Survivability Analysis of Ethernet Passive Optical Network
Applied in Strong Smart Grid

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Abstract

Based on the common topologies applied in distribution system, the corresponding Ethernet Passive Optical Network (EPON) structures are proposed in this paper. The average survivability of each type is quantitatively discussed. According to the simulation results, we demonstrate that the “hand-in-hand” type can provide the highest survivability among them. This connection mode can also be used in electricity utilization information collection system, which is the base to realize intelligent distribution and intelligent utilization.

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1. Introduction

With the economic and social continuous development, the industry has become increasingly dependent on electric power and has more demands for the reliability of power supply and power quality. Therefore, countries around the world carry out the study on the smart grid in succession. In May 2009 State Grid Corporation of China proposed the concept of “Strong Smart Grid”, which is based on the backbone of UHV power grid and on the coordinated development of all levels of strong grid network. Using advanced communications, information and control technology, State Grid Corporation of China is going to build a unified strong and smart grid featured in information technology, automation, interaction. [1]

Smart grid covers generation, transmission, substation, distribution, consumption, dispatching and other links. Power distribution network is relatively weak link among them, because it has characteristics of numerous equipments, wide geographical distribution, scattered nodes, poor operating environment,
uneven distribution, etc. Therefore, intelligent distribution communication network is an important component of strong smart grid, and it is also the basic condition to realize smart distribution system.

An Ethernet Passive Optical Network (EPON) system is a point-to-multipoint, bidirectional optical access network in which unpowered optical splitters are used to enable a single optical fiber to serve multiple premises. [2] Because of its flexible networking, clear hierarchy, higher bandwidth, and low maintenance cost, EPON was born to meet the communication requirements of power distribution network. In addition, EPON can reduce the possibility of lightning strike and interference radiation, because there is no active electronic equipment between optical line terminal (OLT) and optical network units (ONUs).

EPON can be applied in not only distribution automation system but also electricity utilization information collection system in order to implement the functions of smart distribution network and intelligent use of electricity. This paper focuses on the survivability analysis of EPON which is applied in distribution automation communication system. In Section II, three common structures in Distribution Automation System (DAS) are presented. Typical configuration and the features of each type are described. Based on the structures, Section III proposes three corresponding EPON structures. Furthermore, the average survivability is discussed. A summary of this paper is provided in Section IV.

2. Common Topologies in Distribution Automation System

In order to facilitate network monitoring and control, the principle must be complied with during the laying of optical cable that the position of communication equipment tends to be consistent with that of distribution automation terminal. [3] Therefore, the laying of optical cable must go step by step with the extension of power distribution cables. The following section introduces common topology in DAS.

2.1 Single source radial supply network

As shown in Fig. 1, single source radial supply network is a distribution network which provides simple connection, operation convenience, and less investment. When the line or equipment fails, the range of outage is wide which means poor power supply reliability. The trunk line of single source radial supply network generally requires 3 to 4 sections, and supply radius is about 3 to 5 kilometers. [4]

![Figure 1 Single source radial supply connection.](image)

2.2 Hand-in-hand loop distribution line connection
Fig. 2 shows hand-in-hand loop distribution line connection which is the widespread application of urban distribution network. This mode makes the direct contact between the ends of the trunk line, which greatly improves power supply reliability through open-loop operation.

![Figure 2: Hand-in-hand loop distribution line connection](image)

2.3 Double-source twin-T network

Fig. 3 shows double-source twin-T connection mode which takes advantage of T-mode which provides flexible operation mode and saves the amount of power cables. In addition, it is a high reliability connection mode because it provides backup transformer and low voltage distribution system.

![Figure 3: Double-source twin-T connection](image)

3. The Corresponding Topologies and Survivability Analysis of Epon

The corresponding topologies of EPON are presented according to the common topology in distribution automation system. The following section will introduce them and calculate the survivability.

3.1 EPON chain topology network

1) Topology

Fig. 4 shows the EPON topology corresponding to single source radial supply connection. OLT, placed in slave station of distribution automation system, cascades multiple POS (1:2 non-uniform Passive Optical Splitter) which can be placed in each disconnect switch. The maximum distance from OLT to ONU is 20 kilometers which is sufficient for a single power supply range of 3 to 5 kilometers. [5]

2) Survivability analysis
The survivability of network can be defined as the proportion of the traffic $S(\lambda)$ achieved by the network under the influence of disaster $\lambda$ to the traffic carried by the network under normal conditions. [6][7]

\[
P(\Delta L) = \lambda \Delta L.
\]

When the length of the link is $L$, the probability of link failure is

\[
P(L) = \lim_{\Delta L \to 0} (1 - (1 - \lambda \Delta L)^{L/\Delta L}) = 1 - e^{-\lambda L}.
\]

Therefore, the success probability of the link under damage is

\[
P_s = 1 - (1 - e^{-\lambda L}) = e^{-\lambda L}.
\]

Assuming that failure always appears in the link regardless of node failures, because node failure can be transformed into link failure. [8] Assuming that network’s radius is $L$, the communication distance between OLT and POS, from 0 to $L$ conforming to uniform distribution, and the distance between POS and ONU, is $d$, the success probability of the link from OLT to ONU, under damage is

\[
P_i(\lambda) = e^{-\lambda d} e^{-\lambda L}.
\]

Assuming the traffic of each ONU is one unit, the average survivability of the network is

\[
V(\lambda) = \frac{1}{L} \int_0^L P_i(\lambda) dL
\]

\[
= \frac{1}{L} \int_0^L e^{-\lambda d} e^{-\lambda L} dL
\]

\[
= \frac{(1 - e^{-\lambda L})e^{-\lambda d}}{\lambda L}.
\]

3.2 EPON hand-in-hand all-link-protection topology

1) Topology

Fig. 5 shows the topology which completely fit the hand-in-hand loop distribution line connection commonly used in urban power distribution network. The two OLTs are separately placed in each slave station of distribution automation system. The position of ONU and POS can refer to the structure of single source radial supply network. Each ONU have its backup fibers.
2) Survivability analysis

Assuming that the network’s radius referring to OLT\(_1\) is \(L\), the communication distance between OLT\(_1\) and POS\(_i\) from 0 to \(L\) conforming to uniform distribution; and the network’s radius referring to OLT\(_2\) is \(L\) too, the communication distance between OLT2 and POS\(_i\)' from 0 to \(L\) conforming to uniform distribution; the distance from ONU\(_i\) to POS\(_i\) or POS\(_i\)' is \(d\).

The success probability of ONU\(_i\) is:

\[
P_i(\lambda) = 1 - (1 - e^{-\lambda d}) (1 - e^{-\lambda(L-1)}) e^{-\lambda d} = e^{-\lambda d} + e^{-\lambda(L-1)} e^{-\lambda d} - e^{-2\lambda d} e^{-\lambda L}.
\]

The average survivability of the network is:

\[
V(\lambda) = \frac{1}{L} \int_0^L P_i(\lambda) \, dl
\]

\[
= \frac{1}{L} \int_0^L \left[ e^{-\lambda d} + e^{-\lambda(L-1)} e^{-\lambda d} - e^{-2\lambda d} e^{-\lambda L} \right] \, dl
\]

\[
= \frac{1}{\lambda L} \left[ 2e^{-\lambda d} (1 - e^{-\lambda L}) - \lambda L e^{-2\lambda d} e^{-\lambda L} \right].
\]

3.3 EPON twin-T all-link-protection topology

1) Topology

Fig.6 shows the topology corresponding to double-source twin-T connection. OLT\(_1\) and OLT\(_2\) are separately placed in slave station A and slave station B. Compared to “hand-in-hand” structure, the laying position and light direction of OLT\(_1\) and OLT\(_2\) tend to be consistent.
2) Survivability analysis

Assuming that the network’s radius referring to OLT₁ is L, the communication distance between OLT₁ and POSᵢ from 0 to L conforming to uniform distribution; the distribution of OLT₂ and POSᵢ’ is similar to that of OLT₁and POSᵢ.

The success probability of ONUᵢ is:

\[ Pᵢ = 1 - (1 - e^{-\lambda L} e^{-\lambda d})^2 = 2e^{-\lambda L} e^{-2\lambda d} - e^{-2\lambda L} e^{-2\lambda d}. \]

The average survivability of the network is:

\[ V(\lambda) = \frac{1}{L} \int_0^L Pᵢ(\lambda) dl = \frac{1}{L} \int_0^L (2e^{-\lambda L} e^{-\lambda d} - e^{-2\lambda L} e^{-2\lambda d}) dl = \frac{1}{\lambda L} \left[ 2e^{-\lambda L} (1 - e^{-\lambda d}) - \frac{1}{2} e^{-2\lambda L} (1 - e^{-2\lambda L}) \right]. \]

3.4 Comparison

Based on the calculation above, the following section makes a comparison of the three structures applied in distribution network by the simulation in MATLAB.

According to the criterion of goal transmission distance of 1000BASE-PX10U/D and 1000BASE-PX20U/D made in IEEE 802.3-2005, [9] it is assumed that the coverage of EPON is 20 kilometers. In this paper, we make \( d + L \leq 20 \). Furthermore, the distance between POS and ONU is much shorter than that between OLT and POS in practice. So in this paper we make \( d = L \).

Fig. 7, 8 and 9 shows the survivability comparison while the value of \( d \) is fixed and the value of \( L \) varies. Fig. 10 presents the survivability of “hand-in-hand” all-link-protection structure when the value of \( L \) varies.

As Fig. 7-10 shows, the survivability decreases as the value of \( \lambda \) varies from 0 to 1. When the value of \( d \) is fixed, survivability falls with the increases of \( L \). The average survivability of “hand-in-hand” topology is higher than that of “twin-T” structure, which has no relationship with \( L \). The “single source” topology is the worst of the three.
4. Conclusion

Three EPON structures corresponding to the topologies applied in power distribution network are proposed in this paper. We calculate the average survivability of each type. Shown in simulation results, the “hand-in-hand” type can provide the highest survivability among them. This connection mode can also be used in electricity utilization information collection system, which is the base to realize intelligent distribution and intelligent utilization.

Figure 7 Comparison of three modes where $L=5$, $d=1$.

Figure 8 Comparison of three modes where $L=12$, $d=1$. 
Figure 9 Comparison of three modes where \( L=19, \, d=1 \).

Figure 10 Comparison of “hand-in-hand” mode with different \( L \).

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