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A Reliability Evaluation Method for a Power Distribution Cyber-Physical System Based on Wireless Access Networks

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Abstract: The communication network plays an increasingly important function in the Cyber-Physical Distribution System (CPDS) to ensure a dependable power supply as the quantity and type of terminal devices in power distribution systems increase.This article examines CPDS reliability in the context of wireless access conditions. We begin by developing a reliability model specifically for communication channels within a 5G network. Additionally, we introduce an enhanced evaluation method using an improved minimal path approach. Simulation results demonstrate that 5G communication technology significantly enhances system reliability, offering valuable insights for optimizing CPDS operations. Keywords: CPDS reliability, 5G communication network, wireless access, power distribution system,communication network reliability, improved minimal path method.

Keywords: Cyber-physical power distribution system, Distribution wireless communication system, Analytic method, Refined modeling, Reliability assessment

1. Introduction

With the deepening of new power system construction, the dependency of distribution network terminal equipment on communication network is significantly enhanced. The current reliability research of distribution information physical system (CPDS) is mainly based on the wired communication scenario. References [1-8] thoroughly investigate how information disturbances can lead to both direct and indirect impacts on physical systems. These studies examine two primary effects: the direct impact of information disturbances leading to physical failures, and the indirect impact where information failures influence physical systems.The research utilizes component-level reliability models, like the multi-state model of intelligent electronic equipment, employs DFA regional analysis methods, and applies multi-level dependency modeling.This comprehensive approach helps in understanding the complex interactions between information disturbances and system reliability.However, the existing models are faced with significant limitations in practical application:first,over-reliance on wire communication assumptions,and failure to fully quantify the dynamic impact of key factors such as wireless channel interference and base station failure on system reliability;second,the existing methods (such as the interactive model of fault treatment stage in reference [4]) are difficult to adapt to the complex working conditions such as multi-energy coupling of distribution network and strong information uncertainty, and there is a theoretical gap in disaster recovery strategy (such as the natural disaster recovery model in reference [7]) and real-time transmission effectiveness modeling.

To solve the above problems, this paper proposes a two-stage improvement method: first, by establishing a joint probability model of channel attenuation and base station load, analyze the reliability boundary conditions of time-delay sensitive service in 5G wireless communication, and break through the static constraint of traditional wired network analysis; Secondly, based on the indirect conduction path of information failure, the multi-state reliability model of switch is established, and the dynamic weight shortest path algorithm is introduced to solve the evaluation deviation problem of traditional methods in multi-fault concurrent scenarios by modifying the weight coefficient of information-physical coupling path in real time. The experimental results show that, compared with the benchmark model in reference [3], the reliability evaluation error rate of this method in the typical distribution network topology with distributed generation access is reduced by 12% - 18%, especially in the case of intermittent interruption of communication link. This result provides a more accurate reliability pre-judgment tool for 5G enabled new power system.

2. Reliability modeling of 5G communication channel

2.1. Structure of distribution information physical system

The Cyber-Physical Distribution System (CPDS) consists of an information domain and a physical domain. The information domain covers communication equipment, protocols, and network topology. In contrast, the physical domain features conventional primary equipment and renewable energy sources like photovoltaic (PV) systems and wind power, alongside energy storage devices. The information domain adopts a hierarchical architecture: the backbone network connects the main station and sub-stations based on the SDH protocol; the access network links sub-stations and intelligent terminals (IEDs) through a 5G wireless network relying on the IEC104 protocol, forming a bidirectional cyber-physical coupling (closed-loop interaction of control commands → physical states → data feedback).

The system communication layer is divided into highly reliable backbone network (SDH/MSTP optical fiber ring network, supporting channel/multiplexing layer multi-protection) and flexible access network (Ethernet/carrier/wireless hybrid network);The application layer, deployed at the master station or substation, plays a crucial role in decision-making and facilitating human-computer interaction; The interface layer integrates feeder terminal (FTU), station terminal (DTU), inverter and other intelligent equipment to realize the physical-information interface function.

2.2. Wireless channel model

Ensuring the reliability of communication channels is crucial in wireless communication networks.To achieve this, it's essential to establish an accurate wireless channel model. This chapter focuses on evaluating reliability using a comprehensive composite channel fading model that accounts for both path loss and shadow fading.

Data packets are effectively sent over a smooth wireless channel in a wireless communication network. We designate the source node as node 0, the relay node as node $n(n \in \{1,2,\dots,n\})$, and the destination node as node N+1 for simplicity's sake. The signal-to-noise ratio (SNR) at the receiving end determines the quality of the signal that node $n(n \in \{1,2,\dots,n\})$ sends to node n+1. The receiving terminal's SNR can be written as follows:

$$\Gamma_n = \frac{p_n^t h_n}{n_0}, \forall n \in \{1,2,\dots,n\} \quad (1)$$

In this formula, p_n^t stands for node n's transmitting power, and n_0 for the receiver's background noise power, which is represented by h_n. One crucial element is the wireless link's channel gain, which is commonly expressed in decibels (dB) between nodes n and n+1. This is a more thorough explanation:

$$[h_n]_{dB} = [G]_{dB} - \eta\left[\frac{d_n}{d_{ref}}\right]_{dB} - [\xi]_{dB} \tag{2}$$

G is a dimensionless constant that represents the route loss coefficient at reference point d_{ref}, where $[X]_{dB}$ stands for $10\log_{10} x$.This parameter's value depends on the average channel attenuation and antenna characteristics;η is the wireless channel's power loss index, which varies depending on the environment and area where the wireless channel is located; it typically ranges from 2 (free space) to 6 (urban downtown area); d_{ref} is the reference distance (the reference point must be within the antenna's far-field area); and d_n is the straight-line distance between node n and node n+1.ξ stands for signal shadow fading, and ξ typically has a log-normal distribution, meaning that $[\xi]_{dB}$ is a random variable with a normal distribution, meaning that its variance is σ_ξ^2 and its mean is 0.In wireless communication, the signal-to-noise ratio of the received signal must typically surpass a specific threshold, which can be mathematically represented as follows, to guarantee the accuracy of the received signal:

$$\Gamma_n \geq \gamma^t \tag{3}$$

Where in γ^t represents a desired SNR threshold.

3. Reliability action probability of switch element under the influence of information system

3.1. Reliable action probability of circuit breaker

The circuit breaker is responsible for the fault branch isolation function in the distribution network (consistent with the traditional circuit breaker function), but the failure of its transmission mechanism (detection-computation-action module) will lead to the rejection of action, belonging to the scope of secondary equipment failure. The reliable action probability$p_{br}$is defined as the probability that the circuit breaker will not refuse to operate under normal conditions.

3.2. Reliable action probability of section switch

Telemetering of section switch is a key parameter for fault location of distribution network. When the monitoring is abnormal, the system switches to the upstream switch data for positioning, causing the expansion of the fault isolation range. Give priority to sending isolation command to the nearest effective switch after positioning. If the command or feedback is abnormal, trigger the upstream retransmission mechanism. With the monitoring, command, and feedback links operating independently, the upstream switch can effectively respond to commands from the control center. The likelihood that the control center successfully confirms fault isolation by the switch is:

$$P_{ICT,i} = R_{M,i}R_{C,i}R_{F,i} \tag{4}$$

Where: $R_{M,i}$ is the effective probability of monitoring information of switch i; $R_{C,i}$ is the effective probability of control information of switch i; $R_{F,i}$ is the effective probability of control feedback information of switch i; i∈N.

Due to a design flaw in the switch element of the circuit breaker, there's a likelihood of failure even after receiving a control command. Therefore, the probability of successful operation of the section switch remains uncertain:

$$P_{sw,i} = P_{sw} P_{ICT,i} \tag{5}$$

Where: P_{sw} represents the probability of the section switch operating reliably.

4. Reliability evaluation of distribution information physical system under the influence of information system

This paper introduces a method for enhancing power supply reliability by equating the branch reliability parameter to the branch head node. Utilizing the minimum path method, we address power supply reliability for diverse users. With an understanding of information failure characteristics, we have enhanced the equivalent average outage time model specifically for downstream faults controlled by switches. We propose that this equivalent average outage time should reflect the expected outage time in both successful and unsuccessful switch operations. Consequently, we present a calculation method for determining the equivalent failure time that accounts for the involvement of multiple switches in fault isolation.

4.1. Branch reliability parameters with switch action failure are equivalent upward

If a component fails on a branch of the distribution network, it could potentially affect the upstream areas. Fortunately, the circuit breaker can act independently, without needing communication from the control center. This means that once fault current is detected, there is a certain probability P_{br} that the branch will be disconnected promptly. To determine the equivalent fault rate of a feeder equipped with a circuit breaker at its head end, you can follow this formula:

$$\lambda_{eq,f} = (1 - P_{br}) \sum_{i=1}^{N_f} \lambda_i \tag{6}$$

Where: $\lambda_{eq,f}$ is the equivalent failure rate of branch f; λ_i is the failure rate of the upper component or the lower branch of branch i; N_f is the total number of elements on branch f or branches below branch.

When a switch experiences a physical malfunction, it's commonly assumed that a manual reset might resolve the issue. The total downtime from a fault in the downstream area of the switch includes both the switch's activation time and any manual reset time required. However, this manual method does not reflect the efficiency of an automated distribution network's fault self-healing process. To bridge this gap, this paper introduces an updated formula for calculating the switch's equivalent outage time, $r_{eq,f}$,enhancing accuracy and efficiency in fault management.

$$r_{eq,f} = p_{br} t_{br} + (1 - p_{br}) \frac{\sum_{i=1}^{N_f} \lambda_i r_i}{\sum_{i=1}^{N_f} \lambda_i} \tag{7}$$

Where: r_i is the repair time of the upper component or the lower branch of branch i; t_{br} is the action time of switch.

In a distribution network, the containment of a component fault relies on the effective cooperation of all upstream switches, not just one. Each upstream switch plays a vital role in fault isolation, ensuring smooth network operation. Effective fault isolation requires the synchronized efforts of multiple switches. The network branch can be divided into multiple segments or areas, which are managed by section switches. When a fault occurs within the branch, these upstream section switches work under remote control to systematically isolate the fault. As a result, the overall fault rate of the branch is determined by the successful operations of these switches. By incorporating advanced fault management and coordinating the response of section switches, utility providers can significantly improve fault isolation and maintain the reliability of the distribution network.

$$\lambda_{eq,f} = \sum_{i=2}^{N} \left[\lambda_i \prod_{j=i-1}^{M} \left(1 - P_{sw,j}\right)\right] \tag{8}$$

Where, $\lambda_{L,i-1}$ is the failure rate of the i-1st area; M is the number of section switches in the branch.

In the region downstream of switch i, if the switch effectively isolates the fault, the repair time is determined by the action time t_{sw} of the section switch. However, if isolation is unsuccessful, the upstream switch will take action until reaching the branch circuit breaker or branch node. Consequently, for the area downstream of switch i, the equivalent time to failure is calculated based on these parameters.

$$r_{eq,j} = \sum_{i=j}^{M} \left[P_{sw,i} \prod_{k=j}^{i-1} \left(1 - P_{sw,k}\right)\right] t_{sw} + \prod_{i=0}^{M-j} \left(1 - P_{sw,j+i}\right) r_j \tag{9}$$

Inside:

$$r_j = \frac{1}{\sum_{i=1}^{j} \lambda_{L,i}} \left(\lambda_{L,j} r_{L,j} + \sum_{k=1}^{j-1} \lambda_{L,k}\, r_{eq,j-1}\right) \tag{10}$$

Where; r_j is the equivalent outage time in the downstream area of switch j in the branch; $r_{L,j}$ is the repair time of switch j.

4.2. Minimum path based user reliability solution

In the realm of distribution networks and power supply systems, users at the physical layer fall into two primary categories: ordinary users and transferable users. Understanding these categories is crucial for optimizing energy distribution and ensuring efficient power management.

4.2.1. Ordinary user reliability calculation

For everyday users of a power distribution network, understanding the shortest path to the main power supply is crucial for determining their connectivity to the power source. This direct link can help establish the relationship between the user and their power supply point. At the same time, user n can assess their service reliability through metrics such as failure rate and average outage duration.

$$\lambda_{L,n} = \sum_{j=1}^{N_e} \lambda_{eq,j} + \sum_{i=1}^{M_d} \lambda_i \tag{11}$$

$$r_{L,n} = \frac{1}{\lambda_{L,n}} \left(\sum_{j=1}^{N_e} \lambda_{eq,j}\, r_{eq,j} + \sum_{i=1}^{M_d} \lambda_i\, r_i\right) \tag{12}$$

In this formula, $\lambda_{L,n}$ and $r_{L,n}$ represent the failure rate and repair time for user n, respectively. Meanwhile, $\lambda_{eq,j}$ and $r_{eq,j}$ denote the equivalent failure rate and repair time for non-minimum branch j of user n. The variable N_e indicates the number of non-minimum branches i associated with user n. Lastly, the term "M" refers to the minimum number of on-circuit components or equivalent branches necessary to connect a user to the main power supply.

4.2.2. Transferable user reliability calculation

Whether the tie line can supply power for the user that can be transferred depends on the effective action probability of the tie switch and section switch in the area that can be transferred and the capacity of the tie line. Therefore, the probability that the user can recover power supply through connecting line k is:

$$P_{t,k} = P_t P_{is} P_{sw} \tag{13}$$

Where, P_t is the probability that the connecting line can continuously supply load, and the solution method is consistent with P_q .Therefore, the outage rate and average outage time of the transferrable user n are:

$$\lambda_{L,n} = \left(1 - P_{t,k}\right) \sum_{i=1}^{N_{up}} \lambda_i + \lambda_{eq,n} \tag{14}$$

$$r_{L,n} = \frac{1}{\lambda_{L,n}} \left[\left(1 - P_{t,k}\right) \sum_{j=1}^{N_{up}} \lambda_i r_i + \sum_{i=1}^{N_{up}} \lambda_i P_{t,k} t_i + \lambda_{eq,n} r_{eq,n}\right] \tag{15}$$

Where: N_{up} is the number of the minimum on-circuit components or equivalent branches of the transferrable area and the main power supply.

5. Case studies

5.1. Simulation system and parameters

In this paper, we examine the main feeder 4 of the IEEE RBTS BUS6 system. The wiring layout of this system is illustrated in the accompanying figure. The feeder includes 23 load points, 1225 users totaling 34.26MW, 6MW photovoltaic power generation unit, 16MW/32MWh energy storage system and other distributed energy equipment. In this paper, we explore a cutting-edge wireless 5G communication network for the access network. The backbone network for data transmission employs a wired ring network structure, encompassing a total of five strategically-positioned base stations. Each base station's coverage area is illustrated in the accompanying figure. This setup ensures enhanced connectivity, reliability, and seamless data transmission across the entire network.

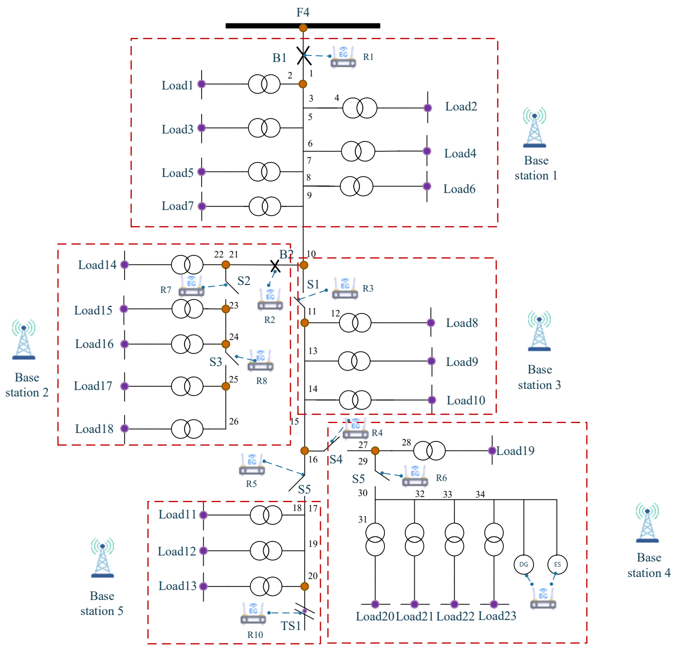

Figure 1: Simulation system structure diagram

5.2. Case results and analysis

This paper examines how information system failures impact system reliability by focusing on two key aspects. First, we delve into the overall impact of information system failures on reliability. Next, we examine how the failure of specific information elements influences the system's dependability.

In examining the impact of information system failures on the reliability of power distribution networks, certain key metrics may not be fully addressed. These metrics include the Average Service Availability Index (ASAI), Expected Energy Not Supplied (EENS), System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), and Average Interruption Duration Index (AIDI) for users. Understanding and integrating these factors are crucial for assessing the reliability and performance of power distribution systems. The information system failure makes the system reliability indicators EENS, SAIDI and SAIFI increase by 2.74%, 7.97% and 6.04% respectively. It can be seen that the information system failure directly increases the outage time and frequency of the system and users, and has an impact on the power supply capacity of the system.

To better understand the impact of information system component failures on overall system reliability, we conducted a detailed analysis. In this study, we adjusted the failure rates of each type of information component—ranging from reducing them to 0% to increasing them to 200% in 10% increments—while keeping the failure rates of other components constant. By running multiple simulations, we obtained average values that allowed us to graph the reliability index curve for four key information components: IED, SDH switch, SDH line, and server communication node. This analysis provides insights into how each component's failure rate affects system reliability, as illustrated in the accompanying figure.

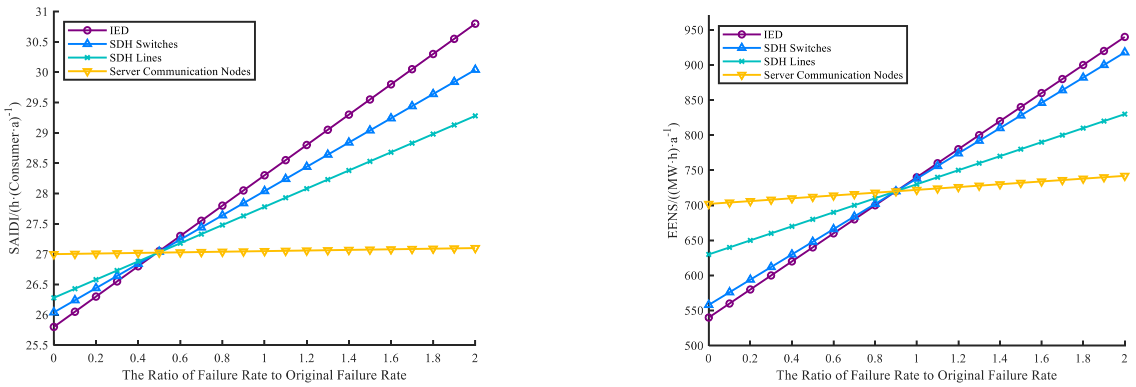

Figure 2: Variation trend of system reliability indexes under different failure rates

It can be seen from the figure that the failure rate change of information equipment from large to small is IED, synchronous digital hierarchy (SDH) line, SDH switch and server communication node. The reliability deterioration of IED will lead to chain failure due to large number and high basic failure rate; Minimal impact on servers due to redundant design. The key measures to improve reliability include: use of high reliability IED, SDH switch redundancy configuration and regular line maintenance.

6. Conclusion

In this paper, we present an innovative method for evaluating the reliability of distribution information systems using wireless access networks. Our approach emphasizes improving the reliability of wireless data transmission within these systems, ultimately boosting system efficiency and performance. We introduce a reliability calculation method that combines the upward

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equivalence approach with the minimum path method, all based on a proven switch model. Key findings from our study include:

A. The failure rate of intelligent electronic devices (IEDs) is a critical factor affecting the reliability of Cyber-Physical Defense Systems (CPDS). Among various information system components, changes in the failure rate of IEDs have the most significant impact. Ensuring these devices function efficiently is essential for maintaining robust CPDS reliability, highlighting the importance of regular maintenance and updates to mitigate potential disruptions;

B. The information system failure makes the reliability of active power distribution network drop slightly, and the distributed new energy generation device with reasonable capacity for the distribution information physical system is beneficial to improving the power supply reliability of the system;

C. With the increase of average load rate of wireless access network and the increase of back-off times of channel detection, the information transmission delay will be increased, the failure probability of information link will be increased, and the reliability of distribution information physical system will be reduced.

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