Research on Time Synchronization Technology for Wide-Area Measurement in the Distribution Network

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Abstract—This paper presents a novel hybrid time synchronization architecture for the distribution network with limited communication resources. Firstly, the synchronization architecture is based on the Wireless Networks for Industrial Automation (WIA) and IEEE-1588 protocols. Based on this architecture, the time synchronization problem of the entire network for the large scale deployment of PMU in complex distribution network can be solved. Furthermore, focusing on the wide-area measurement demand of distribution network, a time synchronization mechanism for WIA wireless network is designed, and then the composition and operation principle of the WIA-and-IEEE-1588-based hybrid time synchronization architecture is introduced. The experimental results have verified the feasibility of the scheme.

Keywords—distribution network; wide-area measurement; time synchronization; WIA; hybrid network

I. INTRODUCTION

With the development of distributed generation and electric vehicles, the problem of controllability and observability in distribution network is more prominent [1]. The wide-area measurement technology of distribution network based on PMU (Phasor Measurement Unit) is an important way to improve the measurability of distribution network, and has great significance for the construction of smart distribution network [2].

At present, the time synchronization of PMU is achieved by combining GPS and IEEE-1588 [3]. However, because of the complexity of the network structure, the difference of regional environments, the numerous and dispersed nodes, and limited fiber coverage in the operation of the distribution network environment, there is few nodes that can take advantage of IEEE-1588 to realize the time synchronization. Meanwhile, the signal stability is hard to be guaranteed in using GPS to realize synchronization [4]. So, it is impossible to achieve the time synchronization by using existing technologies, which seriously affects the large-scale deployment of PMU in the distribution network, and further hinders the improvement of observability in distribution network [5].

According to the actual operating environment of distribution network, this paper proposes a type of hybrid network time synchronization architecture by combining wired IEEE-1588 and wireless WIA (Wireless Networks for Industrial Automation) technologies firstly, and further details the components and functions of each unit. This scheme makes full use of the characteristic of high precision time synchronization in WIA wireless technology Moreover, with fiber Ethernet, it effectively solves the PMU timing synchronization problem in the region that fiber layout is difficulty and GPS signal is unstable.

II. HYBRID NETWORK TIME SYNCHRONIZATION ARCHITECTURE BASED ON WIA AND IEEE-1588

The hybrid network time synchronization architecture by combining wired IEEE-1588 and wireless WIA is shown in Fig.1. It includes the time synchronization management unit, WIA gateway, WIA time synchronization module and IEEE-1588 slave clock module.
Because of the characteristics of the operation environment of distribution network, there are a lot of scattered PMU nodes distributed in the areas without fiber coverage. Therefore, it is very difficult to realize the full coverage of fiber ethernet. In the system architecture proposed in this article, the traditional IEEE-1588 technology is used to realize the time synchronization in the area covered by fiber. As the main clock source, the time synchronization management unit, with GPS and local atomic clock timekeeping ability, obtains the timing signal from GPS, and then converts it into the time synchronization information in conforming the IEEE-1588 protocol, At last, it synchronizes with the IEEE-1588 slave clock modules in the network through the fiber Ethernet.

In the area without fiber coverage, the WIA wireless network is used to realize the time synchronization. The WIA gateway is installed in the fiber coverage area with embedded IEEE-1588 slave clock module. It gets the time synchronization information that conforms to the IEEE-1588 protocol from the time synchronization management unit, and then converts it into the reference synchronous clock source of the WIA wireless network. The synchronization of the WIA wireless network is achieved by using the WIA synchronization modules.

III. DESIGN OF SYNCHRONIZED MECHANISM FOR WIA NETWORK

WIA technology is a high real-time and high reliable wireless communication technology in industrial automation [6]. Aiming at the unique communication environment of distribution network, a variety of mechanisms are designed to ensure the accuracy of network time synchronization.

A. Time synchronization architecture of WIA network

The synchronization algorithm design of wireless sensor networks are generally considered the performance of synchronization accuracy, stability, reliability, rapidity and energy saving [7,8]. In order to meet the requirements of time synchronization in distribution network, this paper proposes a new wireless network synchronization architecture. It utilizes MAC layer timestamp and regression analysis to obtain precise time synchronization. The synchronization stability can be ensured by the operation of the random clock source mechanism. Moreover, it provides a resynchronization mechanism to solve reliable time synchronization in the case of network anomaly. The time synchronization architecture of WIA network is shown in Fig.2.

B. Error correction method based on linear regression model

To further improve the stability of time synchronization, the network eliminates transmission time, access time and receiving time through the MAC layer timestamp. It estimates and compensates the clock drift of node by using the linear regression analysis to improve synchronous precision.

C. Time synchronization method based on random clock source

Reliability is especially important for the time synchronization in the environment with a large number of interferences [9]. Random clock source mechanism selects multiple nodes as the standby clock sources randomly at the same time in current synchronization cycle, and dynamically changes the link information according to the communication situation. The time synchronization doesn’t depend on a single node, so as to ensure the stability of time synchronization.

The implementation of random clock source method is shown in Fig.3:

- The network node gets synchronization packets and checks whether it is available. If it is available, the node will continue the synchronization operation; otherwise, the node will skip the synchronization operation.
- Using linear regression analysis to correct the time.
- Updating the clock source list.
- Determining whether the synchronization operation is completed: if the synchronization operation is completed, the node will broadcast the time information packets to other nodes; otherwise, the
node will continue to get the synchronization information packets.

Figure 3. The flow of method based on random clock source.

D. Resynchronization method

When node enters the status of resynchronization, it will monitor the time packets synchronously and rejoin the network[10]. When the node receives the synchronization packets, it first judges the level of the packets sending node. If the level is less than that of the local node, the time information can be used to synchronize the node. It updates the node time source list at the same time. Because all the nodes at the level that is less than the local level can be used as the resynchronization time source, the nodes can quickly complete the synchronization operation, rejoin the network, and restore the normal network operation.

E. Periodic adaptive time synchronization algorithm

Low power consumption is an important requirement for energy constrained wireless sensor networks [11]. It is also important for distribution network applications. Therefore, a periodically adaptive time synchronization algorithm is proposed, which greatly reduces the demand for energy consumption in synchronization process. The flow of adaptive synchronization is shown in Fig.4. The nodes predict the cumulative error before the new round of synchronization cycle by means of synchronous error prediction mechanism. Then they compensate the error in advance through error compensation mechanism. Therefore, to the mechanism reduces the influence of cumulative error on synchronization accuracy, and is adapted to the synchronization cycle.

IV. SYSTEM HARDWARE DESIGN

A. Time synchronization management unit

The time synchronization management unit, as shown in Fig.5, includes the GPS timing module, rubidium atomic clock time keeping module, IEEE-1588 clock module, processor module and hot backup power module. It receives the GPS timing signal, and calculates the time information for the use of IEEE-1588 clock module. In the case of node failure in receiving the GPS timing signal, the time synchronization signal output by the time synchronization management unit can still maintain high accuracy by rubidium atomic clock. The hot backup power module is used in the case of disconnection of the external power supply to ensure the normal operation of the equipment, and the operation time is not less than 5 hours, the prototype - framework of time synchronization management unit is shown in Fig.6.

The time synchronization management unit is used to receive the timing signal from the GPS, and converts it into to the time synchronization information in conforming to the IEEE-1588 protocol. It synchronizes with the IEEE-1588 slave clock modules in the network through the fiber Ethernet.

Figure 4. The flow of adaptive synchronization periodic.

Figure 5. The composition block diagram of time synchronization management unit.

Figure 6. The prototype picture of time synchronization management unit.
B. WIA gateway

The WIA gateway, as shown in Fig. 7, includes WIA wireless communication module, rubidium atomic clock time keeping module, IEEE-1588 clock module, processor module and hot backup power module. WIA wireless communication module is controlled by processor module. The processor module manages the WIA wireless network to achieve time synchronization. The prototype framework of WIA gateway is shown in Fig. 8.

The WIA gateway is installed in the fiber coverage area. It gets the time synchronization information that conforms to the IEEE-1588 protocol from the time synchronization management unit, and then converts it into the reference synchronous clock source of the WIA wireless network. The synchronization of WIA wireless network is achieved by using the WIA synchronization modules.

C. WIA time synchronization module

The WIA time synchronization module, as shown in Fig. 9, includes WIA wireless communication module, processor module and output interface module. The WIA time synchronization module is connected to the PMU. It synchronizes with the WIA gateway through the wireless network. It converts the time synchronization information obtained from the WIA wireless network into 1PPS (pulse per second) signal to PMU, and realizes time synchronization of no fiber coverage region, the prototype framework of WIA time synchronization module is shown in Fig. 10.

D. IEEE-1588 slave clock module

The IEEE-1588 slave clock module, as shown in Fig. 11, includes IEEE-1588 clock module, processor module and output interface module. The output interface module includes RS232 serial port and TTL level output circuit. It is controlled by the processor module to output the time information in the form of RMC statement and 1PPS pulse signal, the prototype framework of IEEE-1588 slave clock module is shown in Fig. 12.

IEEE-1588 slave clock module is connected to the PMU. It synchronizes with the time synchronization management unit through fiber Ethernet. It converts the time synchronization information obtained from the time synchronization management unit into 1PPS signal to PMU, and realizes time synchronization of the region with fiber coverage.
V. EXPERIMENTAL TEST

In order to verify the feasibility of the scheme, we build the time synchronization accuracy test platform for WIA network based on FPGA. The schematic diagram of the test platform is shown in Fig.13. Each node outputs the inverse operation on the fixed output port at the pre-set logic time \( T \). Because the output ports of each node are connected to the I/O ports of FPGA, the FPGA can immediately capture and record the changing time when the node port output changes. Then the FPGA uploads the data to the host computer for processing and analysis through the USB. Because FPGA has multiple I/Os, we can test the synchronization error of multiple nodes at the same time. This test only needs periodic operation related ports for nodes, without taking up the existing wireless link resources. Moreover, real-time synchronization error monitoring can be carried out.

![Figure 13. The schematic diagram of time synchronization error testing using FPGA.](image)

Fig.14 is the physical picture of the synchronization error test platform. The platform includes WIA gateway, WIA time synchronization modules, FPGA circuit board and host computer. In the figure, the left side is the WIA gateway, the FPGA circuit board and WIA nodes. The output ports of the WIA gateway and nodes are connected to the I/Os of FPGA. The FPGA is connected to the host computer through USB. During the test, the WIA gateway receives the time synchronization signal from the FPGA, and synchronizes with the multiple WIA nodes in the network. Then the output time synchronization signals of the WIA nodes are returned to the FPGA. At last, the host computer analyzes the data and draws the error curves, such as the right screen display in the picture.

![Figure 14. The practical equipments of synchronization error testing platform.](image)

The software interface of error collecting is shown in Fig.15. The figure shows the results of data acquisition for 8 channels synchronization error, and the error acquisition period is 20ms. Hence, the error situation in the synchronization execution process can be tracked and analyzed in the software. Similarly, if we need to analyze long time historical data, we can further analyze it by data recording.

![Figure 15. real-time display of error collecting.](image)

Fig.16 shows the test results of 4 nodes running continuously for 12 hours. It can be seen from the diagram that the error fluctuation of the 4 nodes is relatively stable, and the accuracy of the average synchronization error remains below 5us, which can meet the application requirements of the distribution network state estimation. The experimental results verify the correctness of the designed algorithm in this paper.
In the laboratory, we also test the synchronization accuracy of three different wireless networks, i.e., ZigBee, WIFI, and WIA. The same synchronization time source is used in different networks. The nodes in these three networks run for 12 hours at the same time, and the synchronization accuracy data is collected every hour. As shown in Fig.17, the synchronization accuracy of ZigBee, WIFI, and WIA are about 100us, 50us, and 5us, respectively. It reveals a much higher synchronization for WIA than that of the other two networks.

VI. CONCLUSION

Since the operational environment of the distribution network is complex, and deployed points are numerous and scattered, not all nodes can realize time synchronization through a wired network. So, the time synchronization problem is the main bottleneck that restricts the large-scale application of PMU in distribution networks. In this paper, we use WIA wireless network to achieve time synchronization of scattered PMU nodes, which is a flexible supplement to IEEE-1588 technology. The integration of wired and wireless technologies can effectively solve the problem of time synchronization for large-scale deployment of PMU in the complex distribution network. The scheme is low cost and easy to deploy, and has a good application prospect.

However, there are still various types of challenges in improving the synchronization precision of wireless network. So we still need further study on the time synchronization algorithm of wireless networks.

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