordination of the collection line's protection and reclosing configuration, as well as the cooperation of the outlet circuit breaker and the collection line's load switch.

After the protection is initiated, it assesses whether a fault has occurred in the protected area by using the large difference method as described in Section IV-B. If the fault is in the protected area, the circuit breaker of the collector line outlet in the booster station is directly cleared to isolate the fault from the power grid. Meanwhile, the protection calculates the small area differential of each section. If the i-th section meets the differential operation condition, it indicates a fault in that section. The fan in the fault area can still run for a short time after the circuit breaker of the collector line outlet is removed, but the short-circuit current supplied to the fault point will soon be limited to a small value. The load switches corresponding to the i-th section are cleared when they meet the excision conditions within about 0.1s, and isolate the collector line into the front and back sections. The section near the offshore booster station is the non-fault section, which can resume operation. After a short delay of about 0.5s, the circuit breaker of the collection line outlet can be re-closed. After experiencing transient oscillation, the fan in the non-fault section recovers to normal operation and generation. The sequence diagram of the recovery process for the fault isolation area and the non-fault area is presented in Fig 6.

To evaluate the effectiveness of the fault isolation and system recovery method, a simulation model is built in this paper. As shown in Fig. 3, a fault arises in the collection line area between the second fan and the third fan, i.e., $i = 3$. Verification follows the flow chart shown in Fig. 6. The simulation results of the fan in the non-fault area are shown in Fig. 7. The simulation results demonstrate that the proposed fault isolation and recovery method can meet the operation requirements of the system and the fan.

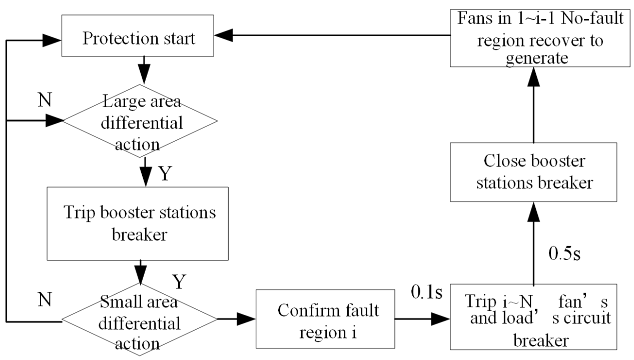

FIGURE 6. Fault isolation and recovery flowchart.

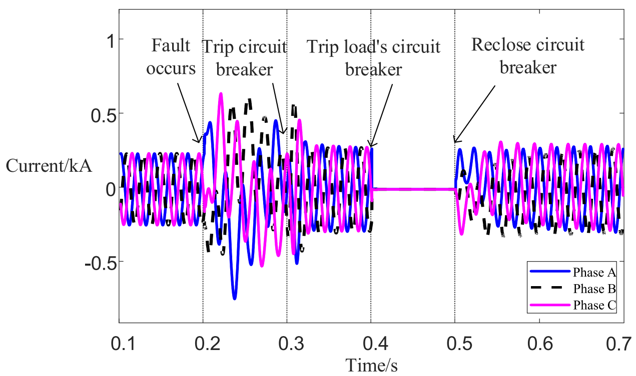

FIGURE 7. Current changes during the process of cutting and restoring the non-faulty area fan.

1) REFLECTIONS ON ENGINEERING APPLICATION

To apply this scheme to engineering applications, the following operation conditions should be comprehensively considered.

1) When the wireless self-organizing network's communication is abnormal and causes the multi-end differential protection channel to be interrupted, the protection host should automatically abort the differential protection and system recovery functions, and switch to the traditional over current protection.

2) After the collection line has a fault and the fans in the fault area are removed, the system recovers generation. The current of the fan that has stopped operating needs to be excluded from the large difference algorithm. If another fault occurs in this operation mode, it needs to remove all the fans related to the fault, and system recovery is not considered, only the fault section is displayed.

V. MULTI-TERMINAL DATA SYNCHRONIZATION

A. DYNAMIC DELAY COMPENSATION-BASED SYNCHRONIZATION METHOS

The implementation of differential protection requires a synchronization method to ensure the synchronization of differential protection data. The common synchronization methods for differential protection include sampling timing adjustment, electric quantity reference synchronization, and satellite-based time synchronization. The sampling timing adjustment method, which follows the ping-pong principle, has low computational complexity, high synchronization accuracy, and easy algorithm implementation. However, it requires strict uniformity of the channel transmission and reception routes. The electric quantity reference synchronization method is influenced by many factors, such as electric quantity measurement accuracy, line parameters, and operation mode, which make it hard to ensure synchronization accuracy. The satellite-based time synchronization method can be applied to various communication systems, but it heavily relies on the satellite time synchronization system, which makes it less secure and reliable. These synchronization methods have some limitations when applied to the scenario of offshore wind power collection lines. Therefore, it is necessary to further study the differential protection data synchronization methods that are suitable for multi-terminal wireless communication [21], [22], [23], [24].

This article proposes a synchronization scheme based on dynamic delay compensation, which integrates the synchronization of self-organizing networks and the synchronization of multi-terminal line differential protection, considering the characteristics of wireless network communication. It adopts a high-precision frame synchronization method to achieve the synchronization of the whole self-organizing network. The self-organizing network module periodically sends synchronization signals to the terminal device, which uses them to calibrate the local crystal clock and generate a microsecond timer to mark the receiving and transmitting times of the terminal message. The receiving and transmitting time information of the message is used to calculate the receiving and transmitting delays of the channel in real-time, and the delay compensation threshold value is dynamically adjusted based on the delay statistics. By comparing the channel delay and the delay compensation threshold, the delay deviation of the receiving and transmitting routes is determined, and the delay compensation method is used to eliminate this deviation. A channel route with consistent receiving and transmitting delays is constructed, and a sampling time adjustment method with one primary and multiple secondaries is used to achieve synchronization of the protection device.

Wireless communication requires the use of spatial electromagnetic waves for transmission, which is susceptible to co-frequency interference. The requirement for multi-terminal data synchronization is to minimize the delay jitter caused by interference. The above problems can be solved through the following measures:

1) By implementing self-measurement and frequency hopping strategy, we can avoid frequency points with interference in wireless channels and maintain the working channel on channels with low interference.

2) Enhance the demodulation capability of channel data, reduce the requirement of channel quality for business transmission, and achieve the effect of anti-interference.

3) When transmitting business data, it is possible to adaptively adjust the business rate based on channel quality, achieving a transmission rate that is compatible with channel quality, and reducing the impact of interference on channel transmission.

B. FRAME SYNCHRONIZATION AND SIGNAL OUTPUT IN SELF-ORGANIZING NETWORKS

The self-organizing network uses a primary-secondary synchronization mechanism to achieve network-wide synchronization through frame synchronization. After the whole self-organizing network is synchronized, the primary and secondary MCU nodes periodically output synchronization signals based on their local clocks. The terminal CPU can obtain synchronization signals in two ways. First, the terminal CPU can directly get the synchronization pulse signal from the self-organizing network MCU through a hardwired connection. Secondly, the terminal CPU can parse the soft message sent by the self-organizing network MCU and extract the synchronization signal from it. To ensure the timeliness of the synchronization signal, each terminal CPU actually uses the hardware pulse signal from the self-organizing network MCU as the synchronization reference.

The network system bandwidth used is 20Mbps, the system frequency band used is 2.4G, and the delay of the primary and secondary nodes in the self-organized network is less than 8ms. The star network version, taking 1V8 networking as an example, has a latency of less than 50ms. The communication distance of the self-organized network is 10 km, and the power consumption of the communication equipment is 2W without adding PA.

C. DYNAMIC COMPENSATION DELAY CALCULATION

The terminal CPU sets the crystal clock to automatically calibrate the periodic pulse signal generated by the self-organizing network MCU, and uses this signal as the reference time 0 to create a nanosecond timer, which measures nanoseconds and produces a nanosecond sequence. After the synchronization of each terminal, the nanosecond counter is used to mark the time of receiving and transmitting the messages from the terminal. As an example, we illustrate the process of marking the communication message sent from the host to the sub-machine: The sub-machine terminal receives the channel message sent by the host protection CPU, obtains the message time T_x of the host protection CPU from the nanosecond sequence mark, and packages the time information and host protection message into a UDP message and transmits it to the sub-machine terminal. The sub-machine terminal CPU marks the message reception time R_x. The specific process is illustrated in Fig. 8.

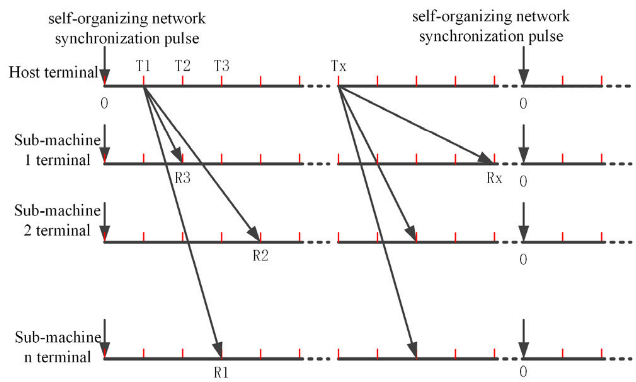

FIGURE 8. Communication message time-stamping schematic.

As shown in Fig. 8, The formula for calculating the one-way communication message transmission and reception delay, ΔT_x, is given by:

$$\Delta T_x = T_x - R_x \tag{8}$$

All terminals obtain the initial time of the self-organizing network synchronization pulse, and the terminal CPU begins to measure the delay of one-way communication for sending and receiving messages within a certain time period T1, and computes the maximum value:

$$\Delta T_{\max} = \max(\Delta T_1, \Delta T_2, \ldots \Delta T_m) \tag{9}$$

where ΔT_{max} is the maximum value of one-way communication transmission and reception delay within time T1, and m is the number of one-way communication message delays counted within time T1, and max is the function for finding the maximum value.

Based on ΔT_{max}, the initial delay compensation threshold value ΔT_{set} is set as follows:

$$\Delta T_{set} = \Delta T_{\max} \tag{10}$$

The system compares ΔT_x and ΔT_{set} in real time after the data arrives. If ΔT_{set} is greater than ΔT_x, it calculates the compensation delay ΔTB_x using formula (11).

$$\Delta TB_x = \Delta T_{set} - \Delta T_x \tag{11}$$

If ΔT_{set} is less than ΔT_x, the device will block the differential protection momentarily because of the effect on synchronization judgment, and then recomputes ΔT_{max}. Based on the new value of ΔT_{max}, it resets ΔT_{set} and recalculates ΔTB_x. The resulting ΔTB_x is the delay that the device needs to compensate for when sending and receiving messages.

D. SYNCHRONOUS DISCRIMINATION

After undergoing the delay compensation discrimination, the device compensates for the transmission delay based on ΔTB_x and establishes a channel transmission route with consistent delay. The protection device uses a synchronous mode with one primary and multiple secondaries, and applies a sampling time adjustment method to achieve synchronous discrimination of multi-terminal lines. The specific implementation process is illustrated in Fig. 9.

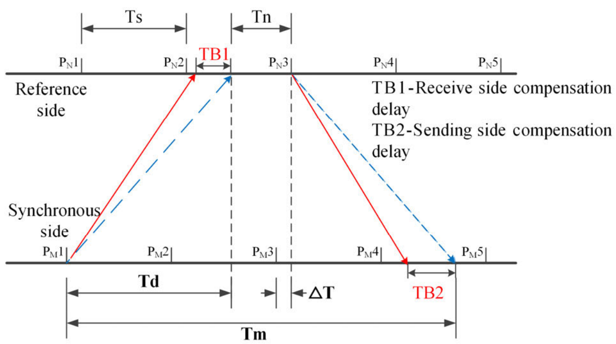

FIGURE 9. Dynamic delay compensation synchronous discrimination schematic.

VI. EXPERIMENTAL VERIFICATION

The test environment, as depicted in Fig. 10, simulates a collection line configuration with three wind turbines. This type of model does not have a standard benchmark. Our model is a universal model for offshore wind power in China, referring to a project in Zhejiang Province. It consists of a single wireless differential protection primary unit and three secondary units. The maximum distance between the primary and secondary units is 2 kilometers. Each device is equipped with its dedicated relay protection test instrument to apply analog quantities for protection testing. To ensure synchronized data acquisition by the test instruments, all four test instruments synchronize their measurements via GPS devices and antennas utilizing optical B-code synchronization. This synchronization mechanism guarantees that phase angles and clock timing remain synchronized during the protection experiments [25], [26].

In the provided test environment, various aspects of protection-related performance are thoroughly evaluated. This includes conducting tests for protection functions, assessing communication performance, and ensuring accurate data synchronization. Protection function testing validates the differential protection operation values and operation times, with test results listed in Table 1.

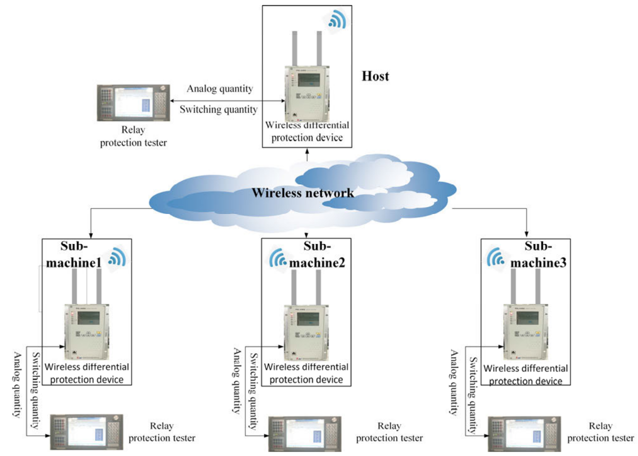

FIGURE 10. Test environment.

TABLE 1. Protection function test results.

Test project	Tuning value	Test phase	Action value and action time	Test conclusion
Multi-terminal differential current setting	0.2A	Phase A	0.19A no-action, 0.21 A action	Error<5%
	1A	Phase B	0.99A no-action, 1.01A action	
	5A	Phase C	4.99A no-action, 5.01A action	
Multi-terminal differential action time	/	Phase A	38.6ms	Action delay <40ms
		Phase B	37.8ms	
		Phase C	38.3ms	

Based on the test results, the action value error of the multi-terminal differential protection is less than 5% and the operation time for the differential protection is less than 40ms, meeting the requirements for the accuracy of the multi-terminal differential protection system and the rapid isolation of collector line faults.

Regarding the communication performance testing, the focus was primarily on channel bit errors, frame loss, and delay characteristics. The results are presented in Table 2.

Based on the test results, the typical delay for multi-terminal communication is less than 12 milliseconds, and the channel performance of the wireless self-organizing network meets the requirements for differential protection.

According to the experimental results, the wireless channel communication performance can be stable, and the

TABLE 2. Communication performance test results.

Delay type	Typical test value
The average transmitted optical power of the optical interface	-9 dBm
The working wavelength of the optical interface	1310 nm
Optical channel bandwidth	2Mbps
Data transmission frequency	600 frame/ s
test duration	24h
Total number of data frames	51,840,000
Message communication time	11628us
Maximum frame delay	15392us

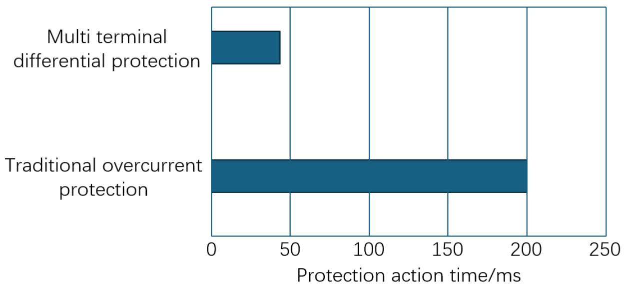

FIGURE 11. Comparison of fault isolation time.

typical delay of multi-terminal communication is less than 12ms, which is a prerequisite for ensuring the reliability of multi-terminal differential protection and significantly improving the speed of protection.

To validate the transmission distance of wireless communication, long-distance transmission experiments were conducted in an unobstructed open-air environment. In a real-world scenario, a maximum interconnection distance of 10 kilometers was achieved with reliable data transmission signal quality. Furthermore, validation was performed in a maritime environment at a wind farm located in Zhejiang Province, China. The primary unit was positioned at the top of a wind turbine tower, while the secondary unit was incrementally moved away via a boat. As the testing distance reached 10 kilometers, the channel delay remained below 12ms, and the signal quality remained consistently strong, which is sufficient to meet the transmission distance of most offshore wind power collection lines and has a wide range of applicability. This demonstrates that the wireless communication module can achieve a transmission distance of up to 10 kilometers, whether in open land environments or at sea.

Data synchronization testing entailed statistical analysis of the phase difference error in the full-wave Fourier components of current after synchronization from all four directions over a two-hour duration. The test results are listed in Table 3.

TABLE 3. Data synchronization test results.

Test mode	Angle range	Description (statistical duration of 2h)
Four-side device optical fiber interconnection	-0.9°~+0.9°	Reflect fiber channel
Four-side device wireless interconnection	-1.8°~+2.2°	Reflects wireless channel data

Based on the test results, the phase difference among multiple terminals after synchronization is less than 3°. This level of accuracy is comparable to the results achieved through fiber optic communication, demonstrating the successful fulfillment of the technical requirements for data synchronization in differential protection.

The traditional method for protecting collection lines is based on the principle of overcurrent protection, which has an action time of hundreds of milliseconds, usually up to 200ms. With the development of new energy, it can no longer meet the demand for quick action and does not have absolute selectivity. Collection lines usually require a protection action time of less than 50ms. The comparison of protection action time is shown in Fig. 11.

According to the experimental results, compared to traditional overcurrent protection, this method has absolute selectivity while ensuring reliability, and significantly reduces fault isolation time, meeting the requirements of the collection line for protection action time.

VII. CONCLUSION

This paper proposes a multi-terminal differential protection method for offshore wind farm collection lines based on self-organizing network communication. The main findings are as follows:

1) A multi-terminal data synchronization technology suitable for wireless self-organizing network communication is developed. It uses real-time measurement and dynamic compensation schemes to achieve a synchronization error of less than 3°. The typical delay for wireless self-organizing network communication is less than 12ms, and the action time for multi-terminal differential protection is less than 40ms.

2) A zone differentiation protection technique based on wireless self-organizing network communication is proposed. It consists of large zone differential protection, which detects faults within the zone, and small zone differential protection, which identifies the fault segment. Furthermore, a fault isolation and recovery scheme for non-faulty segments of the collection line is established. This enables minimal fault isolation and precise fault segment localization for the offshore wind farm collection lines.

Experimental verification confirmed that all technical indicators satisfy the requirements for engineering applications, and have significant potential for further dissemination and implementation.

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