

Reliability Assessment of a Cyber Physical Microgrid System in Island Mode

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Abstract—As cyber physical systems, microgrids (MGs), with distributed generations and energy management systems, can improve the reliability of power supply for customers in MGs. To quantify the reliability of isolated MGs, a cyber-physical assessment model is proposed. In this model, the circuit breakers and distributed energy resources are treated as the coupling elements between the cyber system and physical system, where the circuit breakers are uniquely modelled by using the Markov process theory based on the indirect interdependencies between cyber physical elements. For the cyber system, the reliability model of communication networks is formulated based on the link connectivity evaluation method. For the physical system, a system state generating method is presented to account for the optimal operation strategy, which considers the influence of the optimization strategy on the failure consequence analysis. With the proposed cyber and physical reliability models, the sequential Monte Carlo (SMC) simulation method is adopted to assess the reliability of islanded MGs. Simulations are carried out on a test system, and results verify the feasibility and effectiveness of proposed assessment method. Furthermore, one application of the proposed method is on the parameter setting of the cyber system, in terms of enhancing MGs reliability.

Index Terms—Cyber physical system, island mode, microgrid, reliability assessment, sequential Monte Carlo.

I. INTRODUCTION

THE microgrid (MG) is a promising solution to improve the reliability of power supplying for customers. Recently, it has been recognized that the continuous and stable operation of MGs requires the support of cyber elements, e.g., a control center and local controllers, especially in the island mode [1]. The MG is considered to be a cyber-physical system (CPS) that exploits advanced information and communication technology [2]–[5]. Therefore, how to quantify the reliability of MGs, from the perspective of CPS, is the fundamental problem for MGs planning and design.

There are two major factors that cause CPS reliability problems: external and internal factors. External factors focus on malicious data attacks [6], [7], and internal factors refer to

the function failure of the CPS elements. Furthermore, internal factors include the effectiveness of communication network performance, such as business loss, delay, error [8], [9] and the random failures of cyber elements. This paper assesses the influence of element random failures on the reliability of cyber physical microgrid systems (CPMS).

Due to the cyber physical interdependencies in CPMS, it is necessary to consider not only the random failures of traditional physical elements [10], [11], but also the cyber elements [12] and their coupling relationship, when performing CPMS reliability assessment. From the perspective of reliability assessment, the existing literatures related to CPS reliability assessment are mainly focused on three aspects:

1) *Cyber Physical Failure Interactive Modes*: The power grid's information and communication systems are divided into four parts and the effect of possible cyber failures on the power system state estimation and catastrophic blackouts are described in [13]. In [14], four types of interdependencies between cyber and power systems are defined and the direct and indirect relationships between dual systems are described.

2) *Cyber Physical Reliability Modeling*: A model-based approach is used to formulate a cyber-physical equivalent model for the online closed-loop hierarchical control systems. And the general information flow can be carried out by using the equivalent model [1]. Some studies focus on the reliability modelling of particular functions in the CPS, such as protection [15], operators' performance [16], and control and monitoring of circuit breaker [17].

3) *Reliability Assessment Method*: According to the characteristics of MG elements, the reliability assessment method mainly includes the analytical method [18], [19], non-sequential Monte Carlo method [17] and sequential Monte Carlo (SMC) method [16]. Most studies focus on the SMC method, which is considered to be the mainstream for reliability assessment in sequential analysis issues.

Direct interdependencies between physical and cyber elements are analyzed in the previous works [18], where the analyses of indirect interdependencies are very limited. Reference [19] defines the indirect correlation coefficient by which the availability of physical elements can be changed. This method is suitable for simple failure interactive modes, and is only applicable to analytical methods. This method fails to use the sequential methods for reliability assessment in CPMS where it contains sequential elements. Therefore, for the CPMS, new reliability models need to be established to better assess this indirect interdependencies based on the impact of cyber element failures on the operation of the CPMS.

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Moreover, the strategy of distributed power output also has a great impact on the reliability assessment in the island MG. Different strategies reflect the differences in power states after the elements random failures, including the active power of the diesel generators (DEs) and the state of charge (SOC) of the energy storage system (ESS). The operational strategy used to evaluate the reliability of island MG with ESS is relatively simple in the traditional articles [20], [21]. This simple method does not meet the economic requirements of MG operation, and even reduces the accuracy of reliability indices calculation. Therefore, system state generation taking into account the optimal operation strategy will be necessary in the CPMS reliability assessment.

The main contributions of the paper are as follows: 1) the indirect interdependencies between the intelligent measurement and the circuit breaker are analyzed, and a novel reliability model for the circuit breaker is proposed. This model provides a new method to analyze indirect interdependencies for island MGs; 2) a system state generating method is proposed to take into account the optimal operation strategy, and the optimal mathematical model is established.

The rest of this paper is organized as follows: In Section II, the topology of CPMS is introduced, together with the reliability models of circuit breakers, the communication network and other elements. In Section III, a CPMS reliability assessment method with the optimal operation strategy is proposed. A case study is performed in Section IV to illustrate the performance of the proposed model and assessment approach. In Section V, concluding remarks are provided.

II. RELIABILITY MODELLING OF CPMS

A. Topology of CPMS

The physical system of CPMS includes various physical entities such as distributed generations (DGs), lines, circuit breakers and transformers. Meanwhile, the cyber system includes multiple types of information elements that sense and control the physical system, such as the MG central controller and current transformer. According to IEC61850 standard and Industrial Ethernet technology [22], a typical CPMS structure is established, as shown in Fig. 1.

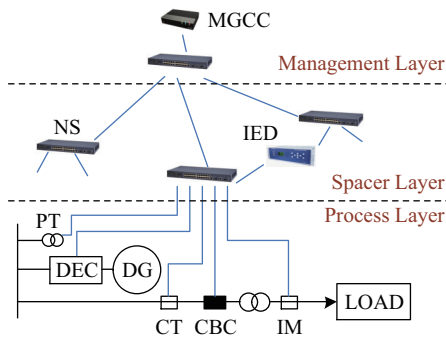


Fig. 1. Topology of cyber physical microgrids.

The cyber system of CPMS can be summarized as three layers [23]: process layer, spacer layer and management layer.

The process layer is the basis for MG operation and it is the direct coupling part between the cyber and physical system. Process layer equipment includes the circuit breaker controllers (CBC), distributed energy controllers (DEC), potential transformer (PT), current transformers (CT), intelligent measurement (IM) and fiber optic lines, etc.

The spacer layer is the bridge and hub between the process layer and the management layer, which includes intelligent electronic devices (IED) of control equipment, network switches (NS) and fiber optic lines. The communication network of the spacer layer can be flexibly configured for specific structures.

The management layer's functions include data calculation, release of control commands and information exchange with the superior power grid. The MG central controller (CC) is the main element of the management layer. Its function is to maintain the power balance and to formulate the operation plan based on the power generation and load forecasting.

The hierarchical architecture of a cyber system based on IEC61850 standard can meet the requirements of state perception and refining control [22], [24] which lays a foundation for further analysis of CPMS reliability coupling characteristics and reliability model establishment.

As shown in Fig. 1, realization of the safe and reliable operation of CPMS requires the coordination of both physical and cyber equipment. Therefore, the CPMS reliability is affected by random failures of both systems' elements. This article only considers the elements which have great impacts on CPMS reliability. The physical elements include DEs, wind turbine (WT), ESS, circuit breakers, lines and transformers, and the cyber elements mainly consider DEC, CT, CBC, IM, IED, switch, lines and CC.

B. Circuit Breaker Model

The process layer elements are classified into two categories, i.e., direct and indirect impacts on the physical system caused by random failures. For the direct impacts, the performance of CBC, CT, and DEC can cause the failure or change the specification of the circuit breakers and DGs. The direct interdependencies between cyber and physical elements are shown in Fig. 2. According to the series network method, the reliability of the system composed of independent components is the reliability multiple of all components. Taking the DE as an example, its element reliability is calculated as follows:

$$R(S) = \prod_{i=1}^n R(i) \quad (1)$$

where $R(S)$ is the series system reliability and $R(i)$ is the i -th element reliability. The equivalent failure rate λ'_{MS} (times/unit · year) and the repair rate μ'_{MS} (times/unit · year) of DE are calculated as follows:

$$\lambda'_{MS} = \lambda_{MS} + \lambda_{DEC} \quad (2)$$

$$\mu'_{MS} = \frac{\lambda_{MS} + \lambda_{DEC}}{\lambda_{MS}r_{MS} + \lambda_{DEC}r_{DEC} + \lambda_{MS}r_{MS}\lambda_{DEC}r_{DEC}} \quad (3)$$

where λ_{MS} , λ_{DEC} and r_{MS} , r_{DEC} are the failure rates and average repair durations of DE and DEC, respectively.

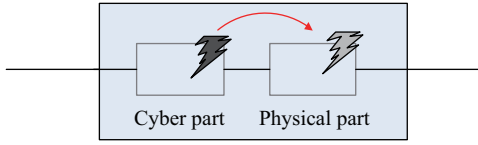


Fig. 2. Penetration process of cyber element failure on the physical element.

For the indirect effects, the failures of the process layer elements do not directly result in failures of physical elements. It is necessary to account for the CPMS operating states, when quantifying these impacts. For example, the failure of IM does not instantly impact the power supply but rather the losses of monitoring the lines and loads. If the power supply does not meet the load requirements during the repair period, the IM upstream branch circuit breaker must be disconnected to reduce the load to maintain the stable operation of the CPMS, without using the pre-scheduled load shedding strategy.

As described above, a circuit breaker is an important coupling point of indirect interdependencies of CPMS, and its traditional two-state model cannot meet the new requirements of reliability assessment. A more complete reliability model is needed to describe the state of the CPMS so that indirect interdependencies can be evaluated. According to the Markov process theory and indirect interdependencies mechanism, a three-state model for circuit breakers is formulated. The state transition is described in Fig. 3.

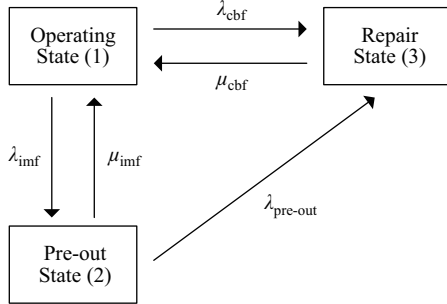


Fig. 3. Markov three-state model of circuit breakers.

The repair state of the circuit breaker is determined by the physical entity, CBC and CT failure rate. The pre-out state is when there is an IM failure under the jurisdiction of the circuit breaker. In this case, the circuit breaker is not out of service and the power adequacy should be determined. If the power supply cannot meet the load requirement, the control center disconnects the circuit breaker, which enters the repair state. Otherwise, IM is repaired and the circuit breaker returns to the operating state. The transfer rate among states can be expressed as follows:

$$\lambda_{cbf} = \lambda_{CBC} + \lambda_{CT} \quad (4)$$

$$\mu_{cbf} = \frac{\lambda_{CBC} + \lambda_{CT}}{\lambda_{CBC}r_{CBC} + \lambda_{CT}r_{CT} + \lambda_{CBC}r_{CBC}\lambda_{CT}r_{CT}} \quad (5)$$

$$\lambda_{imf} = 2\lambda_{IM} \quad (6)$$

$$\mu_{imf} = \mu_{IM} \quad (7)$$

$$\lambda_{pre-out} = \lambda_{ASANI} \quad (8)$$

where λ_{cbf} and μ_{cbf} represent the transfer rates between the operating state and the repair state. λ_{CBC} , λ_{CT} , r_{CBC} and r_{CT} represent the failure rate and average repair duration of CBC and CT, respectively. λ_{imf} and μ_{imf} represent the transfer rates between the operating state and the pre-out state, where λ_{imf} is calculated in parallel mode with two lines. $\lambda_{pre-out}$ is the probability of the pre-out state. λ_{ASANI} represents the probability of average service unavailability under the premise of considering only the adequacy of power generation, which is calculated as follows:

$$\lambda_{ASANI} = \frac{\left(\sum_{i=1}^{N_{inf}} T_{inf,i} \right)}{T} \quad (9)$$

where N_{inf} is the number of power shortages. $T_{inf,i}$ is the duration of the i -th power shortage, and T is the study period. Normally, these three states of the circuit breakers are independent random events, and their steady state probabilities are presented using the Markov method, as follows:

$$P_2 = \frac{\mu_{cbf}\lambda_{imf}}{\mu_{cbf}(\mu_{imf} + \lambda_{pre-out} + \lambda_{imf}) + \lambda_{cbf}(\mu_{imf} + \lambda_{pre-out}) + \lambda_{imf}\lambda_{pre-out}} \quad (10)$$

$$P_3 = \frac{\lambda_{imf}\lambda_{pre-out} + \lambda_{cbf}(\mu_{imf} + \lambda_{pre-out})}{\mu_{cbf}(\mu_{imf} + \lambda_{pre-out} + \lambda_{imf}) + \lambda_{cbf}(\mu_{imf} + \lambda_{pre-out}) + \lambda_{imf}\lambda_{pre-out}} \quad (11)$$

where P_2 and P_3 represent the steady state probabilities of the pre-out state and the repair state, respectively. When simulating the circuit breaker states using the SMC method, it is necessary to increase the state judgment module on the traditional method. For example, the current state $S_{bc,i}(t)$ of the circuit breaker is in the operating state, and the next state can be determined by the following equation, according to the large number theorem:

$$S_{bc,i}(t+1) = \begin{cases} P_2 & \frac{\lambda_{imf}}{\lambda_{imf} + \lambda_{cbf}} \leq x_i \leq 1 \\ P_3 & 0 \leq x_i \leq \frac{\lambda_{imf}}{\lambda_{imf} + \lambda_{cbf}} \end{cases} \quad (12)$$

where x_i is a random scalar within $[0,1]$, which follows uniform distribution. $S_{bc,i}(t+1)$ represents the state of the i -th circuit breaker at the next moment.

C. Communication Network Model

Due to the redundant configuration of spacer layer elements, the failures of communication lines or network switches do not necessarily affect the CPMS operation. The simplified method of using elements series and parallel calculations is not applicable when evaluating the overall network reliability. In addition, the link connectivity evaluation method is adopted which has been widely applied in the reliability assessment of communication networks.

The communication network within CPMS can be represented as a graph. In the graph theory, one graph can be expressed as $G(V, E)$, where V denotes the set of vertices, and E denotes the set of edges. The adjacency matrix is adopted to represent the path of information transmission in the communication network for the path search.

If CPMS, the communication network has n information nodes, the information transmission can be represented by

an $n \times n$ order adjacency matrix $A = (a_{ij})_{n \times n}$, where a_{ij} represents the communication link which describes the communication relationship between the node i and the node j in the cyber system. a_{ij} is defined as follows:

$$a_{ij} = \begin{cases} 1, & \text{Exist a cyber link between node } i \text{ and } j \\ 0, & \text{Does not exist} \end{cases} \quad (13)$$

For instance, according to the network structure in Fig. 7(b), the network adjacency matrix is shown as follows:

$$\begin{bmatrix} 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \quad (14)$$

When the communication structure is described by an adjacency matrix, the information paths can be represented by a set of node sequences. With the adjacency matrix, 7-4-2-1 is the information path between node 7 and node 1, as well as the sequence 7-4-3-1 which has the same illustration.

Depth-first search (DFS) is one of the algorithms for traversing graphs and is widely used in the field of communication networks. When the cyber elements randomly fail and the communication topology may be changed, it is necessary to verify whether there is an information path between the process layer elements and CC. If the information path exists, the process layer elements are not affected by the failure. If not, the corresponding elements passively failed. For example, in Fig. 7(b), when checking whether node 7 and node 1 (CC) are connected or not, we start from line 7 of the matrix to find its connected node, i.e., node 4. Secondly, we start from the fourth line of the matrix to find the connected node, i.e., node 2. Then search line 2 of the matrix. It is shown that node 2 is connected to node 1. It indicates that there is a connection between node 7 and node 1, and the communication lines between them are normal. Fig. 4 shows the link connectivity judgment between two nodes based on the adjacency matrix and DFS.

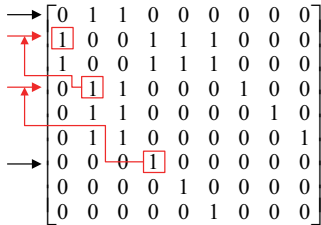


Fig. 4. Link connectivity between two nodes based on the adjacency matrix and DFS.

The communication network connectivity evaluation described in this paper includes three parts: 1) failure elements are obtained by the timing sampling, and the adjacency matrix is modified to obtain the updated information of the

communication network topology; 2) a DFS algorithm is used to search the possible paths for each process layer node to CC; 3) the impact of a random failure on process layer nodes is determined.

It is not necessary to carry out a node search once the process layer node has found a path. Moreover, to prevent the search from entering the loop network, two recursive conditions are proposed in the search function: 1) the searched adjacency nodes must be different from nodes that have been stored in the past; 2) the searched adjacency node is not a terminating node. The next node search is performed, when both conditions are met; otherwise, the recursion fails.

D. Management Layer Elements Model

CC is the central part of CPMS operation and regulation. Theoretically, each DG can continue to run in a peer-to-peer manner after the failure of CC [24]. However, peer-to-peer control does not consider the problem of secondary frequency regulation. The system frequency may have a greater fluctuation when there is a disturbance in the grid, and which may not guarantee the power quality of the MG [25]. So the failure of CC is equivalent to the failure of the whole CPMS.

E. Other Elements Reliability Model

The elements in the CPMS are assumed to be repairable. The outage and operation of elements can be described by the two state models, when the scheduled repair is not considered. It is assumed that the outage of the element is a random event and its running time and failure duration are subject to exponential distribution, as follows:

$$t_1 = - \left(\frac{1}{\lambda} \right) \ln(x_1) \quad (15)$$

$$t_2 = - \left(\frac{1}{\mu} \right) \ln(x_2) \quad (16)$$

where λ (times/year) and μ (times/year) represent the failure rate and repair rate of the elements respectively. t_1 and t_2 represent the time between non-failure and repair time respectively. x_1 and x_2 are random variables that obey the uniform distribution in $[0,1]$.

In addition, controllable DGs (DE, ESS) output models can be found in the literature [26], and the passive random element (WT) is modelled using historical data [27]. The load model is generated from the historical data, from a science and technology park.

III. RELIABILITY ASSESSMENT METHOD OF CPMS

When assessing the reliability of MG in island mode, the sequential states of ESS are obtained by formulating a charge-discharge strategy. However, this approach cannot meet the economic needs of MG operation, and there is an oversimplification when the renewable power is used alone as a stable and continuous power source. This simplification may lead to errors in the calculation of power output states at the moment of elements random failures. This paper considers the optimal operation strategy of the island MG and calculates the sequential power states by solving the nonlinear programming

model, so that the exact outputs and reserve capacity of controllable micro-sources can be calculated and economic requirements of the MG operation can be satisfied. Then, the system state generation method and cyber physical reliability models are combined by the SMC method, and the island CPMS reliability assessment process is proposed.

A. CPMS States Generation Considering Optimal Operation Strategy

Power output states can be calculated by solving the optimization model, and these states are important in fault state assessment after an element failure.

This paper takes the island mode CPMS, containing WT, ESS and DE, as an example. Optimization of DE and ESS is designed to minimize the daily operating costs under the constraint of power balance and maximize the utilization of renewable sources. The objective function can be expressed as follows:

$$\min f = \sum_{t=1}^N f_{DE} + F_{DG} \quad (17)$$

where N is the running time set to 24 h, and f_{DE} represents the fuel cost of DE. F_{DG} represents the maintenance cost of the DGs. f_{DE} and F_{DG} can be calculated according to the following equations:

$$f_{DE} = d + eP_{DE,t} + fP_{DE,t}^2 \quad (18)$$

$$F_{DG} = K_{DE} \cdot P_{DE,t} + K_{ESS} \cdot P_{ESS,t}^d \quad (19)$$

where $P_{DE,t}$ and $P_{ESS,t}^d$ are the output of DE and ESS during time slot t . d , e and f are polynomial coefficients related to distinct DE [28]. In this paper, $d = 3.2584$, $e = 1.7544$, and $f = 0.0556$. K_{DE} and K_{ESS} represent the coefficients for DE and ESS maintenance costs, respectively, and $K_{DE} = 0.0946$, $K_{ESS} = 0.0832$.

The power balance of MG is the system level constraint of the optimal operation, i.e., the output of DGs and the load demand are equal at any time. It is noted that, the network losses are not considered in this paper. The power balance constraint can be expressed as follows:

$$P_{DE,t} + P_{WT,t} + P_{ESS,t} = P_{Demand,t} \quad (20)$$

where $P_{DE,t}$, $P_{WT,t}$, $P_{ESS,t}$, and $P_{Demand,t}$ are the output of DE, WT, ESS and the load demand during time slot t , respectively. DE is the power source to realize the frequency regulation. Its output, i.e., $P_{DE,t}$, should meet the constraint:

$$P_{DE,\min} \leq P_{DE,t} \leq P_{DE,\max} \quad (21)$$

where $P_{DE,\max}$ and $P_{DE,\min}$ represent the upper and lower limits of DE. For maximum utilization of renewable energy, the ESS operation strategy is adopted to store excess electricity when the output of WT and DE are higher than the demand. When the power generation is insufficient, ESS releases the energy as much as possible to meet the load requirement. In order to ensure that ESS has enough remaining energy to participate in fault recovery, a predefined lower limit of the

state of charge (SOC) is used. The constraints related to ESS are shown as follows:

$$S_{oc,t} = S_{oc,t-1} + \frac{\eta_c \Delta T p_{ESS,t}^c - (1/\eta_d) \Delta T p_{ESS,t}^d}{S_{nom}} \quad (22)$$

$$\begin{aligned} \text{s.t.} \quad & S_{oc,\min} \leq S_{oc,t} \leq S_{oc,\max} \\ & p_{BESS,t}^c p_{BESS,t}^d = 0 \\ & p_{BESS,t}^c, p_{BESS,t}^d \leq p_{BESS,\max} \end{aligned} \quad (23)$$

where $S_{oc,t}$ is the SOC of ESS at time t . η_c , η_d , $P_{ESS,t}^c$ and $P_{ESS,t}^d$ represent the charge efficiency, discharge efficiency, charging rate and discharging rate, respectively. ΔT represents the time step, and is set to 1 h.

The optimization problem is a multi-period decision making problem. As a popular modelling tool, YALMIP contains multiple solution algorithms to solve this nonlinear programming problem. The process is depicted as follows:

- 1) Initialize the cycle and step size of the optimization problem. The cycle is 24 hours, and the time step is 1 hour.
- 2) According to the wind speed and WT output model, the WT output is obtained, set the initial SOC status and read the historical load data.
- 3) Initialize the optimization conditions according to (17)–(23).
- 4) Call the YALMIP toolkit to solve the multi-period optimization problem, and obtain the optimized output values of DE and ESS.

B. Reliability Assessment Process of CPMS

Considering the power states generation method in Section III-A and the reliability models in Section II, a CPMS reliability assessment method is proposed based on the sequential Monte Carlo simulation method. The reliability indices utilize the load point and system reliability indices of the traditional distribution networks [29]. The reliability assessment process is shown in Fig. 5, and the specific steps are depicted as follows:

Step 1: Read the data and initialize the simulation process. The system's initial simulation time is $Time = 0$. The initial value of SOC is 0.5. The initial load shedding is $L_{shed} = 0$.

Step 2: Establish the initial adjacency matrix A_{inet} according to the communication network topology.

Step 3: Generate the time between non-failure and repair time of all elements in CPMS according to formulas (15) and (16).

Step 4: Generate the sequential state according to the strategy in the period of non-failure.

Step 5: If the failure element is not a cyber element, go to Step 8; otherwise, check whether the spacer layer element fails. If yes, modify the initial adjacency matrix of the communication network and use the DFS method to evaluate network connectivity using the novel adjacency matrix. If the communication network is normal, go to Step 8; otherwise, record the affected process layer elements and turn into the corresponding physical component failure, and go to Step 9. If the spacer layer element does not fail, go to Step 6.

Step 6: If CC fails, the entire network is out of service, update the load point and the system reliability indices, and go to Step 8; otherwise, go to Step 7.

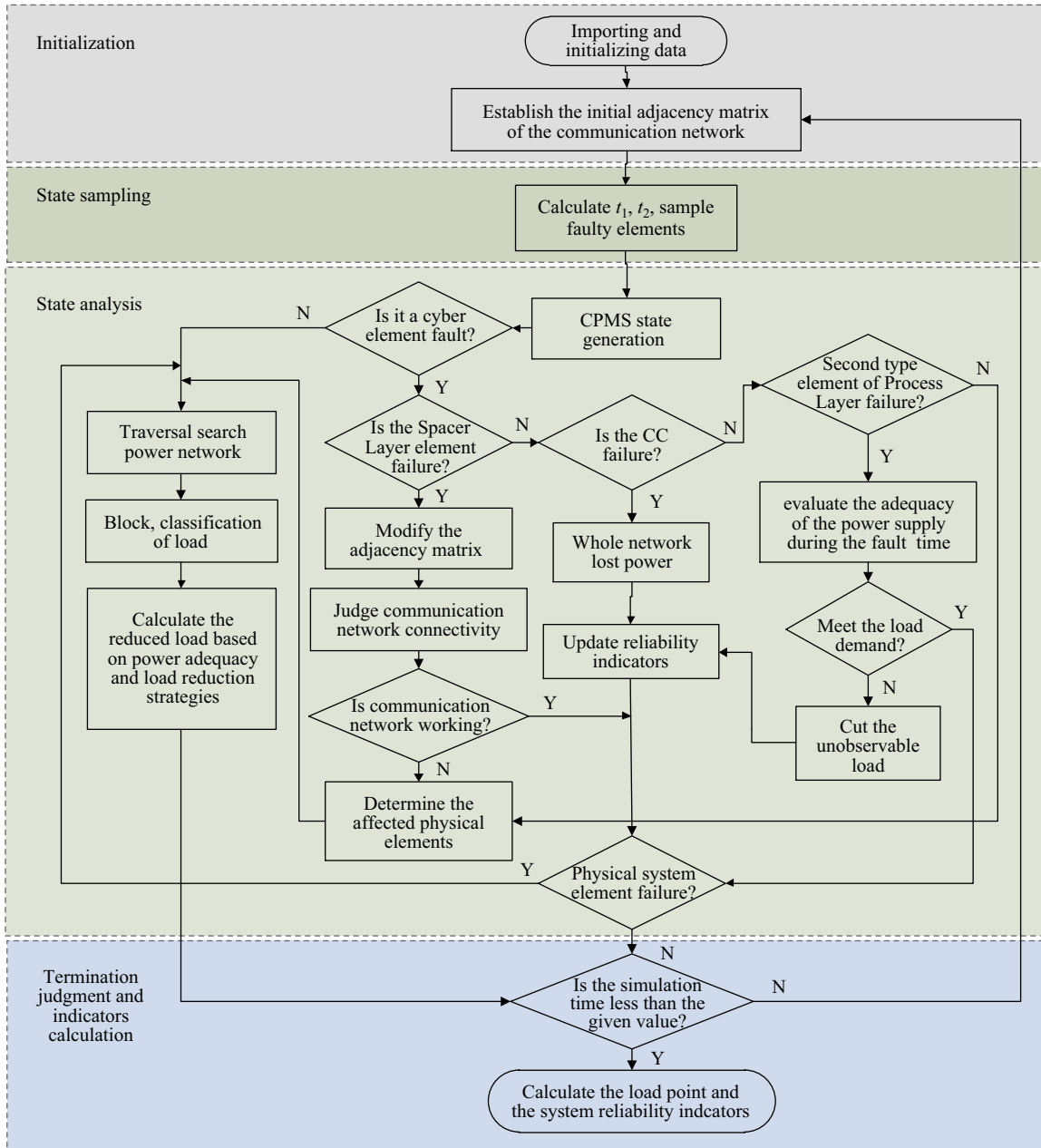


Fig. 5. Reliability assessment process.

Step 7: If the second type element of the process layer fails, it is necessary to reduce the load at the same time. If yes, the second type element failure is equal to the failure of faulty zone circuit breakers, update the reliability indices and go to Step 8. If not, judge the power generation capacity to meet the load demand. If load demand is met, then go to Step 8. If not, reduce the unobservable line load, update the reliability indices and go to Step 8. If the second type elements of the process layer do not fail, the failure elements must be the first type of the process layer. The corresponding physical element failure is identified according to the indirect interdependencies, and go to Step 8.

Step 8: Check whether there is a failure of a physical element. If yes, go to Step 9; otherwise, go to Step 12.

Step 9: The DFS of the power network is carried out

after the corresponding physical element fails and the load is classified by the circuit breaker as the boundary. Type A: this type of load loss connection with DGs will be shut down until the faulty element is repaired. Type B: this type of load connects to the DGs and load reliability will be analyzed based on time series simulation.

Step 10: Calculate the t -th ($t = 1, 2, \dots, t_1 + t_2$) hour power adequacy after the fault based on Step 4. If satisfied, update the SOC sequence and DE output as the input value for the optimized operation. If not satisfied, shed loads according to the predetermined strategy and update the reliability indices.

Step 11: If $t < t_1 + t_2$, make $t = t + 1$ and return to Step 10; otherwise, go to Step 12.

Step 12: Cumulate simulation time $T = T + 1$. If T is less than the given simulation time then return to Step 2; otherwise,

go to the next step.

Step 13: Calculate the reliability indices.

IV. CASE STUDY

A. Test System

A CPMS system is tested with the RBTS Bus 6 F4. Its topology is shown in Fig. 6. The CPMS contains a WT, a DE, an ESS and the capacity of each is 2 MW, 1.25 MVA and 1.5 MWh, respectively. The maximum charge and discharge rate of ESS is 0.375 MW. There are eight load points in CPMS. The average annual load power is 1.56 MW which accounts for 49.19% of the total power supply capacity. According to the load sensitivity to the power quality, the load shedding strategy is: LP39, 40; LP30; LP36–38; LP28, 29. The reliability parameters such as failure rate and repair rate of cyber and physical elements in the system are obtained from [26], [29]. The reliability parameters of cyber devices, in terms of the mean time to repair (MTTR) and the mean time to failure (MTTF) are reported in Table I.

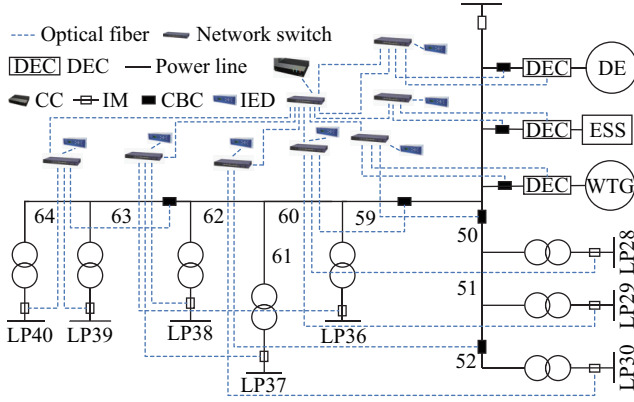


Fig. 6. Topology of CPMS.

TABLE I
RELIABILITY DATA OF CYBER DEVICES

Equipment	MTTF/h	MTTR/h
CC	125,000	48
IED	168,000	48
CT	131,400	48
IM	131,400	48
CBC	131,400	48
Switch	438,000	48
DEC	131,400	48
Optic Fibre (1 km)	2,190,000	48

To study the influence of different communication network structures on CPMS reliability, five different cases are designed:

Case 1: Only physical elements random failures are considered, and the cyber system is completely reliable.

Case 2: Cyber and physical elements random failures are considered and its communication network structure is a single star, as shown in Fig. 7(a).

Case 3: Change the network structure in case 2 to the single ring, as shown in Fig. 7(b).

Case 4: Change the network structure in case 2 to the double star, as shown in Fig. 7(c).

Case 5: Change the network structure in case 2 to the double ring, as shown in Fig. 7(d).

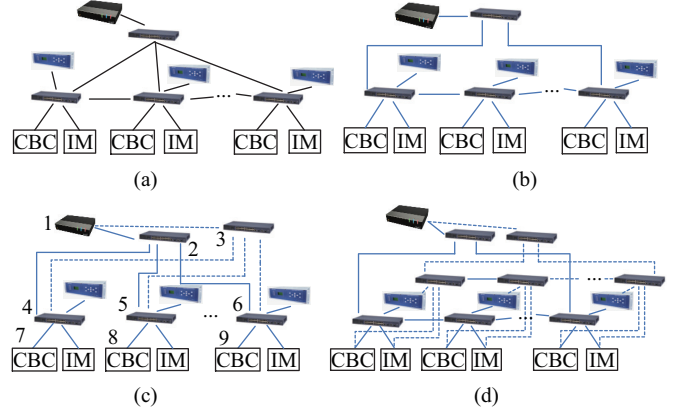


Fig. 7. Different communication structures of CPMS. (a) Single star network. (b) Single ring network. (c) Double star network. (d) Double ring network.

B. Test Results and Analysis

Using the proposed assessment method in Section III, a 100 year simulation is carried out using MATLAB software. The simulation results are analyzed as follows.

1) System States Generation of CPMS

Four typical daily load curves during the year are chosen. When the elements are not faulty, the outputs of DE and ESS at each hour are solved based on the economic dispatching. The adequacy evaluating of power supplies is used to judge whether the load needs to be reduced or not when the element is faulty.

2) Reliability Indices

Load reliability indices include annual average power outage frequency λ /(times/year), annual average power outage time U /(hours/year) and expected energy not supplied $EENS$ /(MWh/year). The system reliability indices include average service availability $ASAI$, system average interruption frequency index $SAIFI$ /(times/year), system average interruption duration index $SAIDI$ [h/(user year)], and expected energy not supplied $EENS$ /(MWh/year). Their corresponding expressions can be described as follows:

$$ASAI = \frac{(\sum N_i \times 8760 - \sum U_i N_i)}{(\sum N_i \times 8760)} \quad (24)$$

$$SAIFI = \frac{\sum \lambda_i N_i}{\sum N_i} \quad (25)$$

$$SAIDI = \frac{\sum U_i N_i}{\sum N_i} \quad (26)$$

$$EENS = \sum L_{(a)i} U_i \quad (27)$$

where U_i , λ_i and N_i are the annual outage time, failure rate and number of customers of load point i , respectively. $L_{(a)i}$ is the average load connected to the load point i . In Table II, the load reliability indices calculation results of case 1 and case 2 are shown. System reliability indices of the 5 cases are shown in Table III.

TABLE II
CASE 1 AND CASE 2 LOAD POINT RELIABILITY INDICES

Load position	λ	Case 1			Case 2		
		U	$EENS_{LP}$	λ	U	$EENS_{LP}$	
LP28	0.22	4.45	0.4811	0.32	13.55	1.6997	
LP29	0.21	6.75	2.3443	0.35	22.51	9.5981	
LP30	0.22	4.32	0.3389	0.37	19.26	2.0046	
LP36	0.22	5.94	2.5678	0.40	14.41	5.6281	
LP37	0.18	2.11	0.3129	0.39	10.63	1.0701	
LP38	0.20	3.58	0.9819	0.38	15.83	4.8788	
LP39	0.24	31.71	4.5419	0.47	47.09	6.4819	
LP40	0.27	37.94	12.0803	0.52	48.83	19.0690	

TABLE III
SYSTEM RELIABILITY INDICES OF DIFFERENT COMMUNICATION NETWORK STRUCTURES

	$ASAI$	$SAIFI$	$SAIDI$	$EENS$
Case1	0.9986	0.2251	12.1424	24.4161
Case2	0.9969	0.3976	26.8437	59.1717
Case3	0.9974	0.3544	22.258	45.3884
Case4	0.9975	0.4069	21.495	40.2744
Case5	0.9982	0.2977	15.9204	36.4615

In order to evaluate the influence of the optimal operation strategy on the CPMS reliability assessment, the strategy adopted in this paper is compared with that of the non-optimized operation strategy in [26], while the other parameters remain the same. The comparison of system reliability indices are shown in Table IV.

TABLE IV
SYSTEM RELIABILITY INDICES UNDER DIFFERENT STRATEGIES

Reliability Indices	Case1	Reference [26]
$ASAI$	0.9986	0.9993
$SAIFI$	0.2251	0.1502
$SAIDI$	12.1424	8.4696
$EENS$	24.4161	16.8403

It can be seen from Table IV that all system reliability indices have different degrees of deterioration after considering the operation strategy. First, the lower limit of DE output is set and the wind resource utilization is reduced. Second, as the cost of ESS is lower than that of DE, ESS will be given priority to power supply in optimal scheduling. During the moment of element failures, the spare capacity of ESS is less than that of the traditional strategy. Therefore, the results are more pessimistic than the traditional strategy in [26]. However, the disadvantage of the proposed approach is that it takes a longer time to calculate. Under the same hardware configuration, the calculation takes about 19 seconds under the traditional strategy and about 118 seconds after adopting the optimization strategy. In conclusion, the proposed method is suitable for the time-insensitive calculation with high accuracy requirements.

In order to evaluate the influence of the three-state circuit breaker model on the reliability of CPMS, the load point reliability indices are compared with the results obtaining by the traditional model. The results are shown in Table V.

Compared with other indices, index λ has undergone major changes when using the three-state model. Comparative analysis is shown in Fig. 8.

As shown in Fig. 8, when using the traditional circuit

TABLE V
SIMULATION RESULTS OF DIFFERENT CIRCUIT BREAKER RELIABILITY MODELS

Load Indices	Three-state model (Case 2)			Traditional model		
	λ	U	$EENS_{LP}$	λ	U	$EENS_{LP}$
LP28	0.32	13.55	1.6997	0.29	12.26	1.723
LP29	0.35	22.51	9.5981	0.30	11.32	4.474
LP30	0.37	19.26	2.0046	0.41	24.86	3.487
LP36	0.40	14.41	5.6281	0.38	13.88	5.462
LP37	0.39	10.63	1.0701	0.37	17.28	2.4414
LP38	0.38	15.83	4.8788	0.37	10.91	4.3367
LP39	0.47	47.09	6.4819	0.48	42.36	8.5018
LP40	0.52	48.83	19.0690	0.53	43.12	17.9539

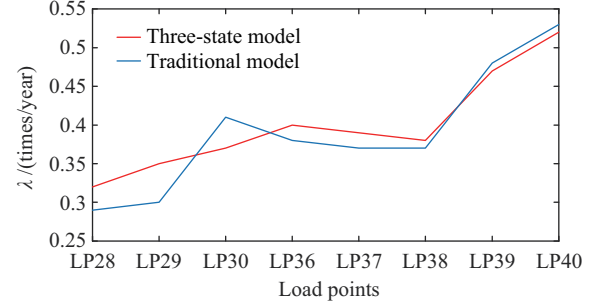


Fig. 8. Comparison of load point index λ under different circuit breaker models.

breaker model, LP30 has a higher annual power interruption frequency than LP36–38 due to different load reduction priorities. However, the annual power interruption frequency of LP30 is lower than LP36–38 after the new model is adopted. That is to say, the relationship between load points' power interruption frequency and load shedding strategy loses correlation after adopting the new model, where the indirect effect of CPS is considered. The reason is that the IM element failure leads to the line unobservable, which increases the risk of power outage on the load points. The new reliability model is conducive to exploring the coupling relationship between cyber and physical systems.

The communication link connectivity evaluation method proposed in this paper is embedded in the reliability assessment and the results are shown in Table III. Compared with the single-star network in case 2, the reliability index $ASAI$ increased by 0.05%, 0.06% and 0.13% in cases 3-5. Other indices have different degrees of reduction, whereas the $EENS$ index is decreased by a maximum of 38.4%. The calculation results verify the effectiveness of the proposed method, quantifying the impacts of communication network structures on CPMS.

Under the premise of unchanging element parameters and network topology, it is possible to improve CPMS reliability by increasing the reliability parameters of the weak element instead of increasing equipment redundancy. Cyber devices using different equipment are not the same degree of impact on the system reliability, that is, the equipment importance is not the same [15]. For the double ring and double star communication network structures, we choose the reliability index $EENS$ as the reference, and then change the element failure rate in accordance with the proportion of 10% (increase

or decrease by up to 50%, while other equipment failure rate remains unchanged). The importance of various cyber elements to the CPMS system is obtained through a number of calculations, which is shown in Fig. 9 and Fig. 10. In order to compare the results clearly, this paper averages the data after the 100 times calculation.

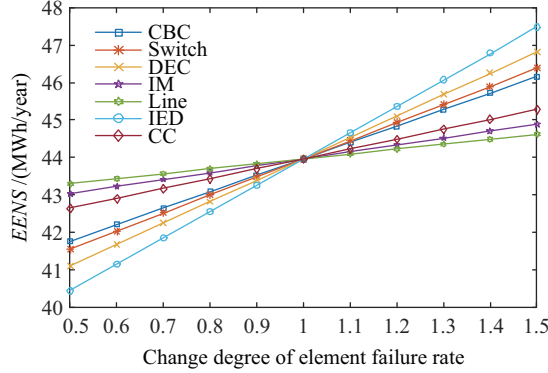


Fig. 9. Significance analysis of cyber elements in the double star structure.

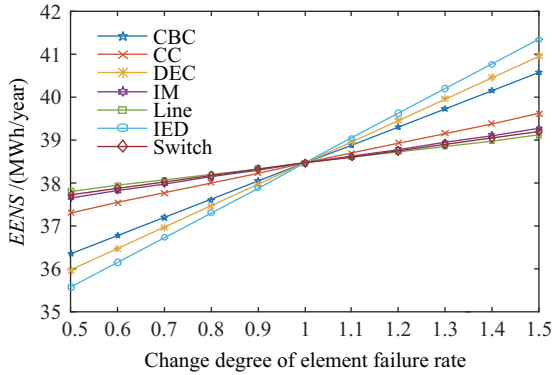


Fig. 10. Significance analysis of cyber elements in the double ring structure.

As shown in Fig. 9 and Fig. 10, the most important element is IED under different communication network structures. The importance order of other elements is the same except for the switches. It can be observed that, the system reliability is not sensitive to changes in the switch failure rate when using the double ring structure. Analysis of the importance of cyber elements can provide a theoretical basis for the cyber equipment selection and maintenance priority in actual projects.

V. CONCLUSION

This paper investigated the reliability assessment issue in the CPMS in island mode. A new three-state reliability model for the circuit breaker is proposed. This new model provides a method that can be used to analyze the indirect interdependencies of island MGs by using SMC method and reveals the relationship between indirect interdependencies and power interruption frequencies at load points. The method of communication network connectivity evaluation is introduced into the reliability assessment process. A system state generating

method is proposed to consider the optimal operation strategy. The effectiveness of this method is verified by the test system.

The results of element importance analysis show that IED in the spacer layer has the most significant impact on system reliability. For a MG project with a similar network structure, we recommend giving priority to high reliability IED devices to improve system reliability.

In our future work, the reliability assessment of the island mode MG will be extended to the analysis of the control system and its impact on the power quality.

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