A Service Restoration Algorithm for Power Distribution Networks Applying the Multi-Agent System

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Abstract - Service restoration is one of the most important missions in distribution system operation. This paper proposes a multi-agent system approach to distribution system restoration. Every relay is developed as an agent by adding its own intelligent, self-tuning and communication ability. The relay agent independently calculates and corrects its restoration index through communication with neighboring agents and its own intelligence. The proposed algorithm is applied to a simple network to demonstrate its soundness and effectiveness.

Keywords: Communication, Distribution Network, Multi-Agent System, Restoration Service

1. Introduction

Customer satisfaction and service reliability are of primary concerns in power distribution systems. Fault location identification and service restoration are important functions in the operation of a distribution system. When a fault occurs, the operators must determine the fault location, isolate the fault area, and restore power to the blacked out regions. Service reliability can be enhanced if fault locations are identified accurately and efficiently and a proper service restoration plan is reached in a short period once the fault has been isolated.

Developing effective service restoration procedures is a cost-effective approach to improve service reliability and consequently, enhance customer satisfaction. Therefore, rapid service restoration has a multi-fold benefit. In actual use, distribution operators are required to restore service to out-of-service areas as soon as possible.

Service restoration for the outage area is considered to be the most vital aspect in distribution system automation and it has a combinatorial nature since it deals with the on/off status of the switches. There have been many research efforts in this area [1-3], most of which adopt the heuristic search approach. A recent study includes the expert system approach [4-6].

How to secure service restoration is one of the biggest concerns to system operators. Load balancing has been a favored means to enhance the restoration capability, but it often fails to provide the appropriate restoration for some fault cases depending on the feeder configuration and the loading. Other factors to be considered include position and number of tie switches [7] and proper power supplying capacity [8].

This paper proposes a new restoration strategy that can determine the most preferable plan applying the multi-agent system.

2. Service Restoration Schemes Using the Multi Agent System

The proposed service restoration algorithm consists of two phases. One is restoration index and the other is integrated restoration scheme using a multi-agent system.

2.1 Evaluation of Restoration Capability

Whether or not the outage load can be restored is determined by the availability of the backup feeder with sufficient margin to pick up the outage load. A backup feeder directly connected to the outage load is called the 'level-1 backup feeder' and it is most preferably utilized for restoration. Sometimes when it lacks the margin, another feeder connected to the level-1 backup feeder is utilized to transfer the live load of the level-1 backup feeder in order to secure the extra margin. From the operators' point of view, a restoration plan involving only a level-1 backup feeder is more preferred to one involving load transfer, i.e., a level-2 backup feeder because of its simplicity, understandability and easiness in system management.

In this section, a condition for 100% restoration of outage load by utilizing a level-1 backup feeder is presented and the restoration index that represents the restoration capability of the feeder is presented. The methodology to determine the restoration capability of the

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feeder is also described.

2.2 Restoration Index

A necessary and sufficient condition for the feeder to have a 100% restoration capability for any fault on the feeder has been identified. It is assumed that a level-1 backup feeder for restoration is utilized, which assures a restoration plan involving no live load transfer. Before introducing the restoration condition, a term 'direct path load' is defined.

2.2.1 Direct Path Load (DPL)

This represents the total load of the direct path from a certain zone to the end zone connected to the adjacent backup feeder. DPL from zone Zi to the backup feeder Fj is denoted by DPLij in this paper. Consider the system shown in Fig. 1. The direct path from zone Z1 to the backup feeder F2 includes zones Z1, Z2, Z4, and Z5, and DPL12 becomes 3000.

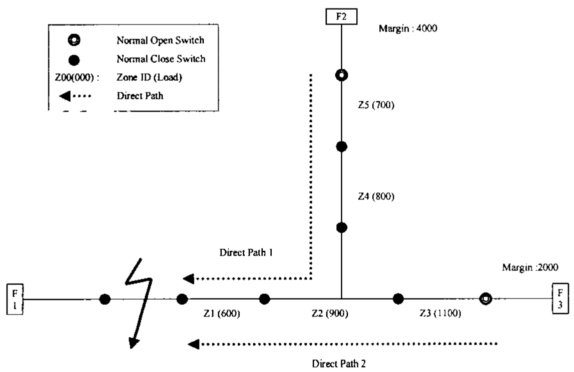

Fig. 1 Three feeder distribution system

2.2.2 Restoration Condition

If there exists at least one level-1 BF that has sufficient margin to pick up the direct path load from any zone of the concerned feeder to the backup feeder itself, then the feeder is secured from any fault as far as the restoration is concerned.

a) Proof

Let's assume a fault on the arbitrary zone on the feeder of concern. Then from the condition, at least one level-1 BF can always be found, which can restore the outage load on the direct path from the load-side switch connected to the faulted zone to the tie switch connected to the backup feeder. For an outage load left out, which is branched from the restored direct path, a new direct path with an associated backup feeder can be identified and can be restored according to the condition. By applying this process repeatedly for the rest of the outage load, the entire outage load can be restored.

Suppose there is a direct path having no level-1 backup feeder with enough margin. For a fault immediately above the direct path to the source-side direction, the load-side zone adjacent to the faulted zone can't be restored since there is no level-1 backup feeder with enough margin.

2.2.3 Restoration Indices

In order to evaluate the restoration capability of the feeder, two restoration indices – zone restoration index and feeder restoration index - are introduced that are based on the availability of the backup feeder's margin.

2.2.4 Zone Supporting Capacity (ZSC)

This represents the backup feeder margin remaining assuming it picked up the DPL associated with the particular zone. ZSC is obtained by subtracting DPL from the original margin of the backup feeder margin. ZSC for zone Z_i by the backup feeder F_j is denoted as ZSC_{ij}. For example, in Fig. 1, ZSC_{12} becomes 1000, which is obtained by subtracting DPL_{12} of 3000 (700+800+900+600) from the feeder F_2 margin of 4000. Similarly ZSC_{13} becomes -600.

2.2.5 Zone Restoration Index (ZRI)

Note that for a certain zone, there might be more than one ZSC depending on the number of level-1 backup feeders. For zone Z_1 in Fig. 1, two ZSCs can be found – ZSC_{12}, ZSC_{13}. For a certain zone, the backup feeder providing the biggest ZSC is defined as the main backup feeder and its associated ZSC is defined as 'zone restoration index (ZRI)'. ZRI for zone Z_i is denoted as ZRI_i and it can be expressed as

$$ZRI_i = \underset{j}{MAX}(ZSC_{ij}) \tag{1}$$

ZRI represents capability as to whether restoration can be guaranteed to the specific zone in case of its source-side fault. The magnitude indicates the extra capability of the main backup feeder to restore the outage load after picking up the associated DPL.

If ZRI is positive, it means that a level-1 backup feeder is available for the restoration of the zone for the fault on the upstream line. A negative ZRI means no level-1 backup feeder for restoration of the zone. For example, the zone restoration index for zone Z_1 is 1000 in Fig. 1 and it indicates that its associated main backup feeder F_2 can pick up additional load capacity up to 1000 besides the Z_1 load.

Note that the restoration condition described in the previous section can be represented in terms of this index as follows:

"If $ZRI_i > 0 \quad \forall i$ then 100% restoration is guaranteed by level-1 backup feeders"

2.2.6 Feeder Restoration Index (FRI)

Another index to indicate the restoration capability of the feeder is introduced and it is defined as the minimum value of the ZRI for zones constructing the feeder.

$$FRI_j = \underset{k}{MIN}(ZSC_k) \tag{2}$$

Note that positive FRI means that service restoration by level-1 backup feeders is secured for any fault on the feeder and negative FRI means not all of the zones of the feeder can be restored when the restoration is performed by utilizing only level-1 backup feeders.

2.2.7 Index Calculation

Owing to the radial structure, the distribution feeder system can be treated as a tree in which the first zone of the feeder become a root node and other zones become offspring nodes. This tree structure provides a convenient way to calculate ZRI, which is summarized as the following recursive algorithm.

```
Calculate_ZRI (node)
  IF node is a leaf
    node->ZRI = connected_BF_margin - node->load
  ELSE
    FOR all offspring_nodes
      Calculate_ZRI (offspring_node)
    END FOR
    node->ZRI = max (offspring_node->ZRI) - node->load
  END IF
```

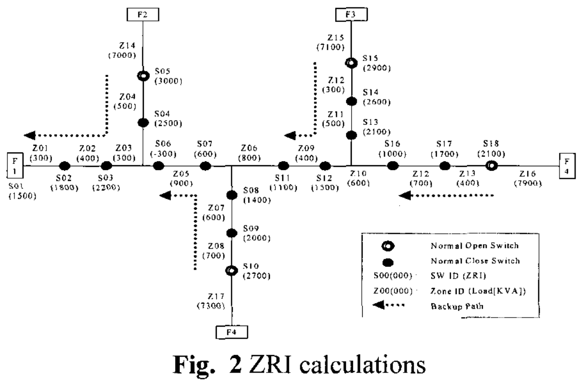

Fig. 2 ZRI calculations

In Fig. 2, calculated ZRI are shown below the corresponding switch and a feasible restoration path having the same main backup feeder is represented by an arrow line. Note that along each path, the source-side ZRI is always smaller than the load-side ZRI and consequently the smallest ZRI can be found on the last point of the path. Therefore the restoration capability of a feeder can be easily identified by checking those source-side end points, i.e., S_{01}, S_{06}, S_{11}, S_{16} instead of checking all points. Further FRI is determined by the minimum of ZRI corresponding to those points. For the system in Fig. 2, FRI is given by a minimum value of (1500,-300, 1100,1000), which is -300.

2.3 Service Restoration Planning

When the actual fault occurs and results in the outage area, the service restoration to put electricity back to the sound area must be performed as quickly as possible. The reserved words used in the communication between agents for service restoration are tabulated in Table 1 with simple explanations.

Table 1 Keywords for restoration

Keyword	Content
Experience	Agent asks whether the load side agent detected the fault current
No-Experience	The response of agent that didn't detect the fault current when agent received Experience message.
Yes-Experience	The response of agent that did detect the fault current when agent received Experience message.
Restoration Open	To open CB for restoration
Restoration Close	To close CB for restoration
Restoration	To carry out restoration plan

When a line to ground fault occurred at zone 1 in Fig. 3, it is assumed that agent 1 tripped the circuit breaker successfully.

In this case, all zones are to be the blacked out. But in fact, the fault area is zone 2. Therefore zone 2 is isolated, and other zones must be restored.

Table 2 MBF OF ZONES

Zone	Z1	Z2	Z3	Z4	Z5	Z6	Z7
MBF	F2	F2	F2	F2	F3	F3	F3

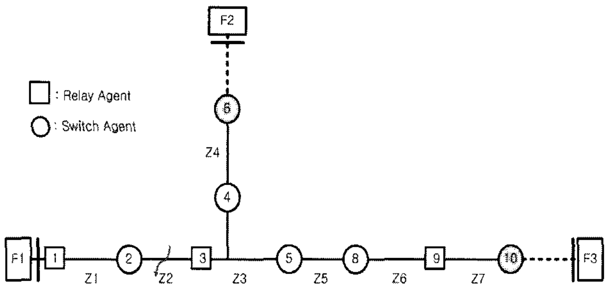

Fig. 3 Diagram for algorithm of service restoration planning

Algorithm for isolating the fault area

- When blacked out, agent checks the fault current.
- If fault current is detected, agent sends the Experience message to the load side agents.
- If agent receives the No-Experience message from

every load side agent, agent trips the circuit breaker and sends the Open message to load side agents.

- In Fig. 3, agents 1 and 2 detect the fault current.
- Agents 1 and 2 send the Experience message to agents 2 and 3 respectively.
- Agent 2 responds to agent 1 by sending the Yes-Experience message.
- Agent 3 sends the No-Experience message.
- Agent 2, who received the No-Experience message from the load side agent recognizes that the fault area is zone 2. So agent 2 sends the open message to the load side agent (agent 3) and sends the close message to the source side agent (agent 1).

The basic restoration scheme can be described as follows:

- First of all , agent compares the source side MBF with the load side MBF.
- If both MBFs are different, the agent of state changes over from ON-STATE to OFF-STATE and sends the Restoration message to the load side agent.
- In case of agent 5, since both MBFs are different, the state is changed.
- Agents 6 and 10 are closed.

Table 3 is the result of restoration.

Table 3 The Result of Restoration

Zone	Z1	Z2	Z3	Z4	Z5	Z6	Z7
Feeder	F1	•	F2	F2	F3	F3	F3

2.4 Enhancement of Restoration Capability

During normal operation, one of the main concerns to the operators is how to secure backup service in the case of a fault. Evaluating the restoration capability of the current system based on the proposed index, the operator could easily see if the system is secured from the fault or not. When any zone has a negative ZRI, which means that the system might have a problem with restoration, the operator needs to take some action to enhance the restoration capability, i.e., to make the system have no negative ZRI.

This can be achieved by repositioning the open switches. Repositioning open switches means redistribution of the load among feeders, which would result in adjustment of the feeder margins. This load redistribution, when performed in an adaptive fashion would keep the system's restoration capability maintained at a high level all the time, greatly increasing the service reliability.

The load redistribution to increase the restoration capability uses the candidate search, which involves searching for the candidate load transfers that satisfy the constraints.

2.4.1 Candidate Search

For the zone with a negative ZRI, the load transfer candidates are first searched for the main backup feeder. Another search is made for the adjacent feeder with the second largest ZSC. The candidate set will consist of those two search results.

In case the most lightly loaded feeder is the main backup feeder, then the load transfer of this feeder will decrease its loading and as a result, severe load unbalance might occur among feeders.

In order to avoid this situation, if there is an adjacent feeder that has a smaller DPL in the problem zone than the one corresponding to the feeder whose load transfer has been identified, one more search is made for that feeder.

For each feeder, more than one load transfer can exist and the one whose transferred load is larger than but closest to the amount required to compensate the negative ZSC is included in the candidate set. Any candidate should satisfy the following constraints:

- Transferred load should be larger than |ZSC|.
- Feeder loading should not exceed the line capacity.
- Voltage deviation for each line section should be smaller than the limit.
- Load transfer should not cause a negative ZRI for other feeders.

The candidate search process can be well understood through the example. Consider the system in Fig. 4. Suppose the evaluation of restoration capability yields a negative ZRI for Z1.

The search begins for feeder F3, the main backup feeder. The load of F3 can be transferred to F2 and F4.

The feasible load transfers from F3 to F2 involve the open position shift from S1 to S2 or S3 or S4. The transfer load that is larger than required, but that is closest to 1000 is determined as S3. In a similar manner, the open position shift from S5 to S6 is selected between F3 and F4.

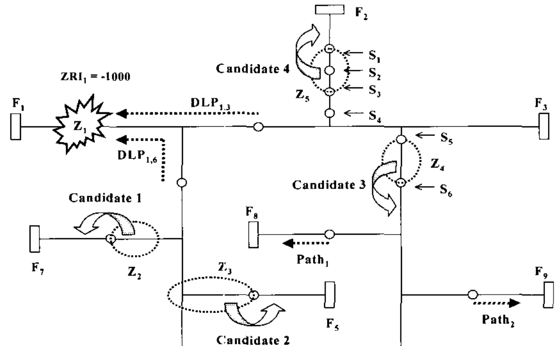

Fig. 4 Load Transfers to secure Restoration Capability

Once the candidate is found, the constraints must be checked. Assuming the initial system has no constraint violation, only the feeder that would experience an increased loading following load transfer is to be checked. For the restoration capability constraint, all adjacent feeders have to be checked. The move from S5 to S6 will result in the reduction of the F4 margin, and if it happens to cause a negative ZRI to F9, then it will be discarded from the candidate set. The same process will repeat for feeder F6, which has yielded the next largest ZSC.

3. Simulation

3.1 Simulation Condition

In order to demonstrate the effectiveness of the proposed service restoration algorithm, it has been applied to a model network that consists of 3 feeder agents, 7 relay agents and 12 switch agents as shown in Fig. 5. Every agent is realized in an individual PC and all PCs are connected through a LAN for communication.

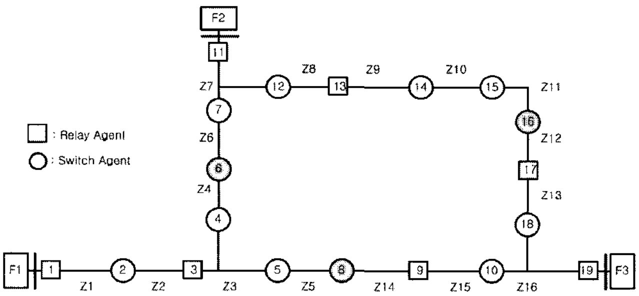

Fig. 5 Simple diagram of the studied network

Each feeder agent is linked to either of the two transformers, one left, and one right. Furthermore, each relay agent is connected to a circuit breaker.

The load of all zones is chosen to be 1000KVA, with line impedance 1 p.u./km. Each feeder's capacity is 10,000KVA.

The setting values for the simulation are given in Table 4.

Table 4 Initial settings of agents

ID	STATE	Feeder	Max. Load (KVA)	ZRI (KVA)	MBF (KVA)
1	ON	F1	5000	1000	F3
2	ON	F1	4000	2000	F3
3	ON	F1	3000	3000	F3
4	ON	F1	1000	3000	F2
5	ON	F1	1000	4000	F3
6	OFF				
7	ON	F2	1000	4000	F1
8	OFF				
9	ON	F3	1000	4000	F1
10	ON	F3	2000	3000	F1
11	ON	F2	6000	3000	F1
12	ON	F2	4000	1000	F3
13	ON	F2	3000	2000	F3
14	ON	F2	2000	3000	F3
15	ON	F2	1000	4000	F3
16	OFF				
17	ON	F3	1000	3000	F2
18	ON	F3	2000	2000	F2
19	ON	F2	5000	2000	F1

3.2 Fault simulation: when a fault occurred at zone 2.

Let's simulate a fault occurred at zone 2 in Fig. 6.

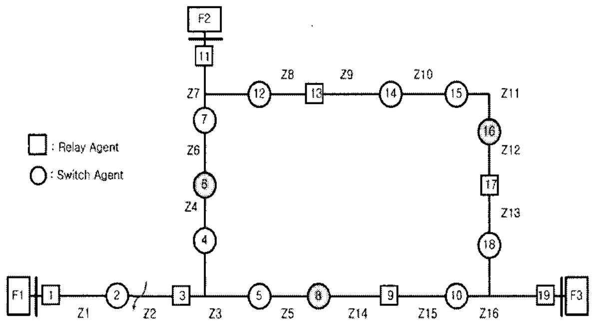

Fig. 6 Simple diagram for fault simulation

- Relay agent 1and switch agent 2 detect the fault current.
- Relay agent 1 trips the circuit breaker.
- Zones are 1~ 5 blacked out.
- Agent 2 sends the Experience message to the load side agent 3.
- Since agent 3 did not detect the fault current, agent 3 sends the Not-Experience message to agent 2.
- The state of agent 2 changes over from ON-STATE to OFF-STATE.
- Agent 2 sends the close message to agent 1 and the Open message to agent 3.
- Agent 1, who received the close message, changes over from OFF-STATE to ON-STATE.
- While isolating the fault area, agent 4 changes over from ON-STATE to OFF-STATE because both the load side MBF and the source side MBF are different.
- Agent 3 and agent 4 send the Restoration message to the load side agent.
- Agent 6 and agent 8, who received the Restoration message, change over from OFF-STATE to ON-STATE.

The above sequence is illustrated in Fig. 7 with signal flows and the action of each agent.

The results of fault simulation are tabulated in Table 5. Comparing this with the initial status given in Table 4 reveals that the state of agents 6 and 8 are changed and the supply feeder of zones 3, 4 and 5 are also changed.

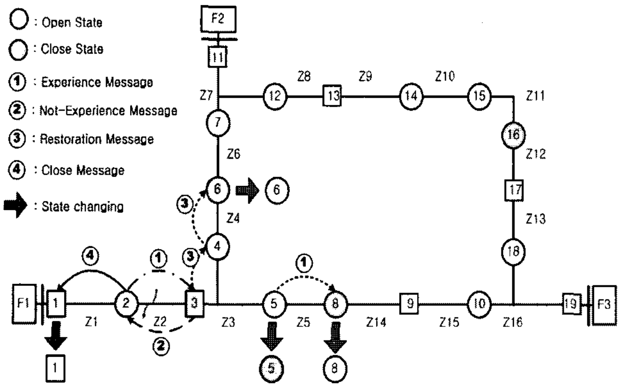

Fig. 7 Signal flow when fault occurred

Table 5 RESULTS OF SIMULATION

Agent ID	State	Feeder	Max. Load (KVA)
1	ON	F1	1000
2	OFF		
3	OFF		
4	ON	F2	1000
5	OFF		
6	ON	F2	2000
7	ON	F2	3000
8	ON	F3	1000
9	ON	F3	2000
10	ON	F3	3000
11	ON	F2	8000
12	ON	F2	4000
13	ON	F2	3000
14	ON	F2	2000
15	ON	F2	1000
16	OFF		
17	ON	F3	1000
18	ON	F3	2000
19	ON	F2	5000

4. Conclusion

In this paper, conditions for the feeder to have a 100% restoration capability for any fault on the feeder have been identified and the methodology to evaluate the restoration capability of the distribution feeder based on the restoration index is proposed. This paper recommends a new service restoration algorithm based on a multi-agent system. Each agent independently calculates the restoration index through communication with neighboring agents, and then plans self-restoration. Both illustrative and real system test results are given to confirm these conclusions.

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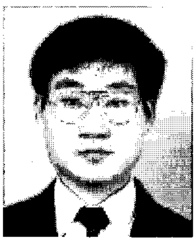

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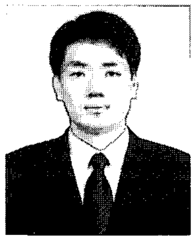

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