Hybrid Multi Agent approach for Power Distribution System Restoration

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Abstract—in this paper a hybrid multi agent system approach for fast power restoration in power distribution systems is presented. Hybrid structure of MAS provides the capability of solving the restoration problem with taking the advantages of both centralized and distributed agent structures. Bottom-up order of agents constructing the MAS is zone agents, feeder and substation agents. In this architecture, agents have the permission to execute a function based on their hierarchy level and the control central supervisory is not always required. After the fault location and isolation, agents start communicating with their higher level agents to initiate the reconfiguration and restoration plans. According to the algorithm, agents try to restore the un-faulted zones as much as possible considering the restoration constraints. An existing Mon Power distribution system with 5 feeders is selected for computer simulation to test the effectiveness of proposed approach. The simulation results show that the proposed multi agent approach is effective and promising.

Index Terms—Hybrid multi agent system, Power distribution system, fault location, isolation and restoration.

I. INTRODUCTION

Electricity utility companies strive to provide a high level of reliability for their customers. They manage generation and transmission lines assets carefully using various measurements and frequent monitoring by Supervisory Control and Data Acquisition (SCADA) systems. By contrast, distribution systems are significantly less smart than generation and transmission lines levels. The logic behind this are that distribution outages affect fewer customers and also the cost of distribution system automation wasn’t feasible.

On the other hand, based on the U.S. Department of Energy (DOE) studies, more than 80% of outages are directly related to distribution systems which cost the nation more than 80 billion dollars annually. Outage causes are commonly grouped into three main areas: vegetation-related failures (32%), equipment failures (31%), and animal/other-related failures (37%). Utility companies are concerned about distribution outages and its impact on their customers. Distribution system automation can help to improve the overall power system reliability and operation efficiency by minimizing the duration of outages as well as the customers interruptions.

Typically, System Average Interruption Duration Index (SAIDI) is the best and most commonly used reliability indicator. SAIDI has a direct relation with “Customer Minutes of Interruption” (CMI) which represents the average annual outage minutes per customer served. In calculating the SAIDI index, just outages lasting 5 minutes or more are considered. Therefore, fast restoration of power to unfauluted parts of the grid can help a lot in improving the grid reliability indexes.

The objective is to minimize the customer’s power interruptions with a self-managing automated network and restoring the power to unfauluted zones. Power restoration after an outage includes locating the faults and isolating them from the remaining power grid and initiating a reconfiguration to restore the power to as much loads as possible. Therefore, distribution systems should be smart, adaptive and with distributed intelligence and not relying on centralized controls to avoid single point of failures. Centralized control approaches have the advantage of having access to all network data and are able to find the optimal solution not the local optimal solutions. But, they tend to be inadequate since they are highly sensitive to system failures and should deal with large amount of data which needs powerful processing capabilities. Furthermore, since distribution systems are complex networks and constantly expanding, high communication capabilities are required in centralized control strategies which are costly.

Distributed control strategies can overcome some of the centralized strategies shortcomings. In distributed control strategies there are more than one decision making units and the data processing can be done in parallel which make it faster and requires less processing capabilities. Less communication capabilities are required in distributed control methods since there is no single central unit which is responsible for all communications.

Multi Agent systems (MAS) are one of the most popular distributed control strategies which are used in power system applications because of their distributed nature and adaptability with dynamic environment of power distribution.
systems. MAS is composed of a number of autonomous agents which work and communicate together to achieve a global goal. Multi agent based power system studies have been done in the protection field [1], energy management markets [2], fault location and isolation [3-6], power system restoration [7-9] and etc. MAS architectures which are used in previous works could be categorized in centralized, hierarchical [10], distributed [8] and hybrid schemes [11]. In the case of application of MAS in power distribution system restoration, Nagata et al. [7] presented a hierarchical MAS which try to restore the loads in order and based on their priority. Reference [3] describes the restoration plan for a radial distribution network and uses JADE for implementing the communications between agents. Ioannis S. et al. [12] proposed a dual level agent structure which distributes the necessary actions among the agents’ communities. They use a distributed MAS structure for meshed structure networks reconfiguration. Authors in [13] proposed a fully distributed MAS based restoration where agents make decisions according to discovered information using communication between immediate neighbor’s data.

These algorithms mostly are trying to solve the restoration problem by decentralized processing to survive in case of single point of failures. While, in this case agents just access to their immediate neighbors information and because of incomplete information necessarily cannot reach the optimal decisions. Hybrid MAS structures can take the advantages of both centralized and decentralized approaches and reach the optimal restoration plan.

In this work the MAS try to solve the restoration problem using hybrid MAS architecture. In this architecture, MAS works in a decentralized manner but agents will have access to information further than the immediate neighbors in the case of availability. Therefore, they can make better decisions and since they are not just relying on centralized data, even failures in accessing the centralized data do not affect the MAS much. Proposed MAS is composed of hierarchical level of agents consisting zone agents, feeder and substation agents. Each feeder agent has a number of zone agents and the feeder agents can solve the restoration problem by themselves and fully distributed. Feeder agents use the substation data as the higher level data in case of availability. The hybrid restoration system performs the restoration as follows. After the fault occurrence and recloser lock out, zone agents locate and isolate the faulted zone and restore power to the unaffected zones. West Run substation feeders are equipped with reclosers. When there is a fault in the system, the recloser will go through its trip and close operations as configured. Feeder agents are located at the recloser place for each feeder.

II. MULTI AGENT SYSTEM FRAMEWORK AND RESTORATION ALGORITHM

A. West Virginia Super Circuit

Fig.1 shows the West Virginia Super Circuit (WVSC). This work is part of the WVSC project which consists of designing MAS for fault detection, isolation and restoration applications. The focus of this paper is on the restoration process. The WVSC is divided into different zones connected through controllable switches, shown with circles in Fig.1. The West Run Substation has five feeders, two of which (WR-3 and WR-4) are monitored for faults. Once a fault is detected, the MAS will locate and isolate the faulted zone and restore power to the unaffected zones. West Run substation feeders are equipped with reclosers. When there is a fault in the system, the recloser will go through its trip and close operations as configured. Feeder agents are located at the recloser place for each feeder.

B. MAS Structure

Agents in MAS are intelligent units that have the problem solving capabilities. Each agent in MAS could communicate, resolve, coordinate and debate with its neighbors and make a decision. Fig.2 shows the structure of an agent which is composed of sensors, actuators, communicators and software parts.

Figure 1. West Virginia Super Circuit

Figure 2. Single Agent Structure
In Fig.3 the MAS architecture used in this paper is presented. Proposed MAS is composed of Zone (ZA), Feeder (FA) and substation agents (SA). Zone agents are the lowest level agents which are in contact with their neighbor. Each feeder agent is in charge of a number of zone agents and is in contact with the other feeder agents. Substation agent covers a number of feeder agents.

![Figure 3. Structure of the Proposed MAS](image)

**C. Restoration Algorithm**

MAS could be in three operational states and agents have different functionalities for each state:

1) Normal state;
2) Fault location and Isolation state;
3) Restoration state.

Agents are in Normal state until a fault occurs. When a fault occurs, reclosers at the top of the faulty feeders will lock out and also Distributed Generation (DG) units in the affected area will trip to prevent islanding operation. Following that, agents transit to second state, where zone agents locate and isolate the fault based on the data received from their immediate neighbor zone agents. Zone agents monitor the load profile, voltage and current phasors for their corresponding zones and inform their neighbor’s about their state frequently in both two first states. Faults could be isolated using a fully distributed structure by the zone agents. More detail about the fault location and isolation algorithm is presented in [6]. After fault location and isolation, the restoration procedure starts execution. Feeder agents are in charge of restoring the power to their zones and they can solve the restoration problem fully distributed and by negotiating with neighboring feeder agents. Zones upstream the fault will be restored by reclosing the recloser and for the downstream zones the process is different. In case of malfunction of a feeder agent, substation agent will take the responsibility of restoring power to the feeder zones. Fig.4 shows the flowchart for the restoration process.

![Figure 4. Work flow chart for Restoration](image)

According to the flowchart, after the fault location and isolation, zones upstream to the fault are restored. Then the feeder agent of the faulty zone sends request for proposals to the neighbor feeder agents which have the capability of transferring power to fault downstream zones through tie switches. Feeder agents are aware of their zones power demand and can respond to a proposal if they can support additional loads that are to be transferred. After receiving all proposals, feeder agent analyzes the proposals and checks the constraints to see what proposals to accept.

Since there are a limited number of switch agents in the WVSC which separate the zones there is no load shedding i.e. partial restoration available in a zone. Therefore, either all the loads in a zone will be restored or the zone will remain out of power.

**D. Restoration Formulation**

Once the feeder agent of the faulty zone received all the proposals, the optimal load restoration decision can be obtained by a mathematical model with the objective function of:

$$\max \sum_{i=1}^{N} p_i \cdot P_i \cdot y_i$$
Where $p_i$ is the load priority for the $i$th zone with the load $P_{zi}$ and $y_i$ is a binary value determining whether the corresponding zone should be restored or not (0: restored; 1: not restored).

And the following constraints:

1. Power balance:
   \[ \sum_{i=1}^{N} P_{zi} - P_{zi} \geq 0 \]
   Loads to be restored must be less than or equal to excessive generation.

2. Branches power flow:
   \[ |T_{ij}| \leq T_{ij,\text{max}} \]
   Where $T$ is the power flow between bus $i$ and $j$.

3. Voltage drop:
   \[ K_{\text{drop}} = \frac{\text{Voltage} - \text{drop} - \text{percent}}{\text{kVA} - \text{mile}} \]
   \[ V_d = K_{\text{drop}} \cdot \text{kVA} \cdot l \quad V_d \leq 5\% \]
   The voltage drop is calculated by the K-factor value which is the voltage drop percent down a line that is one mile long and serving a balanced three-phase load of 1 kVA. $l$ is the one way distance and kVA is the actual load of the line.

   Identifying the zones to be restored or not by the variable $y$ as 0 or 1 makes this problem a nonlinear optimization programming problem which MATLAB optimization toolbox is used to find the optimal solution.

E. Agents Communications

To accommodate the MAS communication, agents should use the same communication language and also their interactions with other agents should be defined. Foundation for intelligent physical agencies (FIPA) is an IEEE standard that defines many issues pertaining to agents [14]. In this paper FIPA is used as standard for agents’ communication and management procedures.

As mentioned before, the fault location and isolation process is to be done by zone agents and restoration goes with the feeder agent’s layer. Each feeder agent makes the decision for its zones restoration based on the information received from neighbor feeder agents and data from its zone agents. The point to point request-respond communication between feeder agents in the restoration process of a fault in Feeder 3 is shown in Fig.5. Feeder agents start communicating to the other feeder agents and start making the restoration decisions right after receiving the fault isolation signal of their zone agents. The zone agents’ communication, shown in Fig.5 starts after FA asks for the fault location (FL) and terminates after informing the FA about the fault location. The communication will be terminated when feeder agents receive the confirmation signal of the corresponding tie switches to be closed.

The communications shown in Fig.5 are for MAS in restoration state and in normal operation agents update their data about neighbors every 5 minutes.

III. SIMULATION STUDIES

To demonstrate the effectiveness of the proposed multi agent methodology, it is tested with WVSC model. The simulation model has two parts. The first part is for simulating power system distribution network which is the WVSC by MATLAB Simpower Toolbox. The second part is the multi agent system which is implemented in MATLAB Simulink by using user defined S-functions. Since both MAS and power system model are implemented in MATLAB Simulink there is no need for an interface between the two models. This means MAS and power system model can work in real time which provides a simpler and more accurate simulation model for investigating MAS applications in power systems.

There are 16 switches and 5 re-closers installed in these five feeders to enable the system. Switches are Cooper DAS-15 type three-phase vacuum switches with 15kV, 630 A ratings. Seven switches are normally closed and the other nine switches will be used for reconfiguration and restoration applications. Transformers in each feeder are 138/12.5 KV and 33.6 MVA. Table I shows the peak load data for each feeder.

| Table I. Feeders peak load data |
|---------------------|-----|-----|-----|-----|-----|-----|
| Feeder # | kW, kVAR |
| A | 1916,746, 1391,198, 1395,-132, 1036,-14, 844,-25, 677,133 |
| B | 1467,455, 1667,355, 1664,26, 773,-162, 1191,167, 549,69 |
| C | 1864,907, 1667,363, 1429,-111, 1237,85, 725,-87, 442,16 |

Figure 5. Agents Communications for fault location and restoration
In this paper, it is assumed all zones are uniformly loaded and zones priority is considered to be equal for all zones. Two cases were considered in order to examine the operation of the proposed MAS. Fig.6 and 7 represent the one-line diagram for the WVSC shown in Fig.1.

A. Fault location: Zone 4 of Feeder 3

In this case, a three phase to ground fault is placed next to switch 5 which is shown in Fig.6 with red color. After fault location, SW5 will open to isolate the fault and feeder agent 3 will initiate the restoration process. Zones upstream the switch 5 will be restored right after isolation. To restore downstream loads can help to improve the simulation to cope with the realistic constraints during the restoration process.

An actual power distribution network (WVSC) with 5 feeders was selected for computer simulations. The MAS communications and power system model which are both modeled using MATLAB toolboxes are synchronized and work in real time. The simulation results show the proposed restoration approach can restore power to the healthy zone as quickly as possible while keeping the voltage amplitude within the limitations.

In future work, authors will add power loss and switching limitation to restoration constraints and implement adaptive learning procedures regarding the restoration management. Another issue is that since in practice, load profiles are time varying, considering the real load profiles instead of constant loads can help to improve the simulation to cope with the realistic constraints during the restoration process.

REFERENCES