Design and Implementation of a Last-Mile Optical Network for Distribution Automation

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Abstract—**In recent years, it has been a worldwide trend that many electric utilities give their attention to applying cutting-edge networking technology to their aging infrastructure and power plants and distribution systems. Following this trend, many power companies have installed optical communication lines for their last mile network, called fiber to the pole, along their power distribution lines and at the same time, have made much effort to develop their own distribution automation (DA). In this paper, new network architecture of optical network using one core is proposed for the DA. The results strongly show that the application of the optical network technology to the DA is potentially beneficial in reliability, speed, and expandability. This paper presents the design principle and its implementation of the optical network for DA.**

Index Terms—**Communication cables, communication system fault tolerance, communication system maintenance, communication system planning, distribution automation, fault location, network fault diagnosis, one-core optical network, optical communication, optical directional coupler.**

I. Introduction

In the past years, most automation in electric utilities has been in the substation and at the enterprise level. This is due primarily to the potentially high cost of implementing distribution automation (DA), the lack of economic justification for such expenditures, and the unique and difficult technical challenges of implementing DA on a widespread basis. However, this situation is changing drastically. There are a number of factors that drive the change within electric companies to apply state-of-the-art information technology (IT). These factors are: increased customer expectations in terms of power quality (PQ) and reliability, the growing number of regulatory incentives, increasing the performance and affordability of DA communication choices, and an increased variety and capability of automation devices and software. An efficient, reliable, and secure communication infrastructure is vital for successful DA implementation.

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In today's competitive electric utility marketplace, reliable real-time information becomes the key factor for reliable delivery of power to the end users, profitability of the electric utility, and customer satisfaction. Unfortunately, there is no unique communication solution or model for success that can be applied to DA in electric utilities. Each utility's unique characteristics will determine the requirements for the communication system.

A DA communication system must address today's needs, while providing the ability to add future functionality. Automation systems have different requirements for networks according to their functions. Most automation systems are operating independently by using dedicated communication networks, leading to duplication.

With the new requirements of the deregulated utility market, it can be assumed that the focus of the utilities will increasingly shift towards networked communication systems. The networked systems are much more far reaching than those of a typical office environment, especially with respect to reliability, operation, and maintenance of different types of applications within the same network. Automation systems are operating increasingly as distributed systems in view of applications [1].

This paper describes a new generation optical communication network for DA. The network has a ring-type topology by using a single line core with a logical redundancy function. Also, we describe the structure of the system, applicable algorithm, implementation, and analysis. Evaluation shows that the proposed one-core network has better performance in reliability, speed, and expandability than the existing dual-core communication network.

II. Distribution Automation

A. Requirement of DA

Important elements of designing automation systems have been mainly automation devices, such as central units (local side-server) and electronic devices (remote side-client). Improving the function of these two devices is important for automation systems, and the functional quality of the devices has become stable in performing automatic operation. However, the communication devices have been the cause of most trouble in an automation system. Therefore, to improve the DA, we must shift our focus to the communication system in the automation system.

Most utilities in North America already have automated individual communication systems to handle various aspects of the utility's operational requirements [2]. Reliability and availability are key requirements in operating the DA. Communication stability is an important factor for the system availability

TABLE I
CANDIDATE COMMUNICATION SYSTEMS FOR DA

	Advantages	Disadvantages
PLC	-Extensive coverage -Cost-effective	-Signal attenuation/distortion -Lack of security -Lack of regulation
Optical	-High bandwidth -Security	-High cost
Satellite	-Global coverage -Rapid installation	-Long delay -High cost
2 way Radio	-Low cost -Rapid installation	-Limited coverage -Low capacity -Lack of security
WSN	-Self configuration -Low cost	-Limited resources -Lack of security

because it is impossible to gather information from remote devices when communication fails. Therefore, it is important to keep the communication devices functioning. Reliable automation systems should have a new feature of overcoming communication failures.

B. Candidate Communication System for DA

Designing a DA communication system requires the consideration of many services, such as remote metering, load control, distribution line automation, and two-way communication for customer information. Also, difficulties must be considered arising from communication noise and electromagnetic interference for communication lines that have been installed alongside the power line. Many researchers and several international organizations are currently developing required communication technologies and international communication standards for electric utilities. Candidate communication media for the last mile are power line communication, optical fiber communication as wire communications, two-way radio, satellite communication, and wireless sensor network as wireless communications. Each communication system has advantages and disadvantages as the last-mile connectivity for electric companies, which is summarized in Table I. It is shown that the optical network is the most desirable candidate for communication media [3].

III. OPTICAL NETWORK FOR DA

A. Existing Network

The most popular optical communication mode at the present DA adopts a double-ring self-recovery network mechanism [4]–[6]. The communication network is normally built along the electric power line with the substation as its center; therefore, the self-recovery function can still be implemented automatically and communication will not be affected even if one node in the ring network is disconnected. Fault diagnosis with conventional optical fiber network communication is mostly implemented by the polling method [7]. The DA can be applicable to many data services, and it can be connected to other network systems by installing an optical network. So far, many electric companies have installed optical networks for integrated automation as well as for the purpose of establishing a communication infrastructure. That is, with the conception that where the distribution line is, there the optical line is. The optical line is installed as a fiber-to-the-pole (FTTP) network. Since the optical lines are installed exactly parallel to the power distribution lines, it is easy to install and maintain them as a local-area network (LAN).

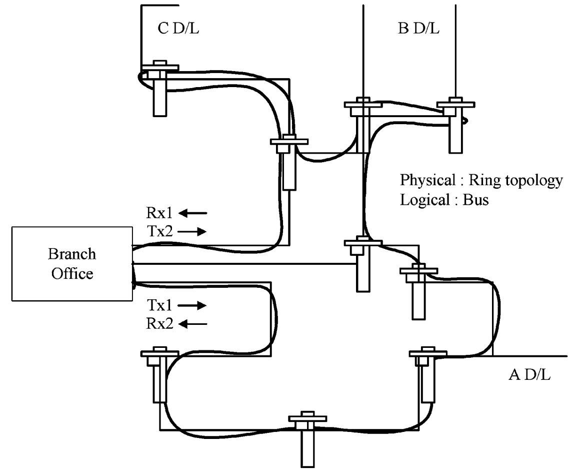


Fig. 1. Loop structure of the optical network.

As an integrated network for managing distribution lines which have multitude of problems, such as ones from typhoons and solar heat in the summer, it is now possible to integrate all branch offices under a single control center for the operation and management of distribution systems.

B. Proposed Network (One-Core Ring Network)

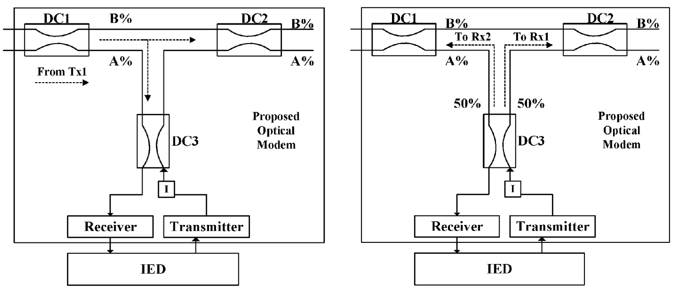
The power distribution lines in most cities have a ring topology for taking an alternative power route in case of a distribution line failure. Thus, it is easy to make the optical line in a ring topology when they are installed along with the distribution lines, and it can be constructed with physically a single line. But the single line can be operated as dual lines when the communication signal runs in two directions. That is, the single line logically has two-directional communication. Fig. 1 shows an example of the structure of the optical loop network.

The central unit in the branch office has two-way communication directions, with two transmitters (Tx1 and Tx2) and receivers (Rx1 and Rx2). Therefore, it can change the communication direction from one to another in the case of communication failures. Not all switches in the distribution lines have automatic function; however, automatic switches are installed in some important places, such as branching points. Usually two to four automatic switches are installed in one distribution line.

However, since the distribution lines in rural areas have a star topology, which is different from a ring topology, it is difficult to install optical lines in those areas. Thus, operating an optical network in rural areas is not economical. It is suggested that a wireless communication network be applied for DA in rural areas [8], [9].

C. Design and Principle

The optical modem in intelligent electronic devices (IEDs) has a laser diode (LD) for the optical transmitter and a photo diode (PD) for the optical receiver to interface with the optical



(a) (b)

Fig. 2. Signal flow in the optical modem. (a) To the IED. (b) From the IED.

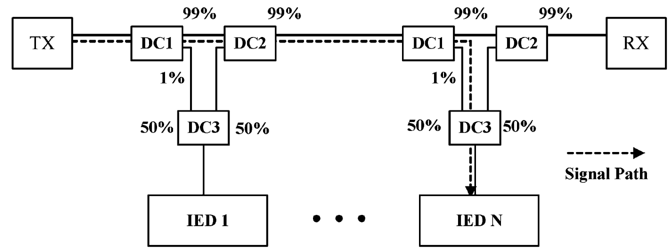


Fig. 3. Longest signal path.

TABLE II
RELATIONSHIP BETWEEN THE TAP RATIO AND THE NUMBER OF IEDS

tap ratio \ # of IED		5	10	15	20	25	30	35	40
1	99	23.43	23.87	24.30	24.74	25.18	25.61	**26.05**	**26.49**
2	98	20.86	21.74	22.62	**23.49**	**24.37**	**25.25**	26.13	27.00
3	97	19.55	20.87	**22.19**	23.52	24.84	26.16	27.48	28.81
4	96	18.75	20.52	22.29	24.07	25.84	27.61	29.39	31.16
5	95	18.23	**20.46**	22.69	24.92	27.14	29.37	31.60	33.83
6	94	17.90	20.59	23.28	25.96	28.65	31.34	34.02	36.71
7	93	17.70	20.85	24.00	27.15	30.30	33.45	36.61	39.76
8	92	17.59	21.21	24.83	28.45	32.07	35.69	39.31	42.93
9	91	**17.55**	21.64	25.74	29.84	33.93	38.03	42.12	46.22

line. A passive splitter with a multidrop is used for interfacing with the optical lines. The disadvantage in an add-drop network is that a problem in one node causes the entire network communication to be disabled. To avoid this disadvantage, a passive connection method is applied to the network, in which communication signals can pass over the problem node [10]. When IEDs are scattered throughout a large expanse of an area and the number of devices to be controlled is large, multiple ring-type networks can be designed by considering the connection losses of many multidrop nodes. Fig. 2 illustrates the connection diagram of the optical line and signal flow in the optical modem.

When the directional coupler 1 (DC1) in Fig. 2(a) receives the communication signal from Tx1, the signal power is divided into coupler 2 (DC2) and coupler 3 (DC3) with a ratio of $B : A$, where $A\%$ of the signal goes to the IED and $B\%$ to the network. DC3 then passes $A\%$ of the signal to the IED, and DC2 transmits $B\%$ of the signal to Rx1. The IED inspects the address on the data frame. If the address is not the same address as the IED, the frame will be discarded. If the address is the same, the IED executes the necessary operation following the command on the frame, and sends the results to DC2 by using the transmitter in the IED. When the IED sends the message to the central unit, DC3 divides the signal into DC1 and DC2 with the ratio of 50:50. Then, $B\%$ of the signal goes to the network and $A\%$ of the signal is dropped. When it comes to designing a network, the maintenance of an adequate level of receiving signal can be achieved by methods, such as increasing the transmission power level or dividing the ring into smaller rings, depending on the system capacity. The signal loss depends on the node-passing loss, the receiver internal loss, and the optical line loss. Each node has two directional couplers, so the total node-passing loss is doubled: $\mathrm{Loss}_{pass} = 2 \times (\mathrm{Loss}(B\%))$. The receiver internal loss relates to two losses: $\mathrm{Loss}(A\%)$ and $\mathrm{Loss}(50\%)$.

In the case of the ratio of 1:99, the signal loss between the directional couplers DC1 and DC3 is $\mathrm{Loss}(99\%) = 10\log_{10}0.99 = 0.043$ dB, and the loss from passing through the DC2 is $\mathrm{Loss}(50\%) = 10\log_{10}0.5 = 3$ dB. The loss in the DC1 of the last node becomes $\mathrm{Loss}(1\%) = 10\log_{10}0.01 = 20$ dB. Thus, the loss from the system can be classified as follows.

- Node-passing loss

$$\mathrm{Loss}_{pass} = 2 \times (\mathrm{Loss}(99\%)) = 2 \times 10\log_{10}0.99 = 0.086 \text{ dB}.$$

- Receiver internal loss

$$\begin{aligned}\mathrm{Loss}_{in} &= (\mathrm{Loss}(1\%)) + (\mathrm{Loss}(50\%)) \\ &= 10\log_{10}0.01 + 10\log_{10}0.5 = 23 \text{ dB}.\end{aligned}$$

- Optical line loss

$$\mathrm{Loss}_{line} = 0.275 \text{ dB/km}.$$

For the same procedure, it is interesting to see how decibel loss depends on the tap ratio and the number of IEDs. This is shown in Table II. As the number of IEDs is increased, minimizing the worst case loss favors the tap ratio 1:99.

Since our proposed network is designed for a large-scale DA, we adopted a 1:99 ratio for the proposed network. In the next section, we analyze the maximum number of optical modems which can communicate without repeaters when we use a 1:99 tapping ratio.

D. Maximum Number of IEDs in a Ring

When an optical modem is designed and developed, it is important that the number of IEDs to be installed in one ring should be determined based on transmission power level, receiving sensitivity, and signal loss in the modems and optical lines. In normal optical communication, sensitivity would be 48 dBm with 1 mW of transmitting power, and the bit-error rate (BER) would be less than 10^{-9}. Fig. 3 illustrates an example with a case of the worst transmission losses, in which the longest transmission length can be decided.

In Fig. 3, when the number of IEDs are N, the biggest signal loss can be made from Tx to IED N, which is the farthest node from Tx. Considering the above signal loss, the maximum number of IEDs can be derived as follows:

$$\begin{aligned}(N-1) \times \mathrm{Loss}_{pass} + \mathrm{Loss}_{in} + \mathrm{Loss}_{line} \\ \leq \text{maximum allowed loss } (\mathrm{Loss}_{max}). \quad (1)\end{aligned}$$

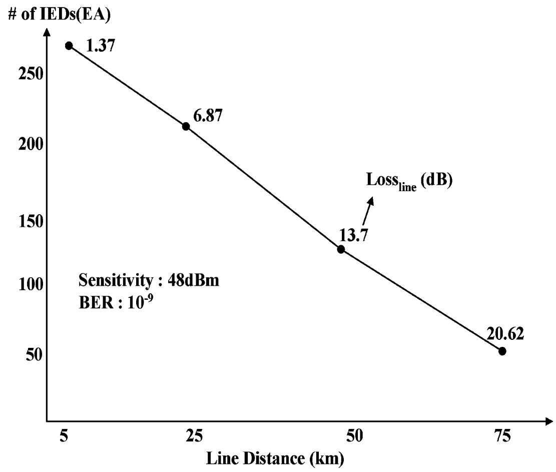


Fig. 4. Relationship between line length and the number of IEDs.

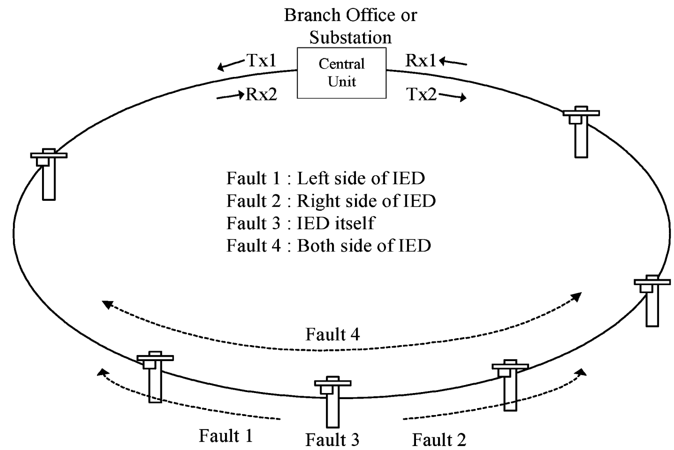


Fig. 5. Potential areas of the communication fault.

TABLE III
THEORETICAL NUMBER OF IEDs WITH LINE LENGTH

Line Length(km)	Signal Loss(dB)	Max. # of IEDs
5	1.375	275
10	2.75	259
25	6.875	211
50	13.75	131
60	16.485	100
75	20.625	51

In (1), the maximum allowed signal loss will be 48 dB, since the sensitivity is 48 dBm. Substituting the three types of signal loss into (1) yields $0.086(N-1)\text{dB} + 23\text{ dB} + \text{Loss}_{line}\text{dB} \leq 48\text{ dB}$. From this N is

$$N \leq \frac{25.086 - \text{Loss}_{line}}{0.086} \tag{2}$$

Fig. 4 shows that the number of IEDs linearly decreases with line length. The following Table III shows the maximum number of IEDs based on (2).

In Table III, 51 IEDs can be installed on the 75 km optical line length. The length of the existing optical ring is less than 25 km for DA. Thus, we can see that 211 or more IEDs can be installed in one ring.

IV. OPERATIONAL ASPECTS

Communication stability is an important factor for the system availability. Therefore, reliable automation systems must have a new structure to overcome communication problems. In this section, we discuss how communication failures are detected and where the network recovery techniques fit into the proposed network architecture.

A. Fault Management

Fault-management processes are crucial from a resiliency point of view, because these processes are responsible for locating and reporting network failures and possibly for triggering network recovery actions.

Although the developed optical network is installed on a single ring, management of the network is based on a dual-bus structure. In normal operation, communication goes from Tx1 to Rx1. When a message, such as monitoring or controlling a specific switch, is sent out to the network from Tx1, the signal is returned to Rx1. The status of the network can be checked from the returned message. Passive devices for the coupler are applied between the IED and the optical ring, so that when the connected node has a communication problem, the messages from other nodes can still pass through.

The specific IED which receives the message from the control center sends out the result to the network in two directions. The central unit can receive the message both from Rx1 and Rx2. If the central unit cannot receive the message through Rx1 within a specified time, it will try to take the message from Rx2. If the transmitted message from Tx1 is not returned to Rx1 or Rx2, the central unit uses Tx2 to send out the command message to the network. Communication problems can be located on four points in the network: 1) the left side of the IED, 2) the right side of the IED, 3) both sides of the IED, and 4) the IED itself. Disconnection of the physical line is the most severe problem for the optical network. The four points around the IED are illustrated in Fig. 5.

The central unit can send the message from Tx1 to Rx1 and from Tx2 to Rx2. In the first case of fault, when Tx1 is set as the main transmitter and the line fault is located at the left side of the IED to communicate with it, Rx1 cannot receive the Tx1 signal and the response message from the IED, and no messages into Rx2. In the second case, if the line fault is located at the right side of the IED to communicate with it, Rx1 cannot receive any message, but Rx2 can receive the response message from the IED. The third case occurs when the IED itself has a problem. Rx1 and Rx2 can receive messages from Tx1 and Tx2, respectively. This means that Rxs can receive the polling message, which is a command from the central unit to IEDs, from Tx through the network. Thus, it can be concluded that the communication lines have no problem. Therefore, it is not necessary for the IED to send out an Acknowledgement (ACK) signal to the control center, which is a response message from IEDs to the central unit. Fig. 6 illustrates the data flow in the fault situation.

B. Fault-Management Algorithm

The most important functions in managing the network are those of checking for abnormal communication, locating the

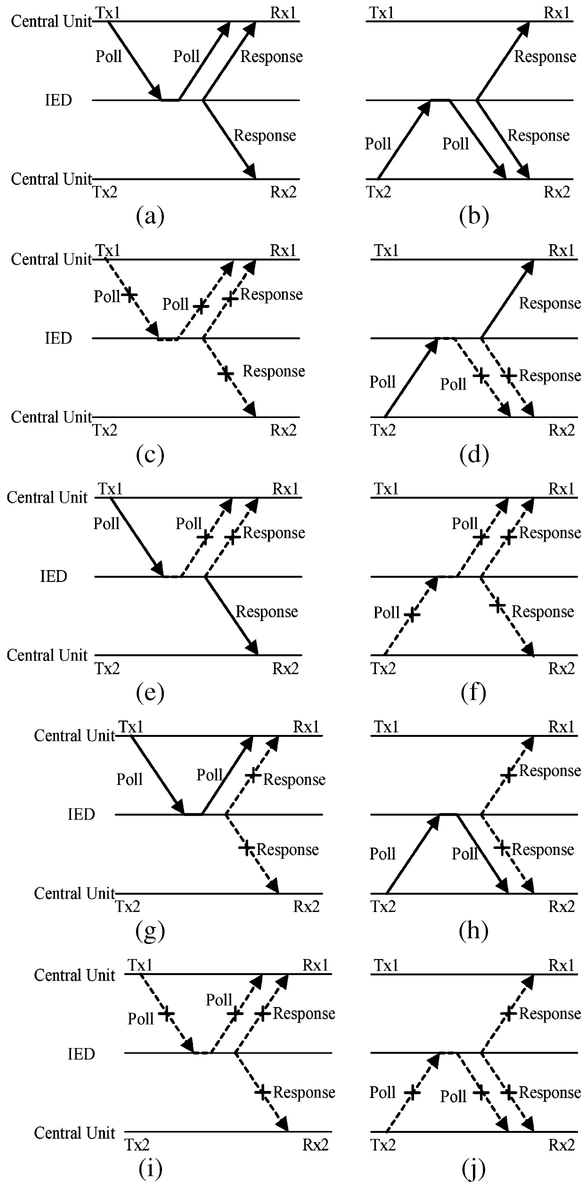


Fig. 6. Data flow at fault situations. (a) Normal—Tx1 send message. (b) Normal—Tx2 send message. (c) fault1(left side of IED)- Tx1 send. (d) fault1(left side of IED)—Tx2 send. (e) fault2 (right side of IED)—Tx1 send. (f) fault2 (right side of IED)—Tx2 send. (g) fault3(IED, modem)—Tx1 send. (h) fault3(IED, Modem)—Tx2 send. (i) fault4 (both sides of IED)—Tx1 send. (j) fault4(both sides of IED)—Tx2 send.

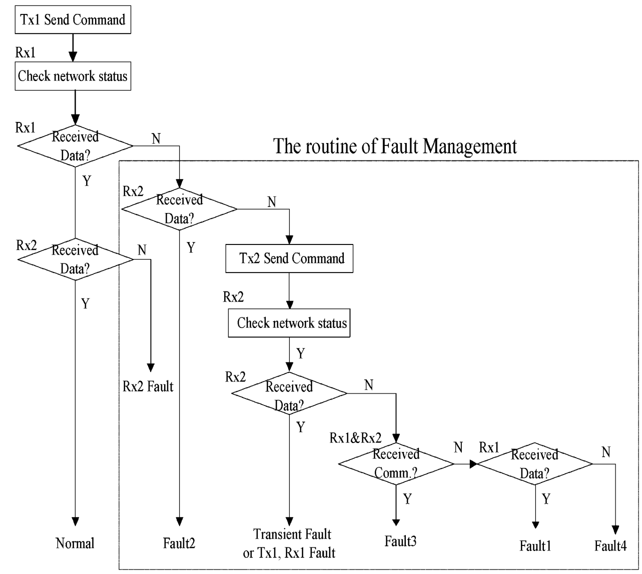


Fig. 7. Flowchart of the fault-management algorithm.

fault boundary, and recovering the network operation. These should be done as early as possible.

In a normal network operation, the main transceiver should be determined with one-directional communication. If Tx1 and Rx1 are selected for the main transceiver, Tx2 and Rx2 are set as a standby transceiver. The central unit transmits a polling message through Tx1 to control and monitor a specific IED in the network. First of all, the central unit checks whether Rx1 received the message from Tx1.

If Rx1 does not receive either the polling message or the response message from the IED, the central unit executes the fault-management program and checks Rx2. If Rx2 has received the response message from the IED, Fault2 (the right side of the IED) has occurred. If not, the central unit checks whether Rx2 has received the polling message after the message was sent with Tx2.

If Rx2 has received the polling message and the response message from Tx2 and the IED, respectively, the fault was a temporary one and the network may function normally. Another possibility of this fault is because Tx1 or Rx1 has been broken. If Rx2 has received the polling message from Tx2, but no response message from the IED, then we should check again whether Rx1 has received the response message from the IED.

If Rx1 received data from the IED, the fault occurred on the left side of the IED (fault 1), but if Rx1 did not receive data, fault 4 occurred which is the worst case fault. If Rx2 has not received the polling message, Tx2 takes the control for communication. Tx2 sends out the same polling message as Tx1 to the network. If Rx1 and Rx2 have received only the polling message, the network works well, but the IED has some problems. In this case, the exact fault position can be located since the location of the IED can be found easily.

In the case of a line fault, it is a bit more difficult to find the exact location. Communication problems due to line faults in a single directional communication can be recovered by the algorithm developed in this paper. Fig. 7 illustrates the fault-management algorithm as a flowchart.

In the next section, we explain how to determine the exact fault location. Since the proposed fault-management algorithm can find the network fault locations, the fault status can be classified as fault 1, fault 2, fault 3, or fault 4, as described before, which we will describe in more detail in the next section.

C. Implementation

To implement the proposed algorithm, the central unit manages two kinds of fault decision tables. One table is for each IED and the other is for the entire system. The central unit maintains Tx1 and Rx1 as the primary transceiver and receiver, respectively. The central unit sends a poll (command) message to the specified IED that wants to communicate. The network operation procedure is shown:

Tx1 sends poll message

If Rx1 receives the poll message from Tx1

    $Poll_{Tx1\rightarrow Rx1} = 0;$

$Poll_{Tx1\rightarrow Rx1} = 1;$

If Rx1 receives data from the IED

    $Data_{Tx1\rightarrow Rx1} = 0;$

    If Rx2 receives data from the IED

        $Data_{Tx1\rightarrow Rx2} = 0;$

        NORMAL;

        Break;

    $Data_{Tx1\rightarrow Rx2} = 1;$

    Fault Rx2 (Receiver 2 is abnormal);

    Break;

$Data_{Tx1\rightarrow Rx1} = 1;$

Call Fault.Management(.);

If *Fault.Management(.)* is called, the fault management routine is activated as shown below.

Fault.Management(.)

If Rx2 receives the data from the IED

    $Data_{Tx1\rightarrow Rx2} = 1;$

    $Fault2 = 1;$

    Break;

Tx2 sends poll message

If Rx2 receives the poll message from Tx2

    $Poll_{Tx2\rightarrow Rx2} = 0;$

$Poll_{Tx2\rightarrow Rx2} = 1;$

If Rx2 receives the data from the IED

    Transient Fault;

    Check Tx1 and Rx1;

    Break;

If $Poll_{Tx1\rightarrow Rx1} = 0$ and $Poll_{Tx2\rightarrow Rx2} = 0$

    $Fault3 = 1;$

    Break;

If Rx1 receives the data from the IED

    $Fault1 = 1;$

    Break;

$Fault4 = 1;$

TABLE IV
FAULT DECISION TABLE FOR IEDS

IED #						
$Poll_{Tx1\rightarrow Rx1}$	$Data_{Tx1\rightarrow Rx1}$	$Data_{Tx1\rightarrow Rx2}$	$Poll_{Tx2\rightarrow Rx2}$	$Data_{Tx2\rightarrow Rx1}$	$Data_{Tx2\rightarrow Rx2}$	
0	0	0	X	X	X	Normal Tx1 send
X	X	X	0	0	0	Normal Tx2 send
1	1	0	1	1	1	Fault 2
1	1	1	1	0	1	Fault 1
0	1	1	0	1	1	Fault 3
1	1	1	1	1	1	Fault 4

0=normal, 1=abnormal, X=don't care

0=normal, 1=abnormal, X=don't care

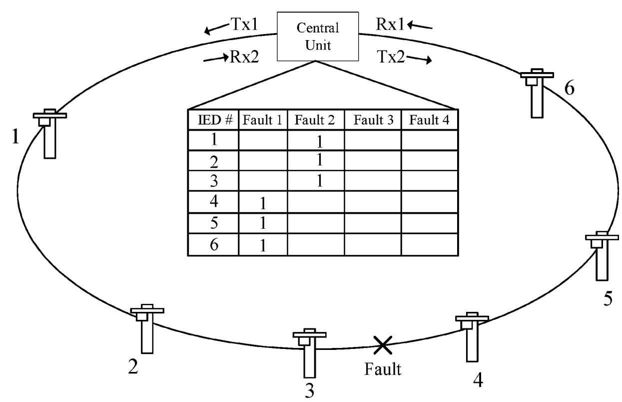


Fig. 8. Fault has occurred between IEDs 3 and 4.

Table IV shows how faults are classified depending on the variables as described before. Based on the fault decision table for IEDs, the central unit makes the fault decision table for the network.

Fig. 8 illustrates how the central unit decides the fault location. In this example, IEDs 1, 2, and 3 have "fault 2" and IEDs 4, 5, and 6 have "fault 1." The central unit makes a decision that a fault has occurred between IEDs 3 and 4 based on the table. If the fault is recovered, the table will be reset according to the algorithm.

Fig. 9 shows the combination of faults and its table contents. In this case, one fault has occurred at IED 3 and another fault has occurred between IEDs 5 and 6.

All single and combination (but separate) faults can be managed by the proposed algorithm. If two or more faults occur concurrently, the proposed algorithm can find the fault area, but cannot determine how many faults and where the faults occurred in the network.

Fig. 10 shows the possible pair of faults according to the fault decision table for the network. There are four possible types of faults. The proposed algorithm can only find that the network has two or more faults between IED 2 and IED 4.

D. *Efficiency Analysis*

There are two kinds of polling methods: 1) roll-call and 2) hub-polling. We use the roll-call polling for the proposed network, because if an IED has a fault in hub-polling, the fault may

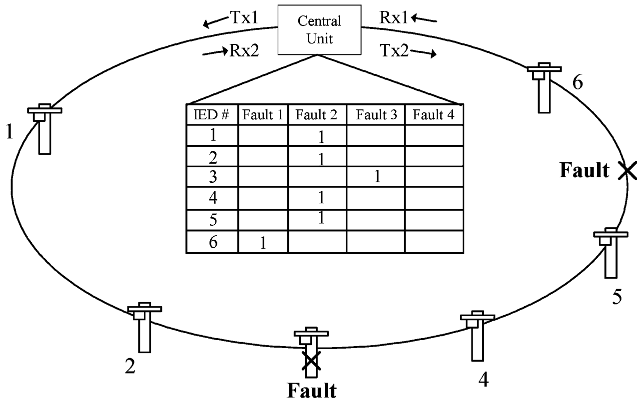


Fig. 9. Combination of faults.

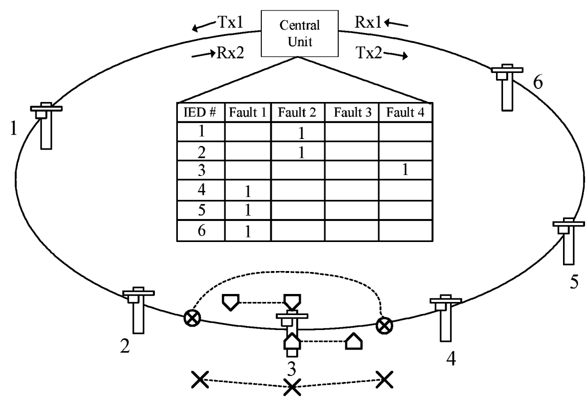


Fig. 10. Four possible pairs of faults.

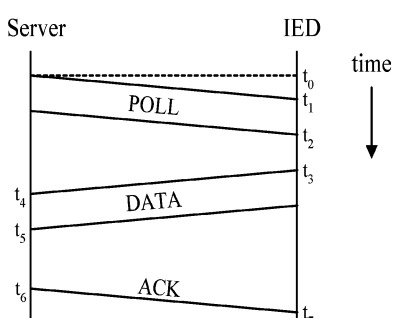


Fig. 11. Polling procedure between a server and an IED.

propagate to the network. Fig. 11 shows the total communication time between a server and an IED.

The total time that it takes to gather the information of all IEDs depends on the following factors: propagation delay from the server to an IED $(t_1 - t_0)$; poll transmission delay $(t_2 - t_1)$; processing time in the IED $(t_3 - t_2)$; propagation delay from the IED to the server $(t_4 - t_3)$; data transmission delay $(t_5 - t_4)$; processing time in the server $(t_6 - t_5)$; and ACK propagation delay and transmission time $(t_7 - t_6)$. We can ignore the ACK propagation and transmission time because ACK is of very small size. Since the processing time depends on processors, we denote this variable T_{proc}. Then, we can calculate the total spending time to communicate with all IEDs, as noted

$$\text{Total time} = \{(2 \times \text{data transmission time}) + (3 \times \text{propagation delay}) + 2T_{\text{proc}}\} \times \text{Number of IEDs}. \quad (3)$$

Let us assume that the propagation delay (t_p) is the time that it takes to reach the furthest IED and N is the number of IEDs. We can make the equation for the total propagation time T_p as follows:

$$\begin{aligned} T_p &= \frac{t_p}{N} + \frac{2t_p}{N} + \mathrm{L} + \frac{N-1}{N}t_p + \frac{N}{N}t_p \\ &= \frac{t_p}{N}(1 + 2 + \mathrm{L} + N) \\ &= \frac{t_p}{2}(N+1). \end{aligned} \quad (4)$$

The total data transmission time, represented by T_t, is fixed. By substituting (4) to (3), we can obtain the total time that it takes to gather the information of all IEDs as follows:

$$T_{\text{total}} = 2NT_t + \frac{3}{2}t_p N(N+1) + 2NT_{\text{proc}}. \quad (5)$$

Let us evaluate the total time by using the sample data as shown [6]:

- number of IEDs $= 100$;
- average distance of optical network $(\mathrm{d}) = 25$ km;
- transmission rate $(\mathrm{R}) = 155$ Mb/s;
- optical velocity $(\mathrm{V}) = 2 \times 10^8$ m/sec;
- average data length $(\mathrm{L}) = 10$ kB.

Propagation delay (t_p) is $\mathrm{d/V} = 1.25 \times 10^{-4}$ sec and transmission time (T_t) is $L/R = 5.1 \times 10^{-4}$ sec. From (5), the total time is $(0.12 + 200 \times T_{\text{proc}})$ sec. From this result, we can see that the total response time depends on the number of IEDs and the processing time of the CPU and IED. We can also calculate the line utilization (U) from (5) as

$$\begin{aligned} U &= \frac{2NT_t}{2NT_t + \frac{3}{2}t_p N(N+1)} \\ &= \frac{T_t}{T_t + \frac{3}{4}t_p(N+1)}. \end{aligned} \quad (6)$$

If we use the aforementioned sample data for this equation, U is 0.915. This result shows that this proposed network has very high utilization and reliability for distribution automation. The optimal operation conditions can be calculated depending on the actual operation environment.

E. Comparison

When there is a communication fault in the existing DA network, the fault locations, at the optical line or IED, cannot be detected. With the use of the proposed algorithm, the existing network fault can be located and fixed, and communication for controlling and monitoring can continue despite the network fault. The existing optical networks for DA have several problems from the point of view of reliability. One of the critical problems is that when an optical modem has a problem, it propagates the problem to the network and causes the network to reconfigure.

TABLE V
COMPARISON OF THE RING NETWORK FOR DA

	The existing dual core ring	Proposed one core ring
Number of core / a ring	2	1
Number of optical modem/a ring	30(max)	Unlimited
Speed of network	2Mbps, 155Mbps	> 155Mps (depends on transceivers)
A modem fault	Propagate to the network	No affect to the network

Many electric companies have developed optical networks for DA, but they simply apply existing optical network technology to their DA [5], [6]. However, distribution systems in electric companies have different requirements from other pure communication systems. From this point of view, we have designed the optical network applicable for a power company. Table V provides a comparison for the ring network for DA.

V. CONCLUSION

This paper suggests a network structure and fault-management algorithm for DA and provides quantitative analysis. The network operating technique in this paper can identify the causes of the communication faults and avoid communication network faults in advance.

Use of the network system developed in this paper is not limited to DA. It can be expanded to many kinds of data services for customers. The proposed network can integrate applications such as a trouble call system (TCS), outage-management system (OMS), asset-management system (AMS), geographic information system (GIS), and work-management system (WMS). Furthermore, this network system can be used for monitoring systems for oil, gas, and water systems and, thus, suggests the direction of the communication network for other types of utilities.

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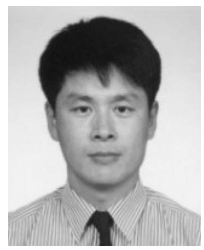

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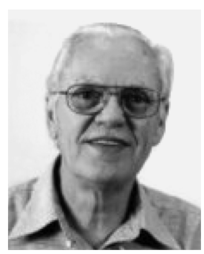

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