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Analytical Reliability Evaluation for Distribution Networks Considering the Effects of Cyber Failures

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Abstract: - During the reliability assessment of active distribution networks, traditional simulation methods encounter numerous challenges, including extensive computational requirements, time-consuming progresses, limited accuracy, and inadequate consideration of cyber failures. Addressing these limitations, this paper introduces an analytical approach tailored for the reliability assessment of distribution network Cyber-Physical Systems, which specifically incorporates the influence of cyber failures. Firstly, the analytical method is employed to model the effectiveness of information systems and the switching efficiency of information coupling. These models aim to enhance computational speed and efficiency, thereby addressing the issues of high computational efforts and time-consuming processes associated with traditional methods. Secondly, in collaboration with a mixed-integer linear programming model, updated formulas are derived for assessing distribution network fault rates and fault repair times, taking into account cyber failures. This integration enables a more comprehensive reliability assessment that incorporates both the physical and cyber components of the system. Finally, numerical results obtained from modified IEEE 33-node and 7-node systems demonstrate the efficiency and applicability of the proposed method. Not only does this approach provide insights into the impact of cyber failures on distribution network reliability, but it also offers valuable technical support for the integration of information systems in smart grids.

Keywords: Distribution networks, Cyber-physical system, Reliability assessment, Cyber failures, Analytic method.

I. INTRODUCTION

With the development of science and technology and the national economy, the demand of users for the quality of power supply has also increased. Distribution networks in the transmission and distribution system are at the end of the position. At the same time, it is directly connected to the user and strongly linked to the quality of the power supply [1]. With the high-speed development of the smart grid, a large number of distributed generators and microgrids combine power production, transmission and delivery to form a joint grid. Modern information and communication technology transmits equipment information and control information in between, which has a vital role in guaranteeing the reliability of the distribution grid.

In recent years, the deployment of information and communication technology (ICT) in distribution systems has increased significantly and plays an important role in ensuring the reliable operation of distribution networks [2]. In addition, faults in information systems can directly affect the reliable operation of distribution grids. For example, the misdirection and loss of information can cause errors in the judgement of faults, which may lead to incorrect action of sectional switches. Communication delay, on the other hand, can cause information transmission failure [3-4]. Especially for unattended substations, the impact of information system failure on distribution network reliability will be more obvious. Therefore, information system failures must be taken into account when considering distribution network reliability.

Nowadays, the methods of traditional distribution network reliability assessments are relatively mature. Many of the previous researches have used simulation to model the occurrence of failures at various locations to judge system reliability. Reference [5] considered the failure rates of switching and renewable distributed generation and evaluated their impact on the cost of system reliability through a Markov approach. Reference [6] investigated the impact of the availability of basic protection elements on the reliability improvement of distribution networks, and used a multilevel Monte Carlo method to accelerate the traditional reliability assessment. Reference [7] constructed a multidimensional network model based on Monte Carlo simulation and proposed a reliability modeling and assessment methodology for distribution networks. Reference [8] considered factors such as multi-component

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characteristics, complex topology in the analysis of the whole process of fault location, isolation and power restoration. The Reliability assessment procedure based on the Monte Carlo method framework was proposed. Reference [9] firstly applied sequential simulation to generate a representative state space of a complex power system. Then non-sequential Monte Carlo sampling was performed to determine the relevant faults induced in the network for reliability assessment. Although the above references have considered the influence of multiple factors on the reliability of distribution networks and innovated the method of assessing the reliability of distribution networks, there are still problems such as large amount of calculation and poor accuracy. It is obviously not suitable for the analysis of complex power systems.

For distribution networks containing cyber-physical systems, reference [10] determined a reliability index for standard networks based on linear programming, which can solve the problem of limited reliability of smart distribution systems in operational and planning models. Reference [11] analyzed the cyber-physical fusion in terms of information component failures and cyber-attacks and proposed a set of distribution network reliability assessments considering information perturbations. Reference [12] proposed a distribution network reliability assessment methodology based on fault trees that considered physical and information system interdependencies. Reference [13] established a no-response probability model and proposed an efficient evaluation system for network link reliability based on frequency-time domain transformation. Reference [14] added the analysis of information physical interdependencies and information transmission faults to the modeling, focusing on the physical uncertainty of the networked system. Reference [15] considered the interdependence of network and physical components, and applied an algorithm to determine the most probable failure configurations to compute the reliability metrics. However, the above references tended to favor more studies on the physical side of the network. Few references have considered the important factor of information system failures. So it led to a more optimistic study.

In conclusion, there is an urgent need for a method that can be solved quickly yet takes into account the high degree of coupling of cyber-physical systems.

The primary contributions of this paper are as follows:

- Information components, information links, and information coupling switch effectiveness are accurately modeled. Information system modeling is complete

- The coupled relationship between the information systems and the physical systems is considered. Both the impact of cyber failures on the physical side and the impact of physical side failure on the information side are taken into account, which applies to the analysis of modern smart grids.

- To address the deficiencies of the simulation method, this paper applies the analytical method, which is less computationally intensive and more accurate.

The rest of this article is structured below: Section 2 describes the modeling of information systems, whose effective probability is calculated by convolution. In Section 3, a new approach for assessing the risk of cyber failures is presented and reliability indicator values are derived. In Section 4, Case studies are carried out to demonstrate the effectiveness of the proposed method. Section 5 concludes the paper and presents an overview of future research perspectives.

II. Introduction to the Structure of Cyber-Physical Distribution Systems

The cyber-physical distribution system is composed of an information system and a physical system, which further ensures the reliability and efficient operation of the distribution networks. The physical side consists of the equipment required to generate, transmit, and distribute electricity in a conventional power system. The information side consists of three main layers: the application control layer, the data transmission layer, and the perception layer. The main components are servers, switches, and intelligent electronic devices (IEDs) for monitoring, controlling, and protecting the physical system [16-17]. Sensors are designed to monitor the operational status of the distribution networks. The communication network transmits information between the control center and the sensing elements, guaranteeing fast fault removal. The coupling of information systems and physical systems allows for a two-way flow of power and information, making it possible to make real-time decisions based on real-time data from the physical layer. A typical system diagram is shown in Fig. 1.

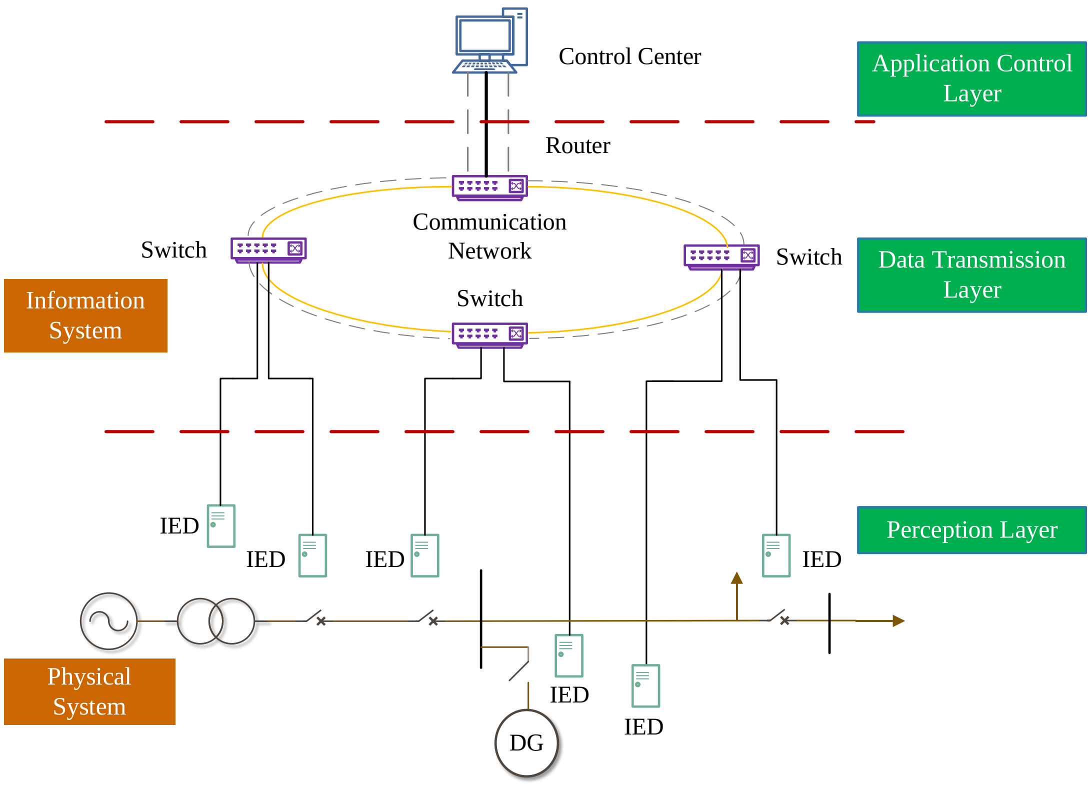

Fig 1: Cyber-Physical Distribution System Structure Diagram

III. Modeling and Evaluation of Information Systems Effectiveness

A. Information Components Usability Modeling

The information components in information systems mainly consist of routers, switches, intelligent electronic devices, and fiber-optic lines connecting these components. All of the above components can be regarded as a two-state model involving "operation-failure-operation" [18]. As shown in Figure 2. λ_i denotes the transfer rate of information element i from the normal state to the faulty state. μ_i denotes the transfer rate of information element i from a faulty state to a normal operating state. If the probability of the normal operating state of component i is a_i, then the probability of the fault state $\overline{a_i}$ can be expressed as $a_i = 1 - \overline{a_i}$.

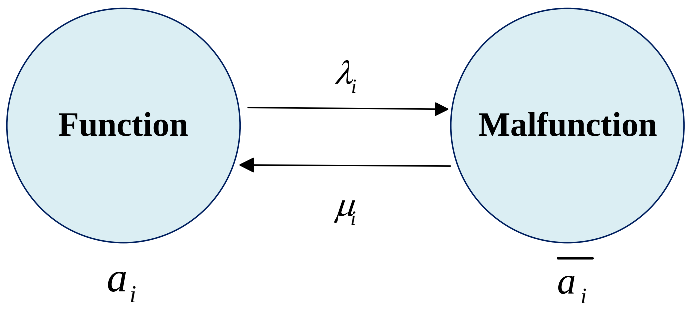

Fig 2: Information Element Two-State Model

From the Markov state equation, the probability that information element i is in a normal operating state is equal to the product of its probability of being in a faulty state and the rate of transfer out of the faulty state, which can be expressed as:

$$\mu_i a_i = \lambda_i \overline{a_i} \tag{1}$$

From equation (1) and the relationship between a_i and $\overline{a_i}$, it can be introduced that the availability of information node i is expressed as:

$$a_i = \frac{\mu_i}{\lambda_i + \mu_i} \tag{2}$$

Correspondingly, the availability of information links i-j connecting between information nodes i,j can be expressed as:

$$a_{i-j} = \frac{\mu_{i-j}}{\lambda_{i-j} + \mu_{i-j}} \tag{3}$$

In the above equation, λ_{i-j} is the failure rate of information lines i-j, μ_{i-j} is the repair rate of information lines i-j.

B. Information Link Effectiveness Modeling

An information system can be represented using an undirected graph G = (V, E). Both information components and information lines are considered as nodes in the undirected graph, i.e. V = {v_1, v_{1-2}, v_2, ⋯, $v_{(n-1)-n}$, v_n}. The connectivity between information components is considered as edges in an undirected graph, i.e. E = {e_1, e_2, ⋯, e_m} [19]. As shown in Figure 3. If there exists any edge in the undirected graph that connects two nodes, the channel is called an information transmission channel. In Figure 3, there are three information transmission channels between information nodes i-j, namely (v_1, v_{1-2}, v_2, v_{2-3}, v_3, v_{3-4}, v_4), (v_1, v_{1-4}, v_4) and (v_1, v_{1-2}, v_2, v_{2-4}, v_4). For the same information transmission channel, its availability is described using the tandem model [20]:

$$A_{i-j} = a_j \prod_{k=i}^{j-1} a_k a_{k-(k+1)} \tag{4}$$

where A_{i-j} is denoted as the availability rate of the information transmission channels i-j. a_j is the availability rate of the information systems end element j. a_k and $a_{k-(k+1)}$ are the availability rates of the information element k as well as the information line k-(k+1), respectively.

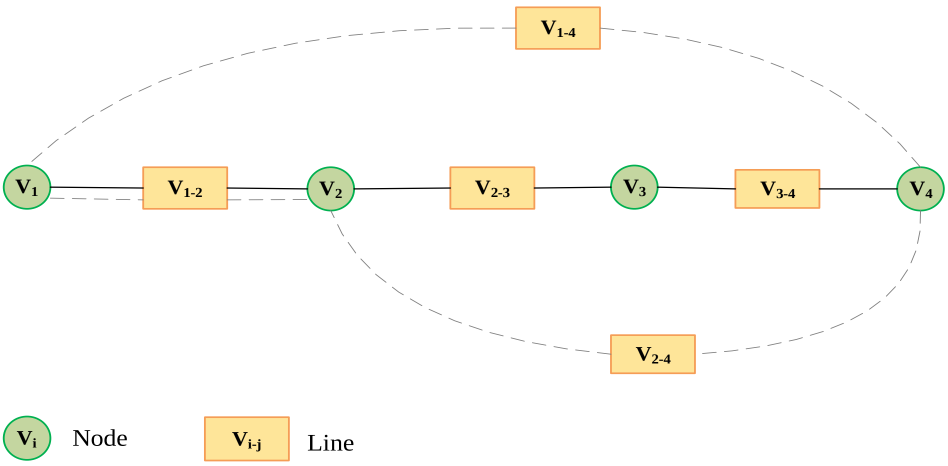

Fig 3: Information System Undirected Diagram

Whether information is transmitted efficiently or not in an information transmission channel is closely related not only to the availability of individual information components but also to the information errors caused by channel errors. The channel error code is related to the performance of the communication equipment itself as well as the anti-interference ability. BER varies from device to device. According to the statistical data in the reference [21], the BER of information nodes such as intelligent electronic devices and switches is 10^{-4} and the BER of fiber optic lines is 10^{-9}, the same as the availability of the information transmission channel. The probability that no BER occurs on the same information transmission channel can also be expressed as the product of the probability that no BER occurs for each information element on the channel as follows:

$$W_{i-j} = w_j \prod_{k=1}^{j-1} w_k w_{k-(k+1)} \tag{5}$$

where W_{i-j} is the probability that no BER occurs for messages i-j of the information transmission channel. w_j is the probability that no BER occurs for message j of the end element of the information systems. w_k and $w_{k-(k+1)}$ are the probabilities that no BER occurs for message k of the information element k as well as for the message on the information line k-(k+1), respectively, where k∈N.

Communication delay also affects the performance of information transmission, and the causes are more complicated. On the one hand, it is related to the load factor of the network, and on the other hand, it is associated with the number of times a message is forwarded [22]. This characteristic can be expressed by the probability density function of information component delay. Different information devices have different transmission delay characteristics: the information transmission delay of switches and routers obeys the Pareto distribution model with parameters 67.9ms and 20, the information transmission delay of intelligent electronic devices obeys the normal distribution model with parameters 68.35 and 11, and the information transmission delay of fiber optic lines usually obeys the exponential distribution model.

Since the information transmission delay of each element upstream in the information transmission channel is continuously accumulated downward, the delay probability density function of the information transmission channel shall be the convolution of the respective delay probability density functions of the information elements on that channel. When the communication delay exceeds a certain threshold, this information transmission is considered to have failed [23]:

$$M_{i-j}(x) = \int_{-\infty}^{x} f_{i-j}^{L}(t)\mathrm{d}t \tag{6}$$

where M_{i-j} is the probability of timely transmission of information from information transmission channel i-j. x is the default delay threshold of the information transmission channel. $f_{i-j}^{L}(t)$ is the delay probability density function of information transmission channel i-j at moment t, which can be expressed as:

$$f_{i-j}^{L}(t) = f_i(t) * f_{i-(i+1)}(t) * \cdots * f_j(t) \tag{7}$$

where $f_i(t)$ is the delay probability density function of the first end element i of the information transmission channel under t moment. $f_{i-(i+1)}$ (t) is the delay probability density function of the information transmission line i-(i+1) under t moment. * is the sign of convolution operation.

Therefore, the effectiveness $p_{i-j}(x)$ of the information transmission channels i-j under a delay threshold of x, described by the tandem model, can be expressed as the product of the information transmission channel availability A_{i-j}. The probability that the information will not be miscoded W_{i-j} and the probability that the information will be transmitted in time $M_{i-j}(x)$:

$$P_{i-j}(x) = A_{i-j} W_{i-j} M_{i-j}(x) \tag{8}$$

As the number of information components in the information transmission channel increases, the amount of convolutional computation generated by calculating the communication delay probability density function increases. For this reason, the communication delay model in the time domain is transformed using the Laplace transform, thus realizing the fast calculation of the probability density function of the i-j delay of the information transmission channel:

$$F_{i-j}(s) = L[f_{i-j}^{L}(t)] \tag{9}$$

According to equations (8) and (9), the validity probability of information transmission channels i-j can be expressed as:

$$P_{i-j}(x) = A_{i-j}W_{i-j}M_{i-j}(x) = \int_{-\infty}^{x} L^{-1}\left[A_{i-j}W_{i-j}F_{i-j}(s)\right]\mathrm{d}t \tag{10}$$

An information link is not the same concept as an information transmission channel. A complete information link should be composed of information elements at both ends of the information transmission channel and multiple mutually alternate information transmission channels between the two information elements. The information link frequency domain effectiveness model is shown in Figure 4.

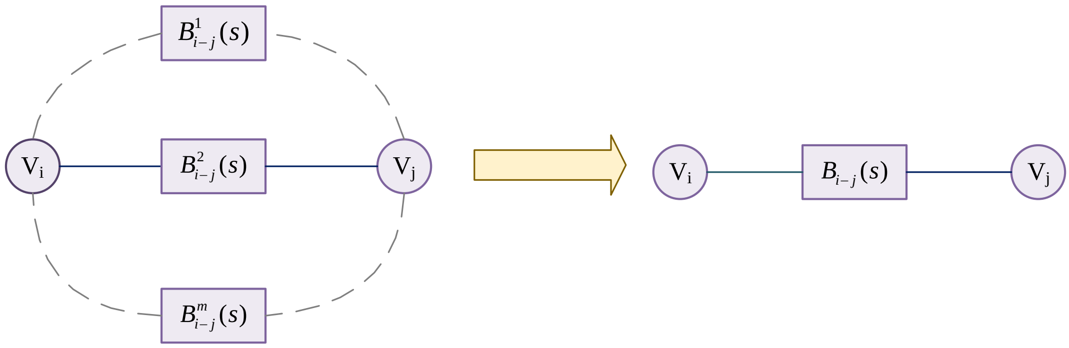

Fig 4: Information Link Effectiveness Model

As shown in Figure 4, assuming that there are m mutually alternate information transmission channels between information nodes i-j, such that the effectiveness model $B^m_{i-j}(s) = A^m_{i-j}W^m_{i-j}F^m_{i-j}(s)$ in the frequency domain of the m^th^ information channel, the effective probability $B_{i\text{-}j}(s)$ of the information link can be expressed as:

$$B_{i-j}(s) = \min\left\{B^1_{i-j}(s), B^2_{i-j}(s), \ldots, B^m_{i-j}(s)\right\} \tag{11}$$

For power distribution networks, to ensure the timeliness of the transmitted information, there exists a delay tolerance upper limit T. Once the delay of the information transmission exceeds the set delay upper limit, this information transmission is considered to be invalid. Therefore, the validity probability of information links i-j can be expressed as:

$$P_{i-j} = P(x < T) = \int_{-\infty}^{T} L^{-1}\left[B_{i-j}(s)\right]\mathrm{d}t \tag{12}$$

C. Modeling the Effectiveness of Information-Coupled Switches

The indirect influence of the information systems on the distribution networks is mainly reflected in the monitoring information of the distribution network monitoring equipment, the control information of the switching elements, and the control feedback information of the switching elements after receiving the successful action of the control commands. The above information primarily affects the fault monitoring, fault isolation, and fault recovery process of the distribution networks. Especially, in the fault recovery process, information plays different roles for different switching elements in the distribution networks such as sectionalized switches and contact switches. Usually, the intelligent electronic devices at the switches need to upload the operation information of the distribution networks to the control center and receive the control commands from the control center. After the switch has completed the corresponding action, it provides timely feedback to the control center. Only when the switching element itself operates reliably and the information link directly connected to it is effective, the control center can effectively control the switching element and thus realize fault recovery [24].

Failures of information components, communication delays, channel errors, and failures of the switching components themselves may cause the switch to fail to act successfully, a condition known as switch refusal. information error codes may convey incorrect information about the switch's operation, leading to switch misoperation, which is referred to as switch misoperation. Neither switch refusal nor switch misoperation can be regarded as a normal operating state. Therefore, the switch state can be simplified as a two-state model, if P_w is utilized to represent the state of normal operation of the switch, then the probability of the switch failure state is 1-P_w, as shown in Fig. 5. This paper focuses on segmented switches, and the modeling process is as follows：

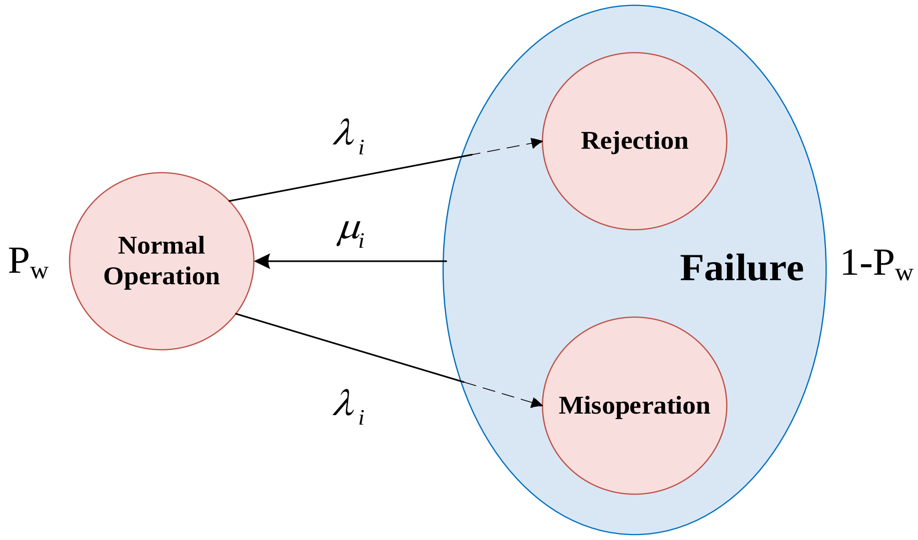

Fig 5: Equivalent two-state model of a switching element

The sectionalized switch is a switch on the main channel of the distribution line, which is mainly responsible for the division of the fault range in the fault isolation process [25]. If the information link directly connected to the sectionalized switch fails during the primary fault processing, the sectionalized switch will not be able to realize the function of fault isolation normally. When the monitoring information on the sectional switch fails, the control center will not be able to accurately judge the current state of the distribution networks. It can only determine the location of the fault through the intelligent electronic equipment of the line upstream of the switch. This will result in the expansion of the fault delineation area and increase the scope of power outages in the distribution networks. The control center will issue a control command to the sectionalized switch that is closest to the upstream of the fault location and has valid monitoring information to achieve isolation of the fault area. After the control command is issued, the command center determines whether the sectionalized switch has successfully completed the opening action based on the control feedback information uploaded by the sectionalized switch. If the command center does not receive the control feedback, it mistakenly believes that the fault isolation has failed. The command center then sends control commands to the sectional switches on the upstream line of the fault until it receives the control feedback to confirm that the fault has been successfully isolated. Therefore, only when the monitoring information, control information and control feedback information on the sectionalized switch are all valid, the sectionalized switch can be considered to be effectively operated, and the fault isolation of the distribution networks can be completed normally.

The information link between information nodes is further divided into uplink and downlink. Since the information uplink and downlink are in the same communication network, the communication equipment and transmission lines that they pass through are the same. In the meantime, the control cycle of the cyber-physical power distribution systems is often only a few milliseconds, and the effective probability of the uplink and downlink is basically the same from the time scale. For this reason, for the same switching element, the effective probability of its monitoring information, control information, and control feedback information within a control cycle can be approximately equal. In addition, during fault processing, the monitoring information (uplink), control information (downlink), and control feedback information (uplink) need to be valid for three short periods to ensure that the fault can be successfully isolated. Due to the short transmission intervals and non-interference between the three, the monitoring information, control information, and control feedback information are independent of each other within a control cycle. Therefore, the probability $P_{ICT,i}$ that the sectionalized switch in the upstream region of the fault can effectively receive control from the control center and feedback that the fault has been successfully isolated is:

$$P_{ICT,i} = P_{M,i} P_{C,i} P_{F,i} \tag{13}$$

In the above equation, $P_{M,i}$ is the valid probability of the monitoring information of sectional switch i. $P_{C,i}$ is the valid probability of the control information of sectional switch i. $P_{F,i}$ is the valid probability of the control feedback information of sectional switch i. There is:

$$P_{M,i} = P_{C,i} = P_{F,i} \tag{14}$$

IV. Mixed-Integer Linear Programming Model Solution Approach

This paper proposes a solution method based on a mixed-integer linear programming model. The method first defines the device installation status and the principles of fault isolation, load transfer, and fault recovery actions after branch failure. Then, a reliability index optimization model based on a mixed-integer linear programming model is constructed for the distribution networks. By solving the model, the value of the reliability index is obtained directly. This method avoids the large number of sampling calculations in the traditional distribution network reliability assessment and can consider the recovery of some fault-affected loads by post-fault network reconfiguration, with high computational efficiency and accuracy.

A. Nomenclature

Due to the large number of variables in the following constraints, they are defined and described in Table 1:

Table 1: Meaning of Different Symbols

Indices	
i,j	Indices for nodes.
x,y	Indices for faulty branch nodes.
B	Indices for circuit breaker action phase.
NO	Indices for normal state of operation.
PF	Indices for Switch action phase
f	Indices for transformers.
Sets	
S	Entire set of system states that cannot satisfy the load demand.
Ψ_i	Set of branches linked to node i.
Ψ^{LN}	Set of load nodes.
Υ	Set of branches.
Ψ^{F}	Set of transformer nodes.
tr^{f}	Set of branches connecting transformer f.
Υ_I^B	Set of branches equipped with circuit breaker at the left end.
Υ_J^B	Set of branches equipped with circuit breaker at the right end.
Υ_I^S	Set of branches equipped with section switch at the left end.
Υ_J^S	Set of branches equipped with section switch at the right end.
Ψ^{SS}	Set of substation nodes.
Parameters	
P_i	Probability of the system being in state i.
C_i	Reduction of load power due to state i.
T	Number of hours or days in a given time interval.
D_i^{xy}	Load at node i in case of a failure at branch xy.
P_{ij}^{xy}	Active power flow through branch ij (from node i to node j) in case of a failure at branch xy.
P_{ji}^{xy}	Active power flow through branch ji (from node j to node i) in case of a failure at branch xy.
M	A positive number.
P_{ij}^{C}	Branch ij rated transmission power.
P_f^{xy}	Power of transformer f in case of a failure at branch xy.

$P_{tr^f}^{xy}$	Power flowing downstream from the transformer node in the event of a failure at branch xy (through branches tr^f).
λ_{xy}	Annual failure rate of branch xy.
τ_{xy}^{SW}	Breakdown repair interruption time for branch connecting nodes x and y.
τ_{xy}^{RP}	Switching action interruption time for faulty branch connecting nodes x and y.
$\lambda_{L,i-1}$	Failure rate of the (i-1)st region.
Z	Number of section switches in branch xy.
t_{sw}	Section switch action time.
$r_{L,j}$	Repair time for switch j.
NC_i	Number of users at load point i.
Binary Variables（∈[0,1]）	
$s_{ij}^{i,xy}$	Equal to 1 when switch closes near node i on branch ij in the event of a failure at branch xy (pathway).
$s_{ij}^{j,xy}$	Equal to 1 when switch closes near node j on branch ij in the event of a failure at branch xy (pathway).
$F_{ij}^{xy,B}$	Equal to 1 when the circuit breaker does not operate the branch circuit ij is not affected by the fault.
$F_{i}^{xy,B}$	Equal to 1 when the circuit breaker does not operate and node i operates normally.
$F_{j}^{xy,B}$	Equal to 1 when the circuit breaker does not operate and node j operates normally.
$s_{ij}^{i,NO}$	Equal to 1 when the switch near node i closes in normal operating conditions.
$s_{ij}^{j,NO}$	Equal to 1 when the switch near node j closes in normal operating conditions.
$b_{ij}^{i,NO}$	Equal to 1 when the circuit breaker near node i closes in the event of a failure at branch xy.
$b_{ij}^{j,NO}$	Equal to 1 when the circuit breaker near node j closes in the event of a failure at branch xy.
$F_{ij}^{xy,PF}$	Equal to 0 when branch ij is in a state of disconnection affected by the maintenance after the failure of the branch xy.
$F_{i}^{xy,PF}$	Equal to 0 when node i is in a state of disconnection affected by the maintenance after the failure at the branch xy.
$F_{j}^{xy,PF}$	Equal to 0 when node j is in a state of disconnection affected by the maintenance after the failure at the branch xy.
p_{i}^{xy}	Equal to 1 when node i is impacted in case of a failure at branch xy.
q_{i}^{xy}	Equal to 1 node i is normally powered after branch xy fails and the switch completes action.

B. Objective Function

In terms of evaluating the effectiveness of the model, the objective function is selected as a traditional power system reliability assessment metric: Expected Energy Not Supplied (EENS). In the event of a system breakdown due to information system failures, it is desired that the system causes the minimum value of load demand power curtailment in a given time interval. As shown in equation (15):

$$EENS = \text{total system outages} = \sum_{i \in S} C_i P_i T \tag{15}$$

C. Power Balance Constraints for Distribution Networks

In distribution systems, when a branch circuit fails, the power distribution of the system will change. However, since nodal power balance is constant, the inflow power at any node is equal to the outflow power. The power at a node is then jointly determined by the power flowing to it from each node. Therefore, the power balance at the node can be obtained as:

$$D_i^{xy} = \sum_{j \in \Psi_i} P_{ji}^{xy}, \forall i \in \Psi^{LN}, \forall xy \in \Upsilon \tag{16}$$

$$P_{ij}^{xy} = -P_{ji}^{xy}, \forall ij \in \Upsilon, \forall xy \in \Upsilon \tag{17}$$

$\forall xy \in \Upsilon$ denotes the scenario of failure of all branches.

D. Branch Circuit Power Constraints

The power on a particular branch of a power system is not static. As a result of a fault on a branch, the sectionalized switch operates, which results in a change in the magnitude and direction of the power on the line. The power of the branch circuit is positive in line with the specified positive direction, and negative in the opposite direction. And for the safety and reliability of the line, the capacity of the branch circuit cannot exceed the rated value. This is shown in the following equation:

$$-Ms_{ij}^{i,xy} \le P_{ij}^{xy} \le Ms_{ij}^{i,xy}, \forall ij \in \Upsilon, \forall xy \in \Upsilon \tag{18}$$

$$-Ms_{ij}^{j,xy} \le P_{ij}^{xy} \le Ms_{ij}^{j,xy}, \forall ij \in \Upsilon, \forall xy \in \Upsilon \tag{19}$$

$$-P_{ij}^{C} \le P_{ij}^{xy} \le P_{ij}^{C}, \forall ij \in \Upsilon, \forall xy \in \Upsilon \tag{20}$$

The first two formulas show that the power on the branch is zero if one of the isolation switches is open. If both of them are closed, the power on the branch is limited by the third formula.

E. Transformer Power Constraints

In the case of a branch failure, the transformer will adjust the power distribution to the branches connected to it to ensure the stability of the system. The power flowing out of the transformer is equal to the sum of the power flowing to the branches connected to it, while the rated delivered power of each branch cannot be exceeded.

$$P_f^{xy} = P_{tr^f}^{xy}, \forall f \in \Psi^F, tr^f \in \Upsilon, \forall xy \in \Upsilon \tag{21}$$

$$P_f^{xy} \le P_f^{C}, \forall f \in \Psi^F, \forall xy \in \Upsilon \tag{22}$$

F. Circuit Breaker Action Constraints

When a fault occurs, the circuit breaker operates immediately. If the fault occurs close to node i at one end of the branch, the circuit breaker on that side automatically operates to remove the fault. The switch also operates at the same time to narrow down the fault. The specific constraints are as follows:

$$F_{xy}^{xy,B} = 0 \tag{23}$$

$$-\left(1 - s_{ij}^{i,\mathrm{NO}}\right) M + F_i^{xy,B} \le F_{ij}^{xy,B} \le \left(1 - s_{ij}^{i,\mathrm{NO}}\right) M + F_i^{xy,B}, \forall ij \in \Upsilon_I^S, ij \notin \Upsilon_I^B \tag{24}$$

$$-\left(1 - s_{ij}^{j,\mathrm{NO}}\right) M + F_j^{xy,B} \le F_{ij}^{xy,B} \le \left(1 - s_{ij}^{j,\mathrm{NO}}\right) M + F_j^{xy,B}, \forall ij \in \Upsilon_J^S, ij \notin \Upsilon_J^B \tag{25}$$

$$-\left(1 - b_{ij}^{i,xy}\right) M + F_i^{xy,B} \le F_{ij}^{xy,B} \le \left(1 - b_{ij}^{i,xy}\right) M + F_i^{xy,B}, \forall ij \in \Upsilon_I^B \tag{26}$$

$$-\left(1 - b_{ij}^{i,xy}\right) M + F_j^{xy,B} \le F_{ij}^{xy,B} \le \left(1 - b_{ij}^{i,xy}\right) M + F_j^{xy,B}, \forall ij \in \Upsilon_J^B \tag{27}$$

The operating state of the branch circuit is jointly determined by the circuit breakers next to the nodes at both ends. It is easy to obtain that there is always and at least one switch that will operate after a fault occurs. And the fault will continue to expand along the branch circuit until the circuit breakers and switches operate to isolate the fault. This not only prevents further degradation of power quality, but also facilitates quick and small overhauls.

$$F_{ij}^{xy,B} = F_i^{xy,B}, \forall ij \notin \Upsilon_I^S, ij \notin \Upsilon_I^B \tag{28}$$

$$F_{ij}^{xy,B} = F_j^{xy,B}, \forall ij \notin \Upsilon_J^S, ij \notin \Upsilon_J^B \tag{29}$$

$$\sum_{ij \in \Upsilon_i^B} b_{ij}^{i,\mathrm{NO}} + \sum_{ij \in \Upsilon_j^B} b_{ij}^{j,\mathrm{NO}} - 1 = \sum_{ij \in \Upsilon_i^B} b_{ij}^{i,xy} + \sum_{ij \in \Upsilon_j^B} b_{ij}^{j,xy} \tag{30}$$

$$0 \le F_i^{xy,B} \le 1, \forall i \in \Psi^{LN} \tag{31}$$

$$0 \le F_{ij}^{xy,B} \le 1, \forall ij \in \Upsilon \tag{32}$$

$$F_i^{xy,B} = 1, \forall i \in \Psi^{SS} \tag{33}$$

$$p_i^{xy} = 1 - F_i^{xy,B}, \forall i \in \Psi^{LN} \tag{34}$$

$$\forall xy \in \Upsilon \tag{35}$$

G. Switching Action Constraints

The switch action constraints are mostly consistent with those of the circuit breaker. In particular, node i can only be restored to normal power supply once fault repair is completed and the circuit breaker and switch are closed together.

$$D_i^{xy} = D_i q_i^{xy}, \forall i \in \Psi^{LN} \tag{36}$$

$$q_i^{xy} = F_{ij}^{xy,PF}, \forall i \in \Psi^{LN} \tag{37}$$

$$1 - p_i^{xy} \le q_i^{xy}, \forall i \in \Psi^{LN} \tag{38}$$

$$\forall xy \in \Upsilon \tag{39}$$

H. Reliability Index Calculation Constraints

Frequency of user interruptions at node i:

$$CIF_i = \sum_{xy \in \Upsilon} \lambda_{xy} p_i^{xy}, \forall i \in \Psi^{LN} \tag{40}$$

The duration of user interruptions at node i:

$$CID_i = \sum_{xy \in \Upsilon} \lambda_{xy} \tau_{xy}^{SW} p_i^{xy} + \sum_{xy \in \Upsilon} \lambda_{xy} (\tau_{xy}^{RP} - \tau_{xy}^{SW})(1 - q_i^{xy}), \forall i \in \Psi^{LN} \tag{41}$$

Since a fault on any element of a distribution branch circuit may spread to the upstream area, whether or not fault spread occurs depends primarily on the successful operation of the branch circuit's switches. For branch circuits containing sectionalized switches, isolating a fault requires multiple switches to cooperate and coordinate with each other to isolate the fault. Therefore, the branch can be divided into N regions based on sectionalized switches. For a distribution branch containing sectionalized switches, once a fault occurs, all of its upstream sectionalized switches will try to isolate the fault sequentially under remote control commands. Therefore， the equivalent fault rate of this branch circuit is:

$$\lambda_{xy} = \sum_{i=2}^{N} \lambda_{L,i-1} \prod_{j=i-1}^{Z} (1 - p_{sw,j}) \tag{42}$$

Accordingly, the equivalent outage time of a switch shall be the expectation of the equivalent outage time in both the successful and failed states of the switch action, instead of the action time of a switch in traditional distribution networks.

The repair time for the region downstream of switch j is the sectionalized switch action time t_{sw} if the switch succeeds in isolating the fault. Otherwise, the upstream switch will actuate up to the branch circuit breaker or branch node. Therefore, for the region downstream of switch j, the equivalent fault time is:

$$\tau_{xy}^{sw} = \sum_{i=j}^{M} [P_{sw,j} \prod_{k=j}^{i-1} (1 - P_{sw,k})] t_{sw} + \prod_{i=0}^{M-j} (1 - P_{sw,j+i}) r_j \tag{43}$$

where

$$r_j = \frac{(\lambda_{L,j} r_{L,j} + \sum_{k=1}^{j-1} \lambda_{L,k} r_{eq,j-1})}{\sum_{i=1}^{j} \lambda_{L,i}} \tag{44}$$

So the expression for the equivalent failure time should be:

$$\tau_{xy}^{sw} = \sum_{i=j}^{M} [P_{sw,j} \prod_{k=j}^{i-1} (1 - P_{sw,k})] t_{sw} + \frac{\prod_{i=0}^{M-j} (1 - P_{sw,j+i})(\lambda_{L,j} r_{L,j} + \sum_{k=1}^{j-1} \lambda_{L,k} r_{eq,j-1})}{\sum_{i=1}^{j} \lambda_{L,i}} \tag{45}$$

The probability of normal switch action is related to the effectiveness of the information link, and it is sufficient to solve for the effectiveness of the information link using the solution method of Chapter 3.

I. Assessment of Indicators

Finally, based on the system reliability index to assess the reliability of power supply in multi-supply level distribution systems [26]. System reliability indicators include average service availability index (ASAI), system average interruption frequency index (SAIFI), and system average interruption duration index (SAIDI). The calculation formulas are as follows:

$$ASAI = 1 - \frac{SAIDI}{8760} \tag{46}$$

$$SAIDI = \frac{\sum_{i \in \Psi^{LN}} NC_i CID_i}{\sum_{i \in \Psi^{LN}} NC_i} \tag{47}$$

$$SAIFI = \frac{\sum_{i \in \Psi^{LN}} NC_i CIF_i}{\sum_{i \in \Psi^{LN}} NC_i} \tag{48}$$

V. CASE STUDIES

To study the impact of information system failures on distribution networks, this paper uses two differently structured arithmetic cases to verify the reliability of the proposed method: a 33-node distribution system and a 7-node ring system. Firstly, the reliability indexes of each load node and the system without considering the cyber failures condition are calculated. Then the reliability indexes of each load node and system were calculated considering information system failures. By comparing the results of reliability calculations under the two conditions, the effect of information system failures on load points and system reliability indexes can be obtained. For the convenience of presenting the conclusions, the diagrams in this section show only the physical side part of cyber-physical distribution systems, and ignore intelligent electronic devices.

A. Case 1

The structure of Case 1 refers to the main feeder 4 of IEEE RBTS BUS 6. The system wiring diagram is shown in Fig. 6. The feeder contains 23 load points and 1183 subscribers. The information systems use the ring structure shown in 3.2 of this paper. In particular, the communication node delay is modeled using a Pareto distribution obeying the parameter 67.9ms vs. 20. The intelligent electronic device forwarding delay is modeled using the N (68.35,11) normal distribution. The communication line delay is modeled using an exponential model. Considering the small scale of the communication system involved in this paper, the upper limit of the delay is taken as 600 ms. The BER of each communication node and intelligent electronic equipment is 10^{-4}, the BER of fiber optic is taken as 10^{-9}, the failure rate of the feeder line is 0.065 times/(km-year), and the duration of the failure is 5 hours/time. The experimental environment is Intel Core i7, 2.2GHz CPU, 16GB running memory, and Windows 10 operating system. It is realized by using MATLAB R2018b software programming.

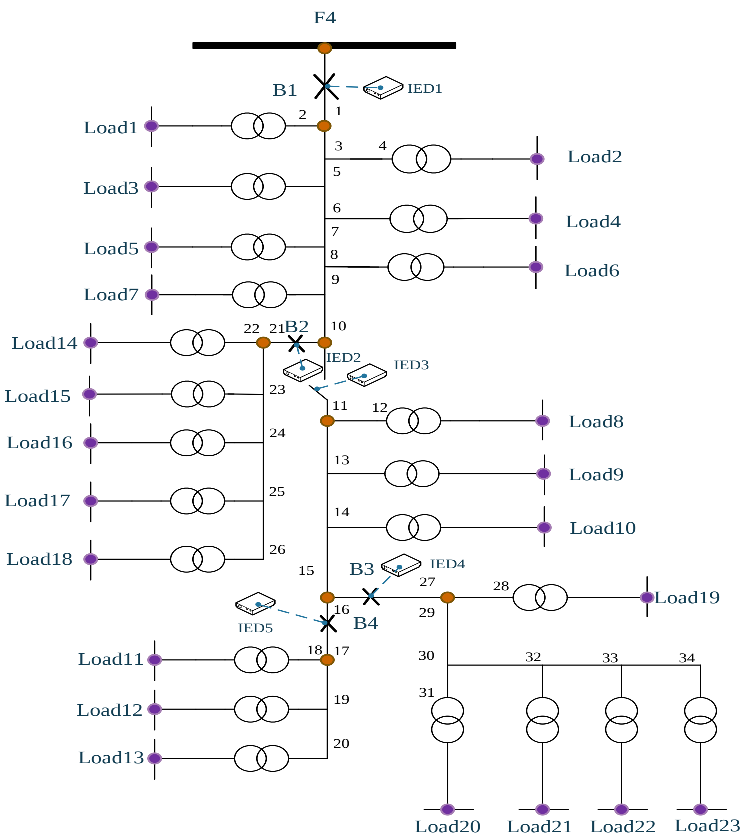

Fig 6: 33-Node System Wiring Diagram

The results of the calculations are included in Table 2.

Table 2: 33-Node System Reliability Calculation Results

	ASAI	SAIFI (times/year)	SAIDI (h/year)
No consideration of cyber failures	0.99874	1.9778	11.0747
Consideration of cyber failures	0.99873	2.8580	11.1147

B. Case 2

To demonstrate visually the effectiveness of the mixed integer linear programming model solution method, a 7-node system was designed as shown in Fig. 7. This system consists of two substation nodes (node 1 and node 7) and five load nodes (node 2-node 6). Branches 5-6 and branches 4-7 are contact lines to form ring distribution networks.

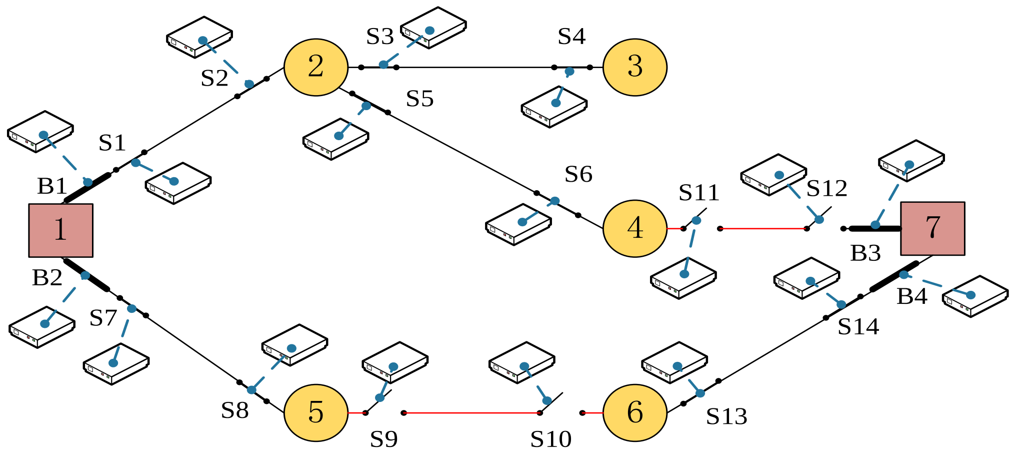

Fig 7: 7-Node System Wiring Diagram

For the convenience of calculation, the transformer failure is ignored, and loads of nodes 2, 3, 4, 5, and 6 are set to be 2.5, 2, 4, 5, and 4, and the corresponding numbers of users are 6, 5, 7, 4, and 5, respectively; the capacity of branch circuits and transformers is set to be 100 p.u.; and the interruption durations are set to be 4.0, 0.5, and 0.1 based on the failure rates of repairing and switching and switching only, as well as each branch circuit, respectively. furthermore, the information systems adopt a ring structure, and the communication node delay adopts a Pareto distribution model obeying parameters of 67.9 ms with 20, the information systems adopt the ring structure, the communication node delay adopts the Pareto distribution model obeying the parameter 67.9ms with 20; the IED forwarding delay adopts the N (68.35, 11) normal distribution model, and the communication line delay adopts the exponential distribution model, and at the same time, taking into account that the scale of the communication system set up in this paper is relatively small, the upper limit of the system delay is taken as the value of 600ms, and the probability of error code of each communication node with the IED BER probability is 10^{-4}. After calculation, the validity gap of the information link connected with the isolation switch is not big, about 0.98, so this value can be set as the validity value of the information links connected with the isolation switch. Considering that the probability of multiple information links failing at the same time is very small, the corrected switch interruption action time obtained by solving at M=4 is used to calculate two different cases, and the failure rate of the line obtained at N=2 is used to replace all the corrected line failure rate increments. The experimental environment is realized on a laptop computer configured with Intel Core i7, 2.2GHz CPU, and 16GB of operating memory, by the medium Windows 10 operating system. It was implemented using the commercial solver software CPLEX 12.6 programming.

The calculated results are included in Table 3.

Table 3: 7-Node System Reliability Calculation Results

	ASAI	SAIFI (times/year)	SAIDI (h/year)
No consideration of cyber failures	0.99968	0.7	2.8
Consideration of cyber failures	0.99967	0.70252	2.8201

C. Case Results and Analysis

As can be seen from the data in Tables 2 and 3, the system reliability indexes obtained under the consideration of the role of cyber failures are slightly larger than those obtained without considering the effect of cyber failures. This conclusion is consistent with the expected results and further validates the reliability of the conclusions. In terms of the means of solving, case 1 is solved using MATLAB, which is convenient and typical for the study. Case 2 is solved using Cplex to solve the mixed-integer linear programming model, which can more accurately evaluate the reliability indexes of the grid distribution system with higher computational efficiency.

VI. Conclusion

This paper proposes a reliability assessment method for distribution networks based on a mixed-integer linear programming model. The method takes into account the specific effects of information system failures. The reliability indexes of the distribution systems are accurately assessed through classical model simulation, and the results obtained are sufficient to prove that the consequences of information system failures cannot be ignored.

Furthermore, the proposed reliability assessment method has promising applications and can be easily incorporated into planning and optimization models to formulate reliability constraints. The application of the model in planning and optimization can be further investigated in future work.

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