Application Notes

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A Fully Decentralized Multi-Agent System for Intelligent Restoration of Power Distribution Network Incorporating Distributed Generations

I. Introduction

In the distribution network fault management, service restoration is a very important component. When a fault occurs, it is necessary to restore power to these deenergized loads as soon as possible. The restoration problem could be formulated as a multi-level, multi-objective optimization problem with constraints [1].

Generally, the approaches to study service restoration in distribution system can be roughly grouped into two categories: centralized methods and distributed methods. Centralized methods include heuristic approaches [2], [3], expert systems (ESs) [4], [5], and mathematical programming (MP) [6], while distributed methods are mainly based on multi-agent system (MAS) technology. The major limitation of centralized methods is that these approaches normally depend on a powerful central facility to handle extremely large amount of data with high communication capability requirement, therefore such approaches tend to lead to single point of failure. To this end, distributed methods such as agent-based approaches have received significantly increased attention recently in the community to handle the complex power system research and development [7]–[12]. For instance, the Foundation for Intelligent Physical Agencies (FIPA) [13] is an IEEE standard organization that promotes the agent-based technology and compatibility with other technologies. It defines many issues pertaining to agents, such as high-level architecture, agent usage, agent communication, agent management, among others.


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In this paper, we focus on the agent-based method for service restoration problem with the integration of DGs. Amongst the many efforts of using agent-based approaches to support the smart grid development, it has been recognized that service restoration problem is an important issue. For instance, load restoration problem of shipboard power system using multi-agent system were studies in [14]–[17]. Nagata et al. proposed a multi-agent system for service restoration of distribution systems [18]–[21], where a special agent was designated to dispatch and manage other agents for the whole system. Solanki et al. proposed a fully decentralized multi-agent system to restore the power supply to the de-energized loads, and also developed the interface between MAS and power system simulation software by FIPA compliant language [22].

The impact of DG technology for power system is twofold. On one hand, it could improve the reliability of distribution system. On the other hand, it could also bring negative influence on distribution system restoration. In general, the structure of traditional distribution system is radial. In such networks, the power flow on any feeder is one-way. However, with the integration of DGs into such systems, the power flow on some feeders will become bidirectional. Therefore, large-scale incorporation of DGs in distribution systems has made it increasingly necessary to develop restoration schemes when integrated with DGs [23]. For instance, in

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A fully decentralized multi-agent system based on bus agents (BAs) is proposed to tackle the complex distribution system restoration problem.

[24], the authors proposed a multi-agent system based on P2P communication mode and applied the contract network protocol (CNP) to the negotiation process between agents. The parameters of CNP are optimized by a genetic algorithm (GA). In [25], the authors adopted a spectral clustering algorithm to partition a large distribution network into logically related clusters, and used agents to manage these clusters.

However, the multi-agent systems proposed in the afore mentioned research are not fully decentralized or are not appropriate for complex distribution systems. In this work, we propose a fully decentralized multi-agent system based on bus agents (BAs) to tackle the complex distribution system restoration problem. Our approach uses a depth-first communication mechanism (DFCM) for effective and efficient information exchange among agents. In brief, the proposed multi-agent system has the following characteristics.

1) The system is able to handle service restoration of complex distribution system with DGs. The agents can constitute island system flexibly under different fault conditions.
2) The system can provide restoration strategies without considering the initial topology of the distribution network. Therefore, it can effectively handle cascading failure and enhance system reliability.
3) The system is fully decentralized, enabling a high degree of scalability for different distribution network topologies.

The rest of this paper is organized as follows. Section II presents a brief introduction to agent and multi-agent system. Section III describes the formulation of restoration problem of distribution system. The restoration MAS framework is presented in detail in Section IV. Finally, the feasibility and performance of the proposed MAS is demonstrated on a complex distribution network in Section V, and a conclusion is given in Section VI.

II. Agent and Multi-Agent System

There is no precise definition of agent at present. Artificial intelligence (AI) researchers generally consider an agent as a form of entity with sensing, decision making, and actuation capabilities [26]. In this article, an agent has all the above characteristics, where it can collect data and make effective decisions according to the sensory information.

Multi-agent system is an extension of the agent technology where a group of loosely connected autonomous agents act in an environment to achieve a common goal [27]. Through a composed agent's behaviors, an MAS is capable of providing different design benefits such as parallelism, robustness, scalability, geographic distribution and cost effectiveness [28] [29]. In MAS, each agent merely collects local information, while communicating with other agents to realize information sharing. The task can be divided into a series of simple subtasks, and then be assigned to different agents. A multi-agent system has the following advantages over a single agent or a centralized approach:

1) The centralized system, requiring a powerful central computer, may lead to a single point of failure. The whole system would be out of control once the central computer is down. The MAS does not suffer from the single point of failure problem since it is decentralized; therefore significantly increasing the system's reliability and security.
2) The MAS can improve system efficiency because of its parallel computation and asynchronous operation.
3) The MAS has a high degree of scalability and flexibility, as such agents can be added or removed as needed.

In this paper, the multi-agent system is implemented using JAVA agent development environment (JADE). Following the FIPA specifications, the JADE is a middleware for the development of multi-agent system with necessary tools to facilitate the debugging process and to track the actions of the agents. Agents in JADE communicate by message passing, where the messages adhere to ACL (Agent Communication Language) standards. For instance, an ACL message has several attributes such as performative, receiver, sender, content and conversation ID.

III. Distribution System Restoration Model

The objective of the mathematical model of a distribution system restoration is to maximize the supply of power for the deenergized loads, giving priority to vital loads

$$\max \sum_{i=1}^{N} \beta_i x_i L_i, \tag{1}$$

where L_i is the load at bus i, x_i is the decision variable representing its status ($x_i = 1$: restored; $x_i = 0$: not restored), β_i is the weight coefficient associated with the load L_i, depending on its priority, and N is the number of the buses in system.

Typical constraints need to be considered for service restoration of distribution network include [19]–[21].

1) Capacity limitation constraint

$$\sum_{i \in B_j} P_i \le C_j, \tag{2}$$

where C_j is the capacity that bus j can provide, B_j is the set of branches which absorb power from bus j, and P_i is the power flow of branch i.

2) Limits on branch power flow

$$|P_i| \le P_{i\max}, \tag{3}$$

where P_i is the power flow on the branch i, and $P_{i\max}$ is the maximum capacity of branch i.

3) Power balance constraint

$$\sum_{i \in T_j} P_i = \sum_{i \in B_j} P_i + x_j L_j, \tag{4}$$

where T_j is the set of branches injecting power to bus j, B_j is the set of branches absorbing power from bus j, and L_j is the load at bus j.

Constraint on radial configuration without considering DGs

$$\sum_{i \in T_j} \gamma_i \leq 1, \qquad (5)$$

where T_j is the set of branches supplying power to bus j and γ_j is the status of branch i.

IV. Restoration MAS Framework

A. MAS Framework

A detailed description of the proposed multi-agent restoration system is as follow. This system includes only one type of agent: bus agents. This means that each BA in the MAS has a high degree of intelligence to complete task independently. As a completely decentralized approach, these BAs merely use local information. They have no topology information and only neighboring BAs in the system are allowed to communicate with each other.

Figure 1 shows an example of a distribution network and its multi-agent system based on BAs. This distribution system includes 2 substations, 9 buses, 8 transmission lines, 23 switches, 4 loads, and 2 DGs. Bus1 and bus7 are substation buses, representing the connection points with power grid. Line AC8 between the bus4 and bus9 is a tie-line. Switch S23 is a tie-switch; in normal operation it needs to be kept open to ensure the radial structure of the system. The numbers around the loads and DGs are their rate power, while the numbers next to the lines are power flow values. The MAS graph describes the communication paths between BAs and the switches managed by each BA.

In most cases, the local information is not enough for a BA to make decisions. The BA needs to communicate with others to obtain additional useful information. Therefore, it is indispensable to develop an effective communication mechanism for BAs. To this end, this article proposes a depth-first communication mechanism (DFCM) to ensure each BA can obtain necessary information from the others. The DFCM is similar to the process of depth-first search (DFS). Figure 2 details the process of BA1 seeking for DG2 using DFCM. The messages 1, 2, 4, 5, 7 are "query" messages, while the messages 3, 6, 8, 9, 10 are "reply" messages for these queries.

When BA2 receives a "query" message from BA1, it will keep it and extract contents from the message to understand the intention of the sender. Although BA2 has no information about DG2, it will not reply to BA1 directly. Because BA2 has two adjacent BAs besides BA1, it will forward the "query" message to them sequentially to assist BA1 to seek for DG2. Once BA2 gets the information about DG2, it will send the information to BA1 immediately. Otherwise, it will forward the "query" message until it receives all the replies, then it will send the search result to BA1.

For each BA, its adjacent BAs are classified to upstream BA, downstream BA and equal BA according to the power flow relationship. Take BA2 and BA4 for instance. The power is transferred from bus2 to bus4, therefore BA2 is an upstream BA for BA4, while BA4 is a downstream BA for BA2. There is no power transmission between bus4 and bus6, so they are equal BAs for each other.

B. Process of Service Restoration

The proposed service restoration procedure in this paper composes three steps, as shown in the Figure 3.

1) Step 1: Update Information After Fault

After fault isolation, the system may be split into several sub-systems. We classify these subsystems to S region, R region and T region according to the power flow relationship, as shown in Figure 4. The S region is the power supply side before the fault, while the R region is the power demand side. If the fault occurs on a line that has no power transmission, the system will then be split into two T regions. For the three regions, if they are connected with the power grid, we call them S-1, R-1, and T-1, otherwise, we call them S-2, R-2, and T-2.

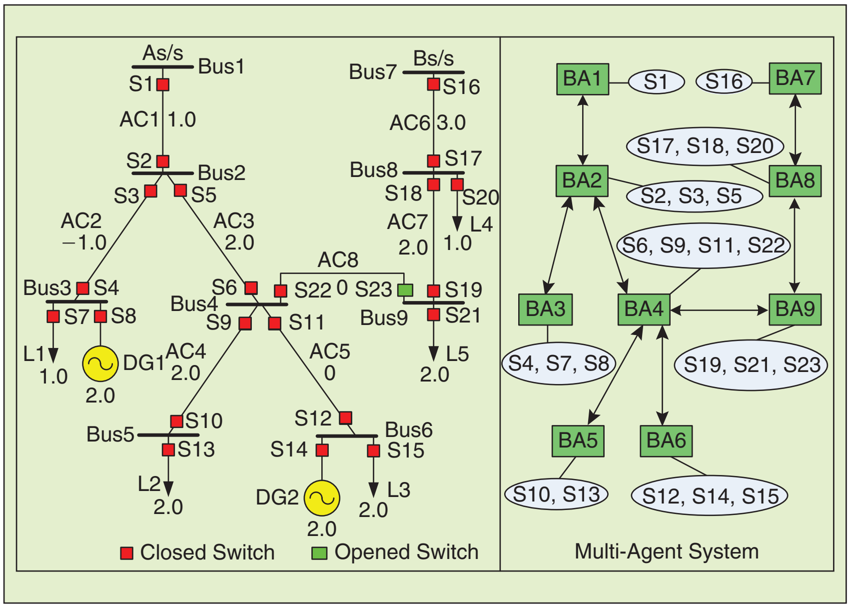

FIGURE 1 Example of distribution network and its multi-agent system.

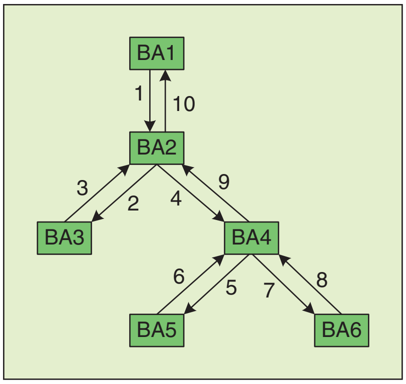

FIGURE 2 Example of the DFCM.

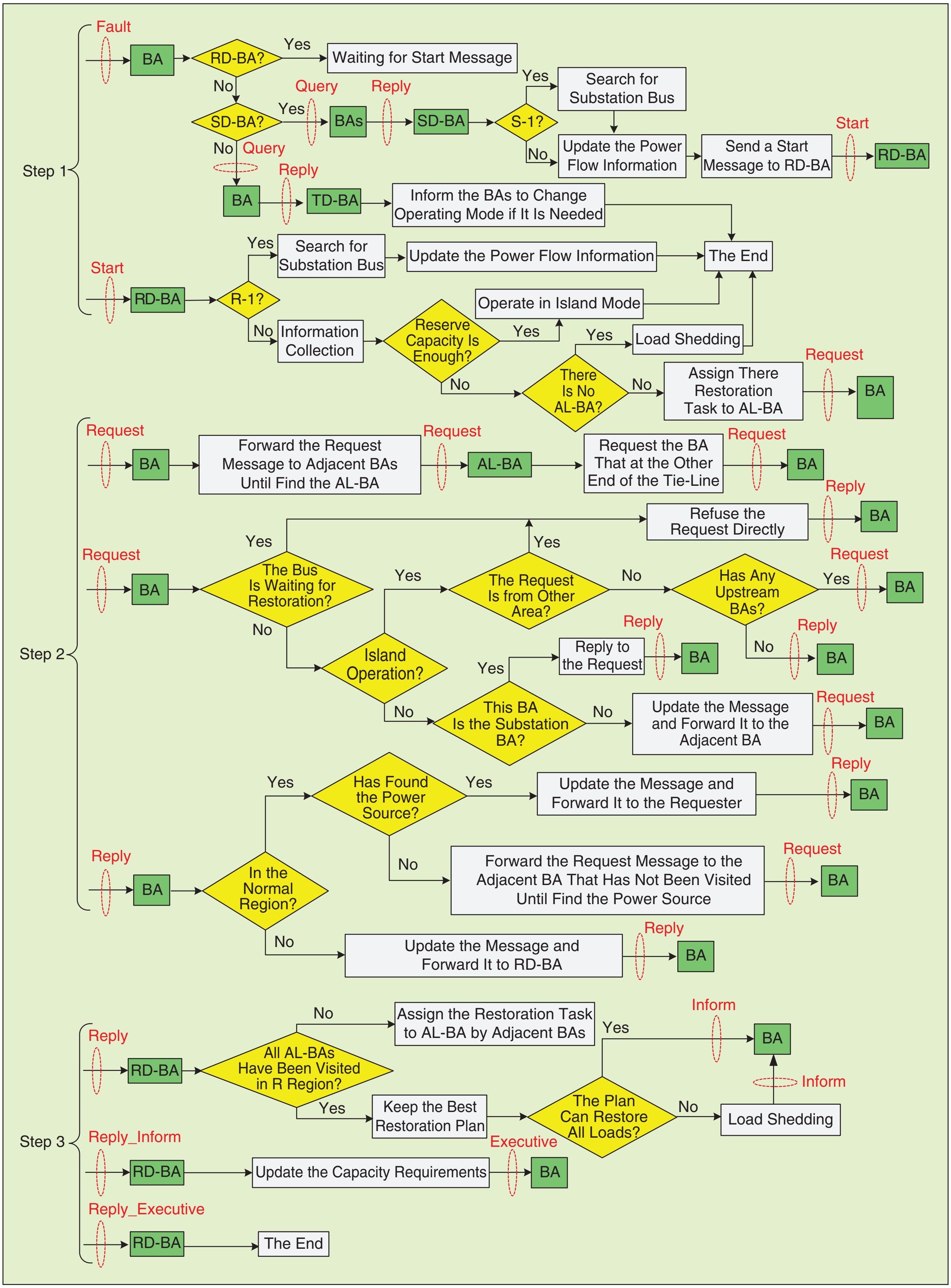

FIGURE 3 The procedure of service restoration.

In this paper, each BA has two operation modes (inter-connected mode and island mode) and three states (normal operation state, waiting-for-restoration state and de-energized state). In the restoration process, we designate a leading BA for each region and the BAs connected with the fault line will take on this role. In this article, the leading BAs of the three regions are called as SD-BA, RD-BA, and TD-BA, respectively. When the BA leader receives any fault information, it will firstly judge the region type (S, R or T), then take action according to its region type.

In step 1, SD-BA needs to complete two tasks by communication. One is to confirm whether the S region is connected with the power grid, and the other is to inform other BAs in the S region to update power flow information and operation mode. After that, SD-BA will send a "start" message to RD-BA.

The "start" message contains information about S region, based on how the RD-BA judges the region type (R-1 or R-2). If the region type is R-1, RD-BA just needs to find out the substation BA and inform other BAs to update information. Otherwise, it needs to communicate with others by taking the following actions:

- If there are some standby power in the R region, it will inform the relevant BAs to put them into use.
- Collect the information of loads and AL-BAs (i.e., the BAs that have alternate line) in R region.
- Update the capacity requirement of R region.

It's important to note that the excess power of DGs involved in this article can be outgoing, and all DGs have the ability of voltage and frequency regulation. Therefore, the BAs can establish island systems flexibly if it meets the capacity constraint.

When fault occurs on a line without power transmission, the power supply of the two T regions will not be affected. However, the BAs' operation mode may be changed. In this way, the TD-BA just needs to inform the others to up-date the power information and change operation mode if necessary.

2) Step 2: Search the Restoration Path

The procedure of service restoration can be described as the process of RD-BA seeking restoration path by communication with other BAs.

Generally, the power supply of R region is restored by closing some tie-lines. Therefore, the AL-BAs play an important role in restoration path searching. RD-BA will assign restoration task to AL-BAs in R region by "request" message and wait for "reply" message one by one. If there are more than one AL-BA in R region, RD-BA will receive more than one restoration schemes accordingly. It will choose to keep the best one according to the evaluation function as follows:

$$\begin{aligned} F = {} & \lambda_1 \cdot C - \lambda_2 \cdot S \\ & + \lambda_3 \cdot M - \lambda_4 \cdot B, \end{aligned} \qquad (6)$$

where C is the capacity which can be restored, S is the cost of switching operation, M is the margin of transmission

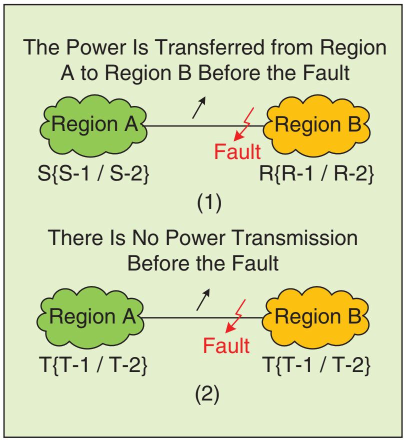

FIGURE 4 The regions caused by fault.

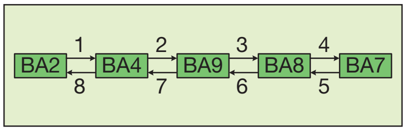

FIGURE 5 The process of seeking for restoration path.

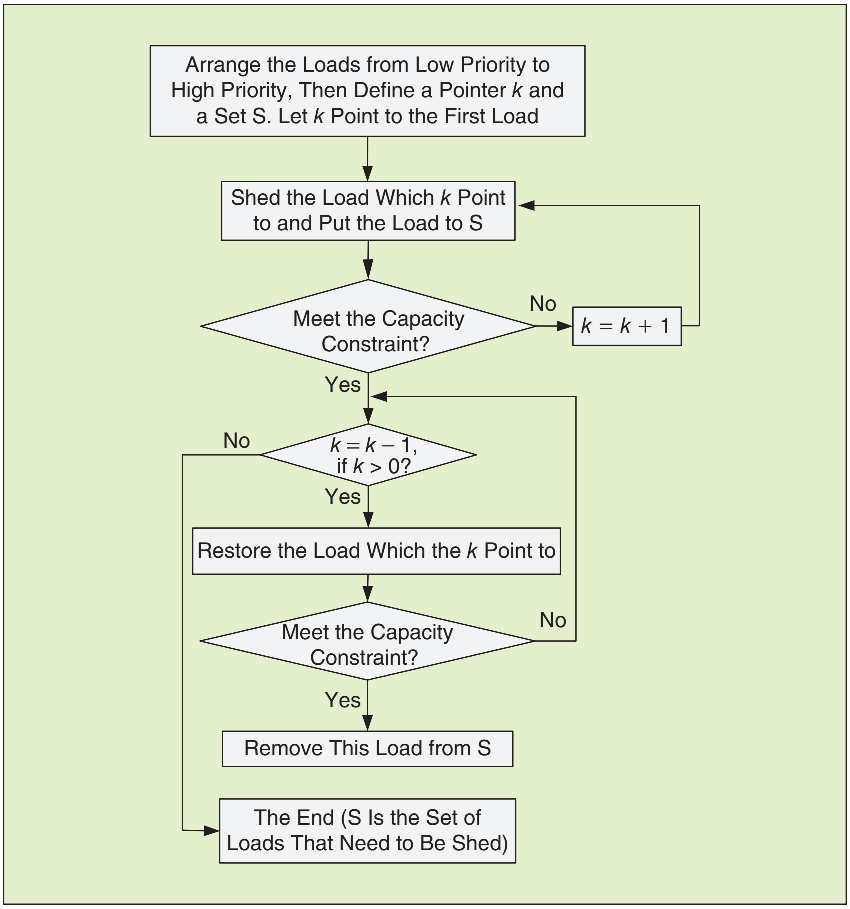

FIGURE 6 The flowchart of load shedding.

TABLE 1 Types of messages exchanged between agents.

MESSAGE TYPE	RECEIVER	THE PURPOSE OF THE MESSAGE
T.QUERY	THE ADJACENT BAs	SEARCH FOR SUBSTATION BA.
T.REPLY-QUERY	THE SENDER OF "T.QUERY" MESSAGE	REPLY TO THE "T.QUERY" MESSAGE.
T.INFORM	THE ADJACENT BAs	INFORM THE BAs IN T REGION TO UPDATE OPERATION MODE.
T.REPLY-INFORM	THE SENDER OF "T.INFORM" MESSAGE	REPLY TO THE "T.INFORM" MESSAGE AFTER UPDATING.
START	THE RD-BA	INFORM RD-BA TO WORK.
S.QUERY	THE ADJACENT BAs	SEARCH FOR SUBSTATION BA AND UPDATE THE POWER FLOW INFORMATION.
S.REPLY-QUERY	THE SENDER OF "S.QUERY" MESSAGE	REPLY TO THE "S.QUERY" MESSAGE.
S.INFORM	THE ADJACENT BAs	INFORM THE BAs TO UPDATE THE POWER FLOW INFORMATION.
S.REPLY-INFORM	THE SENDER OF "S.INFORM" MESSAGE	REPLY TO THE "S.INFORM" MESSAGE.
R.QUERY	THE ADJACENT BAs	QUERY FOR THE RESERVE CAPACITY, LOADS AND AL-BAs.
R.REPLY-QUERY	THE SENDER OF "R.QUERY" MESSAGE	REPLY TO THE "R.QUERY" MESSAGE.
R.INFORM	THE ADJACENT BAs	INFORM THE BAs TO UPDATE INFORMATION.
R.REPLY-INFORM	THE SENDER OF "R.INFORM" MESSAGE	REPLY TO THE "R. INFORM" MESSAGE.
R.REQUEST	THE ADJACENT BAs	REQUEST FOR RESTORATION.
R.REPLY-REQUEST	THE SENDER OF "R.REQUEST" MESSAGE	REPLY TO THE "R. REQUEST" MESSAGE.
R.EXECUTIVE	THE BAs THAT IN THE RESTORATION PLAN	INFORM THE BAs IN THE RESTORATION PLAN TO EXECUTIVE.
R.REPLY-EXECUTIVE	THE SENDER OF "R.EXECUTIVE" MESSAGE	REPLY TO THE "R. EXECUTIVE" MESSAGE.

lines, B is the number of bus in the restoration path, and $\lambda_1 - \lambda_4$ are the weight coefficients.

In the proposed approach, restoration path is consisted of a set of buses. Suppose there is a fault occurring on AC1 in Figure 1. After fault isolation, RD-BA (BA2) assigns the restoration task to an AL-BA (BA4) and receives a restoration scheme (bus2, bus4, bus9, bus8, bus7) at last. The communication process is shown in Figure 5.

In Figure 5, the messages 1–4 are "request" messages, while 5–8 are "reply" messages. When a BA receives a "request" message, it will revise the message content based on the power limit of relevant branches. The modification rule is to select the smaller one to be the new capacity requirement from the transmission line power margin and the capacity requirement in the "request" message. When a BA receives a "reply" message, it will update the F value of the restoration scheme according to local information.

When a BA in R region receives a "request" message, it will forward the message to its adjacent BAs because of its waiting-for-restoration state. When a BA in normal region receives a "request" message, it will revise and forward the message to its adjacent BAs by priority until the message is sent to a substation BA. In this process, the upstream BAs have the highest priority, equal BAs have the middle priority, while downstream BAs have the lowest priority.

In an island system where the power is provided by DGs, there is normally not enough reserved capacity. In this case, when a BA in an island system receives a "request" message from other regions, it will reject the request directly. Every BA will select the best scheme from all the received "reply" messages, update the F value, and then forward it to the requestor until it is sent to RD-BA.

3) Step 3: Execute the Restoration Task

If the best restoration scheme can meet the capacity requirements, RD-BA will inform all BAs involved in the scheme to execute restoration task, while updating power flow information. Otherwise, RD-BA has to shed some loads by priority to meet the capacity constraint.

The primary principle of load shedding is to ensure the power supply of these high priority loads first, and to try to avoid large loss of power. The flowchart of load shedding, as shown in Figure 6, describes the process in detail. Once the scheme of load shedding has been determined, RD-BA will send "inform" messages to the relevant BAs to shed loads, then recalculate the capacity requirements and meanwhile send "executive" message to the BAs included in the final restoration scheme. The whole restoration process is completed when RD-BA receives the "reply-executive" message.

The details of all the messages proposed in this article are presented in Table 1.

V. Result

A. Description of the Test System

In order to demonstrate the effectiveness of the proposed approach, a test system is developed in this work. This network consists of two substations (As/s, Bs/s), 14 buses, 16 transmission

TABLE 2 Capacity of the components in test system.

LINES	MAXIMUM CAPACITY	GENERATORS/ LOADS	RATED CAPACITY
AC1	10.0	DG1	2.0
AC2	10.0		
AC3	10.0	DG2	1.0
AC4	10.0		
AC5	5.0	DG3	2.0
AC6	5.0		
AC7	5.0	DG4	2.0
AC8	5.0		
AC9	3.0	L8	2.0
AC10	3.0	L6	1.0
AC11	3.0	L1	1.0
AC12	3.0	L5	2.0
AC13	10.0	L4	2.0
AC14	4.0	L7	2.0
AC15	4.0	L2	1.0
AC16	4.0	L3	1.0

lines (AC1-AC16), 40 switches (S1-S40), 4 tie-switches (K1-K4), 8 loads (L1-L8) and 4 DGs, as shown in Figure 7. In the system, lines AC13-AC16 are tie-lines. All the DGs have the ability to operate independently. The numbers in brackets are the maximum transmission capacity of the related lines, and the other numbers are the rated capacity of the DGs and loads.

The component parameters of the test system are illustrated in Table 2. The loads in this table are arranged from high priority to low priority (i.e., the load with the highest priority is L8, while with the lowest priority is L3.)

B. Simulation Results

To verify the effectiveness of the proposed approach, a large number of simulations on the test distribution system have been developed under different fault conditions. Due to space constraints, we are only demonstrating three typical examples: island mode test, cascading failures and integration of battery energy storage system (BESS).

1) Island Mode Test

Suppose one fault occurs on AC8. The communication process after fault is shown in Figure 8. FA is a special agent to provide fault information, which will send "fault" messages to the BAs at both ends of the fault line.

Before the fault, there was no power transmission on AC8; therefore, the distribution system is split into two T regions after the fault isolation. The two TD-BAs are BA6 and BA10, respectively. BA6 could find the substation bus via BA4, so it is still connected with the grid (region type T-1). After the query processing, BA10 realizes that this region is disconnected from the power grid, confirming the region type as T-2. Then, it informs all the other BAs in the region to change into island mode. The communication processes of the two T regions are synchronized and the result is shown in Figure 9.

2) Cascading Failures

Here, a cascading failure with 4 faults is analyzed in the distribution system. Suppose 4 faults occur on AC3, AC7, AC5 and AC4 successively. Three steps of communication process about fault 1 are shown in Figure 10 clearly. The distribution system is split into an S region and an R region after fault isolation. In this case, the SD-BA is BA3 and the RD-BA is BA5.

In Figure 10, messages 3–13 represent the updating process of the two regions. The updating of S region is carried out by SD-BA at first. After that, SD-BA sends a "start" message to inform RD-BA to work. By communicating with other BAs in R region, RD-BA obtains the following information:

- ❑ R region has no standby power
- ❑ The loads in R region are L1, L3, L4, L5 and L6

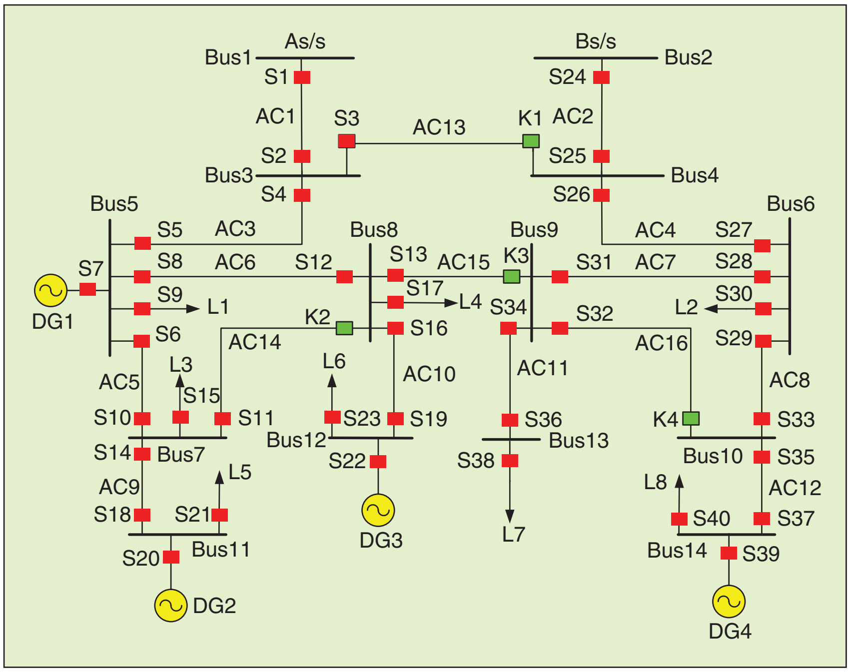

FIGURE 7 The test distribution network.

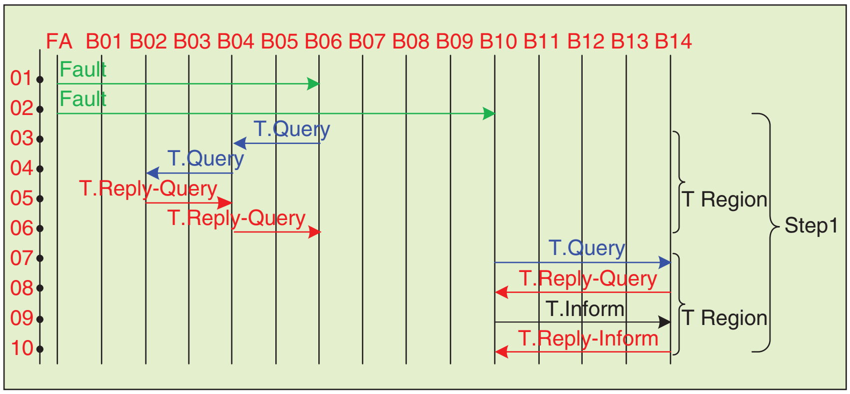

FIGURE 8 The negotiation process of case 1.

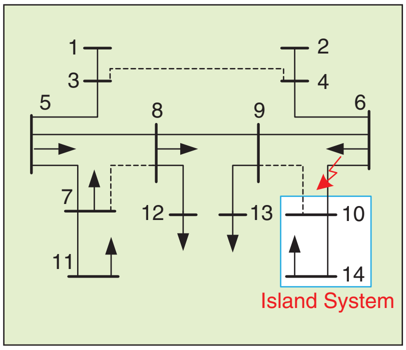

FIGURE 9 The restoration result of case 1.

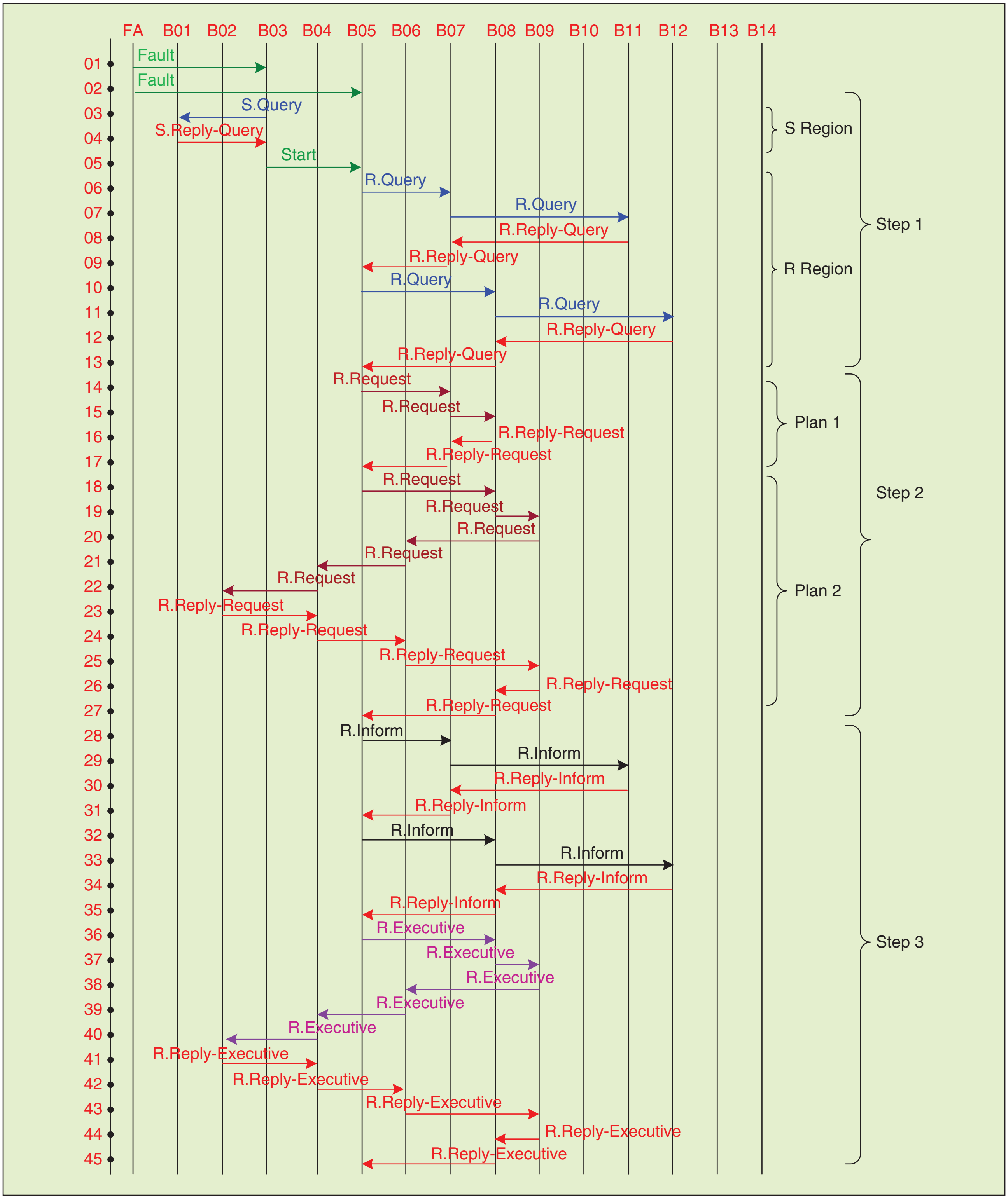

FIGURE 10 The negotiation process of fault 1.

- R region has two AL-BAs: BA7 and BA8
- The capacity requirement of R region is 2 units.

RD-BA assigns the restoration task to BA7 and BA8 in sequence. After receiving the restoration task, BA7 turns to BA8 for help by “request” message. BA8 refuses BA7 directly by message 16, since its state is waiting-for-restoration. In this case, RD-BA receives a restoration scheme provided by BA8 at last. The scheme consists of bus5, bus8, bus9, bus6, bus4 and bus2. It needs to close AC15 to restore all the loads in R region. Then RD-BA informs all the other BAs in R region to change into normal operation state. After that, it notifies the BAs involved in the final scheme to implement the restoration task and update the power flow information.

Restoration results of the cascading failures are shown in Figure 11. The dotted lines represent the opened tie-lines and the red lines represent the lines that need to close after fault. When fault 4 occurs, the capacity requirement of R region is 5 units and there is no way to obtain power supply from other regions. At last, in order to meet the capacity constraint, L3, L4 and L7 are selected to be shed by BAs according to the load priority. Bus5 to bus14 constitute an island power system to supply power to L1, L2, L5, L6 and L8.

3) Integration of Battery Energy Storage System

In this case, a battery energy storage system with two units of capacity is installed on bus7, which can be a standby power for emergency. In order to compare with the original system, the new system is tested under the same cascading failures as shown in case 2. Figure 12 is the restoration results and Figure 13 describes the negotiation process.

After fault 1 occurs, by information collection, BA5 realizes that the capacity of standby power in R region is sufficient. Therefore, it just informs BA7 to put the BESS into service, meanwhile notifying all the other BAs in R region to change into island mode. The negotiation process is described clearly by the messages 3-21 in Figure 13. Finally, bus5, bus7, bus8, bus11 and bus12 change the operation mode into island mode, as shown in Figure 12.

After fault 2 occurs, BA8 receives a "request" message from BA9. BA8 refuses the request directly by message 32, as it is in island mode. As a consequence, AC16 is closed to restore bus9 and bus13.

Before fault 3, there was no power transmission between bus5 and bus7 due to the BESS. The island system is split into two T-2 regions after fault isolation. Since the operation mode is unchanged, these two TD-BAs don't have to inform the other BAs.

After fault 4 occurs, the system needs to shed 3 units of loads. According to the load priority, L2 and L7 are selected to be shed by BA6 and BA13. Due to the BESS, the number of switching operations and the capacity of lost power in this case are less than those in case 2.

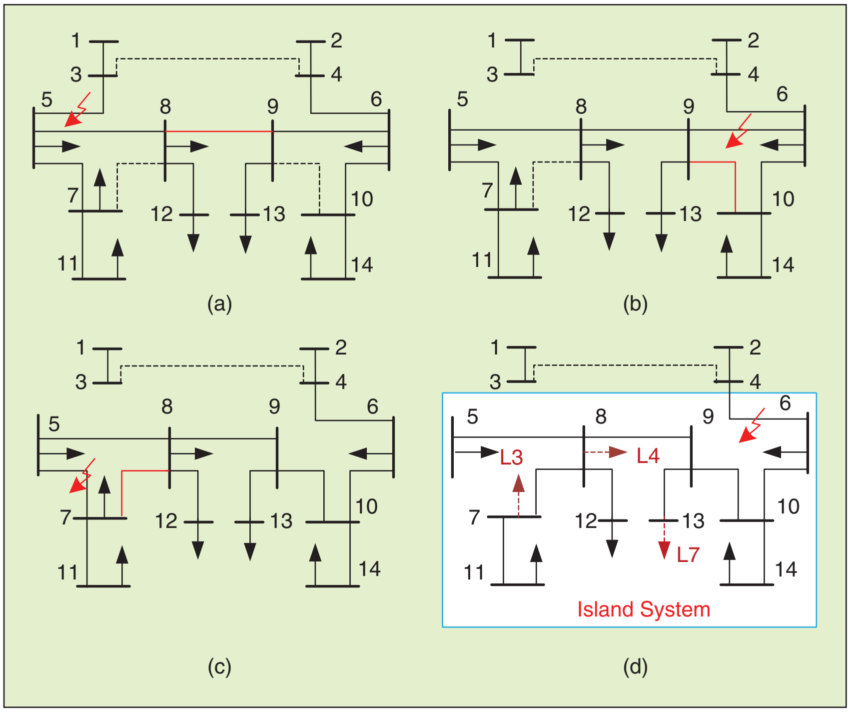

FIGURE 11 The restoration results of case 2.

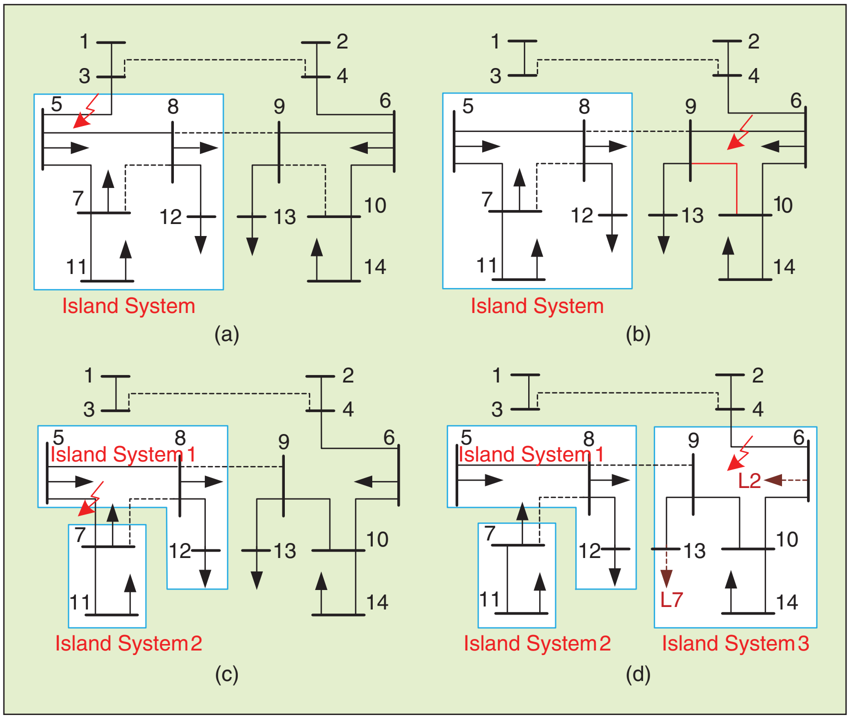

FIGURE 12 The restoration results of the case 3.

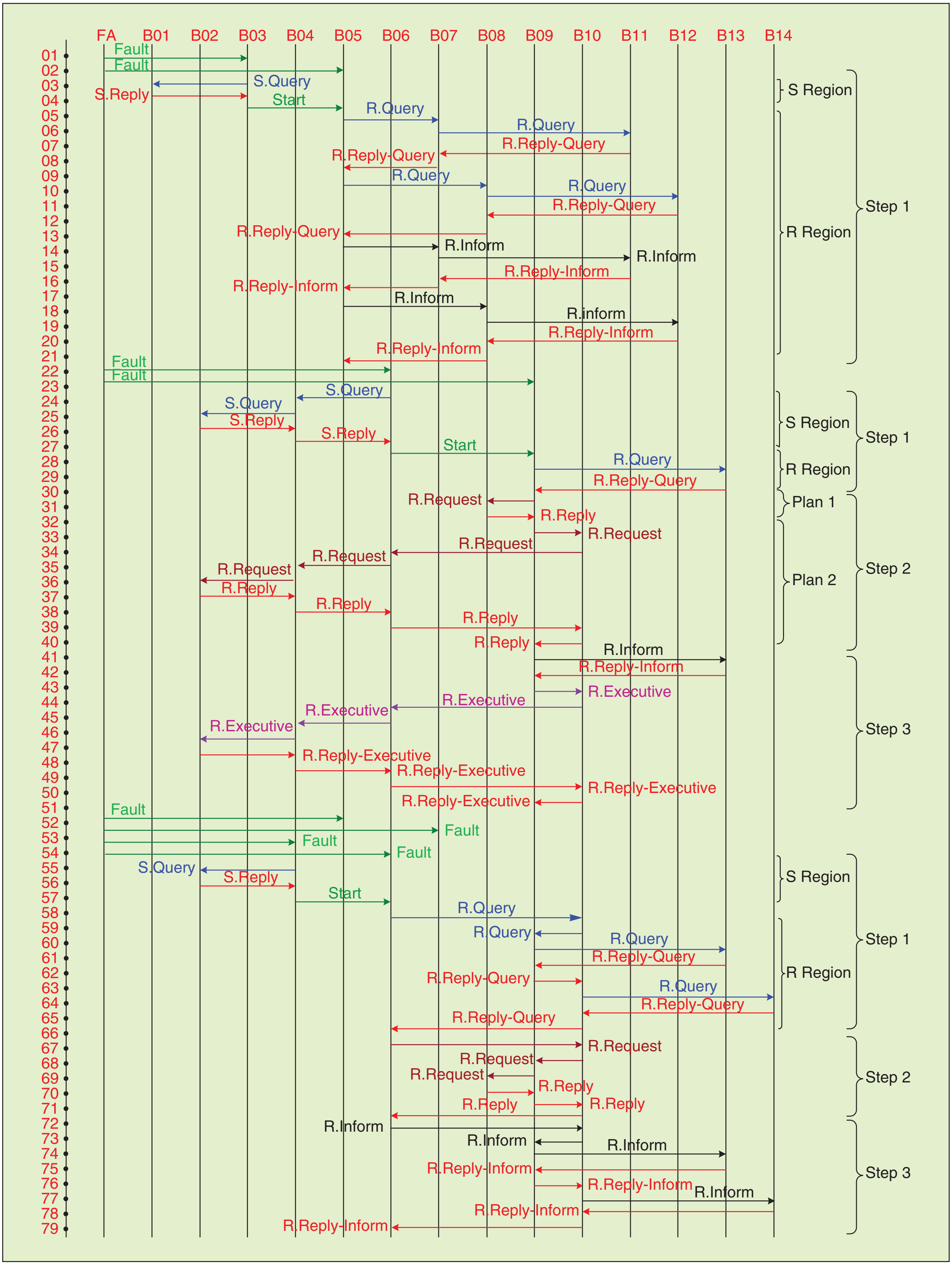

FIGURE 13 The negotiation process of case 3.

> **The proposed MAS system can provide useful solutions to handle the challenging service restoration problem in power distribution network with the integration of DGs… The MAS has the ability to deal with cascading failures to avoid large loss of power.**

VI. Conclusion

In this paper, we propose a fully decentralized multi-agent system approach to tackle the service restoration problem in power distribution network incorporating distributed generations. The proposed MAS includes a number of BAs, which can constitute island system flexibly according to different fault conditions. The MAS has the ability to deal with cascading failures to avoid large loss of power. The effectiveness of the proposed approach has been verified on a test distribution system. Results demonstrate that the MAS can provide restoration strategies for complex distribution networks.

As computational intelligence (CI) techniques have attracted growing attention in the community to support the smart grid research and development, we hope the proposed MAS system can provide useful solutions to handle the challenging service restoration problem in power distribution network with the integration of DGs. We would like to note that in our current work we focus on the analysis of the multi-agent system itself without detailed considerations of the dynamics of DGs. While this is a common assumption for most of the existing literature research on service restoration problem [30] [31] [32], we would like to point out that the dynamics of DGs will also play an important role in such methods. How such agent-based methods will behave with detailed consideration of the DG dynamics will be an interesting and important future research direction. Furthermore, from a practical application point of view, how to bring such multi-agent systems into real power grid to demonstrate their performance will be another critical aspect to bring the essential capability of CI closer to reality in future smart grid. We are currently investigating all these issues and their results will be presented in future studies.

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