

Intelligent Reconfiguration of Smart Distribution Network using Multi-Agent Technology

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Abstract-The distribution network reconfiguration is a process that consists of changing the status of the network switches for re-routing the power after a fault occurrence, or to optimize some given criteria. Traditionally, feeder reconfiguration is a complex combinatorial and constrained optimization problem because of the numerous combinations of candidate switches. A multi-agent based system for distribution network reconfiguration is proposed. The system consists of load agents and switch agents located at the loads and switches in the network and a global agent located at the substation. The objective is to supply the critical loads while maintaining an acceptable system voltage profile. Simulation results are presented for a typical distribution system named Circuit of the Future (CoF), which is developed by Southern California Edison (SCE).

Index Terms- Smart Distribution Network, Fault Reconfiguration, Graph Theory, Multi-agent technology

I. INTRODUCTION

Distribution systems consist of groups of interconnected radial circuits. The configuration may be varied via switching operations to transfer loads among the feeders. Two types of switches are used in primary distribution systems. They are normally closed switches (sectionalizing switches) or normally open switches (tie switches). Both types are designed for both protection and configuration management [1]. Distribution network reconfiguration is a process that consists of changing the status of the network switches in order to resupply the non-energized areas after a fault occurrence, or optimize given criteria. The reconfiguration problem of radial power distribution networks may be stated as follows: given a load profile for a distribution network with a number of tie lines and switching points, find a radial configuration for the network, which minimizes the network losses, supply the critical loads at acceptable voltage levels [2][6]. The problem can be recast into a graph-theoretic framework, where the problem is to find a spanning tree in a graph with weighted nodes and branches, such that an objective function of the weights, obtained by reference to Ohm's and Kirchoff's Laws, is minimized. Feeder reconfiguration is a very important tool to operate the distribution system at a minimum cost and improve the system reliability/security. However, since there are many candidate switching combinations

in the system, the feeder reconfiguration is a complicated problem. The discrete nature of the switch values makes it discrete optimization problem. Network reconfiguration for loss reduction is a highly complex combinatorial, non differentiable and constrained nonlinear mixed integer optimization problem [4][7][8].

With the evolution to the smart grid, more distributed generations, customer participation, etc will be introduced to the system. In this paper, a multi-agent based system is proposed to reconfigure the smart distribution system when faults occur. There are mainly two categories of agents available in the proposed Multi-agent System (MAS) architecture, which are Local Agents (LAG) and Global Agent (GAG). Load Agents (LAGs) and Switch Agents (SAGs) fall into the category of local agents. These agents represent loads and switches in the power distribution system respectively. The reconfiguration algorithm is embedded inside the GAG, such that whenever it receives fault location it starts reconfiguring the network to reroute the power to critical loads. The objective function of reconfiguration is to always supply the critical load without exceeding the line capacity while maintaining the voltage limits at $0.9 < |V| < 1.1$. The simulation results show that our multi-agent based system can reconfigure the system in a way that it always try to supply all the critical loads in the network. When there are multiple solutions available for reconfiguration, the one with good voltage profile and less power loss is selected as the solution.

II. AGENT TECHNOLOGY

An agent is a computer system that is capable of autonomous action in this environment in order to meet its design objectives. Autonomy means that the components in an environment function solely under their own control. Agents operate and exist in some environment, which typically is both computational and physical. The environment provides a computational infrastructure for such interactions to take place. The infrastructure includes communication protocol and interaction protocols.

Communication protocol enables agents to exchange and understand messages. A communication protocol might specify that messages for a particular course of action to be exchanged between two agents. The behavior of a multi-agent depends not just on its component agents, but also on how they interact. In a multi-agent system of sufficient complexity, each agent would not only need to be able to do the tasks that arise locally, but would also need to interact effectively with

other agents. The communication protocols can be regarded as the specification of these interactions. Protocols are a nice way of enforcing modularity in the design of a multi-agent system. They help in separating the interface between agents from their internal design.

III. MULTI-AGENT RECONFIGURATION MODEL

A. Graph representation of system

We model the power system network as a graph G with a single root. A spanning tree T of G represents the current radial power supply system. Each node of the graph G represents either the power source, or a load, each edge of T represents a physical connection by power lines, and edges in G but not in T represent switches, which are open during normal operation, are expressed as $S(G)$.

The tree, T is oriented in such a way that every node other than the source node (root) has in-degree¹ 1. That is, every node n in T can be reached by a unique directed path in T from the source s to n .

For each edge $e \in E(T)$, let

$S(e) = \{X : X \subseteq S, \text{ such that } (T - e) \cup X \text{ is a connected graph}\}$.

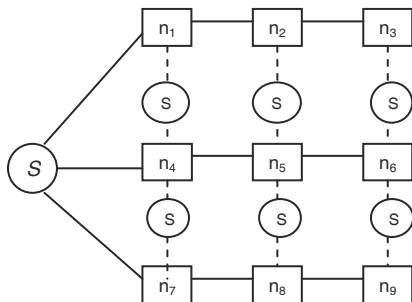


Fig 3.1 Graph model of Power Distribution System

In the above graph model S represents the source such as substation. All feeders $s \rightarrow n_1 \rightarrow n_2 \rightarrow n_3$, $s \rightarrow n_4 \rightarrow n_5 \rightarrow n_6$, and $s \rightarrow n_7 \rightarrow n_8 \rightarrow n_9$ form the spanning tree T . The dashed lines represent the switches and used for fault reconfiguration. This methodology is used to transform the prototype distribution network CoF to a graph. The system graph for CoF is shown in Figure 3.2.

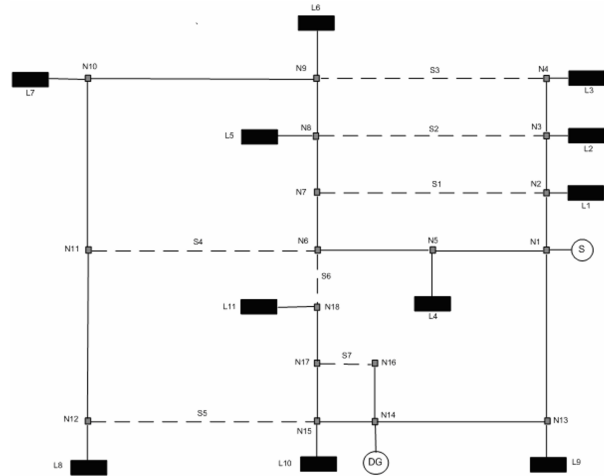


Fig 3.2 System Graph

B. Multi-agent system architecture

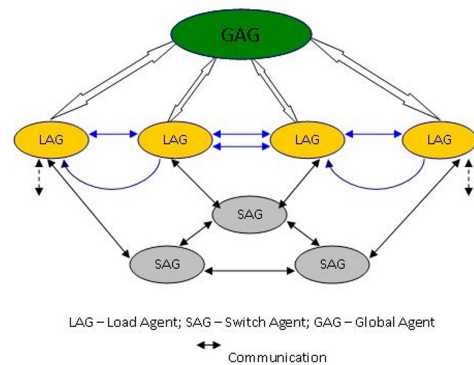


Fig 3.3 Multi-agent architecture

The proposed MAS architecture is illustrated in Figure 3.3. According to the hierarchy, there are mainly two categories of agents available in the proposed MAS architecture. They are Local Agents and Global Agent.

Load Agents (LAGs) and Switch Agents (SAGs) fall into the category of local agents. These agents represent loads and switches in the power distribution system respectively. Any load agent can be associated with a number of switch agents. Whenever there is a fault in the system, load agents and switch agents start communicating and coordinating each other in order to locate the fault location in the network. Once the fault is detected, the fault location is reported to the Global Agent (GAG) by load agents. The reconfiguration algorithm is embedded inside the GAG, such that whenever it receives fault location it starts reconfiguring the network to reroute the power to critical loads.

The local agents such as LAGs and SAGs only can communicate to its neighboring agents. These agents will have local information pertaining to that particular region only. Local agents communicate and coordinate in the sense of decentralized manner, whereas the Global agent operates much in centralized manner. Because of this fact, the proposed MAS architecture is a hybrid MAS architecture. In this hybrid architecture the fault detection is done in a decentralized manner and the fault reconfiguration is done in a centralized fashion.

¹ In-degree of vertex in a graph is defined as the number of edges coming into the vertex.

C. Load Agent

These agents will continuously monitor the loads present in the system. Whenever they sense no power, they start communicating their power flow information to their neighboring agents. Once the fault is detected, the fault location is reported to Global agent (GAG).

D. Switch agent

These agents are the dummy agents, which keep status of the switch position and coordinate with the GAG and LAGs during fault detection and reconfiguration.

E. Global Agent

The Global agent is very important entity in fault reconfiguration. It has all the information regarding network and has the capability of doing load flows. The reconfiguration algorithm is embedded inside the GAG. The objective function of reconfiguration is to always supply the critical load without exceeding the line capacity while maintaining the voltage limits at $0.9 < |V| < 1.1$. GAG will call its Voltage Control routine, whenever there is a need for voltage control. Every time GAG runs the scenario it stores it in its database for learning. When the same scenario happens in the future, GAG recalls its experience and reconfigures the network without using the fault reconfiguration algorithm. This is the main step, GAG employs in reducing the execution time of fault reconfiguration.

Once the fault location has been found and possible switches are explored for reconfiguration. Each time the algorithm executes a scenario, the solution is stored in a database. Next time when the same scenario happens the reconfiguration would run from the database rather than running through the algorithm.

The Fault Reconfiguration algorithm employed in this work is completely based on load flows. The algorithm searches for switches on a particular strategy in which it can reduce number of switch combinations explored for the reconfiguration. For a single fault in the system, the algorithm first searches the single switch combinations which can reconfigure the system. If this switch combination doesn't provide good voltage profile across the network, then the algorithm searches second switch to operate by keeping the first switch on. Some times this will help in establishing voltage profile of the network. If this fails, then the algorithm employs voltage control techniques such as shunt compensation and priority based load shedding for establishing the system voltage profile. The algorithm will choose one reconfiguration with less power losses and good voltage profile as final solution, when multiple solutions are available for reconfiguration. When there are multiple faults in the system, each fault is considered as a single fault and the solutions of all single fault reconfigurations are combined to have the final reconfiguration.

IV. SIMULATION RESULTS

The simulation was carried out based on Power System Simulator, Distributed Engineering Workstation (DEW) and Matlab. Power System Simulator and DEW are applied to model CoF. Reconfiguration algorithm is

developed in Matlab, and MATPOWER. MATPOWER is a MATLAB based power system simulation package [11]. It is a collection of MATLAB m-files to solve the load flow and optimal power flow problems of power system.

CoF has two sources, one is the substation and the other is a distributed generator (DG). The substation is connected with three outgoing feeders, which will serve the loads in the distribution system. This system has 7 switches/disconnectors for the purpose of reconfiguration of faulty network. The distribution network has 14 loads demanding 26.69 MW of real power and 14.578 MVar of reactive power. The network has 14 shunt capacitor banks for the purpose of voltage control. It has two DGs, one for real power generation and other for reactive power generation.

For simplicity purposes the original circuit has been modified by lumping all the loads together without affecting the basic topology and key features of the original CoF circuit. This distribution network from now on will be termed as Simplified CoF. This Simplified CoF has been modeled in Power World Simulator, and is shown in Figure 4.1. The key components of Simplified CoF are listed below,

- 18 Buses
- 17 Distribution lines
- 7 Switchable Distribution lines (Switches/disconnectors)
- 11 fixed loads (P: 26.69 MW, Q:14.578 MVAR)
- 1 DG (P: 3 MW)
- 1 Substation
- 7 shunt capacitor banks (4.5 MVAR)

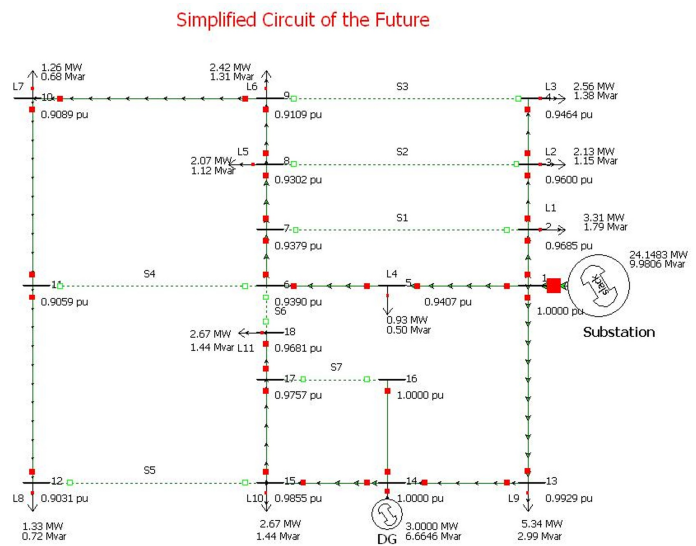


Fig.4.1 The Simplified CoF modeled in Power World Simulator

The 11 loads, which exist in the Simplified COF, have load priorities depending upon the importance of particular load. Loads such as Hospital loads and Industrial loads are given higher priority than any residential loads in the system. This distinction of the

loads is necessary in the load shedding process for voltage control. The loads with lower priority will get shed before the higher priority loads. There are three higher priority loads (L_3 , L_8 and L_{10}), three lowest priority loads (L_7 , L_9 and L_{11}) and five middle priority loads (L_1 , L_2 , L_4 , L_5 and L_6) in the network.

The network has 7 shunt capacitor banks of total rating 4.5 MVAR. These shunt capacitor banks are normally open during normal operation of the system. These will be operated whenever there is a need of voltage support in the network. There is one Distributed Generator (DG) available in the network, which can supply 3 MW of real power to the critical loads connected to it.

The loads in the network are fixed loads and modeled as PQ buses in the load flow formulation. The substation is modeled as a Slack bus and the DG is modeled as a PV bus in the load flow formulation. This load flow formulation is used for fault reconfiguration.

A. Single fault occurred in line N_1N_2

Once the fault is simulated in Power World Simulator, It produces load flow report which is saved in excel file. This report has the power flow values of all loads. Because of the line fault at line 1-2, the loads L_1 , L_2 and L_3 are not supplied at all.

All the LAGs will be created in the particular feeder, but only those agents which sense zero power start communicating with their incoming neighboring Load Agents regarding whether they have power or not. In this particular scenario, the Load Agents LAG1, LAG2 and LAG3 have no power. Once they sense zero power, they start sending the request message to their neighboring Load Agents; to source, LAG1 and LAG2 respectively. Here source will report its power value to LAG1, LAG1 will report its power value to LAG2, and LAG2 will report to LAG3. The communications between Load Agents will detect the fault location. The fault location obtained by Local Agents then will be reported to Global Agent. When fault location is reported to Global Agent, It performs the MATLAB reconfiguration to reconfigure the network.

This test case describes the key execution steps in fault reconfiguration. The possible single switch combinations for reconfiguring the network according to fault reconfiguration algorithm are,

$$S(e_f) = \{S_1, S_2, S_3\}$$

The algorithm first tries closing the switches S_1 , S_2 , and S_3 individually, and the voltage profiles for each combination are shown in Figure 4.2, Figure 4.3, and Figure 4.4.

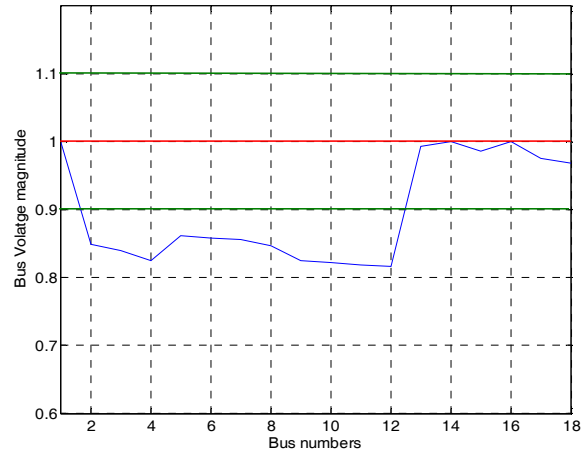


Fig 4.2 voltage profile with S_1 closed for line fault at 1-2

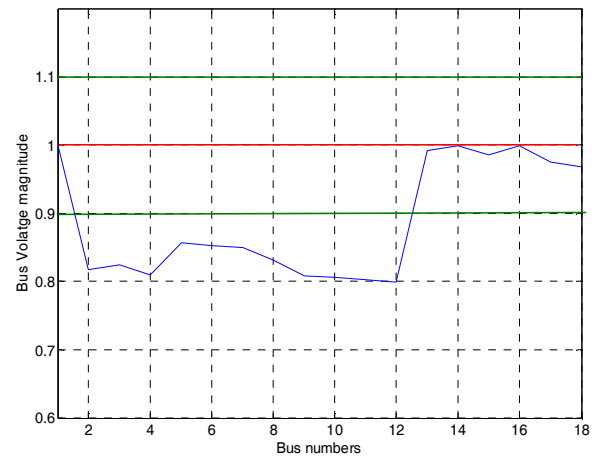


Fig 4.3 Voltage profile with S_2 closed for line fault at 1-2

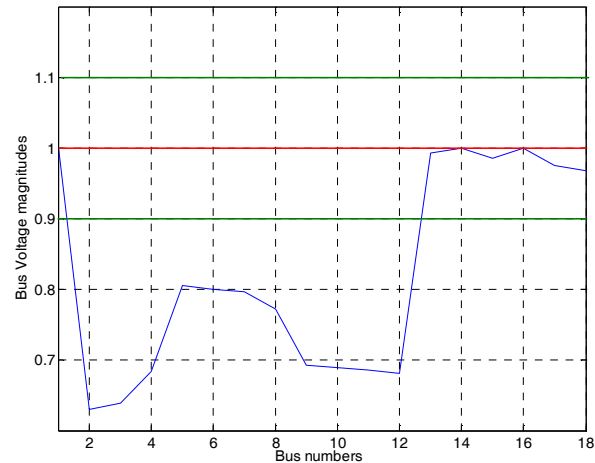


Fig 4.4 voltage profile with S_3 closed for line fault at 1-2

One can observe that none of the individual switch configuration gives the good voltage profile, i.e. voltage magnitude with $\pm 10\%$ tolerance. Now the algorithm searches for one more switch to operate by keeping the S_1 on, which can reconfigure the network with no voltage violation. The same procedure repeats with S_2 and S_3 .

Finally, the fault reconfiguration algorithm finds two switch combinations which have no voltage violations, they are $\{S_2, S_5\}$ and $\{S_1, S_5\}$. The following figures show the voltage profile of the reconfiguration network with the above switch configurations.

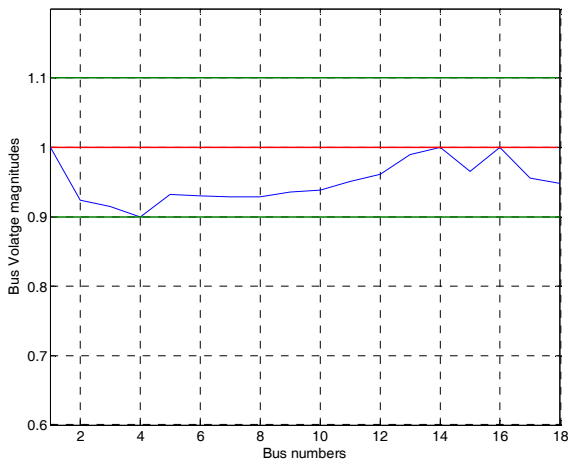


Fig 4.5 voltage profile with S_1 & S_5 closed for line fault at 1-2

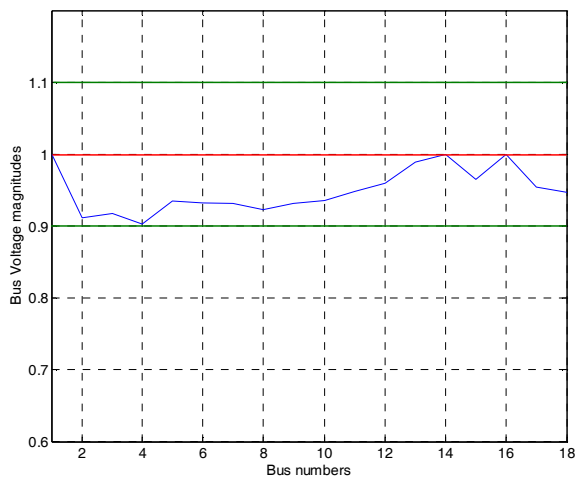


Fig 4.6 voltage profile with S_2 & S_5 closed for line fault at 1-2

Hence there are two solutions for reconfiguring the line fault at 1-2. Whenever there are multiple solutions available for reconfiguration the algorithm chooses the configuration with less power loss. The reconfigured network with $\{S_1, S_5\}$ has 1.087 MW real power loss where as the reconfigured network with $\{S_2, S_5\}$ has 1.151 MW of real power loss. Since, the reconfiguration with $\{S_1, S_5\}$ closed will yield less power loss, this configuration is selected as the final solution for reconfiguration. The final reconfigured network for line fault at 1-2 is shown in the following figure.

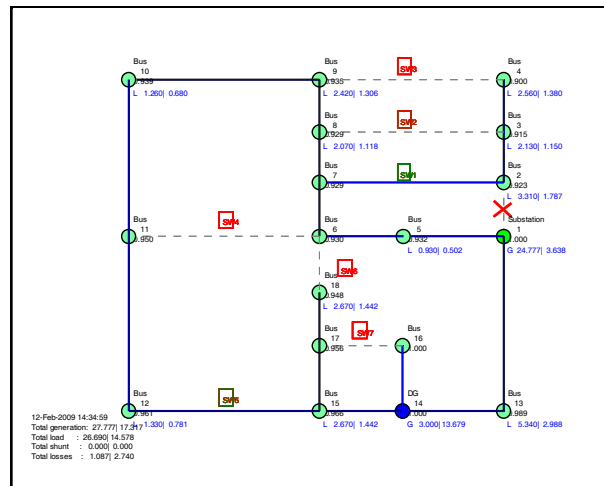


Fig.4.7 Reconfiguration Network for fault at line 1-2

B. Multiple faults occurred in lines N_1N_2 , $N_{14}N_{15}$, and $N_{11}N_{12}$

Let us assume that there are three line faults at 1-2, 14-15, and 11-12. In this scenario, the algorithm comes up with switch combination $\{S_1, S_5, S_7\}$ for reconfiguring the network. The voltage profile with this switch combination is shown in the following figure,

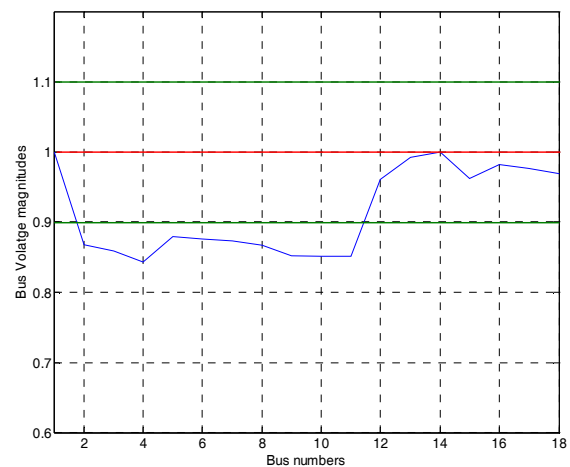


Fig 4.8 voltage profile with S_1 , S_5 & S_7 closed for line fault at 1-2, 14-15 and 11-12

From the above figure it is clear that there is voltage violation. In this scenario, the algorithm calls the voltage control routine to achieve the good voltage profile. The reconfiguration algorithm employs shunt compensation and priority based load shedding for providing good voltage profile across the network. The low priority loads such as, L_{11} , L_9 , L_7 & L_1 are shed and shunt compensation of 4.5 MVARs are provided in order to achieve good voltage profile. The final reconfigured network is shown in the following figure.

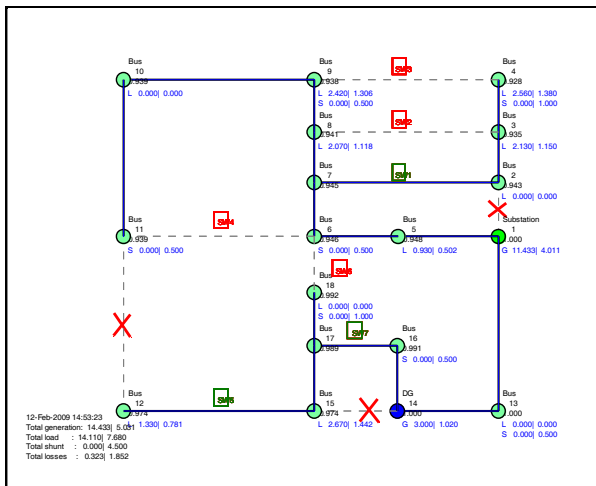


Fig.4.9 Reconfiguration Network for faults at lines 1-2, 14-15 and 11-12

V. CONCLUSION

The approach deploys multi-agent system in conjunction with graph theory algorithms to reconfigure the system. The proposed Multi-agent system makes use of both centralized and decentralized methods to make up for the disadvantages of each method. The proposed model of MAS is tested on proto-type distribution network named Circuit of the Future (CoF). The team is developing multi-agent deployments and application algorithms to reconfigure the system to supply the critical loads and to maintain the good voltage profile across the network even in the event of faults. The fault reconfiguration algorithm makes use of shunt compensation and priority based load shedding in order to control the voltage. The fault reconfiguration algorithm proposed in this paper chooses the best possible switching configuration in regards to voltage profile and real power loss in the system. The results obtained are very promising and show superior ability of Multi-agent systems in the field of fault detection and reconfiguration. The next stage of the work will be focused on reconfiguration in a even more complicated smart system and finding better interface between different simulation platforms for efficiency improvement.

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VII. BIOGRAPHIES

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