MULTI-AGENT SYSTEM DESIGN FOR AUTOMATION OF A CLUSTER OF MICROGRIDS

Mojtaba KHEDERZADEH
Shahid Beheshti University, A.C., – Iran
m_khederzadeh@sbu.ac.ir

ABSTRACT

Breaking down the distribution network into several microgrids with relative balance of supply/demand using the capacity of the embedded DERs is a promising solution to manage the complex distribution systems. Two modes of the operation: normal and self-healing could be considered. Normal mode relates to the minimization of the operation costs of the distribution system. Self-healing mode relates to fast-responding capability to restore service during an outage. In this paper, the distribution network is segmented to a cluster of microgrids. Each microgrid is supported by the adjacent microgrids during power deficiency. A new Multi-Agent System (MAS) is proposed to enhance fault resiliency in the cluster of microgrids firstly by actions within each microgrid including Fault Location, Fault Isolation and Restoration. Secondly, if remedial actions within the faulty microgrid are not sufficient enough to restore the loads, then coupling adjacent microgrids is performed. In other words, self-healing within the faulty microgrid using MAS is the first step. However, due the limited supply of the DERs within a microgrid, power deficiency and vulnerability may occur, so interconnecting the adjacent microgrids is applied. A 4-feeder, 1069-bus unbalanced test system with 4 microgrids is utilized to demonstrate the effectiveness of the proposed method.

INTRODUCTION

Microgrid (MG) is an interesting paradigm to integrate distributed energy resources (DERs) including DGs and distributed storage devices (DSs) into distribution network. However, control of distribution networks has become a complicated task due to the huge number of control variables associated with progressive penetration of DERs. One solution could be breaking down the distribution network into several smaller interconnected sections; each section constituting a MG with relative balance of supply/demand using the capacity of the embedded DERs. IEEE Standard 1547.4 indicates that connecting multiple MGs together, establishing networked MGs could improve system operation and reliability [1]. The advantages of splitting the distribution network into multiple MGs would be coordinated energy management and interactive support and exchange in normal operation and performing as emergency sources to serve critical loads in self-healing mode [2]-[3].

In [4] a resiliency-based methodology is proposed using MGs to restore critical loads on distribution feeders after a major disaster. The critical load restoration problem is formulated as maximizing the cumulative service time of MGs to loads on the distribution feeders weighted by their priority subject to dynamic, generation-resource, operational and topological constraints. The topological constraint is defined as maintaining the radial network structure. It is assumed that a critical load is served by only one MG through one path and the paths for different critical loads do not overlap. It is stated that maintaining a radial structure simplifies some operational issues like synchronization and load sharing among MGs. But the main concern is that maximum benefit from the capacity of MGs would not be achieved. For example, it may be possible that enough Remotely-Controlled Switches (RCS) are not available. So, whenever the demand is more than the MG capacity, it is impossible to restore the load. However, networking different MGs could be a more efficient solution, as the cluster of MGs establishes a cumulative capacity. Moreover, the networked MGs could be beneficial in self-healing. The capability of autonomous restoration after faults is referred to as self-healing. In [5] a methodology for the optimal operation and self-healing of networked MGs is proposed with independent operation of each MG in normal operation to fulfill its own objective. While in self-healing mode upon existence of a fault and its clearing, the affected area will be optimally sectionalized into networked MGs. If any of the MGs in the group would be in emergency, it receives local power support from other MGs.

In this paper, the distribution network is segmented to a cluster of MGs. Each MG may be supported by the adjacent MGs during power deficiency. A new Multi-Agent System (MAS) is proposed to enhance fault resiliency in the cluster of MGs. Whenever, there is a fault in the power distribution system, it is required to firstly locate the fault. For this the related upstream switching devices sense the fault and trip. After final reclosing and lock-out, the related agents would identify the location of the fault. MAS would locate the fault by a pre-defined logic. Relevant switches are opened to isolate the fault from the rest of the system. Restoration is performed by reconfiguration, i.e. closing the tie switches.

The resiliency of the MG is improved by mitigating the overloading of the feeders. Reconfiguration would be used to maintain the loading of the lines less than a specified threshold, so the likelihood of the outage of the feeders due to the overloading is minimized. Since outage of a line could severely impact the path to supply the loads, the resiliency of the MG is enhanced either by avoiding the isolated areas without any supply upon disconnection of the MG from the upstream utility-grid; or identifying the lines with loadings more than a specified threshold in the MG after transferring to autonomous mode. Reconfiguration is applied as remedial actions to alleviate the loadings, so minimizing the possibility of the line outages.

Self-healing within the faulty MG is the first remedial actions that would be performed. However, due the limited supply of the DERs within a MG, it is possible that power deficiency and vulnerability occurs, so interconnecting the adjacent MGs is a solution. The proposed self-healing scheme evaluates the interconnection of adjacent MGs by calculating the balance of power in each MG plus the stored energy and the SOC of energy storage devices such as DC storage systems like batteries and EVs with V2G functionality. The required energy for the deficient MG is supplied by the battery systems in a very rapid manner before DERs could reach to their full capacity. After stabilizing the coupled microgrids, the control system forces the DERs to increase their outputs by virtually decreasing the frequency reference point to a permissible low value. So the battery system starts to charge in order to be ready for the next required operation. After complete charging of the battery system, the frequency set point is set at the nominal frequency, so the DERs would operate at the required output level. The central self-healing system separates the coupled MGs, whenever the conditions for such an operation are satisfied.

MULTI-AGENT SYSTEM (MAS)

An agent is an entity (software/hardware) which is able to autonomously react to the changes in the environment that is placed in [6]. The salient features of agents as intelligent units could be mentioned as: problem solving, communication, coordinating, and debate capabilities in conjunction with the other agents in order to make proper decisions with respect to the objective function. Cooperating and coordinating of agents with each other in a computational system to achieve organizational objectives in a decentralized fashion is interpreted as Multi-Agent System (MAS) [1]. The superiority of MAS with respect to centralized schemes is: in spite of failure of a part of the system, the rest will still continue to work. MAS could be the preferred control scheme for MGs, because it can provide desirable properties such as: Autonomy, Reactivity, and Social ability and pro-activeness [7]. Autonomy refers to the ability of each agent to autonomously manage the behavior of any individual unit in a cooperative or competitive environment. As the control of agents can be implemented asynchronously and in parallel, therefore, MAS is well suited to control the multi-source interconnected complex MGs. Reactivity means that MAS could evaluate the circumstances, so any control based on MAS could adaptability respond to uncertain environment of operation. Social ability and pro-activeness is the property of the MAS that many agents are grouped together forming a community to achieve the goals of individuals and system. It means that upon failure of one agent, other agents interact together to continue the required function. So, MAS is robust to the faults of one or several agents [8]-[9]. MAS, as a distributed method for problem solving has received increased attention in handling the complex problem of fault location, isolation and restoration [10].

FAULT LOCATION AND ISOLATION BY MAS

The proposed MAS has different types of agents: Feeder Agent (FA), Sectionalizing Switch Agents (SSA), Tie Switch Agents (TA), and Microgrid Agent (MGA). These agents are placed at the respective points in the associated IEDs. These agents are organized in different layers in a hierarchical structure. Layer0 is the FA, Layer1 is the SSA and Layer2 is the TA or MA.

Generally, SSA is responsible for monitoring the voltage and current phasors at its location. Fault detection is possible by SSAs using a simple logic. For example, abrupt current change and voltage could be the actuating signal for the overcurrent unit foreseen in this agent. If the current is more than the specified threshold, then passing a fault current from that node is detected and the related flag is declared as TRUE. As a radial structure is considered for the distribution system in normal operation, so it is assumed that the fault current flows from the upstream source to the fault point upon inception of a fault. Therefore, SSAs could locate the fault, as the faulty section has a TRUE flag at its upper node (closer to the upstream source) and FALSE flag at its lower node. Other nodes may have either TRUE flag at both their nodes, i.e., fault through these SSAs, or FALSE flags at both nodes, means the fault is in the upstream part. Each feeder is equipped by a feeder agent, usually, placed in the recloser location.

Restoration is performed by negotiation of the faulty FA with the adjacent feeders to supply the disconnected loads as much as possible based on the available knowledge about the system's state. It is worth mentioning that agents update their knowledge about systems structure whenever there is a change in the system topology through communicating with their neighbors. Therefore, after any reconfiguration, the agents would be updated.

MULTI-AGENT SYSTEM DESCRIPTION ON A SAMPLE SYSTEM

A 4-feeder 1069-bus test system [4] with four MGs is used to validate the effectiveness of the proposed method. The one-line diagram of the test system is shown in Figure 1. It is composed of four "R3–12.47–2" feeders, seven tie switches, in addition to the 4 MGs. It has 156 normally closed sectionalizing switches. The Taxonomy "R3–12.47–2" sample distribution network is a prototypical unbalanced developed by the Pacific Northwest National Laboratory (PNNL) with nominal voltage equal to 12.47 kV and total load, including losses equal to 4.652 MVA [11]. It is composed of single homes, light commercial loads, and a small amount of light industrial loads. R3-12.47-2 has approximately 33% overhead and 67% underground lines. The feeder loading

is limited to 60% to ensure the ability to transfer load to other feeders, and vice versa. Climate region 3 is the non-coastal South West of the United States and is characterized by a hot and arid climate.
Each feeder has the transformer capacity of 7.5 MVA. The active and reactive power limits of the MGs are shown in Table 1. Power flows are calculated by GridLAB-D, a new power distribution system simulation and analysis tool [12]. R3-12.47-2 test system is composed of single-phase, double-phase and three-phase loads. GridLAB-D performs unbalance load flow with the possibility of using single-phase DERs.

Table 1: Maximum Capacity of MGs

MG #	P (MW)	Q (MVar)	S (MVA)
MG1	5.15	2.25	5.62
MG2	1.65	0.95	1.90
MG3	2.50	1.75	3.05
MG4	1.00	0.55	1.14

As can be seen from Figure 1, three types of agents are available in this sample system. Four feeder agents (FAs) for the existing feeders plus four MG agents (MAs) for the available MGs are shown in the figure. It is assumed that all the indicated sectionalizing switches in the figure are equipped with associated agents (SSAs). It is worth noting that distributed methods such as MAS is more commonly accepted than the centralized approaches, due to their decentralized data processing causing efficient task distribution and faster operation and decision making process. It means that utilizing peer to peer communication avoids a single point of failure. So, MAS technology does not need exclusive central control. In MAS technology it is not necessary to transform locally operated switches to remotely controlled switches (RCS), because the switches need only to receive open/close commands from the associated agents and not from the central controller.
In [13], two scenarios are formulated for placement of RCSs. First, it is assumed that there is no switch in the system (planning phase). In this scenario, it is possible to determine the location and status of the switches (open/close) based on the requirements without any constraint. In the second scenario, upgrading of the existing distribution network is the main concern, so a limited number of manual switches are changed to RCSs.

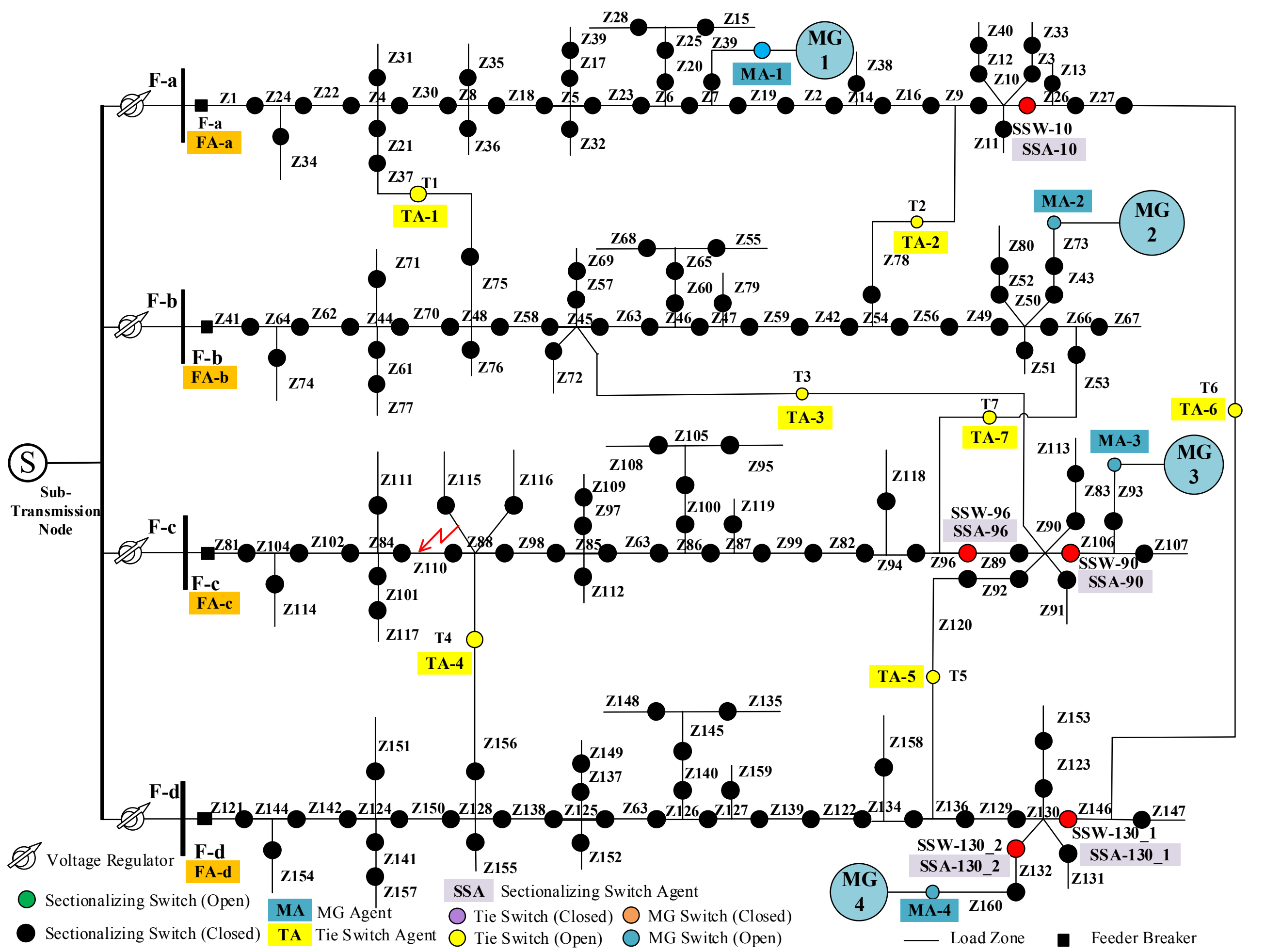

Figure 1: One-line diagram of the 4-feeder 1069-node test system

SIMULATION RESULTS

For example, suppose that there is a fault on Z110 in Figure 1. Feeder *c* as a radial feeder senses the fault and trips and after some reclosing it will be locked out. The sectionalizing switches in at the upstream section of Z110 would be aware of a high through current, while the downstream switches sense no current. Therefore, the agents of Z110 detect the fault and send commands to the related switches to be opened. This is the fault isolation part of the scenario. After that restoration is required. Here, two scenarios are applicable: maintaining radial topology upon using MGs or clustering MGs. In the first scenario, as the capacity of each MG is limited, further sectionalizing is required before connecting any MG in order to avoid its overloading. For scenario 1, it is required to close T6 and then open the sectionalizing switches between Z130-Z146 and Z90-Z106 and then close Z93 to connect MG3. After that it is required to open Z96-Z89 and then close T5; at the next step, open Z110-Z88 and then close T7. If the related switches are manual, it takes a very long time to restore the loads, but if the associated switches that are red marked in Figure 1 are remotely controlled, then the restoration time is considerably reduced [14]-[15]. In this scenario, closing the tie-switches T6, T5, T7 could be performed by communicating between tie-switches and the related feeder agent. But the requirement to open Z130-Z146, Z90-Z106, Z96-Z89 and Z110-Z88 are mainly related to the constraint that the MGs are needed to supply the loads in a radial manner. If the MGs are connected together to form networked MGs, then the restoration scenario could be much simpler and it is not required to perform too many switching actions.

In [4] it is assumed that a catastrophic event is happened and simultaneous faults caused an outage of the entire distribution system. Power from the upstream transmission system is not available any more. Seven simultaneous faults occurred in zones Z22, Z60, Z70, Z98, Z99, Z102, and Z129, as shown in Fig. 2. As already explained, radial structure is a constraint in [4], so it seems that due to the closeness of MG4 to Z132 which has a critical load, it could be a good idea to use it to restore Z132 through path “MG4-Z160-Z132.” Indeed, it is found out that the path is infeasible because the amount of load on zone Z160 is large and the generation capacity of MG4 is relatively small.

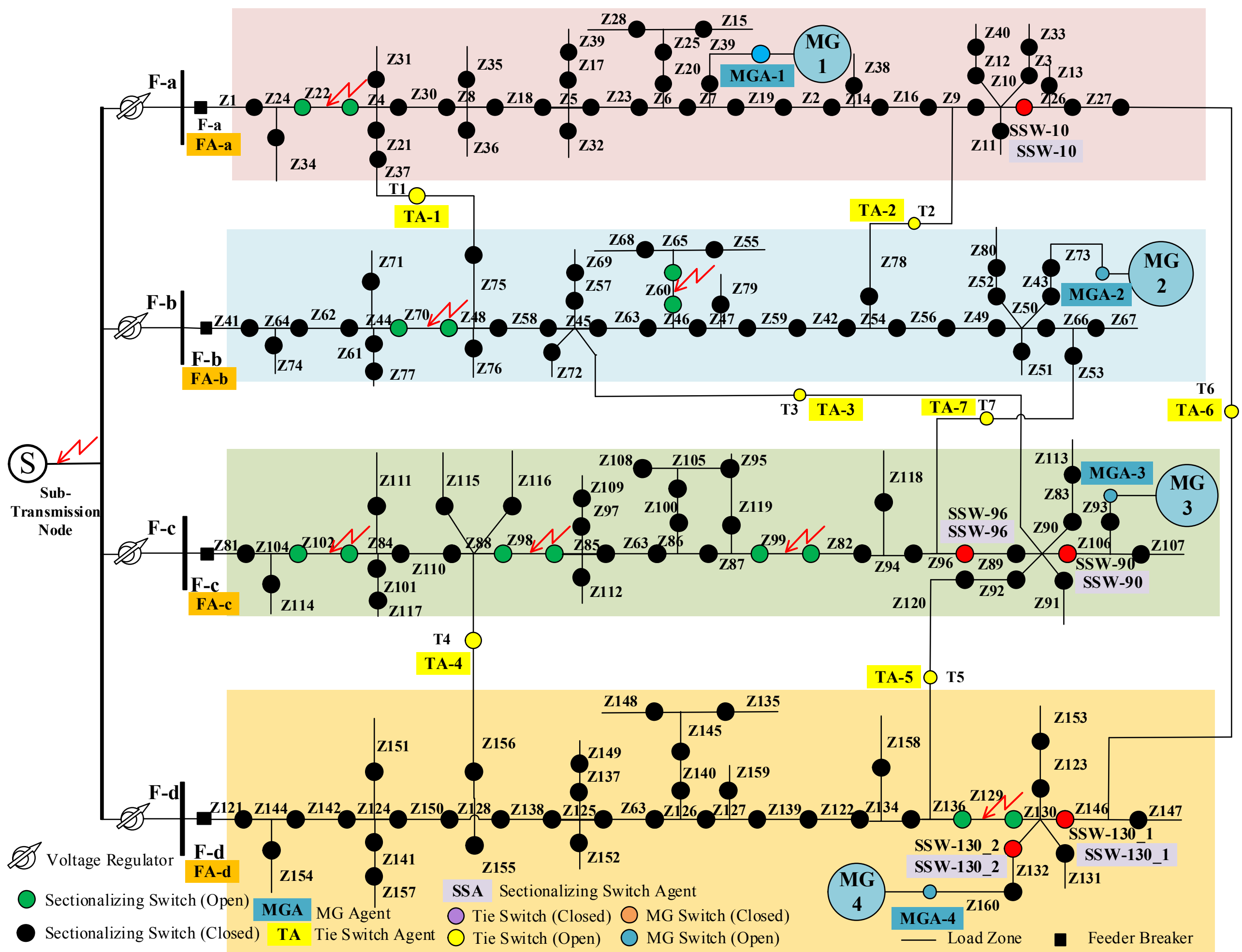

Figure 2: MAS designed for the sample system with indicated simultaneous faults.

The proposed solution in this paper is networking the MGs in order to get all their capacity to supply the loads. Figure 2 shows the extent of supply of each MG. After detection and isolation of all the faulty zones, the agents of the MGs are activated and the MGAs send commands to close the relate switches. As can be seen From Figure 2, it is possible to network the MGs by using T1, T2, T3, (T4 & T5), T6 and T7. Clustering of the MGs assists to restore the loads as much as possible up to the limit of the MGs generations. The agents of tie-switches *TAs* are in contact with the agents of MGs, *MGAs*.
As can be seen from Figure 2, there are 4 feeders that are connected to 4 MGs. If a fault occurs in one these sections that are highlighted, MAS tries to energize the disconnected loads by using the available generation capacity within the MG itself. If there is a power deficiency, MAS would connect the adjacent MGs to form networked MGs with the possibility of power exchange. As Figure 2 shows, there are enough tie-switches between the highlighted MGs, which facilitate to connect any of them to the others. It is worth noting that the MG in Figure 2 could be a simplified MG model composing of an aggregated generator whose capacity equals the total capacity of controllable units and an aggregated load representing critical loads connected at the bus.

CONCLUSIONS

In this paper, a self-healing strategy based on MAS technology is presented. The proposed method would detect the fault, isolate it and restore the de-energized loads automatically using the agents foreseen for different layers, i.e., feeder layers, sectionalizing switch layers, tie-switch layers and MG layers. It is shown MAS could be well used to network the MGs in order to use their full capacity. Because, using the MGs in a radial structure may avoid energizing the loads with the values more than the generation capacity of the related MG. The proposed method firstly tries to restore the interrupted loads within the associated MG. Whenever the MG is confronted with the power deficiency, the multi-agent system would connect it to the adjacent MGs to balance their demand/supply. The proposed method is superior to centralized schemes as in the case of failure of a part of the system; the rest will still continue to work.

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