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RESEARCH ARTICLE

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Simulation study on delay of end-to-end data communication for protective relaying in substations

Abstract The end-to-end delay of protective relaying data flow in a substation was studied by dynamic simulation modeling technology. The distribution characteristics of protective relaying data flow and the constitution of the end-to-end delay of messages were analyzed. The simulation model for digital communication between protective relaying equipment and monitoring equipment of interval layer was suggested. The end-to-end delay of protective relaying data flow in different network configurations was analyzed. It is found that the size and interval of the data frame, utilization of the link background and protocols of higher layer are key factors of real-time performance. Detailed analysis results are presented. A proposal for network configuration is suggested to reduce end-to-end delay of protective relaying data flow.

Keywords protective relaying, OPNET, network simulation, delay

1 Introduction

Protective relaying equipment plays an important role in substation automation systems. According to communication data flow between protective relaying equipment and monitor equipment, operators in a substation can obtain the states of primary equipment, dispose faults, and send control commands to protective relaying equipment. It requires that the transmission time of data and control commands is less than 4 ms in IEC61850 (communication networks and systems in substations), therefore real time transfer of protective relaying data becomes the key element of substation circulation. Indeed, substations have not realized automation [1], and protective relaying equipment at the interval layer and primary equipment at the process layer are still connected via secondary cable. The data communication which reflects the end-to-end delay of protective relaying data flow is centralized between the station layer and interval layer. However, delay of protective relaying data is more than 4 ms in actual substation circulation, so research on end-to-end delay of protective relaying data is necessary.

Along with the development of network technology, Ethernet technology has been applied to substation automation systems. Researches on real time performance of Ethernet have drawn many scholars' attention, and the feasibility of applying Ethernet to substation communication systems has been validated. Real time performance of embedded Ethernet was analyzed in detail in Ref. [1], and the influence of TCP/IP on the end-to-end delay of message was analyzed simply with no further research. In Ref. [2] real time performance of Ethernet (as station bus) was researched, but the variety of data flow and influence of high layer protocols were not considered. In Ref. [3] real time performance of Ethernet (as process bus) was researched, wherein a proposal for switched Ethernet was suggested to solve real time performance of the message, but the real time performance of the message cannot be always guaranteed by using switched Ethernet. In Ref. [4] conditions, part influence factors and evaluating methods of real time performance were suggested for the message in a substation automation system based on Ethernet, but the analysis results have not been given in detail. Considering high layer protocols and the variety of data flow, much more attention should be paid to whether the end-to-end delay of message based on Ethernet meets the requirement of real time performance in substations. Few researches in this aspect were made in the literature.

Combined with the application actuality of Ethernet and transmission characteristic of protective relaying data flow, the simulation model based on TCP/IP and Ethernet for digital communication between protective relaying equipment of interval layer and monitoring equipment of station layer was made by OPNET [5]. Specific research on end-to-end delay of protective relaying data flow was made with the main influence factors and detailed analysis

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results presented. A proposal for network configuration was suggested to reduce end-to-end delay of protective relaying data flow. The research has reference significance on improving the real time performance for protective relaying data flow.

2 Analysis of protective relaying data flow

The protective relaying data flow in a substation can be divided into three types [4]: periodical data flow, paroxysmal data flow and stochastic data flow.

1) Periodical data flow means on-off status message and analog data transmitted from the protective relaying equipment to local monitors under normal conditions, and it occupies a large percent of protective relaying data flow. Periodical data flow can be sprung on schedule, and the length of the message can be confirmed. Therefore, a model of periodical data flow can be made using messages with definite periodicity and fixed length.

2) The paroxysmal data flow means protective action message and sequence of events recording (SER) uploaded from protective relaying equipment, and it occurs when faults emerge. The percent of paroxysmal data flow in protective relaying data flow depends on fault case. When there is a disturbance, or local small influence occurs, the amount of protective action messages and SER is few, and percent in data flow is low; when there is a great fault, such as system surge, whereby switches trip or much protection operation has to be taken, the amount of protective action message and SER will increase, and along with it the percent of paroxysmal data flow will increase. A model of paroxysmal data flow could be made using messages, whose arrival obeys a Poisson distribution, and the length obeys a normal distribution.

3) The stochastic data flow means on-off operation commands, protective setting modification, transformer tapchanger adjustment, etc. Stochastic data flow is few, which occupies a small percent in protective relaying data flow. Whenever a message group appears with p probability, there is no relationship between a message and the one preceding or following it. Therefore, a model of stochastic data flow could be made by using messages whose arrival obeys a Poisson distribution, and the length is fixed.

3 Analysis of end-to-end delay for networks

The end-to-end delay for networks is measured from the time when an application data packet is sent from the source application layer to the time when it is completely received by the application layer in the destination node. During data transfer, delays may occur at any phase. The delays may consist of the processing delay of the source node for transmission, $t_{sa}+t_{st}+t_{se}$, the processing delay of the destination node for receiving $t_{ra}+t_{rt}+t_{re}$, delay of other digital equipment (switch) t_s and link delay t_l, etc.

$$T=t_{sa}+t_{st}+t_{se}+t_l+t_s+t_{ra}+t_{rt}+t_{re}. \tag{1}$$

The digital network studied in this paper adopts the Ethernet as the bottom protocol, TCP/IP as the network layer and transfer layer protocols respectively. The end-to-end delay model of the network is shown in Fig. 1.

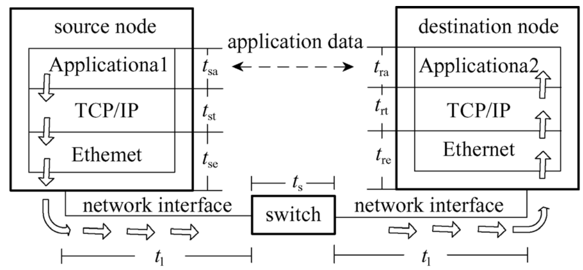

Fig. 1 End-to-end delay of messages

1) The processing delay of the source node is $(t_{sa}+t_{st}+t_{se})$, where t_{sa} means the time needed by the application of the source node when the message is partitioned. t_{sa} is related to the length of original data frames from the source node and the maximum limitation of the data packets in the application layer. t_{st} refers to the time during which a message head for TCP/IP is appended. t_{se} denotes the time during which MAC message head is appended.

2) The processing delay of the destination node is $(t_{ra}+t_{rt}+t_{re})$, where t_{re} means the time needed when MAC message head is removed, t_{rt} refers to the time needed for removing TCP/IP message head, and t_{ra} means the time needed when the application of the source node assembles anew messages.

3) The processing delay of other digital equipment is t_s. It is measured from the time when the message is received to the time when the message is transmitted by switch, and it is related to the transfer strategy and exchanging rate.

4) The transfer delay of the links t_l is measured from the time when the message arrives at the network interface of the source node to the time when the message arrives at the network interface of the destination node (switch delay is not included). It includes queuing delay t_{que}, transmitting delay t_{tra}, and spreading delay t_{pro}:

$$t_l=t_{que}+t_{tra}+t_{pro}. \tag{2}$$

t_{que} is measured from the time when the message queues to the time when it is transmitted. It depends on accessing and controlling methods of the communication network medium. t_{tra} is measured from the time when the source node begins to send the first bit of the message to the time when the last bit is sent. It depends on the length of the message and the transfer rate of data. Let the length of the message be λ B, the transfer rate of data be μ bit/s, consequently the transmitting delay t_{tra} is shown as follows:

$$t_{tra} = \frac{8\lambda}{\mu}. \tag{3}$$

t_{pro} is measured from the time when the source node begins to send the first bit to the time when the last bit is sent. It depends on the transfer distance and propagation. Suppose the transfer distance is l m, and the transmitting rate is v m/s, then the propagation delay t_{pro} is shown as follows:

$$t_{pro} = \frac{1}{v}. \tag{4}$$

4 Modeling and simulation for system

4.1 Establishment of simulation contents and aims

A substation of 220 kV was taken as a case [6]. Simulation models for communication between protective relaying equipment at the interval layer and monitoring equipment at station layer were made using OPNET, but the instrumentation and control equipment was not in the scope of modeling. An analysis of the end-to-end delay of protective relaying data flow was made. The network model that described network topology composed nodes and links. The amount of total nodes in the whole model was 19, including 16 protective relaying equipment at the interval layer, two monitor equipment at the station layer and one switch. The physical topology of the network models took the shape of a star while the logic topology was like a bus. The network topology is shown in Fig. 2.

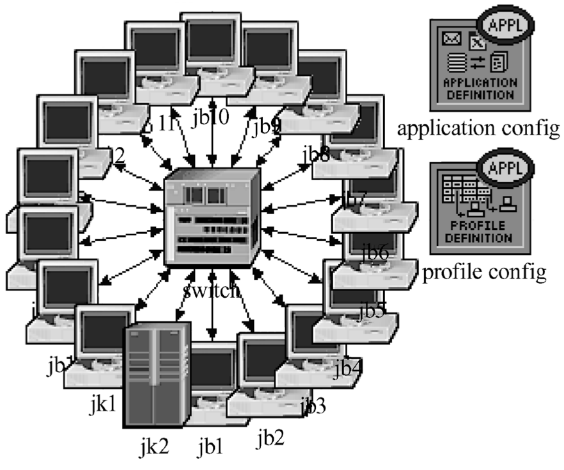

Fig. 2 Communication network simulation model

Each node was connected to the switch by the 10Base-T twisted-pair. Protective equipment sent on-off status messages and analog data periodically to local monitor equipment. The local monitor equipment also sent on-off operation commands and protective setting modification to protective equipment.

The aims of modeling and simulation are shown as follows:

1) Obtain main influence factors of real time performance for protective relaying data flow by network simulation and present analysis results.

2) Analyze the influence of high layer protocol TCP/IP on protective relaying data flow, and consider the influence of high layer protocol on real time performance.

3) Put forward a proposal to reduce the end-to-end delay of protective relaying data flow.

4.2 Analysis of simulation results

After analyzing simulation results, many influence factors of real time performance on the end-to-end delay of protective relaying data flow were presented: size and sending interval of the data frame, background utilization of links, high layer protocols, etc. Some influence curves were given as below.

The end-to-end delay of data frame with different size is shown in Fig. 3.

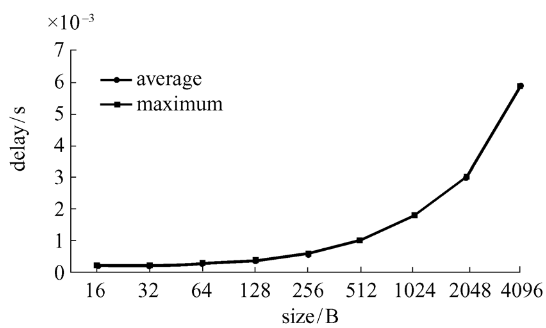

Fig. 3 End-to-end delay of data flow in different sizes

The main parameters for configuration are as follows. The arrival of stochastic data flow obeyed Poisson distribution with parameter $\lambda = 10$, and the length of stochastic data flow was 64 B. The arrival of paroxysmal data flow obeyed a Poisson distribution with parameter $\lambda = 5$, and the length of paroxysmal data flow obeyed a normal distribution with parameter $\mu = 64$ B, $\sigma = 0.01$. The interval of the periodical data flow arrival was 0.02 s. The end-to-end delay of data flow increased with the accretion of the message length. When the message length was fewer than 2 kB, the end-to-end delay was much less than 4 ms, which could meet the time requirement. When the message length increased to 4 kB, the end-to-end delay was just below 6 ms, which could not meet the time requirement. Therefore, under actual network configuration, the message length should be properly limited; for example, the overlong message could be split into multiple short messages.

The end-to-end delay of data frame in different interval is shown in Fig. 4.

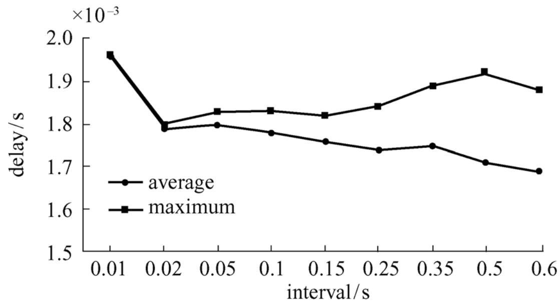

Fig. 4 End-to-end delay of the data flow at different intervals

The main parameters were configured the same as above. Influence of periodical data flow on the end-to-end delay of protective relaying data flow was researched when the sending interval changed. Under the interval of 0.01 s, there was a large data flow in one second, and the delay became very large. The end-to-end delay did not always reduce with the accretion of the interval. The maximum and average of end-to-end delay were not identical. It was related to the time when the stochastic data flow and the paroxysmal data flow engendered. When all kinds of data flow were sent during a short period of time, the data flow would become large, and real time performance would be influenced. Therefore, under actual network configuration, in order to meet time requirement, all kinds of data flow sent at the same time slot should be avoided.

Under the different link background utilization, the delay of the data is shown in Fig. 5.

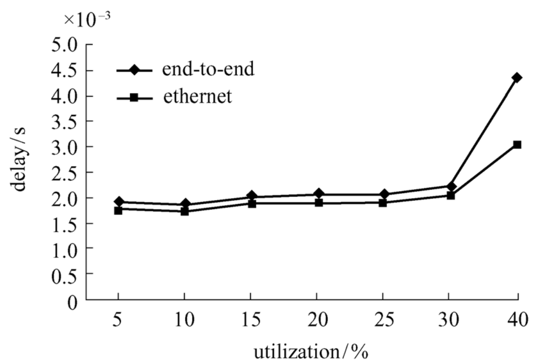

Fig. 5 Delay of different link background utilization status

Other kinds of data flow were recognized as link background utilization. The Ethernet delay and the end-to-end delay of protective relaying data flow increased with the accretion of link background utilization. The end-to-end delay of 40% was already over 4 ms. These could not meet the time requirement. The reason is that the data flow through the station bus increased with the accretion of link background utilization, and the load of the Ethernet was over 37% [7], so that a potential collision reduced the end-to-end delay. These problems could be solved by reducing link background utilization or increasing the bandwidth of the Ethernet. The end-to-end delay was larger than the Ethernet delay. It was caused by encapsulation and un-encapsulation processing time of high layer protocols. The application data of the source node was split and encapsulated with TCP/IP protocol before the transfer. The application data was un-encapsulated and recombined before they arrived at the destination node. These computing processes would spend a few seconds. The time was related to coding and decoding arithmetic of high layer protocols. It was reflected that the high layer protocols had a large influence on the end-to-end delay. In this sense the high layer protocols should be reasonably chosen.

Besides the main influence factors of protective relaying data flow mentioned above, there were other factors. The analysis was given on the network layout and the amount of protective relaying equipment.

The layout of the network decided the transmission distance of the data flow. The delay augmented with the increase of transfer distance. Considering all influence factors, there would be congestion if the configuration was unsuitable. As a result, the data delay would increase. The result is shown in Fig. 6.

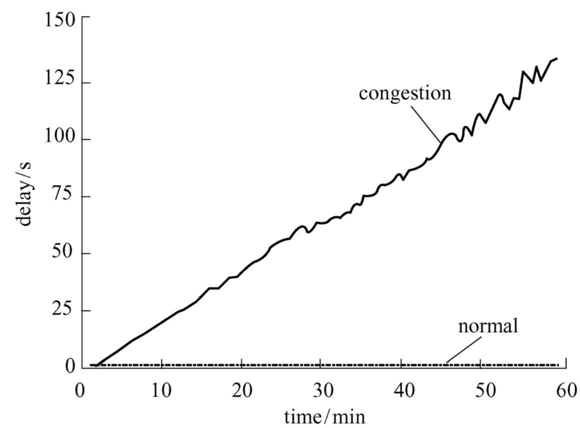

Fig. 6 Packet end-to-end delay

The amount of protective relaying equipment affects the data flow in the substation network. The data flow increases with the increase of the amount of equipment, which would lead to congestion. In this case, there is a bad influence on real time performance. The amount of protective equipment in the substation is determined by the scale of the substation, and cannot be changed frequently. In this case, the subnet solution can be adopted. Protective equipment could be partitioned into different subnets. Each subnet connects with the monitor at the station layer. This solution can reduce network data flow, avoid congestion, and guarantee real time performance.

5 Conclusions

Protective relaying data flow in a substation requires high real time performance. Based on this requirement, the simulation model for digital communication between protective relaying equipment at the interval layer and monitoring equipment at the station layer was made. The end-to-end delay of protective relaying data flow was analyzed. The main influence factors and analysis results of delay were given. A proposal for network configuration was presented to reduce the end-to-end delay of protective relaying data flow:

1) The message size and sending interval are configured according to the protective relaying equipment. To assure integrity of information, the message size should be limited. Large messages should be avoided. The stochastic data flow and the paroxysmal data flow should not be sent at the same time. The utilization of the station bus should be below 37% to ensure real time performance.

2) High layer protocols should be configured according to protective relaying data flow. UDP/IP would be chosen in the high real time case. TCP/IP would be chosen in the high reliability case.

3) Bandwidth of network should be distributed reasonably according to the kind of data flow. The bandwidth requirement of protective relaying data flow which has high real time performance should be guaranteed.

4) To reduce the time delay of protective relaying data flow, the layout of the network should be reasonable. When the amount of protective relaying equipment is large, the subnet solution should be considered.

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