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Structure Design and Performance Analysis of Substation Area Backup Protection Communication Network in Smart Substation

***Abstract**. In this paper, the general design of substation area backup protection (SABP) communication network in smart substation is proposed, and taking a practical 220kV smart substation for the application object, the communication network's specific structure is constructed. Besides, the specific network's real-time performance is studied based on theoretical analysis and OPNET simulation, and its reliability is calculated according to reliability block diagram and fault tree combining with Bayesian technology. The results show that the two performances can meet the requirements.*

***Streszczenie.** W artykule przedstawiono projekt sieci komunikacyjnej na potrzeby rezerwowego systemu zabezpieczeń w obszarze inteligentnej podstacji elektroenergetycznej. Proponowaną strukturę sieci zaimplementowano dla inteligentnej podstacji 220kV. Przeprowadzono także symulacje (OPNET) i analizę teoretyczną wydajności sieci w czasie rzeczywistym oraz parametrycznie określono jej niezawodność. (**Projektowanie struktury i analiza działania sieci komunikacji na potrzeby rezerwowego systemu zabezpieczeń w obszarze inteligentnej podstacji**).*

Keywords: Smart substation, substation area backup protection (SABP), information communication network, performance analysis.
Słowa kluczowe: podstacja inteligentna, rezerwowy system zabezpieczeń podstacji, sieć komunikacyjna, analiza wydajności.

Introduction

Smart grid is the latest development trend of power industry, and it reflects the integrated application of new techniques. As part and parcel of smart grid, smart substation adopts a lot of advanced, environmental-friendly and intelligent devices, for instance, electronic instrument transformer and smart terminal. Combining with the use of high-efficient Ethernet switch, smart substation can be built with whole digital information, networked communication platform and data standardization sharing as its basic characteristics, to achieve the functions such as automatic data acquisition, measurement, metering, control and protection [1, 2, 3]. The application of the above mentioned digital and networked technologies may contribute to simplifying the original data acquisition method, and a uniform data sharing and exchanging platform based on IEC61850 standard will be established. Then, the information isolated island can be eliminated [4, 5], and it will be conductive to the optimization allocation of substation secondary functions. For example, the whole smart substation can be taken as a protection object to allocate its protection functions. Accordingly, the concept of a centralized type substation area backup protection (SABP) using the networked redundant instation information was proposed, and the feasibility of this type backup protection has been preliminarily confirmed [6, 7].

Since the construction of smart substation has just begun in China, the study on the centralized type SABP is relatively less, and the existing research mainly focuses on designing its protection algorithm [8]. As the foundation for implementing the SABP, an information communication network with high performance is undoubtedly needed. The SABP's rapidity will have a direct relation with its related communication network's real-time performance, and the network's reliability will largely affect the reliable operation of the SABP.

This paper discusses the structure planning and performance analysis of the communication network where the SABP can receive and send messages. The principle and characteristics of the SABP and its requirements for the network performances are introduced firstly, and then the general design of the SABP communication network is presented. Furthermore, taking into account a practical 220kV smart substation, the SABP communication network's specific structure is constructed. Based on switch communication theory and OPNET simulation, the time-delay of the networked messages including sampled values (SV) and generic object oriented substation event (GOOSE) are both estimated. According to reliability block diagram and fault tree combining with Bayesian technology, the network's availability is also calculated.

Principle and Characteristics of the SABP

The SABP's schematic diagram is shown in Fig. 1, and a configuration scheme of duplicated SABP located in the bay layer is applied to enhance the device reliability.

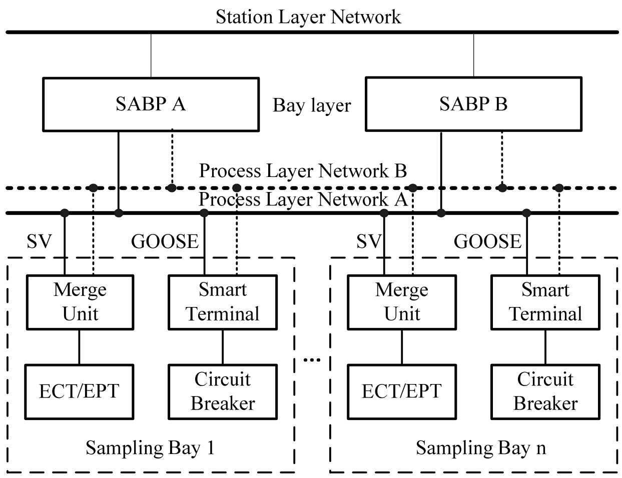

Fig.1. Schematic diagram of the centralized type SABP

On the basis of the process-layer network indicated in Fig. 1, the SABP can expediently collect the substation area information, including the currents and voltages of local electric elements, each circuit breaker's switching status and main protection's action situation. According to multiple algorithm treatments for the required redundant information, the comprehensive fault judgment can be enforced. Consequently, an optimized tripping strategy can be carried out. In a sense, the SABP is similar to wide area backup protection (WABP), but different from it under the range of information sharing and protection object.

Owing to the integration of the whole substation information, the selectivity of the SABP will be undoubtedly better than the traditional backup protection which only protects single electrical element and lacks effective synergy [9]. On the side, due to avoiding the step-by-step cooperation of protection value and action time, the SABP's rapidity will be superior to the conventional backup protection whose operation time may be up to a few seconds [10], as a result of reducing the fault clearance time and increasing the stability of power system.

In the light of the fault direction information matrices coming from the SABP's action algorithm, the circuit breaker failure protection (CBFP) preventing expansion of accidents because of miss operation of the breaker can be realized effectively and conveniently. It is meaningful to the medium voltage and low voltage bus-bars lacking CBFP.

Based on the above presentation and analysis, adpoting the SABP can enhance the performance of existing backup protection. But currently it is not suitable for changing the operation principle and information acquisition mode of main protection by using the sharing network. Since the main protection shall achieve a simple, fast and reliable operation according to its local information, the widely used point-to-point mode is suggested to be reserved for it.

Structure Design of the SABP Communication Network

Among the performance indexes of substation communication network, the real-time, synchronization accuracy and reliability are relatively important, and the SABP's demands for them are briefly expounded as follows.

1) The SABP communication network shall have the abilities of receiving and sending SV and GOOSE messages instantly. According to IEC 61850 protocol [11], the transmission time-delay limitation for SV message is less than 3ms, and 4ms for GOOSE message.

2) So as to ensure the correct operation of the SABP, the communication network shall have outstanding synchronization accuracy. In accordance with IEC61850 protocol, the synchronization accuracy of process-layer network shall reach a microsecond (μs) level. For satisfying this requirement, the time synchronization system based on IEEE1588 which can achieve a sub-microsecond level accuracy, may be applied [12, 13, 14].

3) To guarantee the availability of substation information acquisition, the redundancy technology which refers to multiple duplicate paths in a network may be used, and the communication path numbers between any two network nodes should be not less than two. Moreover, the SABP communication network needs to have the capacity of state self-checking. In case of a communication failure, the alarm signal can be transmitted to the SABP in time for executing an interlock function.

According to the defined network performance requirements, Fig. 2 shows the general design of the SABP communication network. The general SABP network's main structure is selected as star-like type for ensuring its real-time, maintainability and reliability to a certain extent. Taking network redundancy function and construction cost into consideration, the dual-star structure with redundancy is established in the high-voltage (HV) and medium-voltage (MV) sub-networks, and the single-star structure is arranged in the low-voltage (LV) sub-network.

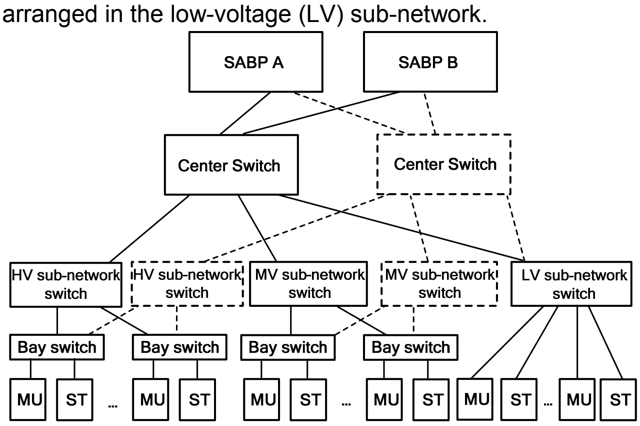

Fig.2. General design of the SABP communication network

Supposing that the sampling rate of merge unit (MU) for relay protection device is 4000 Frame/s, the SV message (IEC 61850-9-2 frame format) traffic of each MU is approximately 7 Mbit/s [15]. Under normal condition, the GOOSE message traffic of smart terminal (ST) is very small (0.02 Mbit/s). According to [16], the SV and GOOSE messages can be transmitted in a same communication network. Thereby, aiming at the substation's each (or each two) high-voltage/medium-voltage bay(s), a bay switch can be configured to reailze the shared-network transmission of the two messages. Directing at the low-voltage sampling bays, the bay switch is ignored, and the sub-network switch is used for playing this role to improve the economy of network construction. Besides, the virtual local area network (VLAN) technology which is the one can be divided into a lot of networks which broadcast the land with independent logic, may be adopted to carry out the data isolation and control the network flow.

A practical 220kV smart substation is chosen here for the SABP's specific application object, and the substation's main connection structure and bay layout are shown in Fig. 3. From the figure, the numbers in those parentheses denote the allocated sampling bays. The sampling bays of the 220kV substation can be divided into four types: 1) Line bays. They are composed of four 220kV transmission lines (L1_220~L4_220), five 110kV transmission lines (L1_110~L5_110), and fourteen 10kV feeder lines (L1_10~L14_10). 2) Bus-bar bays. They include 220kV, 110kV and 10kV buses, named as Bus_220, Bus_110 and Bus_10. 3) Transformer bays. They are consisting of T1 and T2, and each transformer bay includes three MUs and three STs coming from its high voltage, medium voltage and low voltage sides. 4) Bus-couple bay and section-switch bay, named as BC_110, SS_220 and SS_10.

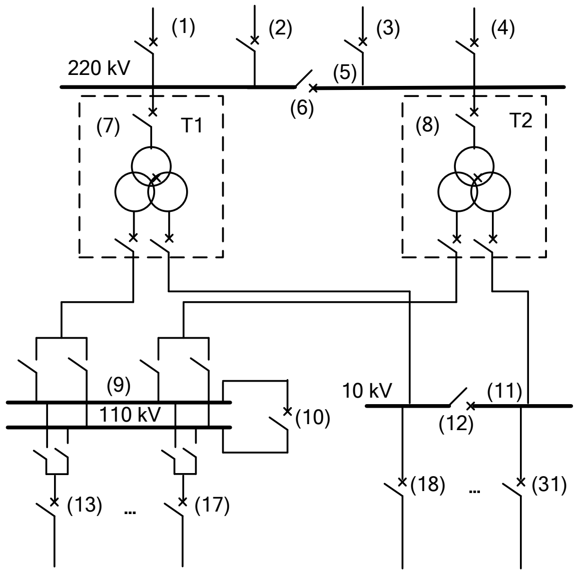

Fig.3. Main structure of a practical 220kV smart substation and its bay layout

Based on the general design, the specific design of the SABP communication network for the practical 220kV smart substation is shown in Fig. 4. The switches SW1~SW2, SW3~SW4, as well as SW5~SW9 are respectively used for the data communication in the 220kV sub-network, 110kV sub-network as well as 10kV sub-network. SW10 is the center switch summarizing all the SV and GOOSE messages inside the smart substation. Moreover, a bay switch is configured at each high-voltage/medium-voltage bay. The network bandwidth of SW1~SW9 and the bay switches will be 100 Mbit/s. Since the data traffic of SW10 may be relatively large, its network bandwidth will be chosen as 1000 Mbit/s to reduce the rate of package loss and enhance the communication capacity. Below is the network performance analysis on real-time and reliability.

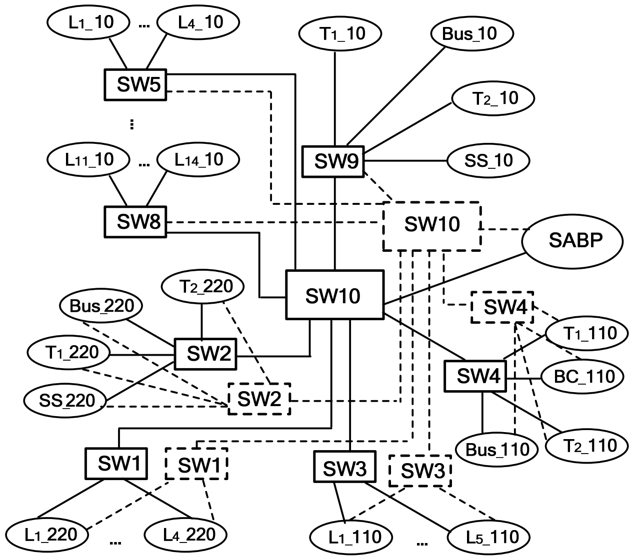

Fig.4. Specific design of the SABP communication network for a practical 220kV smart substation

Network Real-time Analysis

As shown in Fig. 5, it signifies the substation message transmitting procedure [17]. The real-time performance of the networked SV and GOOSE messages may depend upon the four factors: store-and-forward process delay, data exchanging delay, data queuing delay and fibre transmission delay. The preceding three kinds of delays will have direct relationships with message type and switch capacity, and the last one will mainly rely on fibre length.

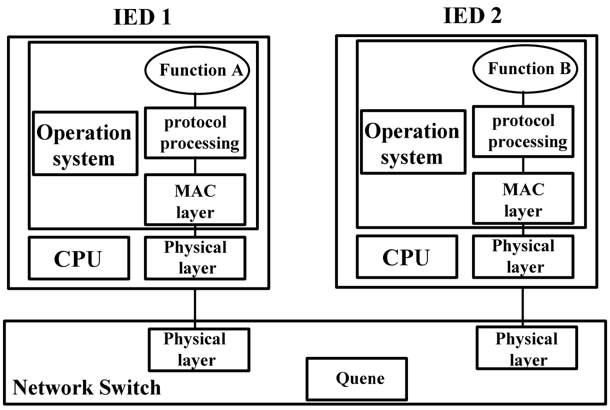

Fig.5. Substation message transmitting procedure.

According to the communication theory of modern switch, its store-and-forward process delay (T_{SF}) can be expressed as the ratio of message width to transmission rate. The SV message's frame length is about 1744 bits, and for the switches SW1~SW9, $T_{SF\text{-}SV\text{-}100}$ is 1744/10^2 =17.44μs, and for the switch SW10, $T_{SF\text{-}SV\text{-}1000}$ =1.744μs. As the GOOSE message's frame length is approximately 230bytes (1840 bits) [18], the delay $T_{SF\text{-}GOOSE\text{-}100}$=18.4μs and $T_{SF\text{-}GOOSE\text{-}1000}$=1.84μs.

The data exchanging delay (T_{DE}) of each switch is actually constant, and its value will depend on the processing time of relevant data operations, such as switch chip dealing with MAC address table and VLAN. In general, T_{DE} can be defined as 7μs. By contrast, the queuing delay (T_Q) of switch is floating. Supposing that a switch has K ports, its longest data queuing delay will be $(K\text{-}1)T_{SF}$, and the shortest delay may even be zero. The transmission delay of optical fibre (T_{FT}) is equal to fibre length divided by two thirds of light velocity, and when the length is 1km, T_{FT} will be roughly 5μs.

Table 1. Theoretical delay calculation of the networked SV and GOOSE messages

Message Type	Real-time performance [μs]	
	Without VLAN	With VLAN
SV	375	81
GOOSE	393	84

In the case that the transmission path of the networked SV and GOOSE messages will pass through N switches, and the theoretical cumulative time-delay (T_C) can be expressed as $T_C= N(T_{SF}+T_{DE}+T_Q)+T_{FT}$. Supposing that each switch has 18 data ports and the total length of the fiber connecting these switches is 1 km. According to the time-delay computational formula, the theoretical real-time characteristics of the networked SV and GOOSE messages are estimated, as shown in Tab. 1, where the conditions with and without VLAN are both considered.

In order to verify the theoretical calculation's correctness and observe the real-time performance of the designed SABP communication network more clearly, the simulation model of the designed process-layer network is constructed using OPNET software. The OPNET simulation platform's working mechanism is based on a three-layer design model, and the three layer models are respectively network model, node model and protocol model. The network model consisting of node models and switch should be according to the network structure of simulation object, and the node model should include protocol modules and define the data direction among these modules.

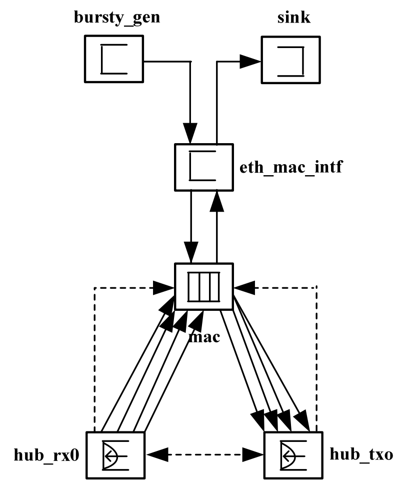

Fig.6. Node model of GOOSE message in OPNET platform.

For the SABP communication network as shown in Fig. 4, the SV and GOOSE node models should be built. Taking the latter for an example, its node model is shown in Fig. 6. It can be observed that, the GOOSE node model will include six sub-modules, and they are respectively named as bursty_gen, sink, eth_mac_intf, mac, hub_rx0, hub_tx0. The module bursty_gen is used for generating and sending the GOOSE message. The module sink is used for receiving and managing the GOOSE message. The module eth_mac_intf undertakes the functions of sending the GOOSE message to the MAC layer and obtaining some feedback information from this layer. The module mac is designed for achieving the MAC protocol and assigning the message transmission from high-level to low-level. The modules hub_rx0 and hub_tx0 are applied for receiving and sending the underlying data.

Under the conditions with and without VLAN, the time-delay characteristics of the networked SV and GOOSE messages are respectively simulated, as shown in Fig. 7.

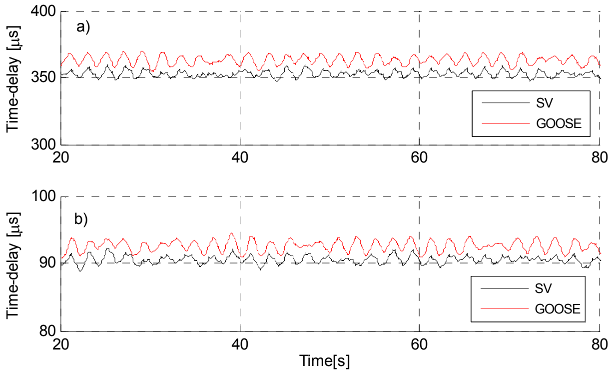

Fig.7. Time-delay simulation characteristics of the networked SV and GOOSE message: (a) without VLAN, (b) with VLAN.

After observing Tab. 1 and Fig. 7, it can be ascertained that the simulation results and theoretical study agree well with each other.

Before the SV and GOOSE messages coming from each bay are transmitted to the SABP, the information path shall be across two 100M/bits switches and one 1000M/bits switch. For example, when the SABP needs to obtain the message data in the bay L1_220, the bay switch, the sub-network switch SW1 and the center switch SW10 will be included in the communication path. Although the real-time performance without VLAN can satisfy the communication demand, after using VLAN technology, the total time-delay will drop dramatically due to the decrease of the data queuing delay, and assuredly it is beneficial to enhancing the SABP's rapidity.

Network Reliability Calculation

In accordance with IEC 60870-4 standard, reliability is described as a measure of the ability of equipment or a system to perform its intended function under specified conditions for a specified period of time. The designed process-layer network's reliability can be studied by the following indexes [19].

1) The degree of reliability $R(t)$. $R(t)$ is the probability of equipment or a system completing fixed process under the certain condition and the certain time. In general, its failure distribution is according to an exponential function. Supposing that λ is the failure rate of equipment, $R(t)=e^{-\lambda t}$ and where $t>0$.

2) Mean time to failure (*MTTF*) and mean time between failures (*MTBF*). *MTTF* means an estimate of the average time until a design's or component's failure. Mean time to repair (*MTTR*) is a basic measure of the maintainability of repairable items, and it represents the average time required a failed component or device. *MTBF* is the predicted elapsed time between inherent failures of a system during operation. The mathematic relation between the indexes can be described as *MTBF= MTTF+MTTR*.

3) Availability (*A*). *A* is typically measured as an important factor of reliability, and this is often described as a mission capable rate. The equation of a system's availability is *A=MTTF*/(*MTTF+MTTR*). The connection relationship between multiple devices or systems can be approximately divided into two categories, and they are series and parallel connections. In the case that a system is composed of *M* devices and the availability of single device is A_i (*i*=1,2,…,m), the series system's availability will be calculated as $A=\prod A_i$ (*i*=1,2,…,m), and the parallel-type system's availability will be described as $A=1-\prod A_i$ (*i*=1,2,…,m).

4) Unavailability (*U*). *U* can be calculated as $U=1-A=MTTR/(MTTF+MTTR)$.

Aiming at the designed SABP communication network's three sub-networks, the reliability of each sub-network corresponding to a substation voltage level is respectively calculated, and further the whole network's reliability is estimated. As shown in Tab. 2, it denotes the reliability data of the smart substation components. According to the detail file provided by device manufacturer, the *MTTF* of single switch can be up to 50 years, and its failure rate is 0.02. Besides, supposing that the used network media's failure rate is lower and the value is 0.001.

Table 2. The reliability data of the smart substation elements

Component	Failure rate	MTTF [year]	Unavailability
Switch	0.02	50	54.792×10^{-6}
Optical fibre	0.001	1000	2.7397×10^{-6}

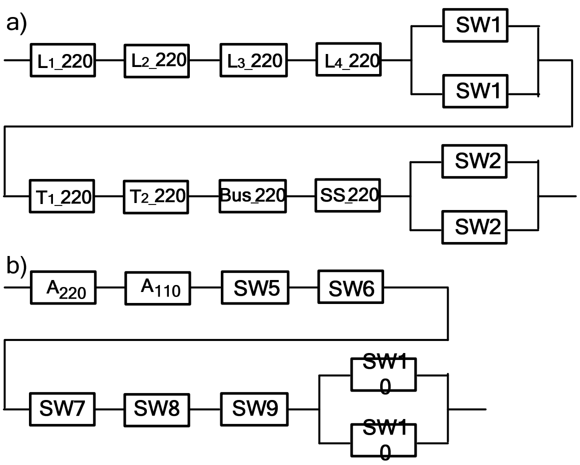

Fig.8. Reliability block diagram of the designed SABP communication network: a) 220kV sub-network, b) whole network.

Since the 220kV level sub-network's structure scheme is the same as 110kV level, the reliabilities of these two sub-networks can be analyzed using a uniform calculation method. As shown in Fig. 8 (a), it indicates the reliability block diagram of the 220kV level sub-network, and the availability can be calculated as:

$$A_{220}=(A_{Sw})^8\times[1-(1-A_{Sw})^2]^2\times(A_{Fiber})^{16}=0.9995179 .$$

The availability of the 110kV level sub-network is

$$A_{110}=(A_{Sw})^9\times[1-(1-A_{Sw})^2]^2\times(A_{Fiber})^{18}=0.9994576 .$$

For the 10kV level sub-network, it can be thought of as a series-type information communication system, and its availability is that

$$A_{10}=(A_{Sw})^5\times(A_{Fiber})^{18}=0.9996768 .$$

Fig. 8 (b) shows the reliability block diagram of the whole communication network. The whole availability is calculated as:

$$A_{whole}=A_{220}\times A_{110}\times A_{10}\times[1-(1-A_{Sw})^2]\times(A_{Fiber})^{20} =0.9986036 .$$

In fact, once the reliability data of the smart substation elements are constant, the network's availability will be basically unchanged under different evaluation methods. For the sake of making the calculation results be more convincing, anther analysis method based on fault tree and Bayesian technology is adopted.

As shown in Fig. 9, it indicates the fault tree and Bayesian model of the 220kV level sub-network, where G1~G6 express the logical relationships.

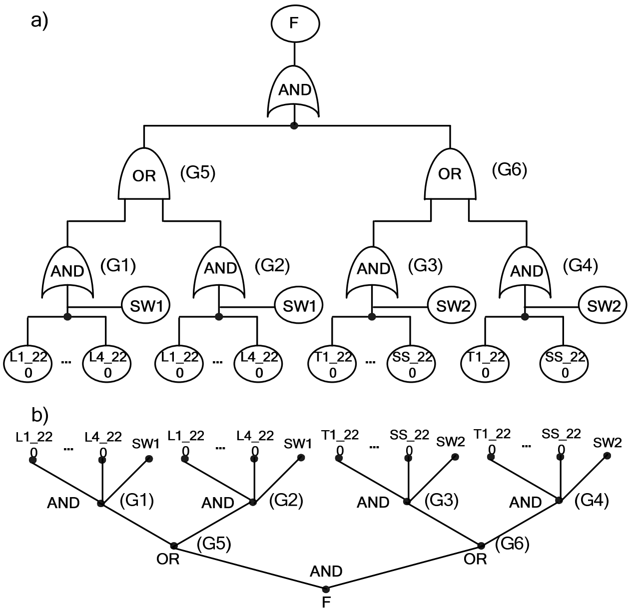

Fig.9. Fault tree and Bayesian model of the 220kV level sub-network: a) fault tree, b) Bayesian model.

The probability of the node F under normal state can be described as:

$$\begin{aligned} P(\mathrm{F}=1) &= P(G5=1)P(G6=1) \\ &= [1-P(G1=0)P(G2=0)][1-P(G3=0)P(G4=0)] \\ &= \{1-[1-P(G1=1)][1-P(G2=1)]\} \\ &\quad \{1-[1-P(G3=1)][1-P(G4=1)]\} = 0.82394 \end{aligned}$$

Where $P(G1=1)$, $P(G2=1)$, $P(G3=1)$ and $P(G4=1)$ have the same probability and the value will have close relationship with the failure rates of Ethernet switch and optical fibre. Since the node's probability is 0.82394, its failure rate will be 0.17606, and the corresponding *MTTF* and availability will be 5.68 years and 0.9995178. As a result, the validities of the calculation results based on reliability block diagram can be proved.

In the light of the reliability grade defined by IEC61508 standard, the availability level of each sub-network can reach the third stage (the fourth stage signifies the highest reliability), and the whole availability level will reach the second stage, it is basically ascertained that the designed SABP communication network has the capability of transmitting the whole substation information reliably.

Conclusions

In this paper, to promote the application of the SABP into a practical 220kV smart substation, the communication network which can achieve the process-layer information transmission and sharing is designed for the SABP, and further this network's real-time performance and availability are both studied. On the basis of analysis results, the real-time characteristics of the networked SV and GOOSE messages can meet the requirements defined by IEC61850 standard, and the designed network's whole availability can reach the second stage defined by IEC61508 standard. Nevertheless, during the network performance research, the work may be strengthened in some areas, and the impacts of the network's synchronization performance and IEEE 1588 technology on the SABP should also be considered in detail. These tasks will be performed in future.

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