Research about the real-time performance and reliability of trip through GOOSE network in smart substation

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***Abstract*—The application of trip through GOOSE (Generic Object Oriented Substation Event) in relay protection is disputed and is not allowed to be used in smart substation of China for the reliability and safety, as it once caused accidents in the earlier stage of the application of IEC61850. Although the technology of process bus including the trip through GOOSE network is mature, it still lacks further and detailed research about the performance of real time and reliability of GOOSE, which is the drive of this paper. The real-time performance of trip through network of GOOSE is discussed in four parts which are the calculation of network delay, the simulation of network latency, the laboratory test and on-site test about the transmission delay. Firstly, the calculation and simulation are presented based on different network structures and schemes. Secondly, the laboratory test is described in detailed through different packet types, priority and background traffic. Thirdly, the on-site test is presented in a 500kV substation and makes a comparison between direct trip and trip through GOOSE network. It can prove that the real-time performance about trip through the network of GOOSE can meet the engineering requirements. At last, the analysis about the reliability based on the MTTF (Mean Time to Failure) of IED (Intelligent Electrical Device) is discussed to provide additional support for the view of paper. The trip through GOOSE network should be recommended in the construction of smart substation.**

***Index Terms*—Smart substation, IEC 61850, GOOSE, SV, reliability, MTTF.**

I. INTRODUCTION

GOOSE is defined in standard of IEC61850 and is derived from GSE (Generic Substation Event). It is one of the important packets of process bus and is widely used in smart substation for the transmission of status information, control command, inter-block information and synchronization-check information [1-2]. As the further development of smart substation, GOOSE is promoted to be used in distributed bus bar protection and distributed under frequency load shedding. The application of GOOSE not only simply the design, construction and test of secondary system, but also solve the problems such as electromagnetic interference, parasitic circuit and poor contact of secondary circuit effectively for the replacement of cable connection [3].

In 2004, IEC 61850 standard was firstly used in substation of China and then became the basic infrastructure of digital substation. In the stage of digital substation, although the trip through GOOSE network was used, a lot of problems such as unawareness of interruption of GOOSE network, abnormal of switch, the circuit breaker cannot trip on time to clear fault still existed and did not be solved. It affected the safety operation of substation and caused that the trip through GOOSE network was not reliable. Although the reference 3 takes a test in large background traffic and wants to prove that the real-time of GOOSE can meet the real-time requirements, the test is simple and the substation is not typical also, so it is not accepted by the operation engineer of power industry.

In 2009, as the State Grid Corporation of China(shorted as SGCC) presented the plan of smart grid, the smart substation ， which was based on IEC 61850 standard became the direction of substation. It was the update of digital substation. In this stage, the trip through GOOSE network was still used in smart substation until 2010 when a new standard "Technical Specification of relay protection in smart substation" was published by the SGCC. The trip of relay protection through GOOSE network was forbidden and the point-to-point connection, which can avoid the delay of switch or network, was recommended in this standard. Also, the requirement that at least 8 net ports of each IED was presented in the standard to meet the need of point-to-point connection in substation. Although the point-to-point way can reduce the cost of switch and avoid the transmission delay of network, it increased the quality of net ports and the cost of IED.

There were several reasons for this result. Firstly, in the early stage of application of trip through GOOSE network, the design about the topology of network was not suitable, as it lacked experience about the stream control and network partition. Secondly, the function of publish/subscribe of GOOSE was not mature as a new technology, a lot of bugs existed in the IED and affected the reliability of GOOSE communication. Thirdly, the test and maintenance were not effectively to find and solve the abnormal situation as most of engineers of SGCC were not familiar with the new technology of GOOSE, it also caused that the test scheme of factory test and on-site test were not available to find the problems. All of these reasons caused that the trip through GOOSE network in digital substation was not reliable.

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As the development of smart substation, the technology of GOOSE is still used and become more and more mature. Especially for the improvement of IED and the technology of GOOSE is understood by more and more engineers, the benefit of GOOSE is further recognized and the opinion that the trip through the GOOSE network is better than point-to-point connection way. The reasons of the change are that, the increase of the net ports of IED causes high temperature and affects the operation reliability of IED. Also, the need to simply the structure of substation and to reduce the cost further is presented with the large scale construction of smart substation, the trip through GOOSE network can meet the requirements and become focus again, So, the research about the performance of GOOSE based on the situation of China is urgently needed now. This paper carries out the analysis and test about the performance of trip through GOOSE network from four parts which are theoretical calculation based on engineering experience, simulation of network with OPNET, the lab test with real IEDs and on-site test in smart substation. At last, the reliability analysis of trip through GOOSE network is discussed, it can support and guide the application of trip through GOOSE network.

II. Calculation of Transmission Delay

Although there is not exactly theory to guide the calculation of the transmission delay of GOOSE network, the engineering experience can provide a similar calculation and provide a quantitatively analysis. It will be helpful to design of GOOSE network.

A. Composition of transmission delay

There are four typical main segments about the transmission delay according to the reference 4-6, which are the transmission delay of wire, store-and-forward delay, inherent delay of switch and queuing delay of packet.

The transmission delay of wire is the time needed for the transmission of packet. As the optical fiber is widely used in process bus and the speed of light in the optical fiber is 2/3 of the normal speed, so the transmission delay of packet in optical fiber is about 5us per 1000 meters. It is marked with T_{WL}.

Store-and-forward delay is the time of packet received completely by the switch from arriving of the first byte of the packet to the last one. This delay is proportion to the length of the packet and is inversely proportion to the transmission bandwidth, as packet length/transmission bandwidth. It is marked with T_{SF}.

The inherent delay of switch is constant for most switches. It is affected by the processing of MAC address, VLAN and priority of network. Although this value may be different from different manufactures, it could not exceed 10 us. And the typical value is 7us. It is marked with T_{SL}.

The queuing delay of packet is the waiting time about the target packet transmitted from the switch. Most of time, the focus is on the worst delay which means that the target packet is transmitted as the last one. It is marked with T_{QL}.

Above all, the total delay (marked with T_{TOTAL}) of one packet through single switch is the sum of these four types delay: $T_{TOTAL} = T_{WL} + T_{SF} + T_{SL} + T_{QL}$. When the packet is transmitted through several switches, the total delay will increase. In order to simple the calculation, the total delay is considered as the linear relationship with the quantity of switch which is marked as N, it is the N times of single delay of switch. It must be stressed that T_{WL} is only affected by the length of optical fiber and has no relationship with quantity of switch. The store-and-forward delay, the queuing delay are nonlinear relationship with switch quantity also. This way of paper is just used to simply the calculation and to get a rough calculation. Although it is not rigorous, it is very helpful to the design and construction of network in smart substation.

B. Calculation of independent network

The performance of trip through GOOSE network is different from different network structures. Although star and ring topology are widely used in the world, only star topology is recommended in China. There are several reasons. Firstly, there is a risk of network storm of ring topology. Secondly, the manufactures of secondary system do not support the communication of ring network, the star topology do not need additional requirements about the IED. Compared with the ring topology, it is easier to be realized. Thirdly, the design engineer, the power supply company (Transmission Supply Origination of each province belong to SGCC) have bad experience on ring topology and find that the star topology is more controllable and easier to realize. Fourthly, the compatibility of ring topology networks is not as well as star topology. As in order to have good performance in recovering time, the switch which supports the ring topology usually uses some private token. It cause that the switches from different vendors cannot interoperate with each other. In order to solve the issues, the utilities have to use the same model switches from one vendor. It limits the selection right of utilities. At last, as the requirement of redundancy configuration of IED in 220 kV and above voltage substation is presented by the SGCC, the advantages of ring topology become worse compared with the star topology. For these reasons, only star topology and related redundancy configuration of IED is allowed to be used in smart substation of China now.

There are three typical basic structures of network which are single switch, cascade switch and two layer networks in the application of star network as figure 1 to figure 4. The complex network is combined based on them.

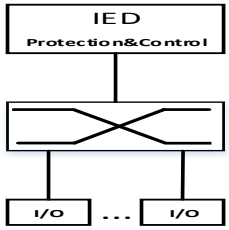


Fig.1 single switch

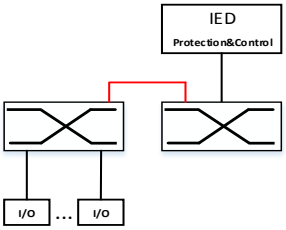


Fig.2 cascade of switch

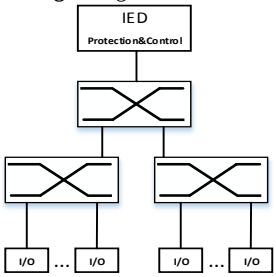
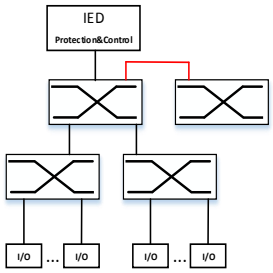


Fig.3 two layer network



F ig.4 two layer cascade network

In figure 1, a simple GOOSE network is created by eight intelligent terminals which are marked as I/O, the bay layer IED (protection & control device) publishes/subscribes the GOOSE packet through the switch. In order to make calculation about the transmission delay, some parameters are set up. The length of fiber is set as 1000 meter, the length of GOOSE packet is set as 284 byte(take a typical packet) and the bandwidth is set as 100M bit/s for calculation. The T_{WL} is 5us, the T_{SF} is 22.72us(284byte/100Mbit/s) and the T_{SL} is 7us. About the queuing delay, the best situation is that there is no queue time about the target packet which is marked with T_{TOTAL}（best）and the worst delay is that the target packet has the longest waiting time in the queue which is marked with T_{TOTAL}（worst）, the calculation is as below:

$$T_{TOTAL}(best)= 5+ 22.72+ 7= 34.72us \quad (1)$$

$$T_{TOTAL}(worst)=5+ 22.72 + 7 + 22.72*7= 193.76us \quad (2)$$

In figure 2, the same GOOSE packet will pass through two switches, so the rough calculation is twice the figure 1 as below:

$$T_{TOTAL}(best)= 2*（5+21.67+7）=2*34.72= 69.44us \quad (3)$$

$$T_{TOTAL}(worst)=2*（5+21.67+ 7 + 22.72*7）=387.52us \quad (4)$$

If there are eight intelligent terminals access the right switch of figure 2, the queuing delay of the worst situation will be double. In figure 3, it is the typical network which is widely used in smart substation, but sometimes, if there are too many bay layer devices, it may need another switch to cascade as the figure 4. In figure 3, eight intelligent terminals are accessed with the first layer switch, the worst situation of target GOOSE packet is that it need to wait the other seven GOOSE packets in the first layer switch and fifteen GOOSE packets in the second layer, the calculation is below:

$$T_{QL}(worst)=22.72*7+22.72*15= 499.84us \quad (5)$$

$$T_{TOTAL}(best)= 2*（5+22.72+7）=2*34.72= 69.44us \quad (6)$$

$$T_{TOTAL}(worst)= T_{TOTAL}(best)+ T_{QL}(worst)= 569.28us \quad (7)$$

According to the calculation, it can be find that, the wire delay, store-and-forward delay and inherent delay of switch can be constant compared with the queue delay which takes the most import impact on the transmission delay. The uncertainty of the queuing delay is the key point of transmission delay of GOOSE.

C. Calculation of shared network

The calculation from figure 1 to figure 4 are based on the independent GOOSE network, but in the real smart substation, the shared network which including GOOSE and SV（Sampling Value） packets, sometime IEEE 1588 packed is included, is also widely used.

The shared network including GOOSE and SV packet can take the figure 3 as reference and change the intelligent terminal of one switch as merging unit. In this situation, the calculation is the same with figure 3. Take a typical length of 126 byte(affected by the length of SvID) according to the 9-2LE(Light Edition for IEC 61850-9-2), the worst queuing delay in figure 3 changes from fifteen GOOSE packets to seven GOOSE packets and eight SV packets. The calculation is as below:

$$T_{QL}(worst)=8*(126*8)/（100*1000*1000）*106+7*22.72+7*22.72==8*10.08+318.08=398.7us \quad (8)$$

$$T_{TOTAL}(best)=2*(5+10.08+7)=2*22.08=44.16us \quad (9)$$

$$T_{TOTAL}(worst)=T_{WL}+T_{SF}+T_{SL}+T_{QL}(worst)=5*2+22.72*2+7*2+398.72=468.16us \quad (10)$$

The calculation above is based on eight line bays (eight intelligent terminals and eight merging units), if the line bay increases, the calculation will be the same with figure 3 and the difference is only the queuing delay. In order to simply the calculation, we can evaluate that the queuing delay of worst situation may be twice the eight line bays, the rough value is 797.44 us, the total transmission delay of worst situation of sixteen line bays become 866.88us. It still should be stressed that it is not rigorous, just for a rough awareness about the transmission delay.

The shared network including GOOSE, SV and IEEE1588 is also used in smart substation and is called as “Triple Play”. The time interval of announce packet and synchronization packet of IEEE1588 are second -level and the typical default value is 1 second or 2 seconds. According to the reference 6, the stream of IEEE1588 is only 3.408kbit/s in the worst situation, so it can be regardless and nearly to be considered as the same with shared network which only includes GOOSE and SV.

III. SIMULATION OF TRANSMISSION DELAY

The calculation of transmission delay of GOOSE only provides a rough assessment about the network delay, the more exactly result should be based on the simulation of network. Although OPNET and NS2 are widely used to realize the simulation of the performance of network in the world, no paper are based on NS2 in substation and only several papers such as reference 7-12 are based on OPNET.

Reference 7 takes simulation about the end-to-end delay while reference 8 makes some research about the uncertainty of delay. Reference 9 presents some simulation about the real-time performance of SV in the star and ring network, while reference 10 introduces the simulation about the process bus and station bus in single bay. Reference 11 provides simulation about the performance of VLAN and reference 12 provides the simulation about the transmission delay of SV and GOOSE packet based on the shared network but the detail of realization is not clear. Although these researches are helpful to understand the performance of transmission delay, they are not based on smart substation and the realization of simulation is not clear. This paper makes a detailed simulation about the delay of GOOSE transmission based on smart substation and can take comparison with the result of calculation in chapter 2.

A. The modeling of simulation

There are different ways to create the model of GOOSE. Reference 9 take the video conference service of OPNET to create a periodically transmission model which simulate the extreme situation of GOOSE. Reference 11 takes the Possion distribution to simulate the character of the randomness of GOOSE. Reference 12 creates the new model and it is more exactly with the real character of GOOSE. Considering the building of model is complicated and which is not the focus of this paper, the simulation of video conference and Possion distribution are used at the same which can make comparison.

B. *Simulation of independent network*

One way of simulation is that the GOOSE packet is generated based on the video conference service and the packet is periodically published with each 2ms(500packets/s), it is the same as the extreme situation which once the GOOSE starts to retransmit, data change appears and new frame of GOOSE starts to transmit again. The other way is that the GOOSE packet is published random based on Possion distribution which the parameter λ is set as 500. In order to compare with the calculation, the length of GOOSE packet is still set as 284 byte.

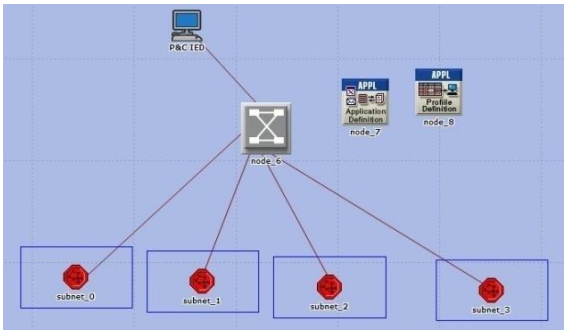
The simulation is compared between the periodically transmission and passion distribution which are both based on the same single switch of figure 1. The average delay of periodically transmission is 57us while the passion distributed is 40us when 4 intelligent terminals access the switch. The delay becomes 86us and 62us separately when 8 intelligent terminals access the same switch. When the 8 intelligent terminals access the switch which cascaded with another switch as figure 2, the average delay of periodically transmission and passion distribution become 124us and 102us separately. When the same 8 intelligent terminal access the switch as figure 3, the average delay of both is nearly the same as 165us.

It can be found that the more intelligent terminals accessed or the larger of the traffic load in the same network, the difference of simulation result between periodically transmission and passion distribution will be less. The delay of each IED accessed with the network is different and they are similar to arithmetic progression which means that the sum of the best delay and worst delay is almost equal the twice of average delay (This is not accurate, but is useful to estimation). Take the simulation based on the figure 2 for example, the delay of each intelligent terminal is 57us, 78us, 98us, 120us, 142us, 162us, 185us and 202us, the average delay, calculated with best delay of 57us and the worst delay of 202us, is nearly 130us, it is very closed with 124us of simulation.

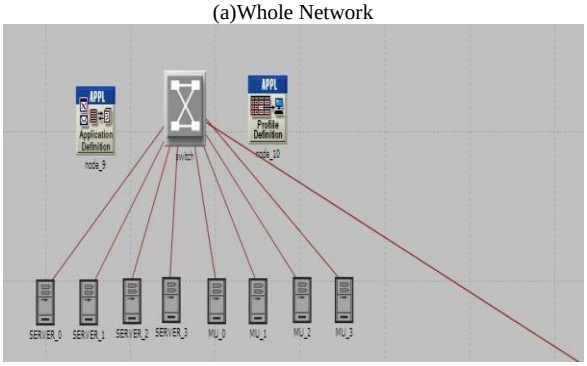
C. *Simulation of shared network*

The simulation of shared network about SV and GOOSE is based on the figure 3 which is typical topology widely used in smart substation. Firstly, 4 merging unit and 4 intelligent terminals are accessed with the network, the length of SV is 126 byte and will be periodically published based on the video conference and is set as 4000 packet/s. About the GOOSE model, the possion distribution is selected because there is little difference between periodically transmission and possion distribution. In this situation, the SV packet and GOOSE packet will affect each other. The average delay is 63us when the GOOSE is not trigged. When the GOOSE generated, the delay become 64us. Of course this delay is more likely about the SV not GOOSE, because the GOOSE packet is taken as the background traffic. But when we change the focus on the intelligent terminal, the delay is similar with calculation.

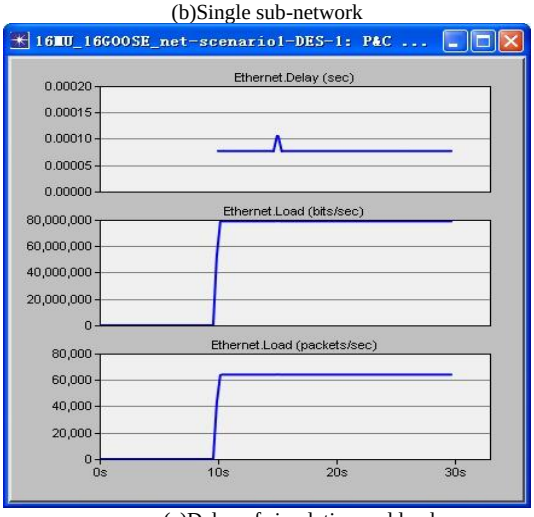
In order to simulate the real situation of smart substation, 16 bays mean that 4 separately sub networks which access 4 merging units and 4 intelligent terminals are simulated. The structure of model is as (a) and (b) of figure 5. Figure (a)is the whole network which is composed with 4 sub-network. Figure (b) is the detailed structure of sub-network:



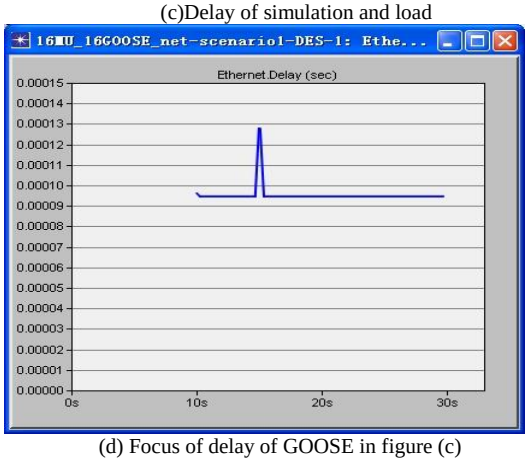
(a)Whole Network



(b)Single sub-network



(c)Delay of simulation and load



(d) Focus of delay of GOOSE in figure (c)

Fig.5 Simulation about the delay of GOOSE

Figure(c) is the average delay and the ehternet load though packeks/second and bandwidth/second sepeartely. Figure (d) is the focus of the average delay. According to the simulation of (c) and (d) of figure 5, the average delay is 95us when the GOOSE is not trigged, but it became 128us when the GOOSE

packet is generated, after a short time, it become 95us again when GOOSE packets become stable. The reason of the increment of average time is the queuing time caused by the GOOSE packet. This delay is also about the SV, but for GOOSE packet, the delay of each IED of these 16 intelligent terminals is from 110us to 750us. The worst delay of simulation is 750us which is closed to the 866.88us of calculation. It should be stressed that, the requirement about the transmission delay of GOOSE used to trip in IEC61850 is less than 3ms, so, there is still large margin.

D. Simulation of VLAN

The VLAN（Virtual Local Area Network）is widely used to separate the network to reduce the quantity of packet of net port of switch and reduce the delay of queuing. The VLAN_10 and VLAN_20 are divided based on the network of figure 3, each switch is a separated VLAN. According to the simulation, it can be found that the average delay reduces to 53us from 63us. Although the VLAN can reduce the delay of network, it is hard to find the quantitative relationship between them.

IV. TEST IN THE LAB ABOUT TRANSMISSION DELAY

The test about real-time performance of GOOSE network can be found in the reference 13 which provides some test schemes to verify the performance of GOOSE and reference 5 which takes a test in the substation to approve that the real-time performance can meet the requirement of project. Although these research are very helpful to understand the real-time performance of GOOSE, the test scenarios are not full and some extreme scenarios are not included, it makes the research is not sufficient. In order to verify the performance of real-time performance of GOOSE further, the test environment is built in the lab for the test. Considering the focus is on the comparison between trip through network and direct connection, the sampling value is point-to-point connection with optical fiber. Several merging units are used to as background because the limit of traffic generator which can only generate 88Mbit/s of each port. As the dual physical A/D is required by SGCC, the length based on the IEC61850-9-2LE will be extended as the voltage and current become dual, so the length is 217byte of each frame and the bandwidth is nearly 6.99Mbit/s according to the sample rate of 80 point per cycle in 50Hz. The quantity of merging unit used to generate the background traffic can be adjusted according to the need. About the GOOSE packet, the priority is set as 6 which is the default value.

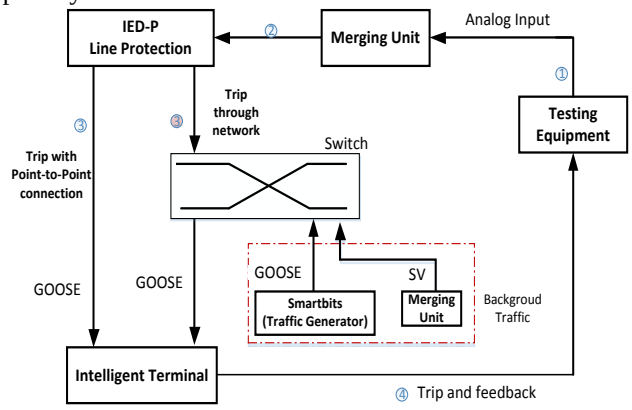


Fig.6 Test scheme of trip with single switch and direct connect model

In order to compare with the performance of trip through network and directly connection of figure 6, eight test schemes are designed as below：(relay protection IED shorted as P-IED)

1) The P-IED trips through directly connection. **(Scheme 1-Directly Trip)**
2) The P-IED trips through GOOSE network without the background traffic.**(Scheme 2-Network Trip)**
3) The P-IED trips through GOOSE network with the background traffic that 88Mbps are generated by the traffic generator and another 2 merging units are used to generate nearly other 14Mbps to reach the 100Mbps, no priority of packet.**(Scheme 3-Network Trip (Priority 6)+88M*GOOSE+2*MU(No Priority))**
4) The P-IED trips though GOOSE network and priority is set as 6, 70Mbps background traffic is generated with the priority of 7. **(Scheme 4-Network Trip (Priority 6)+70M*GOOSE(Priority 7))**
5) The background traffic increase to 88Mbps based on scheme 4 above. **(Scheme 5-Network Trip (Priority 6)+88M*GOOSE(Priority 7))**
6) The background traffic increases to 100Mbps based on scheme 5 and another 2 merging unit which the priority of SV packet is set as 7. **(Scheme 6-Network Trip (Priority 6)+88M*GOOSE(Priority 7)+2*MU(Priority 7))**
7) The background traffic increases to 115Mbps based on scheme 6 above and another 2 merging units which the priority of SV packet are set as 7. **(Scheme 7-Network Trip (Priority 6)+88M*GOOSE(Priority 7)+4*MU(Priority 7))**
8) The P-IED trips through GOOSE network and the priority of GOOSE packet is set as 6, the background traffic is injected through two net ports of traffic generator at the same time which the priority of GOOSE packet is set as 7 and the whole traffic will reach176Mbps. **(Scheme 8-Network Trip (Priority 6)+88M*GOOSE(Priority7)+88M*GOOSE(Priority 7))**

According to the test schemes above, the result is as below：

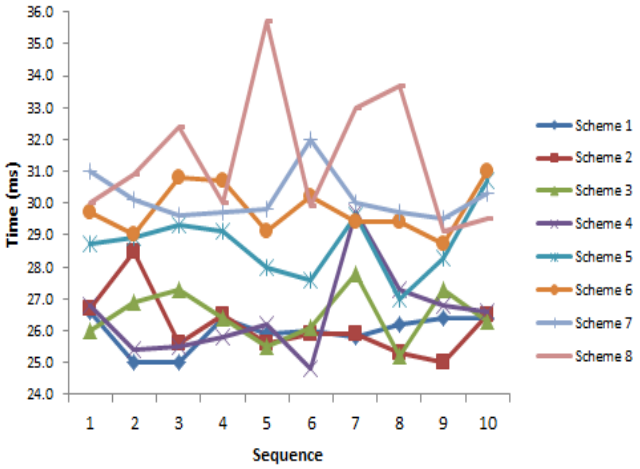


Fig.7 The test result of action time for single switch

From the test result of figure 7, it can be found that, the delay of trip through directly connection and network is nearly the same based on the scheme 1 and 2. Even in the 100Mbps background traffic situation as scheme 3, the difference

between them is little, just 0.3ms. But when the priority of background traffic is higher than the GOOSE packet which is used to trip, the result becomes obvious. When the background reach 70Mbps as scheme 4, there are not difference, but when the background reach 88Mbps as scheme 5 ,the delay of trip though network increase 2ms. Although the time of delay is not stable, the jitter is still in the scope that can be accepted, because the whole time of closed-loop test (from SV to trip) is still less than 30ms required by SGCC for line protection. When the background traffic reaches 100Mbps as scheme 6, although the average time delay is 29.8ms, overrun time (exceed 30ms) appear several times. When the background traffic exceeds 100Mbps as scheme 7 and 8, the average time delay exceed 30ms. So, the performance of real time of GOOSE network cannot be accepted in the scheme 6-8.

In fact, the test schemes of 6-8 are very critical especially the scheme 7 and 8, as the whole traffic of independent GOOSE network or shared network including GOOSE and SV will not exceed the 100Mbps in normal situation. Even in the situation of network storm, the priority of background traffic will not exceed GOOSE, because the priority of GOOSE packet used to trip is set as the highest priority in substation. So, it can be found that the trip through GOOSE network is feasible. At the same time, VLAN is widely used to split the network to reduce the latency of network in smart substation, it will improve the performance and reliability of GOOSE.

In order to test the performance of GOOSE network further, another switch is added into the network in figure 8 which means that the trip command of GOOSE will transmit two switches as figure 3. The step 1 and step 2 in figure 3 are used to provide the sampling value, about the step 3, there are two different ways, one is directly trip based on point-to-point connection from relay protection to intelligent terminal, and the other one is trip through the network.

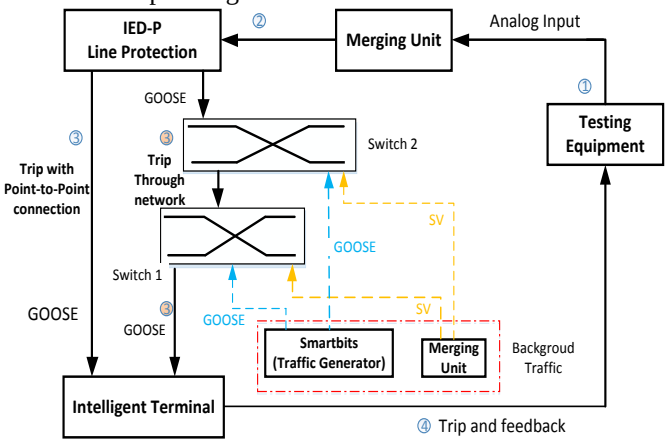


Fig. 8 Test scheme of trip with cascading switches and direct connect model

In order to test the performance of cascading switches, the test schemes are as below:

1) the P-IED trips though GOOSE network without the background traffic.(**C-Scheme 1-Network Trip**)
2) the P-IED trips though GOOSE network with 100Mbps background traffic injected to switch 1, 88 Mbps are generated by the traffic generator and another 2 merging units are used to generate nearly 14Mbps，the priority of them are set the same. (**C-Scheme 2- Network Trip (Same Priority)+88M*GOOSE(Same Priority)+2*MU(Same Priority)**)
3) the P-IED trips though GOOSE network and the priority is set as 6, 100Mbps packet are generated by traffic generator and another 2 merging units from switch 1, the priority of traffic are set as 7（**C-Scheme 3-Network Trip(Priority 6) + 88M GOOSE(Priority 7) + 2*MU（Priority 7)**）
4) The P-IED trips through GOOSE network and the priority of GOOSE packet is set as 6, the background traffic is injected through switch 1 and switch 2 separately from traffic generator at the same time, the priority of GOOSE packet is set as 7 (**C-Scheme 4-Network Trip (Priority 6) + 88M*GOOSE (Priority7) +88M *GOOSE(Priority 7)**)

According to the test scheme above, the test result is as figure 9 below:

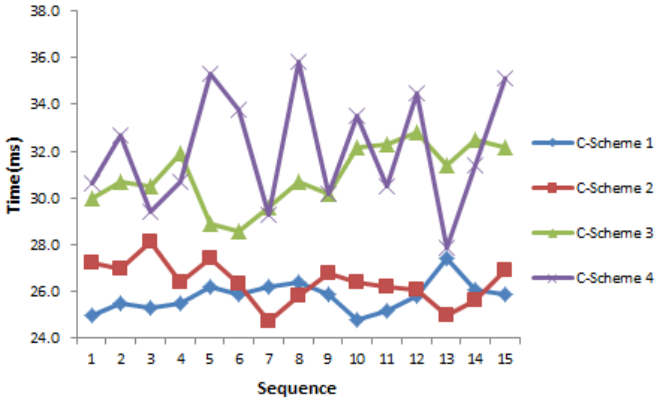


Fig.9 The test result of trip time for cascading network

From the test result of figure 9, it can be found that, even with cascading switch scheme and the background traffic reach 100Mbps without priority as C-Scheme 1 and 2, the delay of trip through GOOSE network can meet the requirement. But when the background traffic of GOOSE packet with the priority is higher than the normal real GOOSE packet of trip such as C-Scheme 3and 4, the whole action time will exceed 30ms in most of time and become not stable. This result is the similar with figure 7.

Then, take a comparison about the single switch and cascading switch which are responded to Scheme1-8 and C-Scheme 1-4. The average action time of different test scheme is as below:

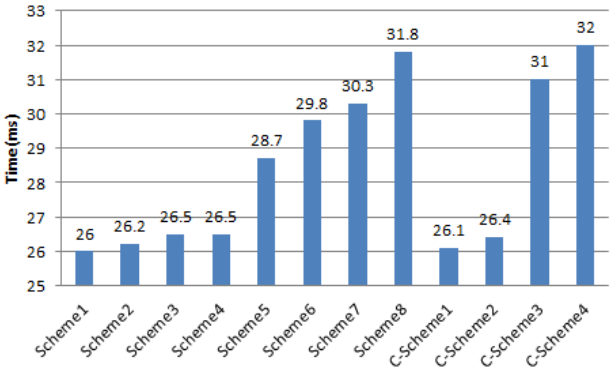


Fig.10 The average action time of different test scheme

From figure 10, it can be seen that, the average action time of scheme 7 ,8 and C-Scheme 3，4 exceed 30ms and cannot meet the requirements of relay protection. Although the action

time of scheme 5 and 6 do not exceed 30ms, they are not stable and sometime the whole action time has exceeded the 30ms during the test. The difference between scheme 5 and 6 is that the background traffic is 70M bps and 100M bps. In order to make sure the high reliability and stability, the scheme 5 and 6 are still considered not to meet the requirements. Take the analysis of Scheme 5-8 and C-Scheme 3-4, it can be found that they have a common character that the priority of GOOSE packet generated as background traffic are higher than normal trip GOOSE packet, it is obvious that this situation is not possible in real substation as the GOOSE packet of trip should have the highest priority among all the different types packet in substation. So, it can be seen that the trip through GOOSE network can meet the real need of substation. The difference about the whole action time between direction trip and network is little, just 0.2ms according to scheme1 and scheme 2 .

V. TEST ON SITE ABOUT THE TRANSMISSION DELAY

In order to understand the performance of trip through GOOSE network further, the test on site is considered and a 500kV substation which has finished all the tests and is ready to put into operation is selected. The test is carried on the 500kV voltage which is one and half topology. As the relay protection is required as point-to-point way about the sampling and trip, there is no network for relay protection except the measure& control device (Also called as Bay Control Unit). Change the connection of trip between relay protection and intelligent terminal and reconnect it with the network for measure & control device. The structure is as below:

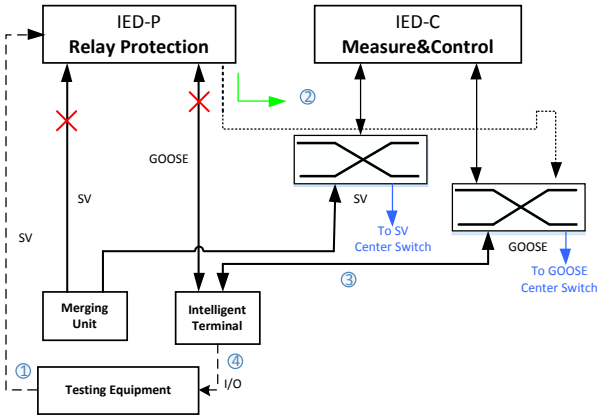


Fig.11 The test scheme on-site

From the figure 11, it can be seen that, the SV of relay protection is still point-to-point way but the merging unit is replaced by the testing equipment as step 1. The trip of relay protection is replaced by the new connection with switch (network of GOOSE) as step 2. In order to make sure the safety of substation, the real control circuit between intelligent terminal and circuit breaker is disconnected, the output of intelligent terminal will connect with testing equipment to build a closed-loop as step 4. The overcurrent protection function is selected with the setting of current is 1 A and the fault current of input is 2A to make the relay protection more sensitive.

In figure 11, it can be seen that, the whole action time from sampling to trip of point-to-point way should be less than trip though network for the delay of network. Although the GOOSE network do not has large traffic, the latency of switch and the queuing time of packet will affect the transmission delay. The test is carried out as pairs test which means “one direct trip and one network trip”, every 10 time tests as a group. Each group is similar and takes one group as example:

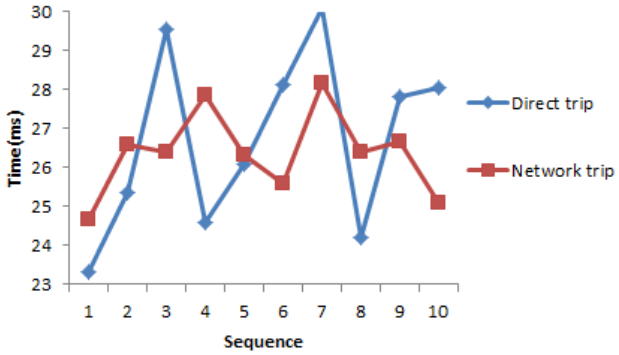


Fig.12 The on-site test result

From the figure 12, it can be seen that there are two typical appearances. One is that the whole action time is not stable for both direct trip and network trip. The reason may be the discreteness of action of relay in the intelligent terminal which cannot be avoided. The typical action time of intelligent terminal should not exceed 7ms according to the requirement of SGCC considering the action discreteness of relay for 3-5ms in the intelligent terminal. The other one is that the delay of network trip is more stable than direct trip, and most of time the network trip is faster than direct trip, which is inconsistent with the analysis above. Take each group of test to analysis, the average action time of direct trip and network trip is 26.73ms and 26.51ms separately. Even delete the biggest and smallest delay value in each group, the average time of direct trip and network trip is still 26.725ms and 26.3625ms separately. It can be found that the delay of trip though network is less than trip through directly connection as 220us-360us. The reason may be caused by the internal data exchange of multi-port of IED. As the relay protection is required as directly connection with sampling and trip, so, not only the relay protection, even the related merging unit and intelligent terminal are required at least eight ports to meet the need of point-to-point connection in engineering project according to the requirement of SGCC. Unfortunately, most of network chip of IED only support two default net ports, in order to realize eight net ports, the extended board which is used to make a copy of the packet to realize the multi-ports communication is widely used in IED as below:

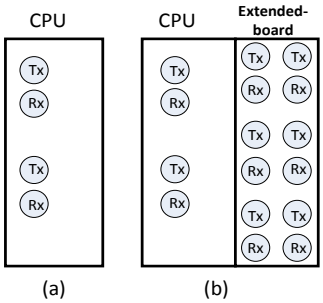


Fig.13 The structure of CPU board of IED

From the figure 13, it can be seen that (a)is the typical structure of IED for network communication and (b)is the typical structure of IED for point-to-point connection which has another extend-board to meet the multi-ports requirement. This means that there will be additional time for data exchange between CPU board and extended board for the design of

multi-ports, which increase the transmission time about the point-to-point connection. So, the sending of relay protection and the receiving of intelligent terminal with point-to-point way in closed-loop test cause the test results as figure 12. It can be found that the point-to-point way is not as well as expected, and most of time it is not better than trip through GOOSE network. Considering the point-to-point way increase the cost of IED and the multi-ports cause the serious heat of IED that affect the operation stability of IED, it seems that this way is being rejected by the operation engineer. In this situation, the trip through the GOOSE network becomes more suitable.

VI. Discussion about reliability

Another reason of rejection about the application of trip through GOOSE network is the reliability. The experts of relay protection in China worry about the reliability of network and think that the direct connection with optical fiber is more reliable. From the analysis of reliability theory, it is truth that the reliability of optical fiber is higher than switch. Although the MTTF(Meant Time To Failure) of optical fiber in China is different from aboard, the shortest time of them is more than 50 years. At the same time, the MTTF of switch is also more than 50 years for most manufactures in the world. In China, the life of IED is required at least 20 years, but in fact, in most of specification of IED for smart substation, the life is required as more than 12 years and the MTTF should exceed 4.5 years. From all the segments of closed-loop test of trip through network, the bottleneck of reliability is the IED itself, so the worry about the switch should not be overstated.

In the point of view of author, although the reliability of direct trip is higher than trip through GOOSE network, both of them can meet the requirement of project. In current situation of China, the vulnerability of smart substation is not the switch or network but the IED. This means that the direct trip of relay protection do not improve the whole reliability of substation. As the same IED, the reliability of direct trip and trip through GOOSE network is nearly the same based on the theory calculation. In order to avoid the repetition, the detailed calculation about reliability can be seen in the reference 14-16. So, the reliability should not be the reason to reject the trip through the GOOSE network.

VII. Conclusion

According to the calculation of transmission delay, the simulation of OPNET, the test in the lab and on-site, and the reliability analysis at last, the trip through GOOSE network can meet the performance requirements of relay protection on real-time and reliability. The conclusion is as below:

1) The real time performance can meet the requirement even in the background traffic of 100Mbps with the same priority of trip packet of GOOSE. In fact, the priority of trip packet of GOOSE should have the highest priority among all the packets in substation.

2) The VLAN which is widely used can improve the performance of real time of GOOSE further, it can provide additional assurance for the application of trip through GOOSE network.

3) The reliability of switch is higher than relay protection IED. The vulnerability of smart substation is not the switch but the IED.

4) The test on site approve that the trip through GOOSE network is faster than direct trip. The reason is that internal data exchange between main CPU board and extended board.

In the all, the trip through GOOSE network is feasible and should be recommended in the construction of smart substation of China.

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