 doi:10.20944/preprints201905.0199.v1

Article

Reliability Evaluation of Multi-Service in Power Wide Area Protection System Considering Network QoS

Kai Yuan [1], June Li [1,2]* and Kaipei Liu [1]

[1] School of Electrical Engineering, Wuhan University, Wuhan 430072, Hubei Province, China;
[2] Key Laboratory of Aerospace Information Security and Trusted Computing, Ministry of Education, School of Cyber Science and Engineering, Wuhan University, Wuhan 430072, Hubei Province, China
* Correspondence: jeli@whu.edu.cn; Tel.: +86-1898-681-3065 (J.L.)

Abstract: Based on the topology of wide area protection system(WAPS), after studying the reliability of hardware system and information flow in the WAPS and establishing the reliability assessment model, the multi-service reliability analysis method with multi monitoring and protection tasks in WAPS was proposed. In the model, the impact of network quality of service (QoS) such as information flow loss and delay, is studied. On the base of the model, the multi-service reliability evaluation method is employed to analyze the reliability of a WAPS of IEEE14 node power system, and the key nodes of the WAPS is given, which provides a basis for improving the reliability of the WAPS.

Keywords: wide area protection system (WAPS); reliability; Fault Tree Analysis (FTA) model; information flow; multi-service

---

1. Introduction

Wide area protection system (WAPS) is a basis for the safe and stable operation of large-scale interconnected power grid. Once the WAPS fails, the power grid may not be control and lead to collapse [1-5].The WAPS collects information (such as voltage, current, frequency, protection and control instruct etc.) of power system for analyzing its operation state. If control or protection events should occur, the control command will be sent to a control component of a domain protection system in substation to operate the power grid. The WAPS involves data acquisition device, protection device, communication network and information flow etc. The WAPS's Reliability would be decided by the reliability of the hardware and the information flow in it.

The reliability research of the WAPS was mainly focused on the reliability analysis of the equipment and components and system hardware, and ignored the impact of the reliability of the information flow [6-8]. Because the communication distance of the WAPS is long, the quality of service (QoS) problems such as packet loss, data error or delayed arrival is prone to occur in the transmission process, and the information flow reliability should not be ignored in studying the WAPS reliability.

In current researches about the WAPS reliability, the reliability calculating is cascade model, that is, a fault of any element means that the WAPS cannot normally operate[9-10].In facts, there are many different systems or services (such as monitoring system, protection system, and control system) which runs in a WAPS. The reliability of each service may depend on different components and information in the WAPS. Therefore, research on multi-service evaluation is necessary to the reliability of WAPS.

doi:10.20944/preprints201905.0199.v1

2. The structure of WAPS

WAPS typically consists of phasor measurement unit (PMU), phasor data concentrator (PDC), control center (CC), execution unit (EU), and backbone network (BN). The structure is shown in Figure 1. The PMU is deployed in the substation to collect measurement data and transmits the information to the PDC over the local area network (LAN). The PDC uploads the measurement data to the control center through the BN. After analyzing and processing, the control command is sent to the EU of the substation through the BN and the LAN. In addition, a high-precision clock synchronization system be used in the WAPS to ensure the data and signal have a uniform time stamp [8-13].

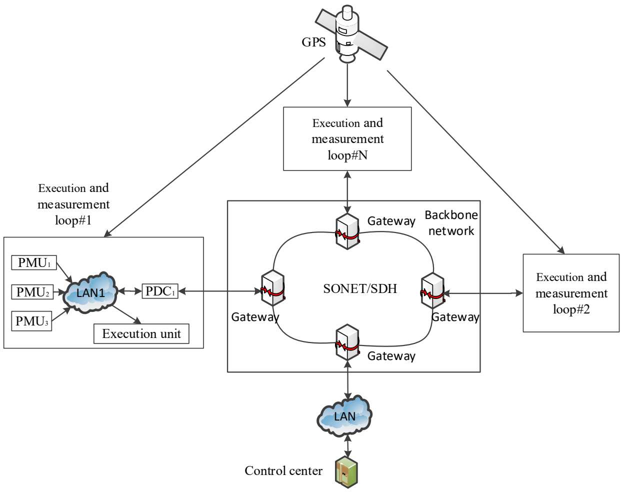

Figure.1 The structure of WAPS

3. Reliability evaluation model of WAPS

The fault tree model of the WAPS can be obtained in the fault tree analysis (FTA) method [15]. It is shown in Figure 2.

According to the fault tree model of WAPS (shown in Figure 2), the reliability is

$$A_{WAPS} = \left(\prod_{i=1}^{n} A_{EXi} \prod_{i=1}^{n} A_{MEi} \right) A_{BN} . A_{DM} . A_{CON} . A_{CC} \tag{1}$$

where A_{EXi} is the reliability of ith execution loop, A_{MEi} is the reliability of ith measurement loop, A_{BN} is the reliability of BN, A_{DM} is the reliability of measurement information flow, A_{CON} is the reliability of control information flow, A_{CC} is the reliability of CC, n is the number of execution and measurement loop in WAPS.

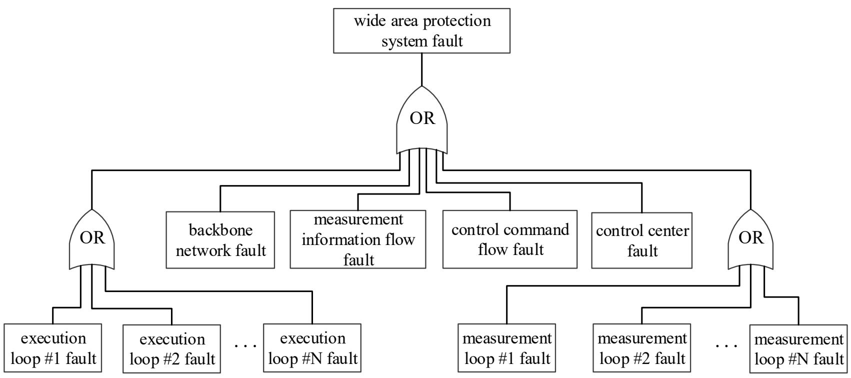

Figure.2 The structure of WAPS

3.1. Reliability model of physical loop

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 May 2019 doi:10.20944/preprints201905.0199.v1

3.1.1. Reliability model of measurement loop in LAN

The measurement loop is composed of a plurality of PMUs, a PDC, and a LAN in Fig. 1. A LAN consists of multiple switches, routers, and transmission media. Considering that the transmission medium of the actual WAPS is generally optical fiber, the reliability model of the measurement loop was established with taking the optical fiber medium as an example. The fault tree model of the measurement loop is shown in Figure 3.

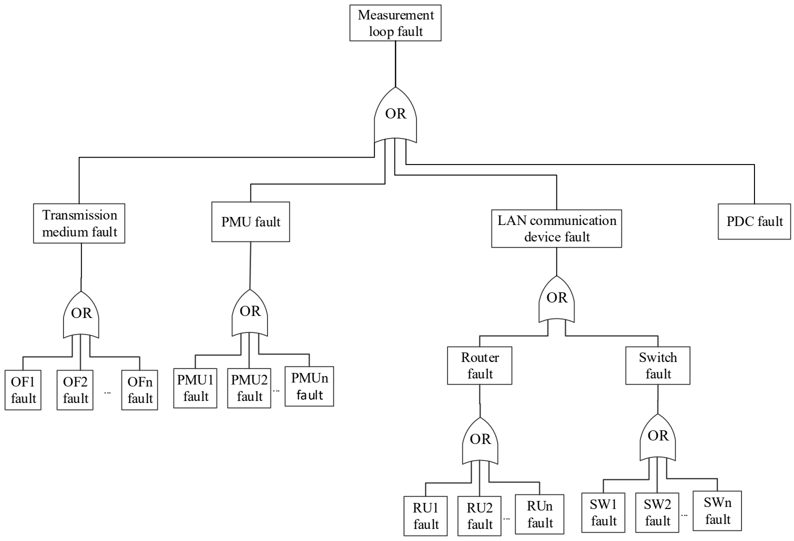

Figure. 3 FTA model of measurement loop

According to the fault tree model of the measurement loop (shown in Figure 3), the reliability is

$$A_{ME} = (\prod_{i=1}^{n} A_{OFi} \prod_{i=1}^{n} A_{PMUi} \prod_{i=1}^{n} A_{RUi} \prod_{i=1}^{n} A_{SWi}) A_{PDC} \tag{2}$$

where A_{PR} is the reliability of measurement loop, A_{OF} is the reliability of fiber medium, A_{PMU} is the reliability of PMU, A_{RU} is the reliability of router, A_{SW} is the reliability of switch, A_{PDC} is the reliability of PDC, n is the number of PMU, fiber, router, and switch in the measurement loop.

3.1.2. Reliability model of execution loop in LAN

The execution loop is composed of a plurality of EUs in Fig. 1. The fault tree model of the execution loop is shown in Figure 4.

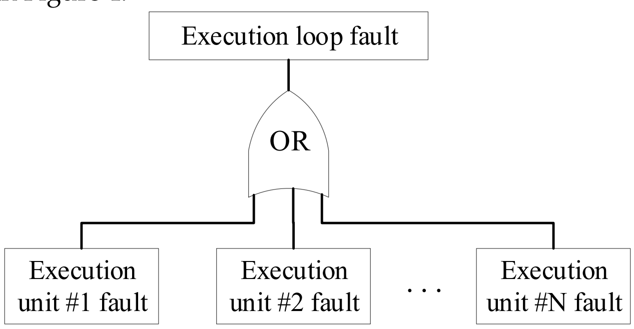

Figure. 4 FTA model of execution loop

According to the fault tree model of the execution loop (shown in Figure 4), the reliability is

$$A_{EX} = \prod_{i=1}^{n} A_{EUi} \tag{3}$$

where A_{EX} is the reliability of execution loop, A_{EU} is the reliability of EU, n is the number of EU.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 May 2019 doi:10.20944/preprints201905.0199.v1

3.1.3. Reliability model of BN

The topology of the BN is shown in Figure 5. The gateways GW1-GWn are sequentially connected to form a dual ring network, and the optical fibers are respectively OF1-2、OF'1-2、OF2-3、OF'2-3… OFn-n-1、OF'n-n-1、OF1-n and OF'1-n.

Considering the need to enhance the ability of the BN to respond to unexpected situations, one loop in the dual ring network serves as the transmission channel for service packets, and the other loop is in the standby state. Therefore, when any gateway in the BN fails or two pairs of fibers fail at the same time, the communication of the BN will be blocked. The fault tree model of BN is shown in Figure 6.

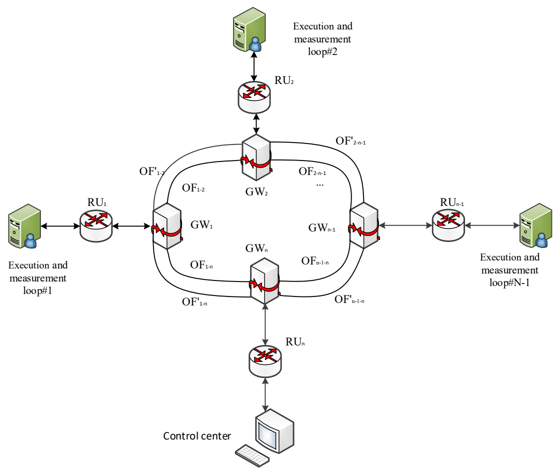

Figure. 5 The structure of BN

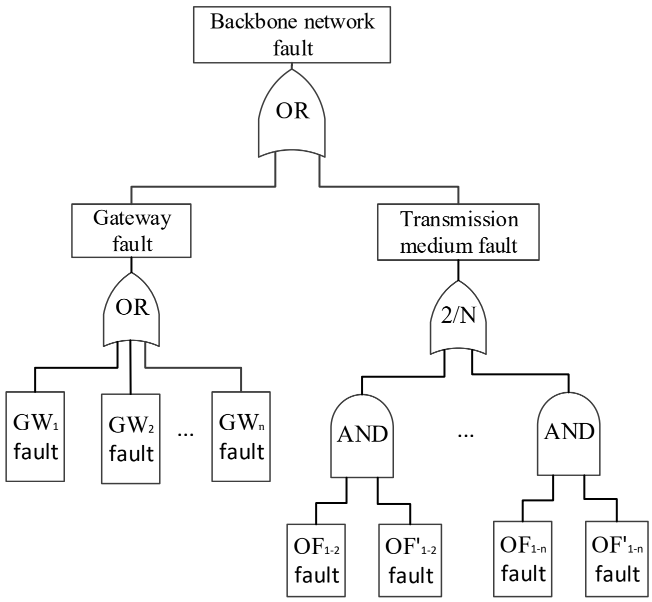

Figure. 6 FTA model of BN

According to the fault tree model of the BN (shown in Figure 6), the reliability is

$$A_{BN} = \left(\prod_{i=1}^{n} A_{GWi}\right) A_{BNOF} \quad (4)$$

$$A_{BNOF} = 1 - C_n^2 P_F \quad (5)$$

where A_{BN} is the reliability of BN, A_{GW} is the reliability of gateway, A_{BNOF} is the reliability of transmission medium, P_F is the failure rate of double fiber.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 May 2019 doi:10.20944/preprints201905.0199.v1

3.2. Reliability model of information flow in WAPS

3.2.1. Reliability model of measurement information flow

MUs are typically deployed inside substations to monitor the operation of the substation. At the same time, the PMU collects the electrical parameters of the substation in real time. The electrical parameters include the amplitude and phase angle of the voltage and current, the amplitude of the frequency, and the state information of the switch.

After the measurement information is collected, it is uploaded to the PDC through the LAN. After the collection is completed, it will be transmitted to the CC by the BN. If the transmission time of the acquired measurement data exceeds a preset delay, or the data is lost or incorrect during transmission, the measurement information should be considered to fail. Suppose the message waiting time for processing is T_0 which preset by the CC, the time to measure phasor data from acquisition to transmission to the CC is T_{PMU} . There is

$$T_{PMU} = T_{LAN} + T_{BN} + T_{BNR} \tag{6}$$

where T_{LAN} is the transmission and processing delay of the LAN in the execution and measurement loop, T_{BN} is the transmission delay of the BN, T_{BNR} is the router processing delay of BN. T_{LAN} can be ignored compared to T_{BN} and T_{BNR} .

The measurement data may be lost or wrong during the transmission process. Under the topology of the communication network and the fixed transmission medium, the packet loss rate P_0 of the measurement data does not change. It is assumed that data collection will not exceed the specified delay under normal network conditions. When the BN is abnormal, the measurement data communication delay will increase, and the probability of packet loss will increase. Assuming the total probability is P_{pmu} when T_{PMU} is more than T_0 and the packet is lost at the same time. According to the above assumption, the message reliability of a single PMU is A_{pmu} .The probability of normal communication network is P_N .The probability of communication network anomaly is P_F . According to the full probability formula and $P_F = 1 - P_N$, there is

$$A_{pmu} = (1 - P_0) \times P_N + (1 - P_{pmu}) \times P_F \tag{7}$$

The WAPS deploys multiple PMUs to measure data from different geographic nodes. Considering that there is no impact between each PMU, the fault tree model of the PMUs is shown in Figure 7.

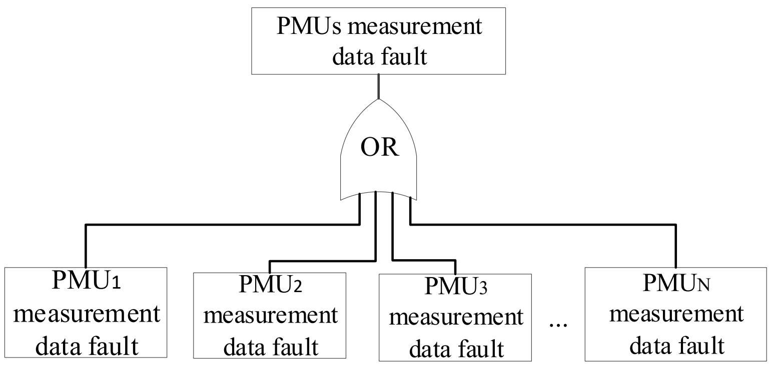

Figure. 7 FTA model of PMUs measurement data

There is

$$A_{DM} = \prod_{i=1}^{n} A_{pmui} \tag{8}$$

where A_{ME} is the reliability of entire PMUs measurement data, A_{pmu} is the reliability of single PMU measurement data, n is the number of PMU in WAPS.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 May 2019 doi:10.20944/preprints201905.0199.v1

3.2.2. Reliability model of control command information flow

After the measurement data of the PMU reaches the CC, the CC will calculates the measurement data, and then transmits the control command information flow to the EU through the BN and LAN to control the power system. The reliability model of the control command is similar to the model of the measurement information flow, so the reliability of the control command is

$$A_{CON} = \prod_{i=1}^{n} A_{odi} \tag{9}$$

$$A_{od} = (1 - P_0) \times P_N + (1 - P_{od}) \times P_F \tag{10}$$

where A_{CON} is the reliability of entire control command information flow, A_{od} is the reliability of single control command information flow, P_0 is the fixed packet loss rate of communication networks, P_{od} is the transmission time of the control command exceeds the preset time when the network is abnormal and packet loss probability, T_{od} is the control command transfer time from CC to EU, T_{C0} is the preset time for reliable execution of control commands, n is the number of execution device for control command.

3.2.3. Reliability model of information interaction between regions

The reliability model of information interaction between regions is similar to the model of the measurement information flow, so the reliability is

$$A_{IIBR} = \prod_{i=1}^{n} A_{rei} \tag{11}$$

$$A_{re} = (1 - P_0) \times P_N + (1 - P_{od}) \times P_F \tag{12}$$

where A_{IIBR} is the reliability of entire information interaction between regions, A_{re} is the reliability of single information interaction between regions, P_0 is the fixed packet loss rate of communication networks, P_{od} is the transmission time of the control command exceeds the preset time when the network is abnormal and packet loss probability, T_{od} is the information interaction transfer time between regions, T_{C0} is the preset time for reliable execution of information interaction between regions, n is the number of device for information interaction between regions.

4. Reliability evaluation model of multi-service in WAPS

There are many services which have different function and transmission path in WAPS. The multi-service mainly includes five services, which only upload measurement information, only send down control command information, measurement and control command information combined, local service in substation and information interaction between regions. The five services respectively denoted as S_{MS}, S_{CS}, S_{MC}, S_{LS} and S_{RE}.

4.1. Reliability evaluation model of only measurement information service in WAPS

Assumes that a service of the WAPS has only upload measurement information, according to the reliability model, the reliability of the service is A_{MS}.Its reliability consists of two parts, that is, 1)the reliability of entire PMUs measurement information flow denoted by A_{DM}; 2) the reliability product of all secondary equipment that the service passes through during communication denoted by A_{ME1}, A_{BN} and A_{CC}. A_{MS} is product of two parts, the reliability of measurement information is

$$A_{MS} = A_{DM} A_{ME1} A_{BN} A_{CC} \tag{13}$$

4.2. Reliability evaluation model of only control command information service in WAPS

Assumes that a service of the WAPS has only send down control command information, according to the reliability model, the reliability of the service is A_{CS}.Its reliability consists of two

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 May 2019 doi:10.20944/preprints201905.0199.v1

parts, that is, 1)the reliability of entire EUs control command information flow denoted by A_{CON}; 2) the reliability product of all secondary equipment that the service passes through during communication denoted by A_{EX1}, A_{BN} and A_{CC}. A_{CS} is product of two parts, the reliability of measurement information is

$$A_{CS} = A_{CON} A_{EX1} A_{BN} A_{CC} \tag{14}$$

4.3. Reliability evaluation model of measurement and control command information service in WAPS

Assumes that a service of the WAPS has upload measurement information and send down control command information, according to the reliability model, the reliability of the service is A_{MC} .Its reliability consists of three parts, that is, 1)the reliability of entire PMUs measurement information flow denoted by A_{DM} ;2)the reliability of entire EUs control command information flow denoted by A_{CON}; 3) the reliability product of all secondary equipment that the service passes through during communication denoted by A_{ME2}, A_{EX2}, A_{BN} and A_{CC}. A_{MC} is product of three parts, the reliability of measurement information is

$$A_{MC} = A_{DM} A_{CON} A_{ME2} A_{EX2} A_{BN} A_{CC} \tag{15}$$

4.4. Reliability evaluation model of local service in substation in WAPS

Assumes that a service of the WAPS has local service in substation, according to the reliability model, the reliability of the service is A_{LS} .Its reliability product of all secondary equipment that the service passes through during communication denoted by A_{ME3} and A_{EX3} .The reliability of local service in substation is

$$A_{LS} = A_{ME3} A_{EX3} \tag{16}$$

4.5 Reliability evaluation model of information interaction between regions in WAPS

Assumes that a service of the WAPS has information interaction between regions, according to the reliability model, the reliability of the service is A_{RE} .Its reliability consists of two parts, that is, 1) the reliability of information interaction between regions denoted by A_{IIBR}; 2) the reliability product of all secondary equipment that the service passes through during communication denoted by A_{ME4}, A_{EX4} and A_{BN}. A_{RE} is product of two parts, the reliability of measurement information is

$$A_{RE} = A_{IIBR} A_{ME4} A_{EX4} A_{BN} \tag{17}$$

4.6 Reliability evaluation model of multi service in WAPS

The reliability of multi service in WAPS is

$$\overrightarrow{A_{WAPS}} = \begin{bmatrix} A_{MS} \\ A_{CS} \\ A_{MC} \\ A_{LS} \\ A_{RE} \end{bmatrix} = \begin{bmatrix} A_{DM} A_{ME1} A_{BN} A_{CC} \\ A_{CON} A_{EX1} A_{BN} A_{CC} \\ A_{DM} A_{CON} A_{ME2} A_{EX2} A_{BN} A_{CC} \\ A_{ME3} A_{EX3} \\ A_{IIBR} A_{ME4} A_{EX4} A_{BN} \end{bmatrix} \tag{18}$$

The node is more important when the node carries more services. For instance, the node of BN carries four services and the node of CC carries three services, therefore the node of BN is more important than the node of CC. The risk value of the node in WAPS will be considered in subsequent research.

5. Case study

Authors should discuss the results and how they can be interpreted in perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 May 2019 doi:10.20944/preprints201905.0199.v1

Taking the IEEE14 node as an example, which is shown in Fig.8, this paper analyzes the reliability of the WAPS to calculate the value of corresponding risk.

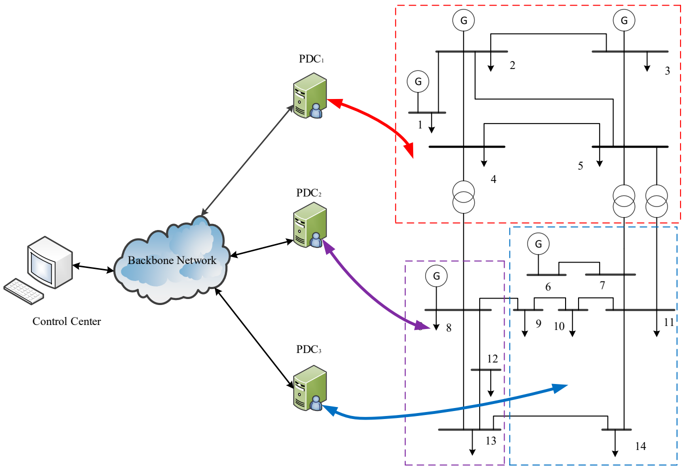

Figure.8 WAPS in IEEE14 nodes system

The IEEE 14 node WAPS in Figure.8 includes three measurement loops that transmit measurement information of the PMU to the CC through the BN, and then the CC transmits control commands to the EU through the BN. The PMU is deployed on 14 bus, denoted as PMU_1, $PMU_2 \ldots PMU_{14}$, for monitoring and collecting the electrical parameters of the system and device status information. PDC1 contains 5 PMU, namely PMU_1, PMU_2, PMU_3, PMU_4 and PMU_5.PDC_2 contains 3 PMU, namely PMU_8, PMU_{12} and PMU_{13}. PDC_3 contains 6 PMU, namely PMU_6, PMU_7, PMU_9, PMU_{10}, PMU_{11} and PMU_{14}.

5.1 Reliability of equipment and information of each node in the WAPS

Since the reliability of the secondary system equipment produced by different manufacturers is different, the reliability of the actual secondary system equipment cannot be used. This paper gives a relatively suitable reliability value based on the reliability values of the actual secondary system equipment. The reliability values of the secondary system equipment given in this paper are assumed, and the reliability values of various secondary system equipment are shown in Table 1.

Table 1. Equipment reliability value of secondary system

Device Name	Reliability Value
PMU	0.9983
PDC	0.9995
EU	0.9996
Router	0.9955
Switch	0.993

5.2 Reliability calculation of secondary equipment in wide area protection system

Since the reliability of the fiber is relatively high, the calculation is negligible. It is assumed that each LAN consists of two routers and one switch, which can be calculated according to the device reliability values in Table 1 and formula (2) and formula (3). The product of the reliability of the measuring unit and the protection unit is shown in Table 2.

Table.2 Reliability of protection and measurement units

A_{PP1}	A_{PP2}	A_{PP3}

0.9745	0.9782	0.9742

As can be seen from Table 1, as the number of PMUs increases, the reliability of the protection and measurement unit decreases. In practice, an increase in the number of PMUs will increase the redundancy of the measurement data, and the reliability of the entire system does not have much influence.

The selected backbone network mainly includes four gateways, and the gateways are all connected by optical fibers. The corresponding FTA reliability model is shown in Fig.5. The reliability data of the backbone network can be obtained from the literature. Calculated by formula (4), the reliability of the backbone network is 0.994.

5.3 Reliability calculation of measurement information

According to the information reliability model of a single PMU in Section 3.4, it is known that the probability of a single PMU device being normal and the failure, the probability of packet loss during transmission, and the probability of exceeding the normal delay are required. With OPNET simulation analysis, when the network scale reaches the provincial protection and control system, the end-to-end delay of measurement information is generally 1.5ms. When the communication network fails, the end-to-end delay of the measurement information exceeds the normal communication delay, and the probability of its occurrence needs to be obtained.

Assuming that the packet loss rate of measurement information transmitted in the fiber is P_0, the value is 0.01. The probability of the normal communication network is P_N, the value is 0.995. The probability of the abnormal communication network is P_F, the value is 0.005. When the network is abnormal, the packet exceeds the delay and the probability of packet loss is P_{pmu}, the value is 0.05. The value of the reliability of a single PMU phasor acquisition message can be calculated according to formula (8).

$$\begin{aligned} A_{pmu} &= (1-P_0)\times P_N + (1-P_{pmu})\times P_F \\ &= (1-0.01)\times 0.995 + (1-0.05)\times 0.005 \\ &= 0.9898 \end{aligned}$$

The IEEE 14-node wide area protection system includes 14 PMU devices. According to formula (9), the reliability of the measurement data of the entire PMUs can be calculated as

$$A_{DM} = \prod_{i=1}^{n} A_{pmui} = \prod_{i=1}^{14} 0.98755 = 0.839$$

5.4 Reliability calculation of control command

Similar to the reliability calculation of the measurement information, the reliability of the control command can be calculated according to the formula (10) and the formula (11). Assuming that the packet loss rate of measurement information transmitted in the fiber is P_0, the value is 0.01. The probability of the normal communication network is P_N, the value is 0.995. The probability of the abnormal communication network is P_F, the value is 0.005. When the network is abnormal, the packet exceeds the delay and the probability of packet loss is P_{od}, the value is 0.04. According to

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 May 2019 doi:10.20944/preprints201905.0199.v1

formula (10), the reliability of a single EU control command can be calculated, and the value is 0.98985.

5.5 Reliability calculation of multi service in WAPS

5.5.1 Reliability calculation of only measurement information in WAPS

Assuming that the only measurement information service consists of all PUMs, the reliability of the service can be calculated according to formula (13). According to Table 2, the reliability of single PMU is 0.9983，the reliability of PDC is 0.9995. Assuming that each LAN consists of two routers and one switch, and the reliability of each router and switch is A_{RU} and A_{SW} ,the value is 0.9955 and 0.9930. According to the previous calculation, the reliability of the backbone network and control center respectively is 0.994 and 0.9985. The single service's reliability of measurement information is A_{pmu} , the value is 0.98985. The reliability of the service is：

$$\begin{aligned} A_{MS} &= A_{DM} A_{ME1} A_{BN} A_{CC} \\ &= \prod_{i=1}^{14} A_{pmui} \prod_{i=1}^{14} A_{PMUi} \prod_{i=1}^{3} (A_{PDCi} A_{RU}{}^{2} A_{SW}) A_{BN} A_{CC} \\ &= 0.8193 \end{aligned}$$

5.5.2 Reliability calculation of only control command information in WAPS

Assuming that only control command information service consists of all EUs, the reliability of a single service can be calculated according to formula (15). According to Table 2, the reliability of single EU is 0.9996. According to the previous calculation, the reliability of the backbone network and control center respectively is 0.994 and 0.9985. The single service's reliability of control command information is A_{od} , the value is 0.98985. The reliability of the service is：

$$\begin{aligned} A_{CS} &= A_{CON} A_{EX1} A_{BN} A_{CC} \\ &= \sum_{i=1}^{3} A_{odi} \sum_{i=1}^{3} A_{EUi} A_{BN} A_{CC} \\ &= 0.9614 \end{aligned}$$

5.5.3 Reliability calculation of measurement and control command information in WAPS

Assuming that the measurement and control command information consists of all PUMs and EUs, the reliability of the service can be calculated according to formula (16). According to Table 2, the reliability of single PMU is 0.9983，the reliability of PDC is 0.9995，the reliability of EUs is 0.9996. Assuming that each LAN consists of two routers and one switch, and the reliability of each router and switch is A_{RU} and A_{SW} , the value is 0.9955 and 0.9930. According to the previous calculation, the reliability of the backbone network and control center respectively is 0.994 and 0.9985. The single service's reliability of measurement information is A_{pmu} , the value is 0.9898.The reliability of a single execution unit control command is A_{od} , the value is 0.98985. The reliability of the service is：

$$\begin{aligned} A_{MC} &= A_{DM} A_{CON} A_{ME2} A_{EX2} A_{BN} A_{CC} \\ &= \prod_{i=1}^{14} A_{pmui} \prod_{i=1}^{14} A_{PMUi} \prod_{i=1}^{3} (A_{PDCi} A_{RU}{}^{2} A_{SW}) \sum_{i=1}^{3} A_{odi} \sum_{i=1}^{3} A_{EUi} A_{BN} A_{CC} \\ &= 0.7936 \end{aligned}$$

5.5.4 Reliability calculation of local service in substation in WAPS

 doi:10.20944/preprints201905.0199.v1

Assuming that the local service in substation consists of five PUMs and one EU, the reliability of the service can be calculated according to formula (16). According to Table 2, the reliability of single PMU is 0.9983, the reliability of PDC is 0.9995,the reliability of execution unit is 0.9996. Assuming that each LAN consists of two routers and one switch, and the reliability of each router and switch is A_{RU} and A_{SW}, the value is 0.9955 and 0.9930. The reliability of the service is:

$$\begin{aligned} A_{LS} &= A_{ME3}A_{EX3} \\ &= \prod_{i=1}^{5} A_{PMUi} A_{RU}{}^{2} A_{SW} A_{EU} A_{PDC} \\ &= 0.9749 \end{aligned}$$

5.5.5 Reliability calculation of information interaction between regions in WAPS

Assuming that the local service in substation consists of five PUMs and one EU, the reliability of the service can be calculated according to formula (17). According to Table 2, the reliability of single PMU is 0.9983, the reliability of PDC is 0.9995, the reliability of execution unit is 0.9996. Assuming that each LAN consists of two routers and one switch, and the reliability of each router and switch is A_{RU} and A_{SW} ,the value is 0.9955 and 0.9930. The reliability of the service is:

$$\begin{aligned} A_{RE} &= A_{IIBR}A_{ME4}A_{EX4}A_{BN} \\ &= \prod_{i=1}^{3} A_{IIBRi} \prod_{i=1}^{3} A_{PMUi} A_{RU}{}^{2} A_{SW} A_{EU} A_{PDC} A_{BN} \\ &= 0.9845 \end{aligned}$$

5.6 Reliability calculation of multi service in wide area protection system

The reliability of five services respectively is

$$\begin{aligned} A_{MS} &= A_{DM}A_{ME1}A_{BN}A_{CC} \\ &= \prod_{i=1}^{14} A_{pmui} \prod_{i=1}^{14} A_{PMUi} \prod_{i=1}^{3} (A_{PDCi} A_{RU}{}^{2} A_{SW}) A_{BN} A_{CC} \end{aligned}$$

$$\begin{aligned} A_{CS} &= A_{CON}A_{EX1}A_{BN}A_{CC} \\ &= \sum_{i=1}^{3} A_{odi} \sum_{i=1}^{3} A_{EUi} A_{BN} A_{CC} \end{aligned}$$

$$\begin{aligned} A_{MC} &= A_{DM}A_{CON}A_{ME2}A_{EX2}A_{BN}A_{CC} \\ &= \prod_{i=1}^{14} A_{pmui} \prod_{i=1}^{14} A_{PMUi} \prod_{i=1}^{3} (A_{PDCi} A_{RU}{}^{2} A_{SW}) \sum_{i=1}^{3} A_{odi} \sum_{i=1}^{3} A_{EUi} A_{BN} A_{CC} \end{aligned}$$

$$\begin{aligned} A_{LS} &= A_{ME3}A_{EX3} \\ &= \prod_{i=1}^{5} A_{PMUi} A_{RU}{}^{2} A_{SW} A_{EU} A_{PDC} \end{aligned}$$

$$\begin{aligned} A_{RE} &= A_{IIBR}A_{ME4}A_{EX4}A_{BN} \\ &= \prod_{i=1}^{3} A_{IIBRi} \prod_{i=1}^{3} A_{PMUi} A_{RU}{}^{2} A_{SW} A_{EU} A_{PDC} A_{BN} \end{aligned}$$

The reliability of the five different services of the wide area protection system is

$$\boldsymbol{A_{ES}} = \begin{bmatrix} A_{MS} \\ A_{CS} \\ A_{MC} \\ A_{LS} \\ A_{RE} \end{bmatrix} = \begin{bmatrix} \prod_{i=1}^{14} A_{pmui} \prod_{i=1}^{14} A_{PMUi} \prod_{i=1}^{3} (A_{PDCi} A_{RU}{}^{2} A_{SW}) A_{BN} A_{CC} \\ \sum_{i=1}^{3} A_{odi} \sum_{i=1}^{3} A_{EUi} A_{BN} A_{CC} \\ \prod_{i=1}^{14} A_{pmui} \prod_{i=1}^{14} A_{PMUi} \prod_{i=1}^{3} (A_{PDCi} A_{RU}{}^{2} A_{SW}) \sum_{i=1}^{3} A_{odi} \sum_{i=1}^{3} A_{EUi} A_{BN} A_{CC} \\ \prod_{i=1}^{5} A_{PMUi} A_{RU}{}^{2} A_{SW} A_{EU} A_{PDC} \\ \prod_{i=1}^{3} A_{IIBRi} \prod_{i=1}^{3} A_{PMUi} A_{RU}{}^{2} A_{SW} A_{EU} A_{PDC} A_{BN} \end{bmatrix}$$

The number of services carried by each node is shown in Table 3.

Table.3 The number of services carried by each node

Node Name	Service Name
CC	S_{MS}, S_{CS}, S_{MC}
BN	S_{MS}, S_{CS}, S_{MC}, S_{RE}
PDC_1	S_{MS}, S_{MC}, S_{LS}
PDC_2	S_{MS}, S_{MC}, S_{RE}
PDC_3	S_{MS}, S_{MC}
PMU_1-PMU_5	S_{MS}, S_{MC}, S_{LS}
PMU_8,PMU_{12} ,PMU_{13}	S_{MS}, S_{MC}, S_{RE}
PMU_6,PMU_7 ,PMU_9 PMU_{10},PMU_{11} ,PMU_{14}	S_{MS}, S_{MC}
EU_1	S_{CS}, S_{MC}, S_{LS}
EU_2	S_{CS}, S_{MC}
EU_3	S_{CS}, S_{MC}, S_{RE}
LAN_1	S_{MS}, S_{MC}, S_{LS}
LAN_2	S_{MS}, S_{MC}, S_{RE}
LAN_3	S_{MS}, S_{MC}

According to the Table 3, the BN carries four different services, so the BN is the most important node in WAPS.

According to the foregoing device reliability values, the reliability of five different services can be calculated, respectively:

$$\boldsymbol{A_{ES}} = \begin{bmatrix} A_{MS} \\ A_{CS} \\ A_{MC} \\ A_{LS} \\ A_{RE} \end{bmatrix} = \begin{bmatrix} 0.8193 \\ 0.9614 \\ 0.7936 \\ 0.9749 \\ 0.9845 \end{bmatrix}$$

It can be seen that the reliability of the monitoring and control protection service running on the same wide-area protection system network is different. Through calculation, the focus of reliability and reliability improvement of specific services can be obtained.

5. Conclusions

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 May 2019 doi:10.20944/preprints201905.0199.v1

Based on the communication network topology of a typical wide-area protection system, this paper conducts a comprehensive assessment of the reliability of the communication network physical equipment and information flow. Through the research on the various aspects of the communication process and the multi-task reliability, the key nodes in the information system are obtained, which provides an analysis method for the design of the wide-area protection system.

In this paper, we need to further study the reliability problems caused by the unsynchronized GPS timing and the measures to improve the reliability of the system by adopting redundant design.

Author Contributions: Writing—original draft, K.Y.; writing—review and editing, J.L.; conceptualization, K.L..

Funding: This work is supported by the science and technology project of State Grid Corporation of China (The security protection technologies for embedded components and control units of power system terminals) and the National Natural Science Foundation of China (Grant No. 51377122).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Joachim Bertsch．Wide-area Protection and Power System Utilization[J]．Proceedings of the IEEE，2005，5(93)：1006-1011．
2. Adamiak M G, Apostolov A P, Begovic M M, et al. Wide area protection technology and infrastructures [J]. IEEE Trans. Power Del., 2006, 2(21): 601-609.
3. M. Begovic, D. Karlsson, and G. Michel. Wide-area protection and emergency control. Proc. IEEE, 2005, 5(93): 876–891.
4. X. Tong, G. Liao, and X. Wang. The analysis of communication architecture and control mode of wide area power systems control. Proceedings Autonomous Decentralized Systems, 2005, 59–65.
5. D. Babazadeh, M. Chenine, K. Zhu, L. Nordstrom, A. Al-Hammouri. A platform for Wide Area Monitoring and Control System ICT analysis anddevelopment. 2013 IEEE Grenoble Conference, 2013, 1-7.
6. Mohammad Shahraeini，Mohammad Hossein Javidi，Mohammad Sadegh Ghazizadeh．Comparison Between Communication Infrastructures of Centralized and Decentralized Wide Area Measurement Systems[J]．IEEE Transactions on Smart Grid，2011，1(12)：206-211．
7. Dai Zhihui，Wang Zengping，Jiao Yanjun．Reliability Evaluation of The Communication Network in Wide-area Protection[J]．IEEE Trans. Power Del，2011，4(26)：2526-2530．
8. Wang Yang，Li Wenyuan，Lu Jiping．Reliability analysis of wide-area measurement system[J]．IEEE Trans. Power Del，2010，3(25)：1483-1491．
9. Vladimir Terzija，Gustavo Valverde，Deyu Cai，et al．Wide-area Monitoring，protection，and control of future electric power networks[J]．Proceedings of the IEEE，2011，1(99)：80-93．
10. Zhu Kun，Moustafa Chenine，Lars Nordström．ICT Architecture Impact on Wide Area Monitoring and Control Systems' Reliability[J]．IEEE Transactions on Power Delivery，2011，4(26)：2801-2808．
11. LI Jungang，ZHANG Aimin，ZHANG Hang，et al．Reliability Evaluation of the Wide Area Protect System[J]．Transactions of China Electrotechnical Society，2015，30(12)：344-350．
12. DAI Zhihui，KONG Linghao，WANG Zengping，et al．Reliability Assessment of Wide Area Protection Scheme[J]．Automation of Electric Power Systems，2013，14(37)：65-69．