A Multi-Agent Approach to Power System Restoration

T. Nagata, *Member, IEEE,* and H. Sasaki, *Member, IEEE*

***Abstract*—This paper proposes a multi-agent approach to power system restoration. The proposed system consists of a number of *bus agents* (BAGs) and a single *facilitator agent* (FAG). BAG is developed to decide a suboptimal target configuration after a fault occurrence by interacting with other BAGs based on only locally available information, while FAG is to act as a manager in the decision process. The interaction of several simple agents leads to a dynamic system, allowing efficient approximation of a solution. Simulation results have demonstrated that this method is able to reach suboptimal target configurations, which are favorably compared with those obtained by a mathematical programming approach.**

***Index Terms*—Agent-oriented programming, Java, multi-agent system, power system, restoration.**

I. INTRODUCTION

WHEN electric power supply interruption is caused by a fault, it is imperative to restore the power system promptly to an optimal target configuration after the fault. The problem of obtaining a target system is referred to as a power system restoration. To obtain the target configuration, various approaches have so far been proposed, which can be roughly classified into four categories: heuristics [1]–[5], [13], expert systems (ESs) [4], [6]–[11], mathematical programming (MP) [11], and soft computing [12]. Heuristics and ESs have been used in industries extensively, but they both have their own deficiency with respect to the optimality of solutions. MP, on the other hand, is able to obtain the optimal solution after the formulation, but it needs some engineering judgment in formulating restoration problems due to its sheer difficulty. Also, its long execution time may sometimes make feel MP in practical considering the time constraints on site. Although soft computing methods are easy to implement, they cannot obtain the optimal solutions in the true sense. Also, they need long computation time until solution.

Currently, agents are the focus of intense attention in many fields in computer science and artificial intelligence. In facts, agents are being used in an increasingly wide variety of applications. Many important computer applications such as planning, process control, communication network configurations, and concurrent systems will be benefited from a multi-agent system approach [14]–[17]. A multi-agent system is a computational system in which several agents cooperate to achieve some task. Multi-agent models are oriented toward interactions, collaborative phenomena, and autonomy.

This paper proposes a multi-agent approach to power system restoration for a local network. The proposed method consists of a number of *bus agents* (BAGs) and a single *facilitator agent* (FAG). BAG is developed to decide a suboptimal target configuration after a fault occurs by interacting with other BAGs, while FAG is developed to act as a manager for the decision process.

The proposed multi-agent system has the following characteristics.

1) In order to realize efficient processing, the types of agents created are restricted to only two types of agents, BAG and FAG, in the proposed multi-agent system. It is postulated that BAG communicates with only its neighboring BAGs, and, furthermore, the number of times of communications is limited for efficiency.
2) FAG is developed by making use of the “singleton design pattern” [18], which insures that only a single instance of FAG exists at the same time.
3) BAG has the following simple negotiation strategies.
    - If there are a plural number of branches that can energize a certain bus, BAG allocated to this particular bus selects a branch with the largest amount of available restoration power.
    - If the amount of available power for restoration is insufficient, BAG tries to restore the bus in charge of by negotiating with its neighboring BAGs.
    - If a load must be shed because of insufficient power, BAG cuts off the load connected to its own bus as small as possible.
4) An object like knowledge query and manipulation language (KQML) [19] is used as a communication message object between *Agents*.

In order to verify the performance of the proposed method, many simulations are carried out using a model system that consists of eight substations and 14 buses. Though this particular example system must be too small if applied to power system algorithms such as load flow, restoration problems are belonging to a class of combinatorial optimization and therefore even an example system of this size is quite practical. Simulation results obtained has demonstrated that the proposed multi-agent system is able to find a suboptimal target configuration in all cases. The solutions are the same as those obtained by the mathematical programming approach that the authors propose [11]. However, it is noted that the proposed approach could reach the right solutions by making use of only local information.

The contribution of this paper can be summarized as follows.

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1) A multi-agent system that consists of a number of BAGs and a single FAG is proposed to efficiently solve power system restoration problems.
2) With embedding simple negotiation strategies into BAGs, each BAG acts to find a solution autonomously by interacting with its neighboring BAGs.
3) Simulation results have made clear that the proposed multi-agent system is effective and efficient considering the fact that the system utilizes only locally available information and simple negotiation strategies.
4) The results of this paper may suggest the practicality of multi-agent approach for handling a much larger system.

II. Power System Restoration Model

The objective of the mathematical model of a power system restoration is to maximize the capacity of the served loads

$$\max \sum_{k \in R} L_k \cdot y_k \tag{1}$$

where L_k is the load at bus k, y_k is the decision variable of expressing its status ($y_k = 1$: restored; $y_k = 0$: not restored), and R denotes the set of de-energized loads.

Typical constraints associated with the restoration model are taken into account in this study.

1) Limit on the capacity of available power source for restoration

$$\sum_{e \in F_q} P_e \cdot x_e \leq G_q \quad (q \in S) \tag{2}$$

where P_e is the power flow on the directed branch e (we assume $P_e \geq 0$), x_e the decision variable of branch e ($x_e = 1 : e$ is included in the restoration path; $x_e = 0$: otherwise), F_q the set of branches with starting node q, G_q the restoration power from the energized bus q, and S the set of energized buses that can be connected to de-energized area.

2) Power balance between supply and demand

$$\sum_{k \in T_i} P_k - \sum_{k \in F_i} P_k - L_i \cdot y_i = 0 \quad (i \in N) \tag{3}$$

where T_i is the set of branches incident to bus i, F_i the set of branches with originating from bus i, L_i the load at bus i, and N the set of buses.

3) Limits on branch power flow

$$|P_k| - U_k \leq 0 \quad (k \in B) \tag{4}$$

where P_k denotes the power flow of branch k, U_k the capacity of branch k, and B the set of directed branches.

4) Constraint on radial configuration:

This constraint means that an obtained target configuration must be radial, and is used mandatory in the actual power system operations. To insure a radial configuration, the total number of branches incident to bus i must be at most unity.

$$\sum_{k \in T_i} x_k \leq 1 \quad (i \in N). \tag{5}$$

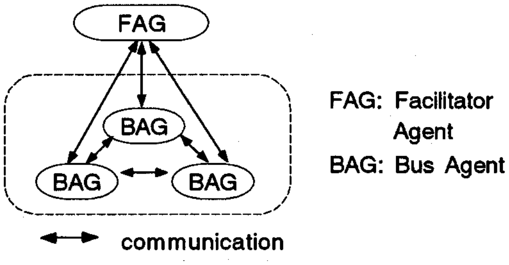


Fig. 1. Architecture of the proposed multi-agent system.

III. Multi-Agent Restoration Framework

In this section, we shall derive a multi-agent architecture for power system restoration using the object-oriented design technique. Since it is essential to develop an efficient solution, we restrict the types of agents and the number of communications between agents. The proposed multi-agent restoration system, as shown in Fig. 1, consists of a single FAG and a number of BAGs. The number of BAGs is the same as the number of buses. In other words, one BAG is allocated to each bus.

A. Bus Agent (BAG)

The purpose of BAG is to restore the load directly connected to its associated bus. BAG has a set of simple rules for restoring its load.

1) If there are several available points for restoration or boundary points between the energized and de-energized area, then BAG has to restore its own bus through one of these points with the maximum capacity.
2) If BAG succeeds the restoration, it tries to make negotiations with the neighboring BAGs.
3) If power available for restoration is insufficient to restore all the load of BAG, then it starts negotiations with the neighboring BAGs trying to energize the unserved load as much as possible.
4) If the load shedding is unavoidable, BAG has to cut off the load as little as possible.

When a fault occurs in a power system network, BAG corresponding to a de-energized bus asks FAG to restore its own bus. Since many buses are de-energized because of a fault, many messages are sent to FAG. The first come message is the trigger to the proposed multi-agent system, that is, the initiation of its function. Responding to the first received message, FAG sends out a start message to the BAG. On receiving the massage, it begins by itself communication with the neighboring BAGs.

B. Facilitator Agent (FAG)

FAG is a special purpose agent that facilitates the negotiation process of the multi-agent system. First, FAG classifies the de-energized buses into several groups, each of which has the same voltage level. Then, FAG selects one of BAGs in the highest voltage group, and sends it out a start message. FAG repeats the same task in parallel to other de-energized groups. This means the parallel processing is carried out to restore de-energized networks. In order to insure that only a single instance of FAG exists at all the time, the singleton design pattern is used [18].

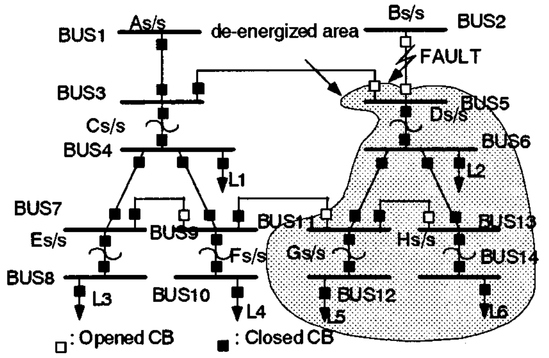


Fig. 2. Example of the post fault network.

C. Negotiation Process Between Bus Agents

Negotiation process is one of the key processes for the multi-agent system to successfully attain its goal. In the following, we shall describe what is negotiations in the restoration process and how BAG makes a negotiations with other BAGs. For ease of understanding of the negotiation process, we explain the restoration process using a model network depicted in Fig. 2, on which we postulate a fault to illustrate the performance of the proposed multi-agent system.

Under this particular fault, the hatched area shown in Fig. 2 has lost power. That is, the line between Bs/s and Ds/s is tripped off because of the assumed fault and three loads, $R = \{L2, L5, L6\}$, are to be resupplied by the agent system. In this particular case, BUS3 and BUS9 have power available for restoration which is denoted as $S = \{\mathrm{BUS3}, \mathrm{BUS9}\}$. A sequence of the negotiations is shown in Fig. 3. In this figure, the hatched rectangular boxes represent BAGs corresponding to de-energized buses, while the other rectangular boxes BAGs associated with energized buses.

The fault has made the following buses de-energized: BUS5, BUS6, BUS11, BUS12, BUS13, and BUS14. De-energized bus BUSi corresponds to *Bus Agents* BAGi as shown in Fig. 3(1).

In this figure, numerals in the parentheses adjacent to BAG3 and BAG9 represent the available power, and figures set beside rectangular boxes signify the load of BAGs. BAG12 starts a coalition task with BAG11 because it can only be energized only through BAG11. The relation between BAG13 and BAG14 is the same as the foregoing.

Therefore, BAG5, BAG6, BAG11, and BAG13 respectively send a message to FAG to ask to restore their own buses. FAG saves these requirements to the de-energized bus list, DEBList, out of which FAG selects a certain starting BAG and sends it a message to start communications for restoration.

In this case, BAG5 is selected since it has the highest voltage level. If there are plural available buses at the highest voltage level, FAG selects one with the largest available power. Then, BAG5 makes negotiations with BAG3 [Fig. 3(b)], since the available power (2.0) is greater than the load at BAG3 (0.0). Next, BAG5 negotiates with BAG6 [Fig. 3(c)]. BUS6 has two neighboring BAGs, that is, BAG11 and BAG13. It is assumed that BAG6 tries to make negotiations with BAG11 first, but BAG11 rejects the request [Fig. 3(d)] since the current available power (1.0) is insufficient to supply its downstream load (2.0).

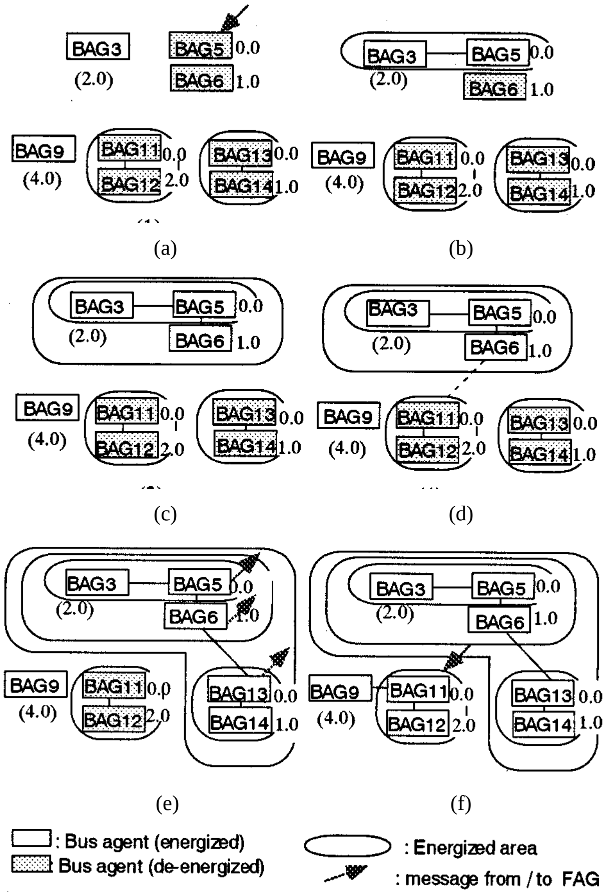


Fig. 3. Example of the coalition formation precess.

BAG6, therefore, tries to negotiate with BAG13, and this time the request is accepted because of the sufficient available power. As BAG13 has no neighboring BAGs except BAG14 at further end, BAG13 gives FAG notice that all the coalition process has been terminated. BAG6 and BAG5 also send the termination message to FAG [Fig. 3(e)].

When FAG receives the termination messages from BAG13, BAG6, and BAG5, it removes these BAGs from the DEBList. BUG11 is still remaining in the DEBList. Then FAG sends a message to BAG11 to start the negotiation process in the same way as BAG5 undertook [Fig. 3(f)]. After these negotiation processes have been completed, a target configuration for restoration is obtained as shown in Fig. 4. It requires two closing and one opening switch operations in order to restore all the loads.

IV. SIMULATION RESULTS

A. Simulation Condition

In order to demonstrate the effectiveness of the proposed approach, it has been applied to a model network which consists of eight substations (As/s-Hs/s) and 14 buses as shown in Fig. 5. Loads are indicated by arrows together with their magnitudes. A pair of figures on a branch shows its line flow capacity (upper row) and the amount of power flow (lower row). A square illustrates the status of a circuit breaker {black square (■): closed; white square (□): open}. It is assumed that a fault has occurred at the point shown by x, and the half-toned buses and loads are

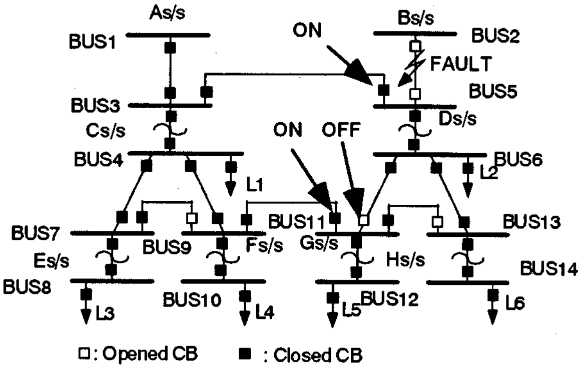


Fig. 4. Target configuration network for restoration.

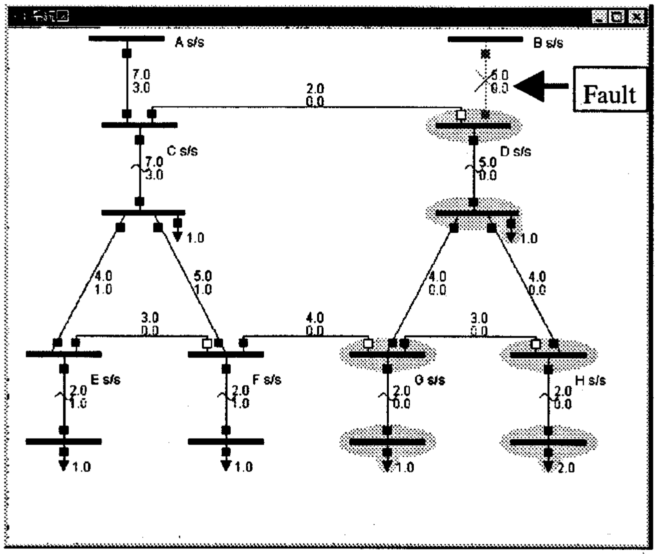
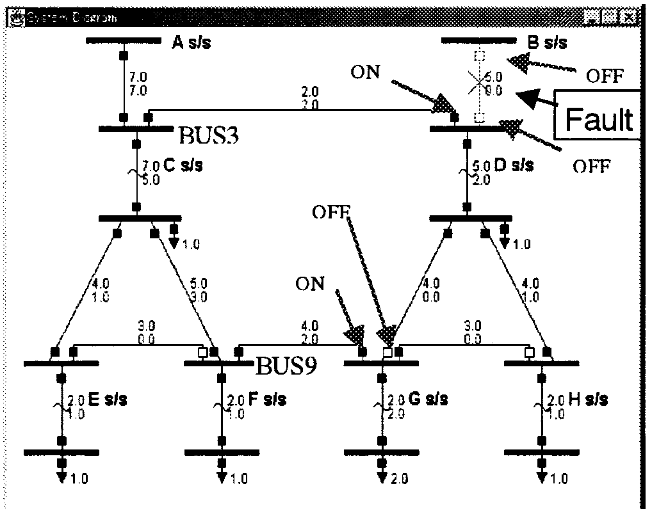
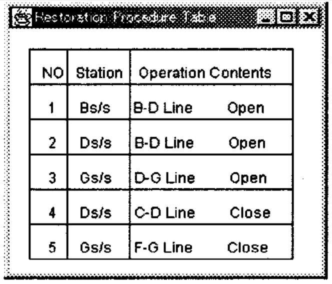


Fig. 5. Model network.



(a) Target configuration



Restoration Procedure Table

NO	Station	Operation Contents	
1	Bs/s	B-D Line	Open
2	Ds/s	B-D Line	Open
3	Gs/s	D-G Line	Open
4	Ds/s	C-D Line	Close
5	Gs/s	F-G Line	Close

(b) Switching operation sequence

Fig. 6. Case 1: Full restoration.

de-energized. This restoration problem is difficult to solve because of a large variety of possible restoration strategies.

The computer program was written in JAVA using JDK 1.1. The computer used for simulations was a PC (550 MHz).

B. Simulation Results

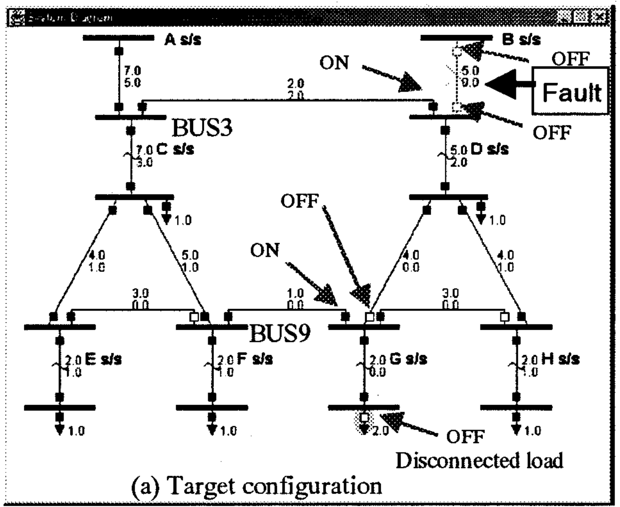
A large number of simulations were carried out on this model network with changing conditions. Here, only three typical examples are shown due to the page limits.

(Case 1) Full Restoration: This is a case in which all loads can be restored, since the amount of available power becomes 6.0 (2.0 from BAG3; 4.0 from BAG9), while the sum of de-energized loads is 4. Fig. 6 shows the simulation results: the optimal target configuration network and the list of switching operation sequence. The negotiation process has turned out to be the same as described in Section III-C. The first two steps in the list correspond to the tripping of the faulted line, and hence the remaining three switching operations (open: 1, close: 2) are required to restore all the loads.

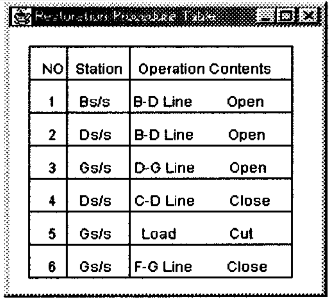
(Case 2) Partial Restoration of Loads: In the next, we shall discuss a case of partial restoration where the amount of available power falls short of the sum of de-energized loads. This case is same to case 1, except the capacity of the line between Fs/s and Gs/s is decreased from 4.0 to 1.0. This means that the available power from BAG9 decreased to 1.0; therefore the amount of available power becomes 3.0. As the total amount of de-energized loads is 4.0 the same as in case 1, the available power is insufficient to restore all the loads. Although one load at Gs/s is unfortunately disconnected as shown in Fig. 7, this is the optimal solution under these conditions. This case requires four switching operations (open: 2, close: 2).

(Case 3) Double Faults: Next, let us consider a specific case where double faults occur at the same time. Fig. 8 shows the post-fault network where the lines between Bs/s and Ds/s and between Cs/s and Es/s are tripped because of the assumed double faults. The simulation condition is same to case 1, except the loads of BUS12 and BUS14 have been changed to 1.0 and 2.0, respectively. In this case, since there are two de-energized bus groups {Ds/s, Gs/s, Hs/s} and {Es/s}, the restoration processes are started individually. Fig. 9 shows the simulation results. Six switching operations (open: 2, close: 4) are required to restore all loads.

It has been demonstrated through the obtained results that the proposed multi-agent system could have found a sub-optimal target configuration in every case. The solutions are the same as those obtained by the mathematical programming approach [11], because the same restoration strategies are included in both approaches. The calculation time is within two seconds in all cases, including the time to form the operation sequence list.



(a) Target configuration



NO	Station	Operation Contents
1	Bs/s	B-D Line Open
2	Ds/s	B-D Line Open
3	Gs/s	D-G Line Open
4	Ds/s	C-D Line Close
5	Gs/s	Load Cut
6	Gs/s	F-G Line Close

(b) Switching operation sequence

Fig. 7. Case 2: Partial restoration of loads.

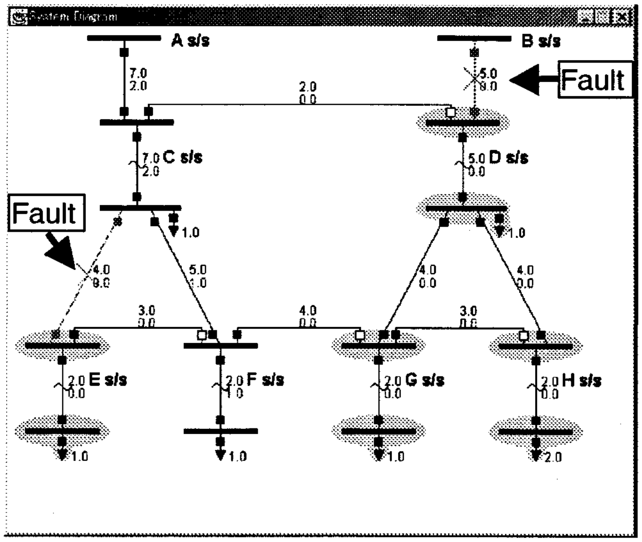
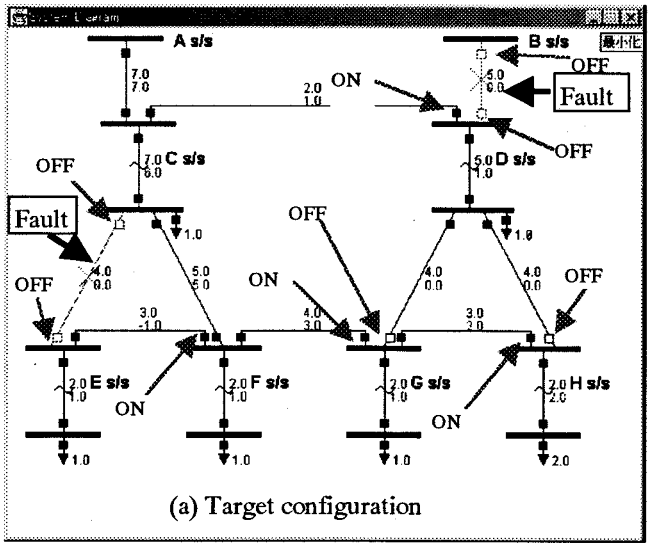


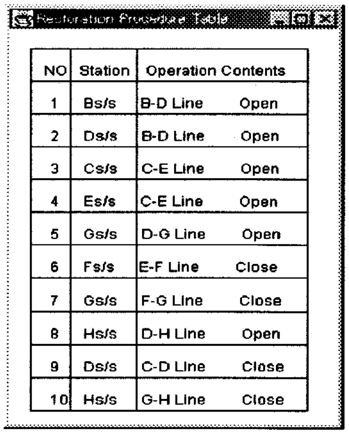
Fig. 8. Case 3: Post-fault network.

V. CONCLUSION

In this paper, we have presented a multi-agent approach to power system restoration. The proposed multi-agent system consists of a number of *Bus Agents* (BAGs) and a single *Facilitator Agent* (FAG). Several simple restoration strategies are imbedded in BAG and it communicates only with its neighboring BAGs, while FAG acts to facilitate the decision process. While BAG intends to conduct the local search, FAG is to carry out the global search. The validity and effectiveness of the proposed multi-agent system have been demonstrated by applying it to a practical size model network. It is noted that the proposed multi-agent system can decide the target configuration and the switching sequence using local information only. This means that the proposed multi-agent system is a promising approach to more complex large-scale networks.



(a) Target configuration



NO	Station	Operation Contents
1	Bs/s	B-D Line Open
2	Ds/s	B-D Line Open
3	Cs/s	C-E Line Open
4	Es/s	C-E Line Open
5	Gs/s	D-G Line Open
6	Fs/s	E-F Line Close
7	Gs/s	F-G Line Close
8	Hs/s	D-H Line Open
9	Ds/s	C-D Line Close
10	Hs/s	G-H Line Close

(b) Switching operation sequence

Fig. 9. Case 3: Double faults.

The next step of this work is to improve the multi-agent system's performance in order for it to cope with the difficulty of multiple faults. Future work should be directed to expanding this approach to handle bulk power restoration problems that involve the control of generators.

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