Smart substation network quality monitoring and fault prediction

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Abstract—The smart substation communication network is the basis for information sharing of various devices in the substation. Its operation status has an important impact on the safe operation of the substation and even the power grid. Therefore, real-time status monitoring of the smart substation communication network is becoming more and more important. Aiming at the problems of single dimension, insufficient real-time performance and manual fault analysis in existing substation communication network state monitoring technology, this paper proposes a method of smart substation communication network state monitoring and fault prediction based on network communication quality. This paper uses switch ACL technology and coloring technology to obtain communication quality indexes such as bandwidth utilization, delay, and packet loss rate in real time; based on a multi-dimensional evaluation algorithm, a comprehensive evaluation model of network communication quality is constructed; the model of the relationship between abnormal network communication quality and failures is established. Finally, real-time monitoring of network communication quality and fault prediction are realized. The application analysis in a typical 110 kV substation shows that this method can effectively evaluate the network communication quality and accurately predict failures, and can guide operationer and maintenaner to quickly restore the normal operation of the communication network.

1. Introduction

The smart substation communication network provides an efficient, safe and reliable information exchange channel for all kinds of equipment in the substation[1-2]. It is the link of information exchange between equipment in the substation and between equipment and system. It is the basis for the realization of smart substation information digitization, information sharing standardization, and advanced application interaction. Its reliability and safety have an important influence on the safe operation of substations and even power grids. With the development of smart substation technology, the types and quantities of communication network access devices are increasing, the amount of service data carried is increasing, and the communication links are becoming more and more complex[3-4]. These changes have led to an increasing number of network failures, which seriously threaten the normal operation of substations[5-6]. Real-time status monitoring of the communication network within the station is becoming more and more important.
However, the existing technology is difficult to quickly and accurately locate and troubleshoot network faults. The network analyzer (hereinafter referred to as NA) is the only way to realize the monitoring and fault diagnosis of the communication network\[7\]. Its essence is the centralized real-time recording of network messages. It only has a simple alarm function and cannot provide real-time information for the nodes in the network. Troubleshooting and analyzing the cause of the failure still need to rely on manual labor. At the same time, because it can only give an alarm after a failure, the real-time performance is poor, and there is no failure early warning function, which will lead to the expansion of the scope of the failure. The smart substation network operation status monitoring and troubleshooting method proposed in the literature\[8-10\] is based on NA to realize message flow statistics and abnormal message analysis, and it has the same limitations as the NA. In the previous article\[11-12\], I and my collaborators proposed a process-level network dynamic monitoring method, which can quickly locate physical link failures and virtual link disconnections, and expand the fault diagnosis scope of NA. However, this method still alarms after the failure, with poor real-time performance, and can only locate physical topology-related failures.

The fundamental reason for the limitations of current network fault monitoring and diagnosis is that faults are only analyzed from the perspective of a single frame of messages, and there is a lack of analysis from the dimension of communication quality. The quality of network communication reflects the running status of network communication in real time. When network communication fails, network communication quality will also be abnormal. Abnormal communication quality is closely related to communication failure\[13-14\]. However, there are many difficulties in real-time monitoring of network communication quality. There are many evaluation indexes, and most indexes are difficult to obtain in real time\[14\]. A single index cannot comprehensively and accurately reflect the quality of network communication, and the degree of influence of abnormalities and failures of different indexes is different\[14-15\]. It is also difficult to evaluate the quality of network communication in a multi-dimensional manner and reveal the relevance of abnormal indicators and faults.

This paper conducts research from the dimension of the network communication quality in the substation, and provides a new perspective for the real-time monitoring of the communication network status of the smart substation. First, the article introduces the construction of the network quality monitoring and fault prediction system framework for smart substation business. Then, it introduces the realization of real-time monitoring of key indicators of network communication quality, and proposes a comprehensive evaluation model of network communication quality and a correlation model of network communication quality abnormalities and faults. Finally, the application of the smart substation network monitoring system based on this technology in the 110kV substation in Guanyinqiao, Sichuan is introduced. The results show that the smart substation network communication quality monitoring and fault prediction technology can realize the timely warning of abnormal conditions, and effectively improve the reliability of communication network operation and the efficiency of maintenance.

2. Smart substation network quality monitoring and fault prediction system framework

The system framework of the smart substation communication network quality monitoring and fault prediction in this paper is shown in Fig.1, which is mainly composed of two key parts: real-time acquisition and predictive analysis.
In the smart substation network, the switch as the transit medium for the transmission of various types of messages, plays an important role in information transmission. Therefore, this paper proposes to use the ACL technology and coloring technology of the switch to obtain the bandwidth utilization, delay, and packet loss rate of virtual links in real time. So as to realize real-time monitoring of physical links and network communication quality index.

Since a single index cannot comprehensively reflect the network communication quality of smart substation network, this paper proposes a comprehensive evaluation method for multiple indexes. First, the three communication indexes of bandwidth utilization, time delay, and packet loss rate are processed in a dimensionless manner. Secondly, according to the importance of influencing communication and the characteristics of smart substation network, weight of each index is assigned. Finally, the comprehensive evaluation value of network communication quality is calculated after the weighted average algorithm.

The quality evaluation value of network communication reflects the operation status of network communication, and abnormal communication quality parameters are closely related to communication failures. This paper proposes a method to adjust the abnormal threshold of quality communication index, analyzes the correlation between abnormal communication indexes and failures, and builds a failure prediction model. When the comprehensive evaluation value of network communication quality exceeds the threshold, the fault prediction module can quickly and accurately predict the cause and scope of the fault.

3. Real-time monitoring of communication key index data

There are many indexes to evaluate the quality of network communication. Common ones are: delay, delay jitter, packet loss rate, device port throughput, bandwidth utilization and load rate, reliability, etc. Different indexes reflect the quality of network communication from different aspects. However, due to the many types of index, obtaining them in real time at the same time will reduce the operating efficiency of the switch. This paper selects three key indexes of bandwidth utilization, time delay, and packet loss rate to comprehensively evaluate the communication quality of the smart substation network. The index selection considers the following three aspects: 1) principles of comprehensiveness, ease of testability, and index-related smallness; 2) characteristics of zero packet loss required for smart substation network transmission; 3) characteristics of high requirements for SV packet transmission delay by protection devices.

In the article in [11-12], the ACL technology of the switch is used to realize the flow statistics of...
GOOSE and SV packets. Based on the literature [11-12], the bandwidth utilization rate can be calculated approximately by dividing the traffic statistics of the virtual link and the physical link by the time slice.

This article uses the packet coloring technology to realize the information statistics of characteristic packets. The specific process is as follows: the switch at the packet sending end adds a flag to the packet for coloring, and the switch at the packet receiving end removes the flag to restore the packet, that is, decoloring. The transmitter and receiver switches respectively count the number of colored packets in the same measurement interval, and can obtain the number of packets lost and the packet loss rate. At the same time, each switch measures the entry time and exit time of the colored packet one by one, and writes the accumulated delay information into the reserved fields of the GOOSE, SV and MMS packets. The receiver switch calculates the delay value of the packet according to the reserved fields. When the network communication is normal, in order not to affect packet forwarding function of the switch, the packets are periodically colored to collect communication quality indexes. But when the network fails, the measurement period can be reduced to obtain more communication quality index values for locating the fault. Fig.2 shows the process of coloring reserved fields in GOOSE, SV packets.

So far, this article uses the ACL technology and coloring technology of the switch to obtain key indexes such as the bandwidth utilization, delay, and packet loss rate of the virtual link in real time, and realizes the real-time monitoring of the communication quality of the physical link and the virtual link.

4. Establishment of network communication quality evaluation model
According to the indexes selected in the previous chapter, each index reflects the performance of the network from different aspects. Due to the complexity of the smart substation business, when a single index is abnormal, it is impossible to accurately determine whether there is a fault [13] and the cause and scope of the fault. In order to scientifically and comprehensively evaluate the communication quality of the smart substation network, this paper proposes an evaluation model for the communication quality of the smart substation network. The three indexes of delay, packet loss rate and bandwidth utilization are calculated through the evaluation model to obtain the comprehensive evaluation value of network communication quality.
Because the units of the indexes of delay, packet loss rate and bandwidth utilization are different, they are of different dimensions. The data values vary greatly and cannot be calculated directly without processing. Therefore, referring to the non-dimensional calculation method of the unit value of the power primary system, the measurement value of the evaluation index is processed in a non-dimensional manner. The size of the measured value is standardized in the interval of [0, 1], and the measured value of each index is dimensionless to form a parameter matrix. Then assign weights to each index according to the characteristics of the smart substation network. Finally, the comprehensive evaluation value of the smart substation network is calculated after weighted average.

4.1 Dimensionless communication indicators
First of all, combined with a large number of project site measured values and the requirements of standards and specifications, the evaluation standard of three indexes are formulated. The evaluation standard of bandwidth utilization are shown in Table.1 below. The evaluation standard for packet transmission delay are shown in Table.2 below. The evaluation standard of the packet loss rate, the score is 1 when there is no packet loss, and the score is 0 when there is packet loss.

| Table.1 Bandwidth utilization index grade standard |
|-----------------------------------------------|
| Grade | 1 | 0.9 | 0.8 | 0.7 | 0.6 | 0.5 | 0 |
|-----------------------------------------------|
| Bandwidth utilization% | <10 | 10-20 | 20-30 | 30-50 | 50-70 | 70-100 | >100 |

| Table.2 Delay utilization index grade standard |
|-----------------------------------------------|
|-----------------------------------------------|
| Grade | 1 | 0.9 | 0.8 | 0.7 | 0.6 | 0.5 | 0 |
|-----------------------------------------------|
| SV/ms | <0.02 | 0.02-0.05 | 0.05-0.1 | 0.1-1 | 1-8 | 8-10 | >10 |
|-----------------------------------------------|
| Variable-bit GOOSE/ms | <0.02 | 0.02-0.05 | 0.05-0.1 | 0.1-0.2 | 0.2-0.6 | 0.6-1 | >1 |
|-----------------------------------------------|
| Heartbeat GOOSE/ms | <0.05 | 0.05-0.5 | 0.5-1 | 1-10 | 10-50 | 50-100 | >100 |

4.2 Communication index empowerment
In this paper, the weighting method based on the principle of ”function-driven” assigns weights to the three indexes of delay, packet loss rate and bandwidth utilization. The weight coefficient is set according to the importance of the indicator's influence on the network communication quality. The importance of each index is graded from 1 to 9, with 9 being the most important, decreasing step by step, and 1 being the least important.

Since the protection device in the smart substation network has strict requirements on the transmission delay of SV messages, and the delay fluctuation is very obvious when the network communication fails \[1^3\], the delay importance level is set to the highest. Because the smart substation network has high redundancy and good reliability, the possibility of packet loss is very small. Once a packet is lost, it can be quickly found through Network Analyzer. Therefore, the importance level of packet loss is set to the lowest. According to the importance of the three indexes of delay, bandwidth, and packet loss, the importance levels of the three indexes of delay, bandwidth utilization, and packet loss rate are divided into 8, 6 and 2. According to the formula (1) ,the weight coefficients of the three indexes of delay, bandwidth utilization, and packet loss rate are calculated to be 0.5, 0.375 and 0.125 respectively.

Suppose a system is composed of m "modules", which are F_1, F_2...F_m, where F_i(i=1,2...m) is the "important" of the i-th "module" ", then the F_i weight coefficient w_i can be defined as formula (1):

\[ w_i = F_i / \sum_{k=1}^{m} F_k, i = 1,2,\cdots m \]

(1)

In the comprehensive evaluation of network message transmission delay indicators, the delay weight values of different types of messages are not the same. According to the priority of packet, the importance level is assigned. The shifted GOOSE message level is 9, the SV message level is 7, the
heartbeat GOOSE message is level 4. The weight values are 0.45, 0.35, and 0.2, respectively.

In the comprehensive evaluation of the network bandwidth utilization index, the link between the switch and the switch is the communication trunk line, and the link between the IED device and the switch is the communication branch line. Since the influence of the disconnection of the communication trunk line is much larger than that of the communication branch line, the importance level of the communication trunk line is divided into 9, and the importance level of the communication branch line is 6. The weight values are 0.6 and 0.4 respectively.

4.3 Communication quality evaluation calculation
Suppose the measurement index has k measurement points (virtual links), and each measurement point is t time, totaling k*t samples, and the corresponding matrix is represented by V, which is shown in matrix (2).

\[
V = \begin{bmatrix}
v_{11} & v_{12} & \cdots & v_{1t} \\
v_{21} & v_{22} & \cdots & v_{2t} \\
\vdots & \vdots & \ddots & \vdots \\
v_{k1} & v_{k2} & \cdots & v_{kt}
\end{bmatrix}
\]  

(2)

The measured value of each index is processed in a dimensionless manner according to the index evaluation standard, and the relative value of each index is obtained. Then this paper uses the weighted average algorithm to calculate the comprehensive evaluation value of the communication quality at a certain measurement point at a certain time. The calculation method is shown in formula (3).

\[
P_j = \left( \sum_{i=1}^{n} w_i x_{ij} + \sum_{i=1}^{m-n} w_i x'_{ij} \right) / \sum_{i=1}^{m} w_i
\]

(3)

In formula (3), \(P_j\) is the communication quality evaluation value of the j-th measurement point, m is the total number of evaluation index, n is the number of positive index in the evaluation index, and \(m-n\) is the number of inverse index in the evaluation index. \(w_i\) is the weight of the i-th index, \(v_{ij}\) is the normalized relative value of the i-th positive index at the j-th measuring point, and \(v'_{ij}\) is the normalized relative value of the i-th inverse index at the j-th measuring point. A positive index is an index that is better evaluated with a larger value, such as available bandwidth, and an inverse index is an index that is better evaluated with a smaller value, such as delay and packet loss rate.

\[
x_{ij} = \frac{v_{ij} - \text{min}}{\text{max} - \text{min}}
\]

\[
x'_{ij} = \frac{\text{max} - v_{ij}}{\text{max} - \text{min}}
\]

(4)

\(v_{ij}\) is the measurement index value of the i-th item of the j-th measuring point. \(\text{min}\) is the minimum value of the measurement index value of the i-th item of the j-th measuring point in t samples. \(\text{max}\) is the maximum value of the measurement index value of the i-th item of the j-th measurement point in t samples.

The comprehensive evaluation value of network communication quality at a certain moment is obtained by comprehensively weighting the comprehensive evaluation values of all measurement points in the network. The calculation formula is shown in equation (5).

\[
P = \left( \sum_{i=1}^{m} P_i w_i \right) / \sum_{i=1}^{m} w_i
\]

(5)

In formula (5), \(P\) is the network performance evaluation index, m is the number of measurement points, \(P_i\) is the comprehensive evaluation value of the communication quality of the i-th measurement point, and \(w_i\) is the weight value of the i-th measurement point.

According to the above research in this article, the evaluation results of the communication quality of each virtual link, physical link and the entire network can be calculated. When the smart substation communication network is operating in real time, the comprehensive evaluation value of network
communication quality is also constantly changing. The operation and maintenance personnel can set
the threshold value according to the experience value or the reference value of the specified range of
the parameter. When the calculated comprehensive evaluation value of network communication
quality changes beyond the threshold, the abnormal situation of the network is early warned.

5. Failure prediction analysis
Due to the burst of GOOSE packets in the smart substation network and a large number of abnormal
index during failure, the accuracy and timeliness of failure prediction is reduced. At the same time,
due to differences in the scale of substation business, and personnel experience, the thresholds set by
operationer or maintenaner are also quite different, which further reduces the accuracy of fault
prediction. This paper designs a fault prediction module based on communication quality indexes,
proposes a general standard process for threshold setting, and analyzes the relationship between
common communication faults and communication quality indexes.

5.1 Threshold setting adjustment
The fault prediction module first detects the communication quality parameters of the entire station,
which is divided into passive detection and active detection. Passive detection refers to the periodic
detection of the communication quality of all virtual links and physical links of the entire station.
Active detection refers to the active detection of the communication quality of one or several specific
virtual links and physical links when the network fails or according to engineering needs. The
measured value of the detected indexes are calculated by the communication quality evaluation
model. The calculated evaluation results are merged, and then filtered and analyzed. According to the
merge result, judge whether there is an abnormal event. According to the correlation between
abnormal communication quality indexes and communication failures, predict the cause of the failure.
Finally, a fault alarm is generated. According to the accuracy of the fault alarm, the maintenaner can
adjust the fault prediction threshold. After the threshold is adjusted, maintenaner need verify the
overall status of the network to ensure the correctness of failure prediction. The general standard
process of threshold setting is shown in Fig.3.
5.2 Judgement of the cause of failure
Before the failure of the smart substation network (such as equipment damage, cable degradation, broadcast storm), the network communication quality will be abnormal. Since communication quality index abnormalities have a certain correlation with communication failures, the cause and scope of the failures can be predicted through the communication quality index abnormalities. The article [11-12] published earlier by myself and my collaborators also proposed a fault diagnosis model. The focus of the diagnosis is physical topology and virtual link connection faults, and it is impossible to diagnose complex communication network faults. This article will further study the relationship between abnormal communication quality indexes and common network communication failures.

Common smart substation communication failures include physical link failures (line disconnection, line aging), switch equipment failures (crash, power-off restart, high working temperature, etc.), network storm (ring network storm), network congestion (SYN Flood storm, ARP request storm) and so on.

When the comprehensive evaluation value of network communication quality is abnormal, check the packet loss rate, bandwidth utilization rate, and delay indexes of each physical link and virtual link. Define the abbreviation of packet loss rate as loss, bandwidth utilization abbreviation as band, delay abbreviation as delay, device abbreviation as IED, switch abbreviation as SW, single physical link abbreviated as SL, multiple physical links abbreviated as ML, virtual link abbreviated as VL. According to the following steps to predict and diagnose the fault, the specific process is shown in Fig.4.

Fig.4 Process of failure prediction
(1) If the packet loss rate of a single physical link is 100%, the cause of the failure is judged to be a disconnection of the physical link (cable disconnection or interface disconnection);
(2) If the packet loss rate of a single physical link is not 100% and the delay change is small, the cause of the fault is judged to be the aging of the line or the loose interface:
(3) If the packet loss rate of multiple physical links is 100%, and these physical links are connected to the same device, the cause of the failure is judged to be an abnormal device (halt or communication interruption);

(4) If the packet loss rate of multiple physical links is not 100% and the delay change is small, and these physical links are connected to the same device, the cause of the failure is judged to be an abnormal device (restart the device or packet loss due to excessive temperature);

(5) If the bandwidth utilization of the physical link gradually increases, and the bandwidth utilization and delay of each virtual link do not increase significantly, the cause of the fault is judged to be network congestion (non-business packets);

(6) If the bandwidth utilization of the physical link gradually increases, and the bandwidth utilization and delay of each virtual link also increase significantly, the cause of the fault is judged to be ring network storm;

(7) If the bandwidth utilization of the physical link gradually increases, and the bandwidth utilization and delay of the goose virtual link increase significantly, and the bandwidth utilization and delay of the sv virtual link do not increase significantly, the cause of the phenomenon is the burst of GOOSE packets. It is not a fault.

The above process analyzes the relationship between common network faults in smart substation networks and abnormal communication parameters. As for unknown or unusual failures, abnormal values of communication quality indexes can be collected when the failure occurs. By these abnormal values, the communication quality change characteristics of the fault can be geted. In this way, the scope of the failure prediction model is continuously expanded.

6. Case verification
The research results of this paper have been successfully used in the pilot project of the 110kV substation in Guanyinqiao, Sichuan. This paper uses the data collected during the trial operation to verify the effectiveness of the method. The topological structure of the process layer network of the station is shown in Fig.5. The process layer network adopts star connection and consists of five subnets, including two subnets of 110KV line, two subnets of main transformer and a subnet of bus. In Figure 5, the twenty one ports connected to the IED and the switch are numbered in sequence, and the IED devices connected to the port numbers are shown in Table.3.

Fig.5 Topology structure of the process layer network
Table 3. IED name and port number

| Port | IED name                  | Port | IED name                        |
|------|---------------------------|------|---------------------------------|
| 1    | line protection & measure | 10   | transformer high side intelligent terminal |
| 2    | line intelligent terminal | 11   | transformer low side intelligent terminal |
| 3    | line merging unit         | 12   | transformer protection & measure |
| 7    | transformer low side merging unit | 19   | bus protection & measure       |
| 8    | transformer high side merging unit | 20   | bus intelligent terminal      |
| 9    | transformer itself intelligent terminal | 21   | bus merging unit               |

As shown in Table 4. The bandwidth and delay values of the GOOSE and SV packets sent by some IED devices collected by the switch, including the bandwidth and delay values of the service virtual links in steady-state operation and service failure.

Table 4. Bandwidth and delay values of virtual links in steady-state and fault-state

| Virtual link                      | Bandwidth of steady state (bit/s) | Delay of steady state (us) | Bandwidth of fault state (bit/s) | Delay of fault state (us) |
|-----------------------------------|-----------------------------------|-----------------------------|---------------------------------|---------------------------|
| line 1# MU SV                    | 7.751M                            | 47.308                      | 9.75M                           | 61.286                    |
| line 1# PL GOOSE                 | 314                               | 52.586                      | 420                             | 84.358                    |
| line 1# intelligent terminal GOOSE1 | 604                              | 58.240                      | 726                             | 89.295                    |
| line 1# intelligent terminal GOOSE2 | 1597                             | 81.538                      | 1916                            | 152.586                   |
| line 1# intelligent terminal GOOSE3 | 291                              | 30.460                      | 397                             | 164.556                   |
| transformer 1# MU SV             | 7.751M                            | 49.216                      | 8.35M                           | 204.947                   |
| transformer 1# PL GOOSE          | 376                               | 34.295                      | 587                             | 59.275                    |
| transformer 1# high side intelligent terminal GOOSE1 | 601                               | 59.275                      | 926                             | 82.725                    |
| transformer 1# high side intelligent terminal GOOSE2 | 1596                             | 82.725                      | 1816                            | 91.521                    |
| transformer 1# high side intelligent terminal GOOSE3 | 292                               | 31.521                      | 501                             | 48.214                    |
| bus MU GOOSE1                    | 274                               | 99.748                      | 486                             | 186.318                   |
| bus MU GOOSE2                    | 269                               | 96.992                      | 677                             | 197.256                   |
| bus MU GOOSE3                    | 271                               | 92.482                      | 583                             | 193.573                   |

Through the network communication quality evaluation model, the network evaluation index values under steady state and failure are calculated respectively, as shown in Table 5. Through comparison, it is found that the network communication quality index drops significantly when a fault occurs. According to the method of fault prediction in this paper, because the bandwidth and delay of each virtual link are increasing, the fault is judged as a ring network storm fault. According to the results of the failure prediction, the operation and maintenance personnel found that the line 1# switch and the main transformer 1# switch were interconnected, forming a ring network. This case proves the accuracy of failure prediction.

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Table 5. Comprehensive evaluation value of index

| Comprehensive evaluation value | Steady state | Fault state |
|--------------------------------|--------------|-------------|
| Bandwidth utilization          | 84.15        | 63.78       |
| Delay                          | 83.93        | 59.31       |
| Packet loss rate               | 100          | 100         |
| Network communication quality  | 86.049       | 66.631      |

It can be seen, the method of smart substation network communication quality monitoring and fault prediction in this article can scientifically evaluate the network communication quality and accurately predict the cause of the fault. This method can help operationer or maintenaner to quickly find the fault location, quickly restore the normal operation of the process layer network, and improve the operational reliability of the secondary system of the smart substation.
7. Conclusion
This paper studies the method of smart substation network communication quality monitoring and fault prediction. This method can obtain the communication parameters of the virtual link and physical link of the packet in real time through the switch. This method constructs a network communication quality evaluation model. This method can predict the cause and scope of the failure based on the abnormality of the network communication quality evaluation index. The case results show that the method can effectively improve the operation and maintenance efficiency of smart substations, promptly warn of abnormal conditions, and improve the reliability of communication network.

The method proposed in this paper can provide a new perspective for smart substation network monitoring and fault diagnosis, and has a wide range of application prospects in engineering applications. In future research, we will further monitor more communication quality indexes and expand fault models to improve the comprehensiveness and accuracy of smart substation network communication quality detection and fault prediction technologies.

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References
[1]. Hao Shaohua, Li Yong, Zhang Tiefeng. Scheme of communication network and network management system for new generation smart substation. (2017) Automation of Electric Power Systems, 41(17): 148-154.
[2]. Zhang Yanxu, Cai Zexiang, Li Xiaohua, et al. Analytical modeling of traffic flow in substation communication network. (2015) IEEE Transactions on Power Delivery, 30(5): 2119-2127.
[3]. Zhu Lin, Wang Pengyuan, Shi Dongyuan. Status monitoring information model and configuration description of communication network in smart substation. (2013) Automation of Electric Power Systems, 37(11): 87-92.
[4]. Wang Haizhu, Zhang Yanxu, Cai Zexiang, et al. Information flow calculation model and method for process bus network in smart substation. (2013) Power System Technology, 37(9): 2602-2607.
[5]. Zhang Yanxu, Cai Zexiang, Long Pianpian, et al. Real-time fault diagnosis models and method for communication network in smart substation. (2016) Power System Technology, 40(6): 1851-1857.
[6]. Gao Lei. Yang Yi, Liu Yu, et al. Proof table based fault location method for process level channel in smart substations. (2015) Automation of Electric Power Systems, 39(4): 147-151.
[7]. Yuan Hao, Qu Gang, Zhuang Weijin, et al. Discussion on condition monitoring contents of secondary equipment in power grid. (2014) Automation of Electric Power Systems, 38(12): 100-106.
[8]. Xu Weiguo, Zhang Liang. Design and application of on-line fault diagnosis system for network communication of digital substation. (2010) Electric Power Automation Equipment, 30(6): 121-124.
[9]. Zhang Jinsong, Yu Jianyu. Application of network analyzer in smart substations. (2011) East China Electric Power, 39(4): 665-668.
[10]. Ding Xiuling, Zhang Yanxu, Cai Zexiang, et al. A protection method of abnormal information flow in process layer network based on packet analysis. (2013) Power System Protection and Control, 41(13): 58-63.
[11]. Li Chao, Luo Linglu, Wang Dehui, et al. Design and implementation of process layer network monitoring and fault location system for smart substation. (2019) Power engineering technology, v.38; No.184(02):123-128+147.
[12]. Luo Linglu, Peng Qi, Wang Dehui, Li Chao, et al. Monitoring method of process level network in smart substation. (2018) Automation of Electric Power Systems, 42(11): 151-156.

[13]. Chen Qingtao, Yang Haitao, Ding Guocheng, et al. Qualitative analysis of data flow in smart substations and simulation of communication network performance. (2017) Electrical Application, 036(023): 22-25.112-115.

[14]. Ouyang Fan, Liu Haifeng, Zhao Yongsheng, et al. Analysis of the communication network congestion fault of smart substation and its preventive measures. (2011) Power System Technology, 11: 7-11.

[15]. Tan Xiliu. State evaluation and abnormal analysis of smart substation communication network. (2017) North China Electric Power University (Baoding).