Reliability Evaluation of Cyber Physical Distribution System considering EPON

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Abstract. As cyber-physics highly coupled distribution system, the influence of communication network on the reliability of power supply can not be ignored. Based on the EPON redundant protection network, this paper analyzes the influence of the loss of cyber link effectiveness on the self-healing control process in the process of power distribution network failure. With the help of the region adjacency matrix, combined with the cyber system failure model, the classification algorithm of the region after failure is given, and a reliability evaluation method coveannular different cyber system failure modes is proposed. Finally, the feasibility of this method is verified by a case study, and the influence of EPON cyber element failure rate and EPON networking mode on the reliability indices is compared and analyzed.

1. Introduction

With the improvement of power system automation, the traditional power distribution network is gradually upgraded to CPDS (cyber physical distribution system)[1-2], which integrates computing system, communication network and physical environment. The communication network mainly uses EPON (ethernet passive optical network), industrial ethernet, power carrier, wireless public network, wireless private network and other methods, but the communication quality is poor due to the large scale, complex environment, economic constraints and other factors.

The reliability of CPDS has become one of the current research hotspots. Ref.[3] discussed the key technologies of CPDS reliability evaluation, analyzed the risk sources of cyber and physical system, and prospected the methods and indicators of CPDS reliability evaluation. In Ref.[4], the reliability of physical system is evaluated for the distribution network with multiple automation modes, combined with the characteristics of this kind of distribution network, but the influence of cyber system on the evaluation results is not considered. So the influence process of cyber system on physical system can be analyzed from three aspects: cyber system function, failure reason and influence. Firstly, the functions of the cyber system include circuit breaker and transformer control [5], circuit breaker monitor [6], and FLISR(fault location, isolation and service restoration) [7]. Secondly, high network load rate and wrong terminal data transmission [8] are the common causes of cyber system failure. Ref.[9] introduced network connectivity model and data transmission delay model to support cyber system failure. Finally, in the aspect of influence, Ref. [10] used the failure consequence model to analyze the impact of cyber system failure on power system.

Fault self-healing processing is the core function to ensure the reliability of the system. When the function fails, Ref.[11] used simulation method to evaluate the reliability of CPDS, but this method needs to simulate a large number of operation modes, and the calculation is time-consuming. This
method is not suitable for solving optimization models with many feasible solutions, such as intelligent terminal configuration. The realization of self-healing function depends on the normal communication of intelligent terminals such as fault detector (FD) and intelligent remote control switch (RCS) [12]. When the cyber element fails, on the one hand, the network connectivity is destroyed and the data transmission is terminated; on the other hand, redundant protected links are configured to automatically switch routes and switch to standby lines, which may cause data transmission delay and also affect the effectiveness of communication links.

Based on the above analysis, firstly, based on the EPON redundant protection networking mode, FD and RCS are taken as the information physical connection points, by analyzing the interaction effect of cyber physical system when the cyber link fails, a reliability evaluation method integrating different cyber system failure modes is proposed, which can accurately determine the failure status of each area of the distribution network.

2. Cyber physical distribution system

2.1. Structure of CPDS

The CPDS in Fig.1 can be divided into backbone network and access network. The backbone network should adopt the synchronous digital hierarchy transmission network. EPON composed of optical line terminal, passive optical splatter, optical network unit and other elements is considered in the access network in this paper.

![Fig. 1. Structure of cyber system.](image)

The validity of cyber link means that data meets requirements of connectivity, timeliness and accuracy duannular transmission process[7]. The application of EPON redundant protection networkenhances the validity of cyber link in connectivity.

2.2 Influence of cyber system on FLISR process

When the distribution network is out of work, the control master station receives the failure data uploaded by FD, determines the failure area, issues the action command to control the opening and closing of the corresponding RCS, and completes the operation after confirming the feedback signal of the action switch , therefore FLISR process is completed. The FLISR process is shown in Fig.2. Failure of FD and RCS themselves or interruption of communication with control center will lead to failure of their function. FD, RCS failure rate is shown in (1).

\[
\begin{align*}
  p_f &= p_{f_1} + (1-p_{f_1})p_{f_2} \\
  p_r &= p_{r_1} + (1-p_{r_1})p_{r_2} + (1-p_{r_1})(1-p_{r_2})p_{r_3}
\end{align*}
\]
Where $p_{fd} \cdot p_{rcs}$ is the failure rate of FD and RCS; $p_{fr}$ means failure to report fault information; $p_{af}$ means the action signal is not received; $p_{ak}$ indicates that the reverse signal transmission fails. In Fig.2, if the FLISR process is normal, the master station receives the fault information reported by switch S1, S2 and judges that the fault area is between S2 and S3, and issues the command to disconnect the switches S2, S3 to isolate the fault area.

In case of fault isolation, if switch S2 refuses to operate or the feedback signal transmission fails, the master station will issue a command to the next switch closest to the fault point, switch S1 operates to isolate the area between S1 and S3.

If switch S2 fails to report fault information, the master station only receives switch S1. The reported information misjudges the area between S1, S2 as fault area, issues command to disconnect switch S1, S2, and closes contact switch S5. At this time, because there is still a fault in the line, the master station receives the fault information from switch S3 and issues a command to disconnect switch S3, which also causes the expansion of the isolation area.

Fig. 2. Process of FLISR of distribution network.

3. Area Classification Algorithm
The regional topology of distribution network can be represented by the regional adjacency matrix, and the elements in the regional adjacency matrix represent the connection relationship between regions. In this paper, element 2 is set to represent branch line fuse; elements 3 and 4 refer to controllable and uncontrollable disconnectors respectively; element 5 refers to bus outlet circuit breaker and interconnection switch. The region reachability matrix is calculated from the region adjacency matrix, and the connectivity between regions is known from the region reachability matrix.

3.1 Type of Regional Fault
The types of post fault areas can be divided into five categories according to the different fault time: 1) Not affected by the fault (the area where the power supply is restored after the automatic isolation area is isolated can be regarded as not affected approximately), 2) Operation time of disconnector, 3) Repair time of fault, 4) Manual troubleshooting time, 5) Operation time of disconnector plus manual troubleshooting time.

3.2 Classification considering cyber failure
Suppose a distribution network has s areas, except for the bus area and the contact area. The number of bus area is 0 and of contact area is $M$ ($M > s$). Construct region adjacency matrix $A$. Suppose $An$ fails ($n \neq 0, M$). The area classification after failure in three modes of normal FLISR process, RCS operation failure and FD failure is shown in Tab.1. Fig.3 is a schematic diagram of area classification, assuming that S3 is not an RCS.
Table 1. Region classification after grid failure.

| Failure mode | Classification basis | Classification result |
|--------------|----------------------|-----------------------|
| FLISR is normal | End switches of $A_n$ are all RCS? | yes | a c |
| RCS is failure | --- | --- | a bc |
| FD is failure | End switches of fault area are all RCS? | yes | a d c |
| | no | | ab e c |

Fig. 3. Regional classification diagram.

3.2.1 Classification algorithm when FLISR is normal
In Fig. 3 (a), the FLISR process is normal, and the areas between $S_2$ and $S_3$ are of class C region, the areas between $S_3$ and $S_4$ are of class B region, and the rest are of class A region. $a_i \neq 2$ or 4 is used to determine whether the end switches in the fault area are all RCS.

3.2.2 Classification algorithm when RSC is failure
In Fig. 3 (b), if $S_4$ and operation fail, the automatic isolation area will expand. $S_3$ and $S_5$ are of class B region, and the scope of class B region in Fig. 3 (a) and Fig. 3 (b) is expanded.

3.2.3 Classification algorithm when FD is failure
In Fig. 3 (c), $A_n$ in point switch $S_2$ cannot report fault information, and power supply of misjudged area can be recovered after troubleshooting manually. Compared with Fig. 3(a), Fig. 3(c) adds the category E region between $S_1$ and $S_2$. The position of $S_2$ in matrix $A$ is $(n+1, m+1)$.

3.3 Generation of failure influence matrix
Suppose that there are $k$ end switches in the auto isolation area of $A_n$. In case of failure of $A_n$, when FLISR is normal, FD fails and RCS operation fails, the type of each area of power grid shall be determined respectively. Establish $B_{ln(1×s)}, C_{nk(1×s)}, D_{nh(1×s)}$ a total of $(k+2)$ failure influence arrays, whose elements represent the failure time of the corresponding region. The equivalent failure influence array $f_{ln(1×s)}$ for $A_n$. Calculate according to formula (2). List all the faults in the area and build the fault impact matrix $F_{(s×s)}$. 
4. Reliability evaluation
In this paper, SAIDI, SAIFI and ENS as reliability indices are calculated and analyzed, the evaluation flow of reliability indices is shown in Fig.4.

![Reliability indices calculation process diagram](image)

Regional failure rate matrix \( \lambda_{(s \times 1)} \) is shown in (3), and its element \( \lambda_n \) is in (4). Regional annual failure time matrix \( T_{(s \times 1)} \) is shown in (5), its element \( T_n \) represents the annual failure time of \( A_n \). Set the non-zero element in matrix \( F_{(s \times s)} \) to 1 to get matrix \( F'_{(s \times s)} \). Regional annual failure frequency matrix \( L_{(s \times 1)} \) is shown in (6), its element \( L_n \) represents the annual failure times of \( A_n \), \( P_n \) represents the average load of \( A_n \). The reliability index is shown in (8) ~ (10).

\[
\begin{align*}
  f_{x_1, x_2} &= pC + p \sum_{x_3} D_x + [1 - p + p_x]B_x \\
  p_x &= p(1 - p)^{x-1} 
\end{align*}
\]  

\[
\begin{align*}
  \lambda_{x_1} &= \lambda_1, \lambda_2, \ldots, \lambda_s \\
  \lambda &= \sum_{x_1} \lambda_{x_1} \\
  T_{(s \times 1)} &= [T_1, T_2, \ldots, T_s] = F'_{(s \times 1)} \lambda_{(s \times 1)} \\
  L_{(s \times 1)} &= [L_1, L_2, \ldots, L_s] = F'_{(s \times 1)} \lambda_{(s \times 1)} \\
  P_{(s \times 1)} &= [P_1, P_2, \ldots, P_s] \\
  SAIDI &= \frac{\sum_{x_1} T_{x_1} N_{x_1}}{\sum_{x_1} N_{x_1}} \\
  ENS &= P_{(s \times 1)} T_{(s \times 1)} \\
  SAIFI &= \frac{\sum_{x_1} L_{x_1} N_{x_1}}{\sum_{x_1} N_{x_1}}
\end{align*}
\]
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Where  \( g \) is the number of power components in \( \mathcal{A}_n \);  \( N_n \) is the number of users.

5. Case study
IEEE RBTS is shown in Fig.5, and its reliability index is calculated and analyzed. Suppose \( p_{fd}=p_{rc}=0.01 \), manual investigation time is 1.6h, and other power system reliability calculation parameters are detailed in Ref.[13].

![Fig. 5. Distribution system for IEEE RTBS.](image)

5.1 Consider FLISR Process Failure
Segment switch \( S_1-S_{10} \) and tie switch are set as RCS, EPON is chain structure, and the power supply reliability index in case 1 and 2 is calculated.

- Case 1: automation system and FLISR are normal.
- Case 2: consider FLISR process failure.

The comparison results of Case 1 and Case 2 are shown in Tab. 2. Considering the failure of FLISR process, many of the original class a areas are converted to class B, D or E areas, so the \( \text{SAIFI} \) increases significantly, which means that the outage frequency of users increases significantly. Therefore, it is necessary to consider the impact of FLISR failure when analyzing the reliability of distribution network.

| Case | \( \text{SAIDI} \) | \( \text{SAIFI} \) |
|------|----------------|----------------|
| Case1 | 3.475 | 0.111 |
| Case2 | 3.509 | 0.185 |

5.2 Effect of EPON element failure on reliability
In order to analyze the sensitivity of CPS reliability to failure rate of different cyber element, take F4 feeder as an example (assuming \( S_8 \) is not RCS), EPON redundant network structure is shown in Fig.6, calculation formula of link effectiveness and reference of failure rate of cyber element under each network mode. F4 feeder adopts tree type communication network. Under the condition that the failure rate of other information equipment does not change, the failure rate of a certain information equipment is changed according to the ratio of 0:0.1:2, and the reliability index of F4 feeder power supply is calculated. The reliability change trend is shown in Fig.7.
Fig. 6. EPON redundant networking structure.

Fig. 7. Influence of cyber element on CPS reliability.

It can be seen from Fig. 7 that for the tree network, compared with ONU, POS and OLT, the change of failure rate has a greater impact on the reliability of CPS, because POS and OLT are in the key node of the tree network, and their failure will cause all cyber links are in failure state. Among the four onus, the reliability of CPS is more sensitive to the failure rate of ONUI and ONU3. Because the segment switches S8 and S10 are located at both ends of the line, the failure of their communication may cause the grid fault to spread to the whole feeder, while the switch S9 corresponding to ONU2 does not have the remote control breaking ability, so the failure rate of ONU2 has the least impact on the reliability of CPS. It can be seen that the sensitivity of CPS reliability to cyber elements is related to the position of cyber elements in the network structure and the importance of power elements coupled with cyber elements.

5.3 Effect of EPON networking on reliability

EPON adopts redundant protection network structure to improve the reliability of CPS. Compare the sensitivity of different networking structures to ONU, POS and OLT failure rates, and the calculation results are shown in Fig. 8.
It can be seen from Fig. 8 that the tree structure is more sensitive to ONU, POS and OLT failure rate, so it has poor effect on improving the reliability of CPS; the double-T, hand in hand and annular structures are less sensitive to POS and OLT failure rate; although the annular structure is similar to the hand in hand structure, there is no standby OLT in the annular structure, so it has relatively high sensitivity to OLT failure rate.

6. Conclusion

CPDS is a complex integrated system which integrates computing system, communication network and distribution network. The reliability evaluation of power network alone can not meet the actual needs. In this paper, a reliability evaluation method of CPDS based on EPON consider different failure modes of cyber system is proposed, which can quantify the impact of cyber system on the reliability of distribution network power supply.

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