Research on Intelligent Substation Redundant Communication Network Based on AFDX

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Abstract - The intelligent substation is an important part of smart grid and the reliability and real-time of intelligent substation communication network is essential for its stable operation. This paper proposes a new redundant communication network structure based on AFDX in the typical terminal substation and elaborates the reliability and real-time theory of this redundant communication network. The SKRM redundancy algorithm was applied to ensure the reliability of the network communication. Besides, based on OPNET 14.5, simulation is conducted to prove the effectiveness of the redundancy algorithm and network delay calculation results. The simulation results show that the redundant communication network based on AFDX scheme can meet the requirements of IEC61850 on intelligent substation communication network.

Keywords - AFDX, Dual-star network, SKRM, Real-time, OPNET simulation

1. Introduction

As an international substation communication standard, IEC61850 has gained wide recognition and application [1]. However, IEC61850 doesn’t propose specific network topology requirements of the redundant communication system. As a result, many manufacturers have proposed their own private redundancy network solutions with incompatible defect, which doesn’t be comply with the demand for openness and compatibility of IEC61850. So far, a complete set of redundant communication network system in compliance with IEC61850 hasn’t been proposed.

AFDX (Avionics Full Duplex Switched Ethernet) is a deterministic network of high reliability and hard real-time, which has been successfully applied on the A380 and got widely recognized in the field of aviation [2]. The perfect virtual link scheduling, traffic shaping and redundancy management mechanism of AFDX technology can meet the requirements of the redundancy communication network of intelligent substation. According to the typical terminal substation network structure, this paper proposes a complete set of redundant networking scheme based on AFDX. Besides, some key technologies in the network are verified by simulation.

2. Analysis on redundant communication networking in the intelligent substation based on AFDX

A. Network architecture of typical terminal substation

A terminal substation is illustrated in Fig. 1.

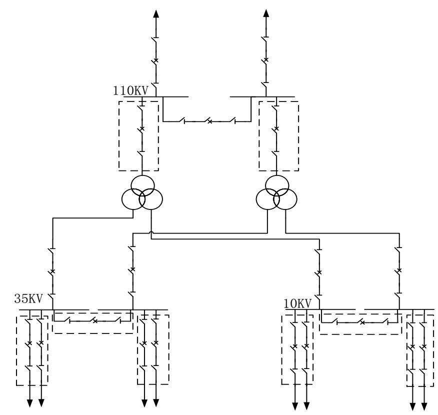

Fig. 1. The main connection of a terminal substation

As it is showed in Fig. 1, the substation has a total of 12 bays, including two transformer bays, four feeder bays and one bus bay for 35KV outgoing lines, four feeder bays and one bus bay for 10KV outgoing lines.

The bay is used to realize the function of signal acquisition, protection, monitoring and control. According to the different functional requirements, each bay contains a different number of IEDs (Intelligent Electronic Device). In the substation, each transformer bay contains one MU (Merging Unit), two P&CUs (Protection and Control Unit), two CBs (Circuit Breaker). Similarly, there are two CBs, one MU, one P&CU in each feeder bay and one CB, one MU, one P&CU in each bus bay.

B. Network structure of AFDX

A typical AFDX network system consists of three parts, including an ES (Ending System), an electronic subsystem and an AFDX Switch. The ES is the interface of AFDX Switch and electronic subsystem. Also, the checksum and management of network data is executed in ES. A simple AFDX network system is illustrated in Fig. 2.

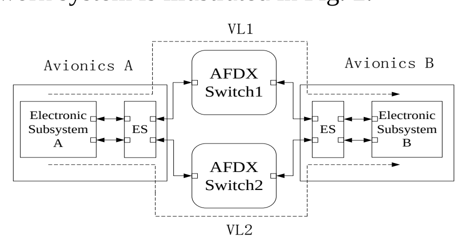

Fig. 2. A simple AFDX network system

The simple AFDX network system has two separate redundant switch network. One is consist of avionics A, AFDX Switch1 and avionics B. The other one is consist of avionics A, AFDX Switch2 and avionics B. A virtual link is a unidirectional data channel between two end systems. The essence of virtual link is the time division multiplexing of bandwidth. When data transmitting, data frame from Electronic Subsystem will be copied in the ES firstly. Then, two of the same data frame will be sent out in the two separate redundant switch network. At last, the ES in the receiving terminal will pick out one of the two data frame and discard the other one based on the redundancy algorithm.

C. Dual-star redundant communication network structure based on AFDX

The communication network topology in substation can be classified into three kinds of star network, ring network and bus network. Taking into issues such as cost, reliability and delay account, we find that dual-star network is most appropriate for substation [3-6].

Each bay unit is equipped with a single AFDX slave switch as the central node. Each IED contains an internal ES, and the IEDs and switches are connected via optical fiber. Also, the host switches and slave switches are connected with optical fiber. The network structure of this scheme is illustrated as Fig. 3.

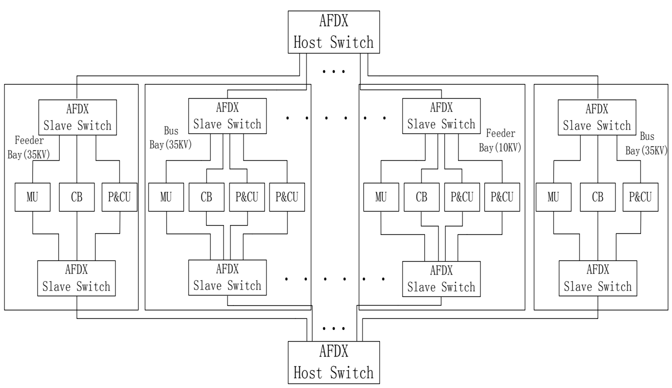

Fig. 3. Dual-star redundant communication network scheme based on AFDX

3. Redundancy control and simulation analysis of substation communication network based on AFDX

A. AFDX redundancy algorithm

(1) AFDX date frame

As the data in AFDX will transmit through the two isolate redundancy network, the ES of receiving terminal will get the same two data. In order to distribute the data from the two networks, a data segment of 1-byte (SN) is added in AFDX data frame as showed in Fig. 4.

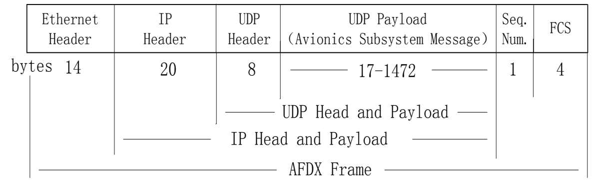

Fig. 4. The structure of AFDX frame

The range of SN is from 1 to 255, 0 is reserved for the reset of ES. The SN will add one when one date is transmitted, as it goes to 255, it will back to 1.

(2) SKRM

Reference [7] put forward 13 redundancy algorithms through deep analyzing on AFDX network. The article will introduce SKRM which is commonly accepted.

The SKRM algorithm is illustrated in Fig. 5. SN represents the sequence number of the frame that just reached, while PSN represents the frame that ES saved currently. Considering that frames dropping event may occur during data transmission, SkewMax is introduced, which represents the longest delay time that ES can wait for redundant frames. The SKEW event indicates that the time ES waits for the redundant frame have exceeded SkewMax, so the ES will join the currently received frame into the queue automatically.

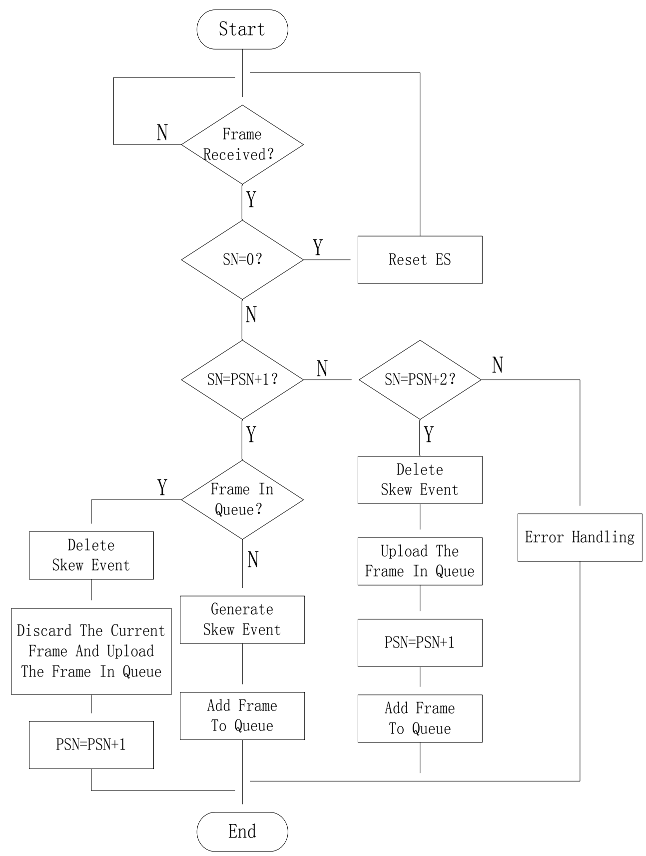

Fig. 5. SKRM redundancy algorithm

B. Simulation module of the redundant communication network

According to the network scheme above, the simulation is launched on OPNET 14.5.The IEDs in the same bay are placed in a subnet model. Then a simulation model of the entire redundant network is created as Fig. 6 shows.

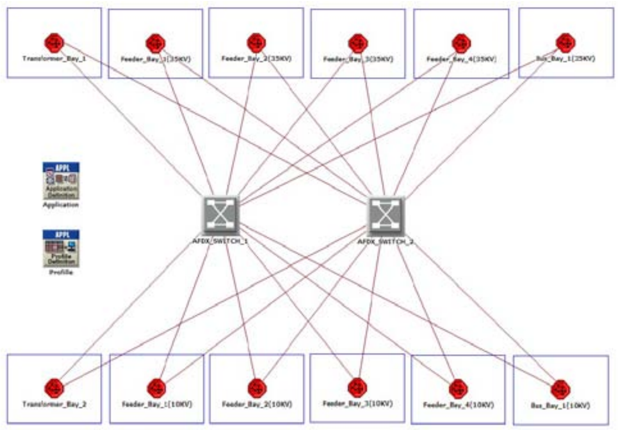

Fig. 6. Redundant network module

C. Simulation results and analysis of SKRM redundancy algorithm

Assumed that a circuit error happens in the feeder bay of 35KV, a Trip message will be transmitted from P&CU to CB. Running the simulation and we can obtain the results of link utilizations in CB as shown in Fig. 7.

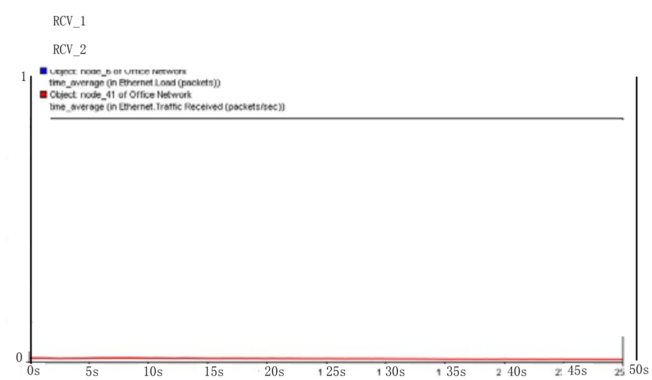

Fig. 7. Simulation result of link utilization in CB

Seen from Fig.7, one link utilization of the CB receiving interface (RCV_1) is close to 1(shown in blue line), while the other one (RCV_2) is close to 0 (shown in red line). The result indicates that CB accepts the data frame from one of the redundant network and discards the data frame from the other one according to SKRM algorithm. Therefore, we can conclude that SKRM meets the needs of redundant communication in substation.

4. Real-time analysis and OPNET simulation of redundant communication network for substation

A. Real-time principle of AFDX

(1) Virtual link mechanism of AFDX

The data transmission in AFDX network is realized by virtual link. Virtual links are distributed and established by the global system before communication, and disappeared after communication [8].

In order to ensure the real-time and reliability of the data transmission in the network, the ES of AFDX processes the data by traffic shaping and virtual link scheduling. The mechanism of virtual link is shown in Figure 8.

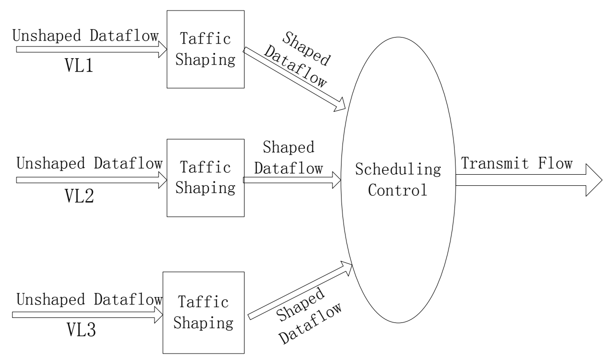

Fig.8. The traffic control of ES

(2) Traffic shaping

The traffic shaping configures two important parameters of virtual link, that's bandwidth allocation gap (BAG) and maximum frame length (L_{max}). BAG defines the minimum time gap of two adjacent data frames in the same virtual link, and L_{max} defines the allowable maximum length of data frame in the virtual link. The maximum transfer rate of virtual link (V_{max}) is determined by the two parameters as it is showed in the following Formula.

$$V_{max} = \frac{L_{max} \times 8}{BAG \times 10^{-3}} \qquad (1)$$

(3) Virtual link scheduling

The actual bandwidth of physical link (NBW) in the AFDX network is generally 100Mbit/s. However, one physical link is usually shared by multiple virtual links. Virtual link scheduling integrates multiple virtual links into one physical link. When multiple virtual links are to be scheduled, the data transmission time of some virtual link will lag, and the delay time is defined by JITTER. In order to ensure the real-time of AFDX network, a maximum limit value of JITTER is defined as MAX_JITTER, which can be expressed in the following formula:

$$\text{MAX\_JITTER} \le 40us + \frac{\sum_{i=1}^{n}(20 + L_{max}^{i}) \times 8}{\text{NBW}} \le 500us \qquad (2)$$

Through virtual link scheduling, multiple virtual links will be integrated into one data stream to make full use of bandwidth. If the priority sorting algorithm is used at the same time, the virtual link scheduling can also guarantees the secure transmission of important data to improve the reliability of the system.

B. *Real-time analysis of redundant communication network scheme*

Messages can be classified into seven categories according to IEC61850, IEC 61850 also specifies the maximum delay time of these messages [9]. Aiming at the kind of fast message with highest delay requirement (delay of 3ms), this paper chooses the most typical tripping GOOSE message and status GOOSE message to analyze the real-time performance of the redundant communication network scheme. The configurations of tripping GOOSE message and status GOOSE message are illustrated in table 1.

Table 1 Attributes of message

Message	L_{max} **(Byte)**	**BAG (ms)**	**VL quantity**
Trip	130	0,1,2…	10
State GOOSE	100	20	10

According to the ARINC664 part 7 agreements [10], the technical delay constraints of various parts of AFDX network are shown as follows:

1) The transmitting delay of ES:

$$D_s < 150us + T_{m1} \quad (3)$$

2) The receiving delay of ES:

$$D_r < 150us \quad (4)$$

3) The forwarding delay of Switch:

$$D_{sw} < 100us + T_{m2} \quad (5)$$

4) $$T_{m1} \approx T_{m2} = \frac{(20 + \sum_{i=1}^{n} L_{max}{}^{i}) \times 8}{NBW} \quad (6)$$

In the formulas above, T_{m1} and T_{m2} respectively represents the transfer delay of the ES and the forward delay of switch. State GOOSE message is issued by the CB of 35KV feeder bay, after transferred by three AFDX switches, received by the P&CU of 35KV bus bay. Tripping GOOSE message is issued by the P&CU of 35kV feeder bay, after transferred by one AFDX switches, received by the CB of same bay. Considering that the transfer delay in the physic link is 5us, combined with the former formulas, the delay can be calculated as 0.831ms and 0.668ms, which meet the upper requirements of IEC61850 (3ms).

C. *Real-time simulation*

With the redundant network module in Fig. 6, the real-time simulation is launched on OPNET 14.5. The simulation result is shown in Figure 9.

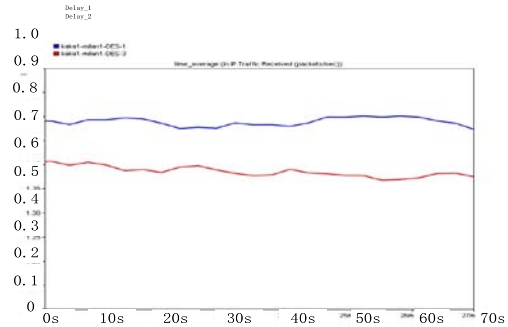

Fig.9. Real-time simulation result

In Figure 8, the unit of ordinate is ms, and the red line represents the delay of tripping GOOSE message, the blue line represents the delay of status GOOSE message. It is clear that the simulation results are basically consistent with the calculated results and meet the requirements of GOOSE packet delay in IEC61850.

5. Conclusion

This paper introduces the mature AFDX technology into the redundant communication network of intelligent substation. Furthermore, it forms a Dual-Star redundant communication network in intelligent substation based on AFDX, and makes theoretical explanations and simulations to some key technologies. The research results show that, the network scheme based on AFDX meets the requirements of IEC61850 for intelligent substation communication network.

Acknowledgment

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