The optimization of networking method for the system protection communication networks based on the delay analysis

Yanan Wang¹, Ke Wang²,¹, Ran Zhang², Geng Zhang¹ and Yang Wang¹

¹ China Electric Power Research Institute, Beijing, 100192, China
² North China Electric Power University, Beijing, 102206, China
*Corresponding author e-mail: happyandluck_wk@163.com

Abstract: The real-time requirements of the data transmission for the power communication systems are very high, and the system protection demands the communication delay more stringent. The consequences of the malfunction or refusal of the grid control system caused by the communication delay are much more serious than those of other communications. Because the grid stability control system involves the entire system, the malfunction or refusal may lead the entire grid to be disassembled or collapsed. A new networking method is proposed based on the analysis of the existing power communication networking technology in this paper. And the delay of this new networking method is analyzed by analyzing the mechanism of the delay generation. So that the adaptability of the new networking method in the system protection communication networks is determined from the delay level. It is intended to provide the reference and guidance for the construction of a high-real-time system protection communication networks.

1. Introduction

According to the communication requirements of the power system, the maximum transmission distance is considered to be 3,000 kilometers (in the region) and 5,000 kilometers (between the regions). The system protection communication network is required to perform the fault defense control on the important disturbances of the power generation, transmission and distribution in the grid within 300ms. The panoramic state monitoring of the DC system is limited to 60ms, and the acquisition and control of the communication delay should be controlled at 50ms. However, as a matter of fact, a medium-sized regional grid stability control system generally spans a prefecture-level city and the large-scale regional security control systems may even involve multiple substations and power plants in a province or more. Therefore, the grid stability control system is more demanding on the delay of communication. Moreover, one data or command at least should be exchanged within 1.667ms in the two stations of the power communication, and the action must be taken after 3 frames of control commands (5ms) are received continuously. Therefore, the malfunction or the delay action of the grid stability control system caused by the delay may lead the entire grid to be disassembled or collapsed. The communication networking method of the system protection communication network needs to have the characteristics as follows: 1) The reliability requirements of the channel are very high; 2) The speed of the channel should be as fast as possible; 3) The delay of each link of the channel should be as small as possible; 4) The channel should have a certain redundancy and
invulnerability; 5) In addition to the normal communication, the channel should be equipped with the corresponding emergency communication method.

2. The networking method of the system protection communication network

2.1. The analysis of the normal networking technology

The power communication system is based on the collection and transmission of the multi-point information. And the strict requirements for the real-time and reliability of the communication depend on the development of the modern communication technology. The favorable opportunity and technical support for the construction of the grid system protection communication network is provided by the wide application and development of the SDH, OTN, PTN and IP switching technology in the various communication fields [1]. The network performance of the normal networking technologies is as shown in table 1.

| Networking method | SDH | OTN | PTN | IP Switching |
|-------------------|-----|-----|-----|--------------|
| Multiplexing system | Time division | Wavelength division | Packet division | Packet division |
| Switching characteristics | Time slot exchange | Time slot exchange | Packet switching | Packet switching |
| Channel bandwidth | ≥10G | ≥40G | ≥10G | ≥40G |
| Business reliability | Channel protection | Channel protection | Channel protection | Channel protection |
| Bandwidth particle | 2M particles | 1G particles | Arbitrary particles | Arbitrary particles |
| Delay | Satisfied | Satisfied | Partially satisfied | Partially satisfied |
| Delay consistency | Good | General | General | General |
| Frequency synchronization | Support | Support | Partial support | Partial support |
| Time synchronization | Optional | Optional | Support | Support |
| Multicast | Limited support | Limited support | Support | Support |
| Safety | High | High | Poor | Poor |

It can be seen from the performance comparison of the networking technologies in table 1 that the SDH networking method can meet the reliability requirements of the system protection service, but it also has the disadvantage of poor scalability and the insufficient bandwidth at the branch node and root node [2]. The OTN networking method meets the system protection service requirements, while its cost performance is relatively low based on the delay and uncontrollability which are caused by the system conversion. The PTN networking method also meets the system protection service requirements with the characteristics of small overall delay but uncontrollable, the access network and the transmission network are well connected, but the information security does not meet the requirements. The performance of the IP data network can meet the bandwidth and other requirements, while it has the risk of the uncontrollable delay, and its security also needs a certain protection. In
addition to the above normal networking technologies, the dispatching data network of the State Grid, as a dedicated data network for the power dispatching production services, is also the basis for the grid dispatching automation and the management modernization and the important means for ensuring the safe, stable and economic operation of the power grid. However, since there are many services carried on the dispatching data network, the greater risks will be brought if the system protection service is still carried on this network. And the topology of the dispatching data network will also have a greater impact on the delay at the same time.

At present, the existing stable control protection system is mainly carried on the E1/2M dedicated line, and the PMU/WAMS system is mainly carried in the dispatching data network. An effective local communication networking method is proposed in this paper named SDH+EOS networking method by combining the advantages and disadvantages of the above five networking technologies with the requirements of the system protection services to realize the integration of measurement and control of the two mentioned above.

2.2. SDH+EOS networking technology

The normal wide-area stability control is carried on the 2M dedicated line service. And the dedicated line service can be considered to expand to the service of supporting 10M bandwidth to meet the needs of the system protection communication network. Since the substation uses the optical fiber or 100M Ethernet for data transmission, the expansion of the interface bandwidth can be learned from the method of SDH/MSTP. The EOS (Ethernet over SDH) access mode provided by the MSTP equipment is used, and the router or switch adopts the interface of the Ethernet directly. The MSTP is interconnected by the common RJ45 (10/100BaseT) interface which can save the cost of the optical port interconnection greatly, and the end-to-end service management can be realized through the unified network management of MSTP [3]. The MSTP device featuring the EOS (Ethernet Over SDH) technology can form a point-to-point dedicated line based on the transmission equipment, and enter the network in the form of a dedicated "pipe" in different granularities such as STM-1 and STM-4, which conforms the real-time and wide-area local communication scenario. Each layer of the three-layer power communication network is divided into two layers of the main station and substation in this networking method, the status information in the substation acquisition system is transmitted to the main station, and the main station transmits the control commands to the substation. Taking the integration of measurement and control of the system protection communication network into consideration, the internal communication mode of the substation is shown in figure 1.

![Figure 1. The networking method of the SDH+EOS in the substation](image)

The substation includes a multi-channel PMU device and a multi-channel stability control device in the networking method. The optical fiber signal of the stability control device is mapped to the
photoelectric conversion and proprietary protocols by the protocol gateway, and then the data is connected to the conversion router through the Ethernet, while the data of the PMU device is directly connected to the conversion router through the Ethernet. The conversion router converts the 2M signal of the stability control device into the data of E1, and then combines the Ethernet signal of the PMU to the SDH device, finally the data is packaged into the SDH device through the EOS technology of the MSTP, and transmitted to the main station through the distribution frame.

As is shown in figure 2, there is a corresponding networking method inside the main station.

![Figure 2. The networking method of the SDH+EOS in the main station](image)

The communication process in the main station is the inverse process of that in the substation. The stability control device and the WAMS system send the control information to each substation and collect the wide-area measurement data from the PMU of them. There is the information interaction between the WAMS system and the stability control device to achieve the real-time decision for the stable control.

The internal communication mode of the substation and the main station are shown above. The wide-area communication networking architecture between the stations should be considered to achieve the wide-area communication. The communication networking method in the wide area is shown in figure 3.

![Figure 3. The wide-area networking architecture of SDH+EOS](image)

According to the level of the communication architecture, it can be divided into three layers of the communication network which is in the local area, in the region and between the regions. The figure
above shows an inter-domain transmission network consisting of two regional transmission networks, each of which contains two local transmission networks. The main station of the local transmission network communicates with its substation while also interacting with the substation of the regional transmission network. Similarly, the main station of the regional transmission network communicates with its substation and the substation of the inter-domain transmission network meanwhile. The local transmission network mainly uses 10G SDH/MSTP/ASON for networking, and inter-station transmission can select the OTN and other methods. The regional transmission network and the inter-domain transmission network can also be networked by using the OTN.

This networking mode is characterized by the exclusive channel, controllable delay and high security.

The method of the architecture above is feasible. The adaptability of the SDH+EOS networking will be analyzed and verified by using the main factor named delay which affects the network performance in the following.

3. The delay analysis

3.1. The generation mechanism of delay

In the grid communication, the factors which cause the delay are roughly divided into three categories: The delay caused by the transmission channel, the delay generated by the network node and other digital devices and the delay introduced by other factors.

3.1.1. The delay caused by the transmission channel

Both the electrical signal and the optical signal are the electromagnetic wave. And the propagation speed of the electromagnetic wave is limited in a certain transmission medium, which is mainly depended on the refractive index of the medium. For example, the transmission delay \( t_o \) of the optical wave signal passing through the optical fiber can be expressed as follows:

\[
t_o = L \times \frac{n}{c}
\]

(1)

In equation (1), \( c \) is the speed of light in vacuum \((3 \times 10^5 \text{ km/s})\), \( L \) represents the transmission distance \((\text{km})\), the index of refraction of the fiber core is expressed as \( n \) with the typical value \( 1.48 \). Then it can be calculated that the transmission delay of the optical signal in the optical fiber is approximately 4.93 \( \mu \text{s} \) per kilometer.

3.1.2. The delay generated by the network node and other digital devices

In a digital connection, the network node devices such as digital switches, digital cross-connect devices, buffers, time slot switching units, and other digital processing devices generate transmission delays in addition to the delay caused by the transmission system. Furthermore, PCM terminals, multiplexers and multiplex converters also produce varying degrees of delay.

3.1.3. The delay introduced by other factors

New technologies are emerging in the field of the optical fiber communication, and the introduction of them may decrease or increase the delay which is depended on its working mechanism. For example, the SDH technology can increase the transmission delay by completing the synchronous multiplexing, mapping, positioning, various types of the overhead processing, pointer adjustment and connection processing. In addition, the changes in the network structure, the quality of the installation and construction can also affect the transmission delay \([4]\).

The delay factors caused by the different transmission modes are different in general. Specifically, it is mainly composed of a terminal SDH device, a network node device, and a fiber channel and the like. The typical delay values are shown in table 2.
Table 2. The composition of the transmission delay

| Device            | Terminal SDH/μs | Network node /μs | Optical fiber /μs |
|-------------------|-----------------|------------------|-------------------|
| Private channel   | NO              | NO               | 4.93              |
| Multiplex channel | 64K             | 10–60            | 20–125            | 4.93              |
| 2M                | 10–60           | 20–125           | 4.93              |

3.2 The analysis and calculation of the delay

3.2.1. The calculation formula of the determined value delay

Combined with the above analysis of the delay factors, the delay $t$ of the SDH+EOS networking method when transmitting the data can be expressed by equation (2).

$$t = t_{SDH} + n t_i + t_O$$  \hspace{1cm} (2)

In equation (2), $t_{SDH}$ is the multiplexing and demultiplexing delay of the SDH device, $n$ represents the total number of the intermediate node device. $t_i$ is the delay of the intermediate node device, such as the forwarding delay of the relay node device, the input and output delay, the router processing delay, the photoelectric conversion delay and the service transmission delay. However, the internal structure of the intermediate node is different from that of the terminal SDH device, so the delay generated is also different.

$t_O$ is the delay generated by the fiber transmission channel, and $t_O = 4.93L(\text{us})$ [5].

3.2.2. The random delay model

The delay value of the calculation model listed in equation (2) is calculated based on the determined value. This calculation method is relatively simple and can obtain a typical value that conforms to the actual situation based on a large amount of data, while the randomness of the delay is not considered to describe the probability of the delay value. The delay of the transmission equipment is a random value in a certain range to meet the certain change trend, not a fixed value in the signal transmission of the actual system protection communication network. While the system protection communication network should anticipate these trends and pre-process the places with too long delays as early as possible. Therefore, some parameters in the above equation should be set as the random variables and the probability model should be established to describe the change of the delay more accurately.

Compared with the deterministic calculations, the random delay model has the following advantages:

(1) The trend of delay can be described more accurately.

(2) The delay value calculated by the random delay model is more general and more consistent with the actual situation.

(3) The probability of the refusal or malfunction of the system protection device can be estimated roughly by establishing a random delay model. On the contrary, the maximum number of the nodes allowed in the network is derived from the national delay standard.

According to the typical values of the device delay and the actual data measured in the paper, it is found that the delay of the protection transmission delay in the system protection communication network has the following characteristics:

(1) The device delay value is concentrated in a certain time interval.

(2) The line delay is relatively fixed, while the device delay is mostly close to the typical value with a normal distribution.

(3) The impact of the delay of each part of the transmission channel on the total delay is different.

Based on the above reasons, $t_{SDH}$ and $t_i$ are random variables which are represented by $T_{SDH}$ and $T_i$ respectively in equation (2). The above random variables obey the Uniform distribution and the normal distribution respectively, and the distribution parameters are set as shown in table 2. The
The variance of the random variables is used as a variable to substitute the different values for the comparison calculation in the subsequent calculation [6].

The probability distribution expression is difficult to be derived by the mathematical modeling because of the large number of random variables. Therefore, the MATLAB simulation method is selected to study the random distribution characteristics of the total delay more intuitively.

1000000 random numbers obeying the uniform distribution or the normal distribution were generated by MATLAB based on the parameters listed in table 2, and 1000000 samples were taken as the random delay samples. According to the delay calculation formula, the total delay was calculated by the random delay to obtain a sample space composed of 1000000 total delay values. The probability density function of the total delay can be obtained by the ecdfhist function of MATLAB and the cumulative probability distribution function can be obtained by ecdf.

The degree of dispersion of a data set can be reflected by the standard deviation. The same average does not mean that the standard deviation is the same. The extent to which the delay value deviates from the mean is reflected by the magnitude of the standard deviation when the random variable obeys the normal distribution. As is shown in figure 4, the probability distribution curves with different delays can be got by setting the different standard deviations.

![Figure 4](image)

Figure 4. The effect of standard deviation on distribution during the normal distribution

As can be seen from figure 4, the larger the standard deviation is, the steeper the cumulative probability distribution curve is, and the smaller the variation range of the total delay is when the random delay satisfies the normal distribution. The standard deviation in the subsequent simulation delay is taken as 5 to facilitate the study [7].

L is equal to 40, 60, 80, 100, and 120 km, respectively, the number of the network nodes N is 10. The result of the program is shown in figure5.
Figure 5. The effect of the change of $L$ on the probability distribution of delay

As can be seen from figure 5, the five curves are the probability cumulative distribution function from left to right respectively for $L=40, 60, 80, 100, \text{ and } 120$. The transmission delay gradually increases as the transmission distance increases. When the transmission distance is 120 km, the maximum delay is no more than 7 ms which is much less than the standard 15 ms. When comparing the two types of transmission channels which obey the uniform distribution and the normal distribution respectively, it can be seen that the maximum delay of the random delay which obeys the normal distribution is slightly smaller than that of the uniform distribution. And the change extent of the total delay is greater as the transmission distance increases.

The number $N$ of the network nodes is equal to 10, 15, 20, 25, 30, respectively, $L = 100$ km. The result of the program is shown in figure 6.
Figure 6. The effect of the change of N on the probability distribution of delay

As can be seen from Figure 6, the five curves are the probability cumulative distribution function from left to right respectively for N=10, 15, 20, 25, and 30. The transmission delay gradually increases as the number of the network nodes increases. When the network node is 30, the maximum delay is no more than 10 ms which is much less than the standard 15 ms. Similar to the case of the change of L, the maximum delay of the random delay which obeys the normal distribution is slightly smaller than that of the uniform distribution.

The following conclusions can be drawn referring to figure 4, figure 5 and figure 6.

1) The standard deviation has a certain influence on the distribution of the total delay when the random delay satisfies the normal distribution. Therefore, the effect of the variation range of each device delay on the total delay cannot be ignored.

2) It can be seen from the cumulative distribution curve that the curve is steeper in the case of obeying the normal distribution which shows that the value of the delay is more concentrated under the normal distribution. Meanwhile, the value of the delay under the normal distribution is smaller than that under the uniform distribution, and the maximum delay is smaller [8].

3) The increase or decrease of the number of network nodes has a greater impact on the total transmission delay compared with the transmission distance. Therefore, the number of the network nodes should be fully considered to avoid the excessive delay due to the excessive network nodes in the actual networking.

4) Due to the delay generated by the PCM device in the 64k interface accounts for a large proportion of the entire channel delay, the total delay of the 64k interface is greater than that of the 2M interface while regardless of the distribution of the random delay. Therefore, the intermediate link should be avoided to transfer at 64kbps to reduce the total channel delay [9].
4. The SDH+EOS networking technology delay analysis

With the above analysis of the determination of delay and random delay, the delay of the commonly used power communication equipment is investigated. The delay of each equipment is as follows:

1. The relay node device needs to forward each hop for 7 μs.
2. The router processing time (including the forwarding time) is 100 μs.
3. The time of the router packages the SDH is 150 μs.
4. The transmission time from the access device to the transmission device is 100 μs.
5. The time for transmitting information from the upper to lower service station is 150 μs.
6. The photoelectric conversion time of the router is 150 μs, FEC + dispersion + transmission delay plus 10% of the time.

The processing delay based on the SDH+EOS networking is

\[ 150 + 2 \times (150 \times 110\%) + n \times [7 + 2 \times (150 \times 110\%) + 100 + 150 + 100] + 4.93L = 150 + 330 + 687n + 4.93L \]

by using the equation (2) and the random delay model to assume that there are n hops in the topology.

According to the communication requirements between the regions in the power system, the maximum transmission distance is considered to be 3,000 kilometers (in the region) and 5,000 kilometers (between the regions). It is assumed that the maximum transmission distance in the region is 3,000 km, and the transmission delay of the optical fiber on the entire link is about 14790 us by equation (1). And because the communication delay requirement of the wide-area security and stability control system is not higher than 50 ms, then \((480 + 687n) + 14790 \leq 50\). The solution is \(n \leq 50\), that is, the maximum hop count allowed in the region is 50 hops. Assuming that the maximum transmission distance between the regions is 5000 km, similarly, the maximum number of the hops allowed between the regions is 36 hops. Therefore, the networking method of SDH+EOS satisfies the high real-time requirement of the system protection communication network as long as the hop count does not exceed the above two values in the case of satisfying the maximum transmission distance.

5. Conclusion

The main functions of the system protection include the AC/DC cooperative control, the disconnect control, the separation control, the precise load shedding and the panoramic state sensing. The current communication network is difficult to meet the high-speed and high-real-time requirements of the above-mentioned acquisition and control information. Therefore, a new networking method is proposed based on the analysis of the existing networking technology of the power system in this paper. Then the mechanism of the communication delay is introduced in detail and the adaptability of the SDH+EOS networking is verified based on the advantages and disadvantages of the delay performance. The final result shows that the new networking method has a better network performance than the existing networking method as long as the number of the nodes (hop count) in the communication network does not exceed a certain limit value (50 hops within the region, 36 hops between the regions) when the system protection communication network is in the case of the maximum transmission distance. It can meet the need for the long distance transmission of the system protection communication network.

Acknowledgments

This paper was supported by the science and technology project from State Grid Corporation of China: “Research on Distributed Simulation and optimization technology of optical transmission network for Electric power communication(5442XX180003-XX71-18-006)”

References

[1] Cao N., LI G., Wang D Q.(2011) Key technologies and construction methods of smart substation, Power System Protection and Control, 39:63-68

[2] Zhang Q H,Mu C F,Lu J Y,Liu S.(2016) Research on Construction of Provincial Communication Network for Power Communication, Digital technology and application, 34:45-47
[3] Wang Z Q, Liu W X, Fan Y F, Liu N, (2008) A Reliability Study Framework for Wide Area Measurement System, Automation of Electric Power Systems, 32:25-29

[4] Chen W Q, Ma Q F, Zhao J L, (2011) Research on the reliability evaluation of Power optical fiber transmission network, Telecommunications for Electric Power System, 32:11-15

[5] Wu Y M, Ding J J, He X X, (2016) Secure consensus control for multi-agent systems under communication delay, Control Theory & Applications, 33:1040-1045

[6] Yang B, Wei L P, Zhan Z B, (2015) Analysis on Characteristics of Communication Delay in Wide Area Measurement System Based on Probability Distribution, Automation of Electric Power Systems, 39:28-55

[7] Liu J, Li D Q, (2013) Distributed Subgradient Method for Multi-Agent Optimization with Communication Delays, Journal of Hefei University of Technology, 36:559-565

[8] Liu X L, Xu B G, (2012) Distributed H∞ consensus control for multiple-agent systems with communication delays, Control and Decision, 27:494-500

[9] Liu C L, Tian Y P, (2009) Survey on consensus problem of multagent systems with time delays, Control and Decision, 24:1601-1609