Design and Implementation of Multiagent-Based Distributed Restoration System in DAS

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***Abstract*—A distribution automation system (DAS) is a power automation system to operate a power distribution network efficiently through remote control and monitoring. The most important function of the DAS is the restoration of a stable power supply to the customer when a fault occurs. Since the DAS has a centralized structure, the restoration time of the DAS takes place in about 5 min. This is too long for a customer in the digital age, so a distributed restoration system, which can shorten the restoration time from 5 min to less than 1 min is proposed in this paper. The concept of a multiagent system (MAS) for a distributed control system is applied to the proposed system to enhance its operational reliability, but there is a belief that the MAS-based distributed operations system is just a future technology. So an application method is proposed in this paper for an MAS-based distributed restoration system without significant changes to the existing DAS. The proposed system was applied to an existing DAS and tested in the Gochang Power Testing Center. The test results showed that in the most complex case, the DAS restoration time was 48 s using a code-division multiple-access module and 10 s using an Ethernet communication module.**

***Index Terms*—Distribution automation system (DAS), distributed operation system, multiagent, power distribution system, restoration.**

I. Introduction

IN ORDER to improve the power-supply reliability, a distribution automation system (DAS) has been used for increasing the operational efficiency of power distribution systems. The DAS is defined as a multifunction system to monitor and control the scattered feeder remote terminal unit (FRTU) in a wide area, among which, a restoration of the DAS is the most important function for improving the power-supply reliability in the DAS [1].

The restoration of the DAS is defined as the process to restore the power supply to customers of a blackout area after a fault has been detected through remote control. This process includes the fault section detection, the fault section isolation, and the restoration by connecting to other healthy feeders through a system reconfiguration of the power distribution system [2].

The DAS is based on a centralized system, where the central server receives all information from the field, and has full authorization for the monitoring and the control of the remote FRTUs. A centralized system-based DAS can accomplish a complete restoration in about 5 min after a fault [3]. The 5 min for the restoration is too long in an era where even a 1-s power outage would be unacceptable. However, if operating under the highest efficiency with the existing technology, it is possible that the restoration time can be shortened to several seconds by introducing new concepts and improvements.

The system configuration of DAS was made centralized because there was no choice due to the need for operational reliability and the technical limitations at that time. However, as the functions and the configurations for the restoration have become more complex, the DAS needs to collect a massive amount of information, and give a large number of control commands, which limits further improvements in the operating efficiency of a centralized system. With the latest technology, it is possible to change the centralized structure to a distributed one for the DAS to enhance its operating efficiency. In particular, the restoration time can be shortened from minutes to seconds by achieving a higher operating efficiency. However, the introduction of a distributed system requires large costs and it is very difficult to implement from a technical standpoint.

To realize power distribution system operation and restoration using a distributed DAS, some researchers have proposed the inclusion of artificial intelligence to produce a more intelligent system. Many algorithms based on artificial intelligence have been used to improve the efficiency of the fault restoration system, including genetic/fuzzy algorithms [4], [5]. Zero-sequence current transformer-based algorithms to determine the appropriate fault section [6], restoration algorithms based on tie-switch moving [7], and restoration algorithms by load equalization [8] are proposed. Although these algorithms improve the reliability of a distributed operation, it is not a completely distributed configuration because it has to wait for the data processing and decision of the control center after fault occurrences.

Therefore, a new concept needs to be introduced for realizing a distributed control system. In this paper, the concept of a multiagent system (MAS) is proposed to achieve regional objectives and overall goals by mutual cooperation between distributed agents and through independent judgment by each agent which

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is able to respond actively to their environment change. So, the concept of the MAS can be considered as the best choice for the implementation of a distributed system [9], [10]. There has also been some research using the MAS to achieve efficient fault restoration. [11]–[13] introduced the concept of the MAS to switches, loads and feeders in a power distribution system to quickly and proactively perform a power system restoration. [14] proposed a centralized system to control all central and terminal operations in the control center.

However, they didn't consider some problems which are the unclear definition of the MAS, ambiguous application targets, and the environmental constraints in field utilization. In addition, the proposed systems in literature are MAS-based DSs, but actually all actions were done by the control center. So the system proposed in the literature cannot be considered as a proper MAS-based distributed system structure.

In this paper, design and implementation of he MAS-based distributed restoration system applicable to the current DAS are proposed. A concept of the distributed restoration system is based on the premise that terminal agents accomplish a restoration by cooperation among themselves without commands from central server. Also, an implementation method of the MAS-based distributed restoration system to current DAS was proposed. The proposed system was directly implemented and tested for validating results in the Gochang Power Testing Center (GPTC).

In Section II, a restoration scheme and environment in a current DAS, a definition of MAS, and requirement for applying the MAS to a DAS are presented. An algorithm of the MAS-based restoration is illustrated in Section III. Section IV presents a design and implementation of the proposed system to the current DAS environment. Test results of the proposed system in the GPTC are given in Section V.

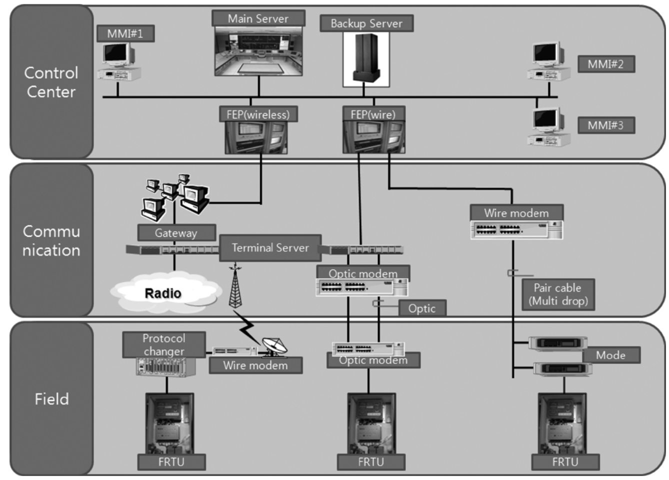

Fig. 1. DAS structure.

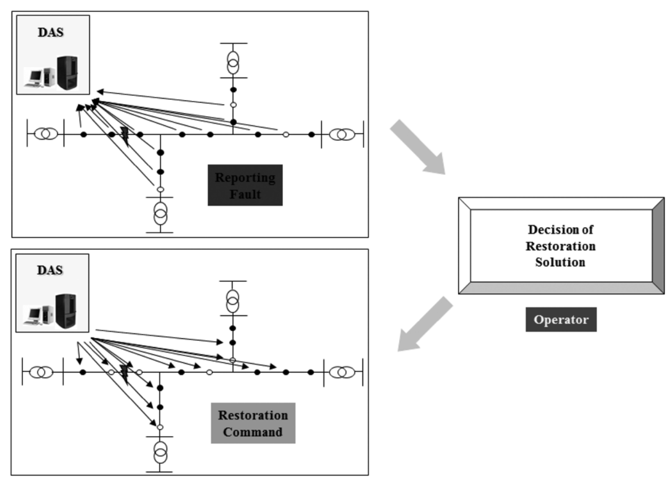

Fig. 2. Restoration scheme of a DAS.

II. MAS Application Environment to DAS Restoration

A. Restoration in a DAS

A DAS is operating through remote control and monitoring of the FRTUs (and reclosers) using communication with the control center as shown in Fig. 1. The restoration scheme for the DAS is shown in Fig. 2. If a fault occurs in a power distribution system, all information should be sent from FRTUs to the control center, and the control center performs fault section detection, fault section minimization, and restoration of the blackout area.

If a fault occurs in the radial power distribution system, the fault current flows only from the source side to the fault location, and, at that time, the fault indicator (FI) would transfer fault currents immediately to the DAS server. After making a judgment, the operator would send information requests to all FRTUs in the faulted power distribution line. After receiving the requested information, the DAS server would locate and isolate the fault section and a restoration process would be started.

The restoration ability of the DAS has established a much greater reliability of the power supply to customers than the former power distribution operation systems did. Currently, the restoration time of the DAS is normally about 5 min, and this is the most efficient result that can be acquired through the techniques applied until this time. However, considering recently developed techniques, the restoration efficiency of the DAS can be increased by adopting a DS.

If a fault occurs on a power distribution line as assumed in the power distribution system as shown in Fig. 2, all information would be transmitted to the control center and control commands would be given to the FRTUs after fault section detection. A restoration strategy is decided on by the control center, but restoration actions are conducted through the FRTUs. If the restoration strategy can be decided and stored before a fault at the FRTUs, more rapid restoration action will be possible as shown in Fig. 3(b). This scheme involves communication among the FRTUs. The concept of the MAS needs to be introduced into the distributed system for fault section isolation and restoration by the FRTUs themselves.

B. Multiagent System for Power Engineering Applications

The concept of multiagent was defined first through computer engineering and there are many opinions about the definitions

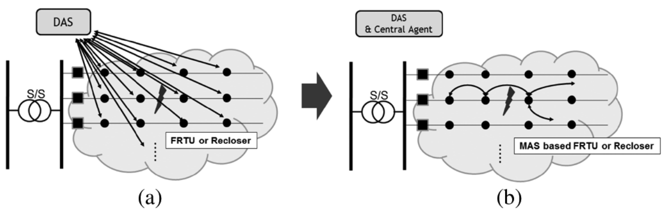

Fig. 3. MAS-based distributed restoration concept.

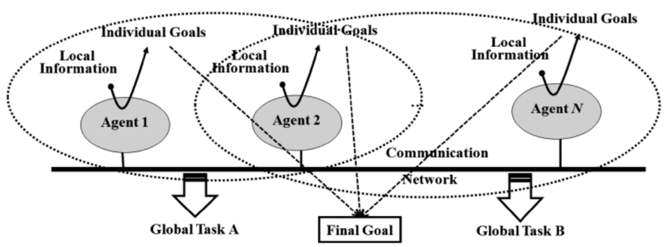

Fig. 4. Final goal in the complete concept for the multiagent system.

of the terms "agent" and "multiagent". Similarly, many investigations have been made about the definition application of the use of the agent concept in a power system.

The IEEE Power Engineering Society's (PES) Intelligent System Subcommittee (within the PSACE Committee) has formed a Working Group to investigate these questions about the use of multi-agent systems.

An agent concept is defined by Wooldridge as "a software (or hardware) entity that is situated in some environment and is able to autonomously react to changes in that environment [15]." An intelligent agent concept emphasized a flexible autonomy and had the three characteristics of reactivity, proactiveness, and social ability. Each characteristic is defined as follows:

- Reactivity: an intelligent agent is able to react to changes in its environment in a timely fashion, and takes some action based on those changes and the function it is designed to achieve.
- Proactiveness: intelligent agents exhibit goal-directed behavior. Goal-directed behavior connotes that an agent will dynamically change its behavior in order to achieve its goals.
- Social ability: intelligent agents are able to interact with other intelligent agents. Social ability connotes more than the simple passing of data between different software and hardware entities, something many traditional systems do.

In this paper, MAS is defined simply as a system comprised of two or more agents or intelligent agents, as defined by the research results of the PSACE Working Group [9], [10]. The basic components for applying the MAS to a power system are a platform design, database standardization, P2P-based communication, and network security [10].

C. Requirements for Applying the MAS to a DAS

Why is the DAS the easiest target for applying the MAS among all of the different parts of the power system? The reason is that the DAS already has many of the basic components which are necessary for an MAS-based system environment.

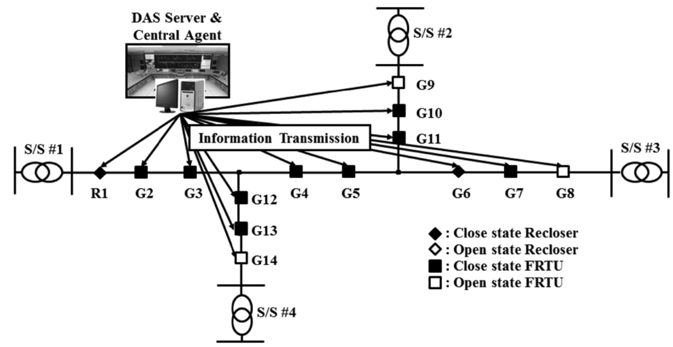

Fig. 5. Information transmission from the central agent to terminal agent.

The MAS-based system requires proactive action using three characteristics of MAS for an environmental change, mutual cooperation, and self-judgment. The system should be able to use P2P communication because these three characteristics are reflected throughout all system information. Also, the FRTUs must cooperate closely with the control center when special circumstances occur that are difficult for the FRTUs to judge.

Furthermore, because of the complexity of the power distribution system operations, the DAS operating efficiency should be considered. Compared to the structure of the distributed system or the centralized system, the MAS-based distributed system structure can actively deal with a variety of environmental changes to get maximized efficiency from the complex power distribution system.

Accordingly, in particular, MAS application research is being considered and applied more positively to situations where the system structure has become more and more complex, such as a smart grid and a micro-grid in conjunction with distributed generators. Thus, the concept of the MAS applied to a DAS can be the most suitable technique for adopting the MAS into power systems. Among all the functions of a DAS, the restoration system is considered as the most suitable area to realize the application of the MAS with high efficiency.

III. Multiagent-Based Distributed Restoration System Algorithm

A. Preparation for MAS-Based Distributed Restoration

The MAS-based distributed restoration system that is proposed in this paper consists of a central agent and several terminal agents. The central agent has the role of providing necessary information and transmitting restoration strategies to the terminal agents to produce an active restoration under fault conditions. The terminal agent has the role of obtaining information from the central agent and from the other terminal agents and then performing the restoration directly.

The reliability of an action is considered the most important element in a distributed system. So in order to guarantee reliability, the central agent must transmit a restoration strategy and necessary information to the terminal agents as shown in Fig. 5.

At this time, the most important feature is a restoration strategy that decides which switch should be opened or closed. With the concept of the MAS and through information exchange among the terminal agents, the terminal agents are capable of solving any problem through cooperation with the other terminal agents.

However, for making restoration strategies, it needs all available system information. It is also difficult to verify the reliability of the restoration strategy made by the terminal agents. Research reposted in this paper, is concerned about the application of this system in the field, the proposed restoration strategy of the distributed restoration system uses a model where the control center of a DAS makes a restoration strategy using rules [1], [2].

In the system structure proposed above, the terminal agent is located between the FRTU (or the recloser) and the control center. So, the terminal agent can monitor and judge the system state from transmitted information between the FRTU (or the recloser) and the control center. If it's instructed to act by itself, it would dynamically collect the required information, give suitable commands to the switches, and send commands to other terminal agents to perform restoration.

B. Algorithm for MAS-Based Distributed Restoration

The algorithm is based on the concept that terminal agents accomplish restoration through cooperation with other terminal agents without commands of the central server in a DAS. This algorithm consists of two parts: fault section detection and isolation, and restoration.

For distributed restoration, accurate and rapid fault section detection and isolation must be fulfilled prior to restoration action. If a fault occurs on a power distribution line, fault current would flow from source to fault location. With the fault location, MAS-based FRTUs of the source side would detect a fault current but other MAS-based FRTUs of the load side would not measure a fault current. At this time, the MAS-based FRTUs obtain information about which of the FRTUs have detected a fault current or not using mutual communication. If an MAS-based FRTU has detected a fault current and an MAS-based FRTU of the load side could not measure a fault current, the MAS-based FRTUs can recognize that a fault occurred between the two MAS-based FRTUs. After recognizing fault section and a position from a fault location, the MAS-based FRTUs open their switches for separating fault section from the power distribution system.

Next, the MAS-based FRTU of the source side sends close command to the protection device as a recloser or OCR which covers a protection of its area. The MAS-based FRTU of the load side should perform restoration by a received restoration strategy from the DAS server. At first, the MAS-based FRTU sends open commands according to the restoration strategy for dividing the blackout load. Then, the MAS-based FRTU transmits close commands for supplying power to the blackout area.

A restoration in DAS environment is accomplished by the section unit between automatic switches. So a restoration strategy for a fault at a section can be determined and stored in the DAS server before a fault occurrence. Restoration strategies are used by the MAS-based FRTU of the load side and the FRTU would be the main agent for restoration. Depending on the characteristics of the MAS-based DAS, the terminal agent performs its role as the heart of the restoration through confirmation of the system operating state, fault section detection, fault section isolation, and restoration.

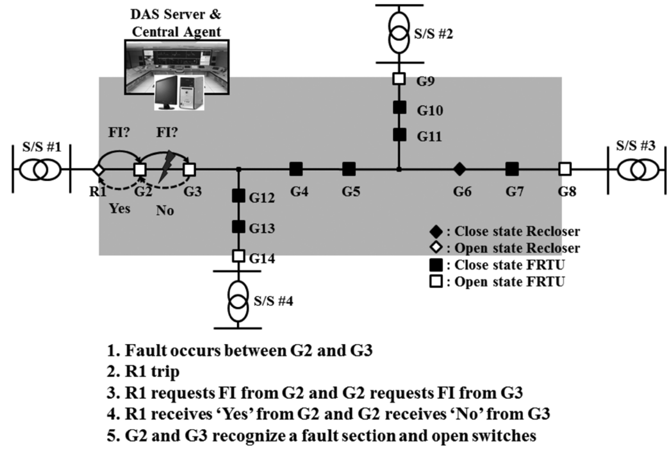

Fig. 6. MAS-based fault section detection in the proposed system.

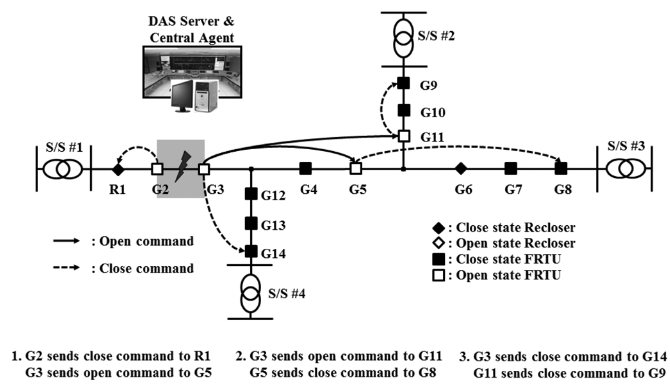

Fig. 7. MAS-based distributed restoration process in the proposed system.

For further understanding, the algorithm is explained using examples. In Fig. 6, R is a Recloser and G is an automatic switch. If a fault occurs between G2 and G3, R1 in the faulted feeder would trip the CB after reclosing and it'll cause a blackout in the R1-G9-G8-G14 areas. Here, R1 and G2 experience a fault current so a FI is generated at the two locations. But, the load side of the fault location on the faulted distribution line does not experience a fault current so their FI is not generated from G3 to the load side after a fault occurrence. The R1 and G2 immediately request about the fault current experience to the next terminal agent on the load side of the distribution line, R1 will get the information that G2 experiences a fault current, and at the same time, G2 will get a response from G3 that it did not experience a fault current. Therefore, G2 and G3 can know that the fault occurred in the section between them, and opened their switches to isolate the fault section.

Since only the source side of G2 was tripped by R1, it could be restored by giving a close order to R1. The outage loads on the load side of G3 could be restored by the restoration strategy of ordering a switch to open/close for the purpose of dividing the blackout load suitably and supplying power to the blackout area through a connection with other feeders. To prevent a multi-source operating condition, G3 first requests G5 and G11 to open their switches. After G5 receives the open com-

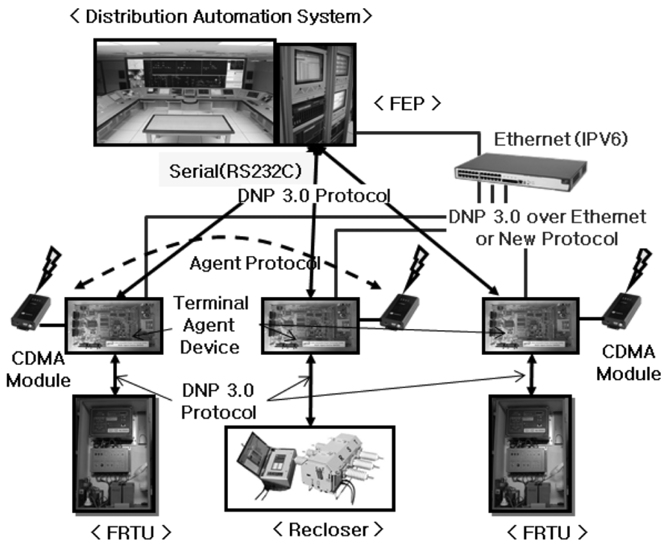

Fig. 8. Proposed system structure with terminal agents.

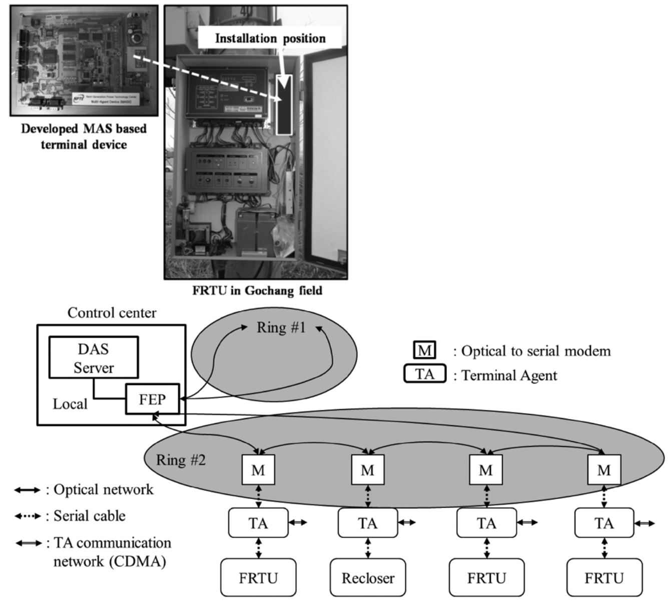

Fig. 9. MAS-based terminal agent device installation in the GPTC.

mand and makes sure the switch status is open, it will give G8 a command to close. Similarly, G11 will give a close command to G9. And G14 will give a close command to complete the restoration. These restoration schemes are a typical application case using the three main characteristics of the MAS, first small goals are completed, and then, finally, full restoration can be accomplished.

IV. Implementation of the Multiagent-Based Distributed Restoration System in DAS

A. MAS-Based System Design for the Implementation of the Proposed System

The advantage of the system proposed in this paper is that the concept of MAS can be directly applied into the restoration function of a currently operating DAS without changing the hardware and software. The terminal agent device was designed to realize the proposed system without changing the currently operating DAS. The structure of the proposed system with the designed terminal agents is illustrated in Fig. 8. The function of the terminal agents, installed in Fig. 9, is to get system information from the central server and the terminals. Fig. 9 shows the real installation position of terminal agent in an FRTU in the field. Terminal agent can determine the network condition by analyzing of a message from FRTU to DAS server. Also, the terminal agent in Fig. 9 has an ability to control its own FRTU.

The protocol structure of the terminal agent to realize this function is shown in Fig. 10. The FRTU (and recloser) has the slave structure of DNP 3.0, and the front-end processor (FEP) of the DAS has the master structure of DNP 3.0. Since the terminal agent has no need to know the messages from the FEP, it is bypassed to the FRTUs through the terminal agents. Messages sent from a slave of the FRTU (recloser) need to be analyzed, and this task is fulfilled by the master of DNP 3.0 of the terminal agent. So the messages are bypassed to the FEP and analyzed

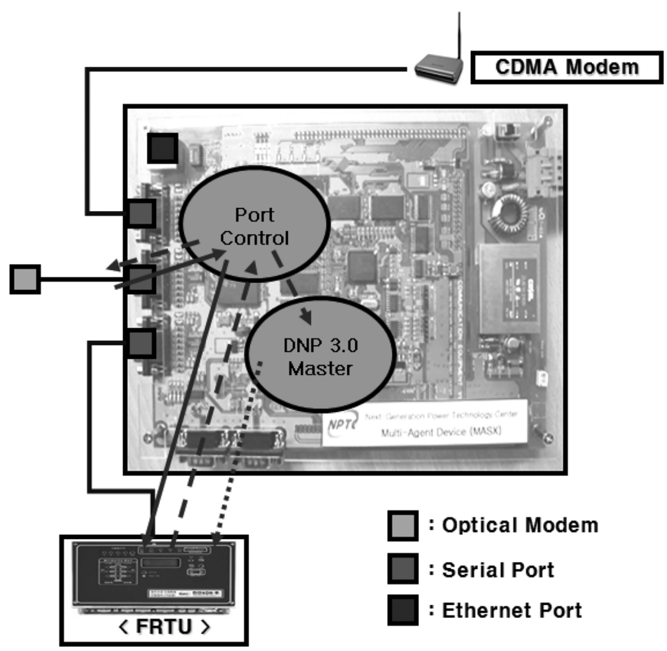

Fig. 10. DNP 3.0-based protocol structure in the terminal agent device.

at the terminal agent–overall, the operating state of the current system does not affect the structure.

Based on the aforementioned structure, the concept of the MAS can be applied directly to a current operating DAS without any changes in hardware or software and distributed restoration can then be accomplished.

B. Algorithm for a Field Operation Problem

The proposed system in this paper can be applied directly in the field. The system structure and all equipment can be prepared for applying the proposed system to the current DAS, but if there are no considerations made about equipment failure or network failure, the proposed system cannot be applied to a field

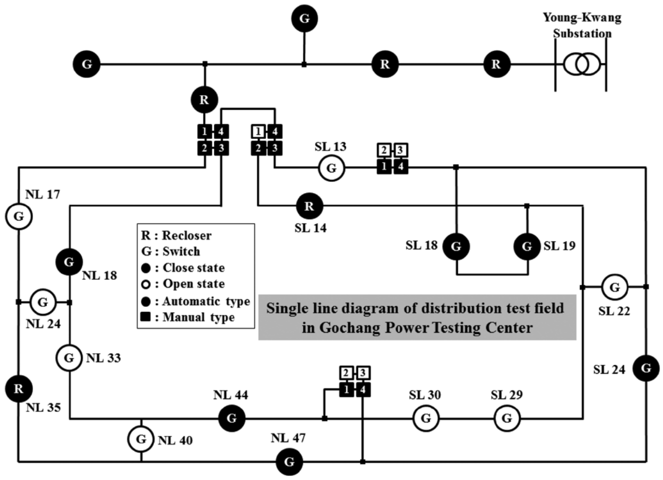

Fig. 11. Single-line diagram of the test power distribution network in GPTC.

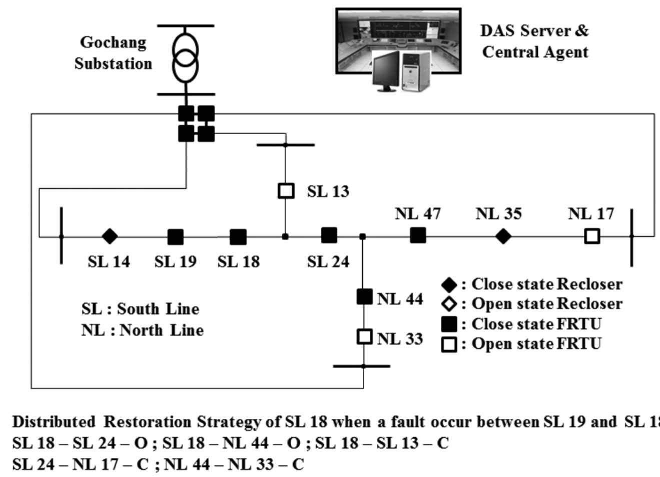

Fig. 12. Single-line diagram of the example network in GPTC.

system. In this paper, an algorithm is proposed to solve potential basic problems in the field using the concept of the MAS.

The most common problem in the field can often be caused by the switches or the failure of FRTUs. If an abnormal event occurs on the FRTU or a relevant switch, the proposed MAS-based system, as well as the existing DAS, cannot resolve the problem remotely. With active usage of the MAS concept and recognition of environmental changes according to its three characteristics, this problem could be solved proactively by a mutual exchange of information.

When a fault occurs on the terminal agent device, a fast and accurate restoration is the most important. Since field device problems are not repaired immediately, in the MAS-based system, they should be solved first through changing the system environment autonomously with the knowledge that the relevant terminal agent does not exist. After this, a more precisely controlled operation can be used to perform a restoration by using the existing DAS. With a fault section isolated, the MAS-based distributed restoration could be accomplished in a few seconds, and the blackout sections can be restored within several minutes using existing restoration techniques. When an abnormal event occurs in system communication, a backup needs to be ready to allow for the continual use of the current system.

V. Case Study

A. CDMA-Based Test in the Gochang Power Testing Center

The proposed MAS-based distributed restoration system has been tested in the GPTC. The single-line diagram of the GPTC is shown in Fig. 11. Due to its high cost and onerous work for installation of an extra communication network in the test center, the code-division multiple-access (CDMA) communication network was chosen for its easy application among the many wireless networks. A wireless network-based test will need CDMA modems and control technology, since s its signal is already supplied by the wireless communications company.

In order to test the system proposed in this paper, the distribution network in Fig. 11 was operated with the switch status

TABLE I
Comparison of Communication Performance Between Current Restoration of a DAS- and MAS-Based Distributed Restoration

Number	Current restoration	MAS based Distributed Restoration
Start	After fault section detection	After fault occurrence
1	Open SL 19	Fault section detection (check FI)
2	Open SL 18	SL 18 – SL 24 – O SL 19 – SL 14 – C
3	Close SL 14	SL 18 – NL 44 – O SL 24 – NL 17 – C
4	Open SL 24	SL 18 – NL 13 – C NL 44 – NL 33 - C
5	Open NL 44	-
6	Close SL 13	-
7	Close NL 17	-
8	Close NL 33	-

configuration as shown in Fig. 12. The result can be easily indicated by a single-line diagram like a power distribution line as shown in Fig. 12.

As shown in Fig. 12, an artificial fault generator (AFG) was used to generate a single-line-to-ground fault. If the fault occurs between SL 18 and SL 19, a distributed restoration strategy, as given at the bottom of Fig. 12, is transmitted to SL 18 from the central agent in the control center. "SL 18—SL 24—O" means that SL 18 sends an open command to SL 24. This restoration strategy was made in consideration of a complex three-links case in the power distribution system.

The centralized DAS system needs to communicate with a terminal device for a total of eight times for fault section detection and restoration action to occur when implementing the restoration strategy in the bottom of Fig. 12, but the restoration system proposed in this paper just required parallel communication four times in the same situation. Here, parallel communication means A and B communicate with each other while C and D are communicating at the same time as shown Table I.

The flowchart in Fig. 13 shows the process of the proposed system. A central agent (CA) in a DAS server checks the configuration of the power distribution line with terminal agents (TAs). The CA generates information regarding restoration strategy and communication data for each TA. After that, the

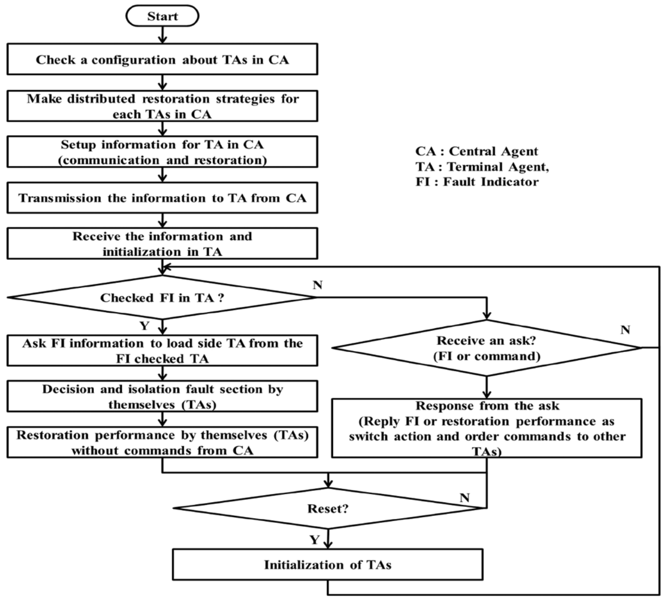

Fig. 13. Process flowchart of the proposed system.

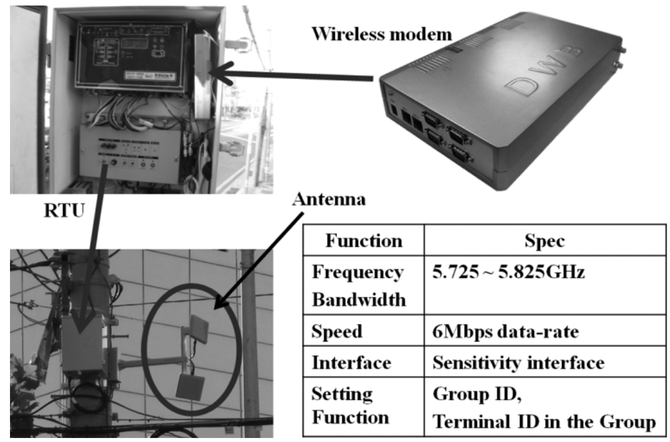

Fig. 14. Specifics of the wireless modem.

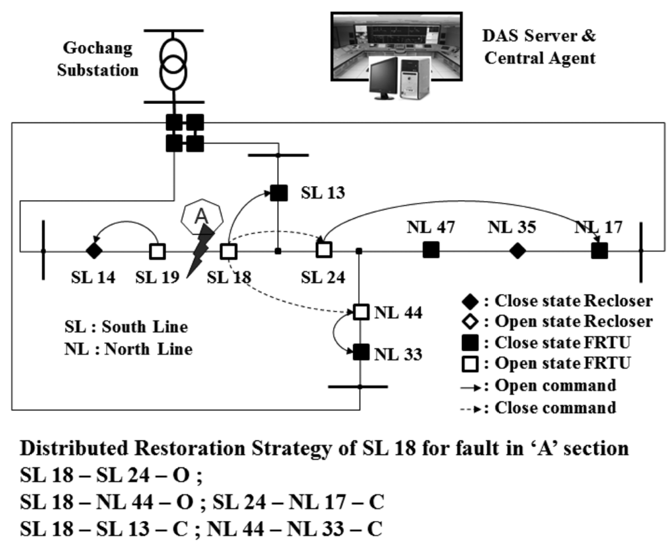

Fig. 15. Test result of the proposed distributed restoration system in the GPTC.

CA transmits the information to each TA. Once the TA receives the information, it starts their initialization. The TAs check FI information. When a fault is detected at a TA, the TA checks for the fault from load-side TA. If the reply is “Yes,” the TA does not take any action. If it is “o”N, the TA and its load-side TA decide that a section between them is faulted, then they isolate the faulted section and the TAs start restoration action. By this process, the field test was accomplished.

The restoration time was measured from the time of fault occurrence until the restoration was done by using a stopwatch at NL 33 because the final switch action according to the restoration strategy was the closing of NL 33 by a command from NL 44.

Although eight switch actions are required for restoration in an existing DAS, the parallel communication methods of the proposed system need only four times because of the distributed structure. The connection and disconnection of the CDMA consumed about 9 s. The time for confirming the switch actions is within 3 s, and considering a 0.3-s time delay for the internal processing time of the FRTUs (and reclosers), the total restoration time was expected to be under 49.2 s.

The average time from the five tests was about 48 s. When compared to the restoration time of 5 min in an existing DAS, the restoration time for the proposed system in this paper can likely be shortened to within 1 min. The test results show that the time for data collection and judgment can be shortened and higher efficiency levels for the power distribution system operation can be achieved if the functions are executed according to the concept of the MAS.

B. Ethernet-Based Test

The CDMA is an inefficient communication method with extremely low reliability, but in this paper, it has to be adopted because of the special communication environment of the GPTC. The application of Ethernet-based communication networks will be a trend in the future, so in this paper, an Ethernet-based wireless local-area network was also used for testing the proposed system in the field.

The specifics for the wireless modem, which completed the field test in the real system and were used in the test of the Ethernet-based proposed system, are shown in Fig. 14. The Ethernet-based test was performed in the same environment and scenario as the CDMA-based test in Fig. 15. The restoration time was measured by the Ethernet network at the central server of the distributed restoration system.

With consideration of the Ethernet communication time being approximately within 0.1 s, the time required to confirm after switch actions being within 3 s and an internal processing time within 0.3 s, this result is fast enough that the complete restoration time will take approximately 13.6 s. The average time after the test was run five times was 10.5 s for fault section detection and restoration. If the time for switching and confirmation can be shortened, the restoration time will be reduced even further.

VI. Conclusion

The current DAS is an efficient system for improving operating efficiency of power distribution systems and promoting power-supply reliability. Restoration is the most important function of a DAS in increasing system efficiency and current restoration by the DAS needs about 5 min. The control center needs to receive all of the information, make restoration strategies, and then send commands one by one to the terminals so a restoration time of several minutes is needed.

Accordingly, in this paper, an MAS-based distributed restoration system is proposed. The proposed distributed restoration system is based on the MAS configured by a central agent and terminal agents. Making good use of the characteristics of the MAS, such as its social ability, reactivity, and proactivity, faster restoration could be performed effectively in a distributed way instead of a centralized form.

The proposed system was tested at the GPTC. The average restoration times of the CDMA and Ethernet environments were 48 s and 10.5 s, respectively, including time for switching and confirmations.

As discussed in this paper, a possible method for using the concept of the MAS has been applied to the power system operation in an existing power system. The application of the MAS is no longer a problem and an MAS-based operating era could be just around the corner. The system proposed in this paper was applied to an intelligent distribution-management system (IDMS) which was upgraded from a DAS, and prepared for the practical applications within KEPCO.

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