Application of Multi-Agents for Fault Detection and Reconfiguration of Power Distribution Systems

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***Abstract*--The electric power system has become a very complicated network at present because of re-structuring and the penetration of distributed generation and storage. A single fault can lead to massive cascading effects affecting power supply and power quality. An overall systematic solution for these issues could be obtained by an artificial intelligent mechanism called the multi-agent system.**

This paper presents a multi-agent system model for fault detection and reconfiguration based on graph theory and mathematical programming. The multi-agent models are simulated in Java Agent Development Framework and Matlab® and are applied to a power system model designed in the commercial software, the Distributed Engineering Workstation©. The circuit that is used to model the power distribution system is a simplified model of the Circuit of the Future, developed by Southern California Edison.

Possible fault cases were tested and a few critical test scenarios are presented in this paper. The results obtained were promising and were as expected.

***Index Terms*—Multi-agent System, Fault Detection, Power System Reconfiguration**

I. Introduction

THE electric power system has become a very complicated network at present because of restructuring and the penetration of distributed energy resources. In addition, due to increasing demand for power, issues such as transmission congestion have made the power system stressed. A single fault can lead to massive cascading effects, affecting the power supply and power quality. The massive 2003 Northeast Blackout is a very good example for this type of failure. An overall solution for these issues can be obtained by a new artificial intelligent mechanism called the multi-agent system.

An agent is defined as "an autonomous computational entity such as a software program that can be viewed as perceiving its environment through sensors and acting upon this environment through its effectors" [1]. A multi-agent system is a collection of agents, which senses the environmental changes and acts diligently on the environment in order to achieve its objectives. Due to the increasing speed and decreasing cost in communication and computation of complex matrices, multi-agent system promise to be a viable solution for today's intrinsic network problems.

Conventionally, many applications in power system were solved by human actions by obtaining information from the system. These same actions when operated by agents, can give timely and more reliable decisions with less human intervention. In addition, agents can learn from their previous experiences and act accordingly during different fault situations.

Multi agent system have been applied to several areas in power systems, such as reconfiguration and restoration, fault detection, protection coordination, voltage stability control, reactive power control, electricity market pricing etc. These theoretical based researches are being applied, at present, to terrestrial power systems to test the reliability of MAS. Recently more research work based on complicated applications in the real world is being carried out. In their paper, Cartes and Srivastava analyze the potential of agent application and their future in power industry [2]. They present a SWOT Analysis (Strengths, Weaknesses, Opportunities and Threats) framework for agent based applications in the area of power systems.

Moreover, several authors have addressed the issue of fault diagnosis and reconfiguration specifically. The paper by Li Liu et al. [3] describes the need for fault detection in naval shipboard power system. The paper discusses the practical fault detection and diagnosis problem along with prognostics from control engineering perspective. In their fault diagnostic framework, the task has been defined as to constantly monitor the process and from the available observations, to identify an indication to decide whether there is a fault or not, and to identify the fault location.

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Different approaches are followed for dynamic fault detection process, such as modeling and estimation method [4], [5], using analytical redundancy [6], [7], factorization approaches [8], etc. More recently, Huang et al. [9] have presented a multi agent approach for fault detection. The fault is detected by using nonlinear parameter identification techniques. Once the fault is detected, the diagnosis agent makes further decisions on the fault mode, fault location and fault severity. This study has been performed by using a particle swarm optimization approach.

Many authors have conducted research in the area of reconfiguration and restoration of power systems, primarily for shipboard power systems. Solanki et al. [10], [11], have presented different approaches for restoration of power system by distributed reconfiguration.

In this paper, a new approach based on graph theory and mathematical programming is presented for fault detection and reconfiguration of power distribution systems. Section II will portray the issue analysis and how it is addressed. Section III will discuss the mathematical model and finally, Section IV will present the results of the simulations.

II. Problem Statement

This paper will focus on the application of MAS for fault detection, reconfiguration and restoration. The study is based on a proto-type circuit, the Circuit of the Future (CoF) developed by Southern California Edison (SCE).

The algorithm ensures that the multi-agents, which are installed at all the nodes, sources, loads and switches, will communicate and co-ordinate with their neighboring agents, in order to provide a reliable power supply. This is achieved by re-routing the power flow when there is a line fault, and supplying the high priority loads, when there is a shortage of power supply and also switching on the Distributed Generation (DG) when the need arises.

The circuit is modeled using the Distributed Engineering Workstation (DEW), a power distribution software developed by Electrical Distribution Design Inc. The software used to design the MAS is the Java Agent Development (JADE) framework and Matlab. Fault detection algorithm is developed by JADE and reconfiguration algorithm is implemented in Matlab agent model to allow conditional switching. Different fault scenarios were studied and the circuit was analyzed for better performance.

III. Mathematical Model

An agent application has to be first modeled mathematically, which can be then translated to software packages for implementation. Thereby, this section presents a new algorithm for fault detection and reconfiguration, based on graph theory.

A. *Graph Theory*

Graph Theory is a study of graphs and mathematical structures that can represent any network applications. Graph is a context, refers to a collection of vertices or nodes and a collection of edges or arcs that connect pairs of vertices. Many practical applications, which can be represented as networks, can be modeled based on graph theory. Therefore, a power system, which is a very complicated network, is modeled as a graph in this work.

The power system network is modeled as a graph, *G*, with a single root, as shown in Figure 1. A spanning tree, *T* of *G* represents a radial power distribution feeder. Each node of the graph represents a power source, a node or a load and each edge of *T* represents a physical connection of different nodes through distribution lines. The edges in *G*, but not in *T*, represent switches, which are normally in an open state.

Notations:

G - graph, represents the power system network

T - spanning tree, represents a radial feeder of the power system

N - set of nodes in the network that is modeled as a graph *G*, represents source, buses, switches or loads

E - set of directed edges, usually called arcs of *G*, represents the distribution lines

s - power source, represents a substation or a DG

S(E)- set of edges in G, but not in *T*, represents the set of switches in the system

An agent is placed at every node and every switch.

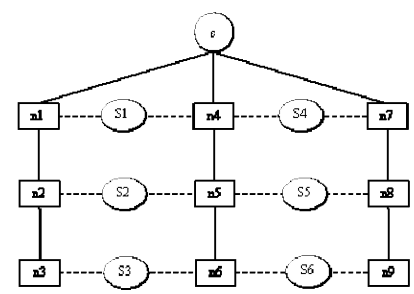

Fig. 1. Diagram of the notation of a Graph

In the above graph, *G*, each branch, $s \to n_1 \to n_2 \to n_3$, $s \to n_4 \to n_5 \to n_6$, $s \to n_7 \to n_8 \to n_9$ is a tree. The edges which are in the graph, but not in the trees are the switches, *S1-S6*.

Orientation of T:

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

Presetting:

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

S(e) = {X:X⊆S, such that (T-e)∪X is a connected graph}.

B. Fault Detection Algorithm

The first step towards the reconfiguration is to identify the fault location precisely. The fault detection algorithm constantly monitors the power flowing into each load and follows the algorithm described below to identify the fault location.

Let us assume that the fault location detected by the node agents is at n_f. Suppose a node agent n identifies that the power flowing into its node is zero, then on the unique directed path from s to n, say $s \to n_1 \to n_2 \to n_3 \to ...... \to n_k$, where $n=n_k$, n_k will request n_{k-1}, whether it has power. Subsequently, n_{k-1} will request n_{k-2} for its power. When for some *i*, n_i does not have power, but n_{i-1} has power, the faulty edge can be identified as, $e_f = (n_{i-1}, n_i)$.

Once the fault location is identified, the edge e_f is isolated and agents that are controlling each switch $X \in S(e_f)$ will communicate and coordinate with each other to decide on the particular switch or switches that have to be switched on, so that $(T - e_f) \bigcup X$ will continue to be a fully supplied network.

The mixed programming algorithm for reconfiguration through selection of proper switching is given in the next section.

C. Reconfiguration & Restoration Algorithm

It is vital to restore the power supply promptly by re-routing the power flow through a target configuration, when the power supply is interrupted by a fault. The problem of obtaining a target system is referred to as power system restoration [12].

The fault location, e_f, has been found from the previous algorithm and a collection of possible switches, $S(e_f)$ have been provided. Thereby, the graph $G(e_f)$ is the graph obtained by incorporating $T - e_f$ and all the edges as a member in the collection $S(e_f)$. This algorithm assumes that each edge in the tree can be isolated in order to reconfigure the system.

Let, P_s be the total amount of available power from the source in the system.

For a node *i*, let P_{L_i} denote the active power consumed by the load at *i* and,

$O_i = \{(i,j) \in E : j \in N\}$, out flow from node *i* and,

$I_i = \{(j,i) \in E : j \in N\}$, in flow to node *i*.

For an oriented edge, *e*, let P_e denote the amount of power flowing through *e*, and let Y_e denote the state indicator variable:

$$Y_e = \begin{cases} 1 & \text{if } e \text{ is closed} \\ 0 & \text{if } e \text{ is open} \end{cases}$$

It is prudent to assume that for each edge $e \in (E(T) - \{e_f\})$, $Y_e = 1$. Therefore, the only fact that has to be decided is which of the switches will be closed and which should remain open.

Objective Function:

Maximize $\sum_{i \in N} W_i P_{L_i}$

Where, W_i is the priority of the load, given as a weight, and P_{Li} the supplied load. N is the number of all load agents.

Subject to constraints:

- $P_S \geq \sum_{i \in N} P_{L_i}$

i.e. the total load should not exceed the total capacity of the source

- $P_{ij} \leq P_{ij,\max}$

i.e. the power flow through any arc or directed edge, *e*, when it is closed, should not exceed the capacity of the edge. Where P_{ij} is the real power flowing through the line connecting nodes *i* and *j* and $P_{ij} \leq P_{ij,\max}$ is the maximum allowable power through that line.

A node that is not a source node is called an intermediate node.

- At a non load intermediate node *i*, the amount of power flowing in should be the same as the amount flowing out.
  $$\sum_{e \in I_i} P_e - \sum_{e \in O_i} P_e = 0$$
- At a load node *i*, the amount of power flowing in should be equal to the sum of the amount flowing out and the load at *i*.
  $$\sum_{e \in I_i} P_e - \sum_{e \in O_i} P_e = P_{L_i}$$
- The distribution system is radial, i.e., the total number of incoming edges at any node is at most unity.
  $$\sum_{k \in I_i} e_k \leq 1$$

A reconfigured topology is achieved by selecting from the choice of $S(e_f)$, which comply with the objective function and the constraints listed above.

IV. Simulations & Results

The new algorithms for fault detection and reconfiguration have been tested for different scenarios. The fault detection was simulated in JADE and reconfiguration was tested in Matlab. Both the results were combined with DEW for power system simulation and the results were tested for voltage compliance.

A general model for the application of MAS in the power system engineering is shown in Figure 2. The proposed MAS architecture is illustrated in Figure 3. It consists of Load Agents (LAGs), one for each load, and Switch Agents (SAGs), corresponding to each switch or disconnector in the system. Any LAG in the circuit can be associated with one or more SAGs. These agents coordinate with each other in order to detect the faults in the system and re-route the power flow to better serve the customers.

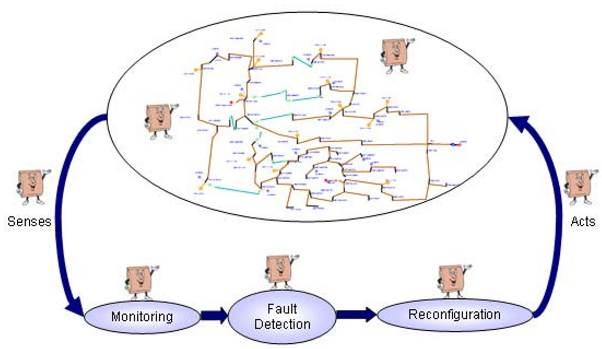

Fig. 2. Generic model of the MAS application in Power Distribution System.

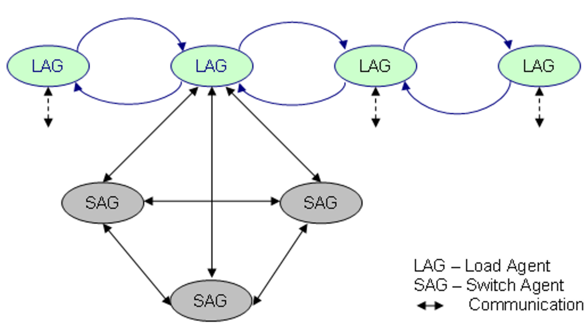

Fig. 3. Architecture of the Proposed MAS.

The simulations were carried out for a proto-type power distribution system, a simplified model of the Circuit of the Future (CoF), developed by Southern California Edison (SCE). The CoF modeled in DEW, has a single substation, with three main feeders, which are also connected for flexible re-routing of power flow, through 7 switches/disconnectors which are normally open. The circuit has 14 loads demanding total real power load of 24 MW and reactive power load of 12.96 MVar. It has 14 Capacitor banks for providing Var support and two DGs, one providing real power and the other reactive power. Since the capacitor banks can cater for the entire reactive power loads and losses in the system, only the active power flow is considered in the simulations.

For simplicity for simulation purposes, the original circuit is slightly modified by lumping certain loads without affecting all of its 7 switching locations and the original system topology. The modified CoF will have 11 loads, 7 switches, 18 nodes, a Substation and a Distributed Generating Source, which provides real power. The distribution system is considered to be a radial system in all system configurations. For simulation purposes of serving the high priority loads, when there is a power shortage, three loads have been chosen to be high priority loads and two loads have been chosen as low priority loads. The rest of the loads are given medium priorities.

A. *JADE Fault Detection Simulation*

JADE Fault detection simulation can be initiated by creating JADE agents from reading a text file, which is generated by DEW after running the load flow application.

Test Case 1: Single Line Fault

The system is simulated for a single line fault at the very beginning of one of the three main feeders.

When the JADE MAS is applied, the relevant load agents communicate with each other to find out the fault location. The message passing is clearly shown in the JADE Sniffer agent GUI in Figure 4.

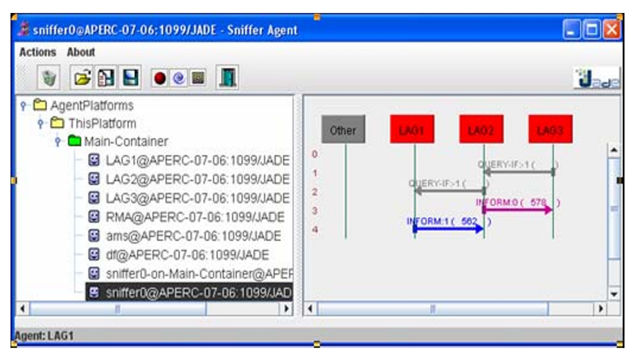

Fig. 4. JADE Message Passing to identify the fault location for a single line fault.

All the LAGs will be created in the particular feeder. But only those LAGs which identify, that they have no power flowing in, will send a request message to its incoming neighboring agents whether the neighboring agents have their loads supplied or not and wait for their reply. Since, this particular feeder has only three loads, all three LAGs, do not have power flowing into their loads due to the fault at the beginning of the feeder. Hence the LAGs which receive the request message reply to the sender with their flow values. Since all the LAGs have zero flows, the fault location can be identified accordingly.

Test Case 2: Multiple Faults

For testing a multiple fault scenario, let us assume that there are 3 faults in all three feeders at different locations. This situation has been run in JADE fault detection program and the message passing between the LAGs have been observed to be as shown in the following figure.

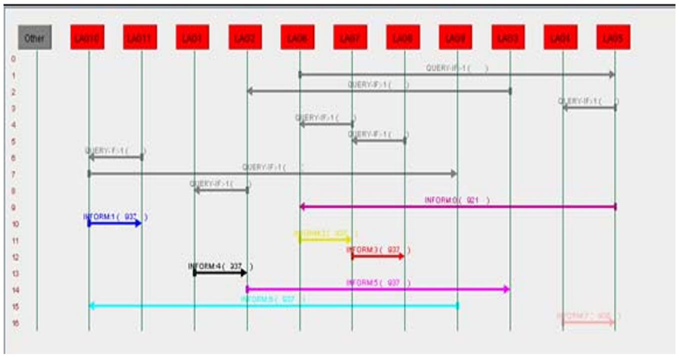

Fig. 5. Sniffer Agent GUI for Multiple Fault Scenarios.

B. Matlab Reconfiguration Simulation

Reconfiguration of the CoF has been implemented in Matlab using graph theory. As in the Fault Detection algorithm, each fault location will be identified by the relevant LAG, and will have corresponding combination of SAGs for reconfiguration. Each proposal is reconfigured using the Matlab Energy Management System [13], to find the best solution for CoF. All the possible fault cases have been tested in the model.

Reconfiguration is carried out based on maximum flow algorithm. The maximum flow principle is a branch of graph theory and combinatorial optimization. It seeks a feasible solution that sends the maximum possible flow from a source to a sink node. In the reconfiguration of energy management system, maximum flow algorithm represents the power system as graph orientations [13].

A GUI is developed for easy user interaction for carrying out simulations. Four different scenarios can be developed. A line fault can be created by specifying the 'from node' and the 'to node' agent names. The source capacity can be decreased to test the shortage of supply from the substation, by entering the new capacity. It is also possible to change the capacity of the DG and the priorities of the loads for testing purposes. Multiple types of fault scenarios can also be simulated.

Test Case 3: Line Fault

Assume that a fault is identified between agent numbers 2 and 3. The algorithm is run to reconfigure the system in order to achieve the objective function and satisfy all the constraints, explained in the previous sections. Figure 6 shows the reconfigured circuit.

It can be seen that, from all the switching possibilities, switch 1 and 5 are operated in order to supply the loads in the faulty feeder. However, since, this fault is in one of the three main feeders, the total load of 24 MW, cannot be supplied due to capacity constraints of the other two main feeders. Within the available capacity, all the high and medium priority loads are supplied and only the least prioritized loads are not supplied fully due to capacity constraints.

Out of all the possible line faults that can occur in the CoF, this particular fault, is the least desirable fault, where the total load cannot be supplied without overloading the distribution lines. In all other line fault cases, combination of switches can be found for system reconfiguration, without curtailing the power supply to any loads.

Test Case 4: Shortage of Source Capacity

In the event that the source has a shortage of capacity, the new topology of the system is found in such a way to ensure that with the available source capacity, first the high priority loads are supplied. In case, there is still remaining source power available, the lower priority loads are supplied in the priority order.

In this test case, it is assumed, that the source capacity is reduced to 3 MW, from 24 MW. From the reconfigured network, shown in Figure 7, it can be observed that 3 MW is not even adequate to supply the high priority loads. Hence, to supply the remaining high priority loads, the DG is switched on. However, since the source and DG have a total source of 4 MW, but the high priority loads add up to 6.56 MW, even the total prioritized loads cannot be supplied fully with both the substation and the DG sources**.**

C. Algorithm Execution Duration

Both the fault detection and reconfiguration algorithms are tested for the duration of operation. Time durations obtained from the testing of several executions are plotted. Figure 8 shows the execution time taken for 100 samples of fault detection processes. It can be seen that the average time taken for execution of fault detection is 22.4 ms. Figure 9 shows the execution time taken for reconfiguration for 50 sample executions. The average time taken for the reconfiguration process is 14.5 seconds.

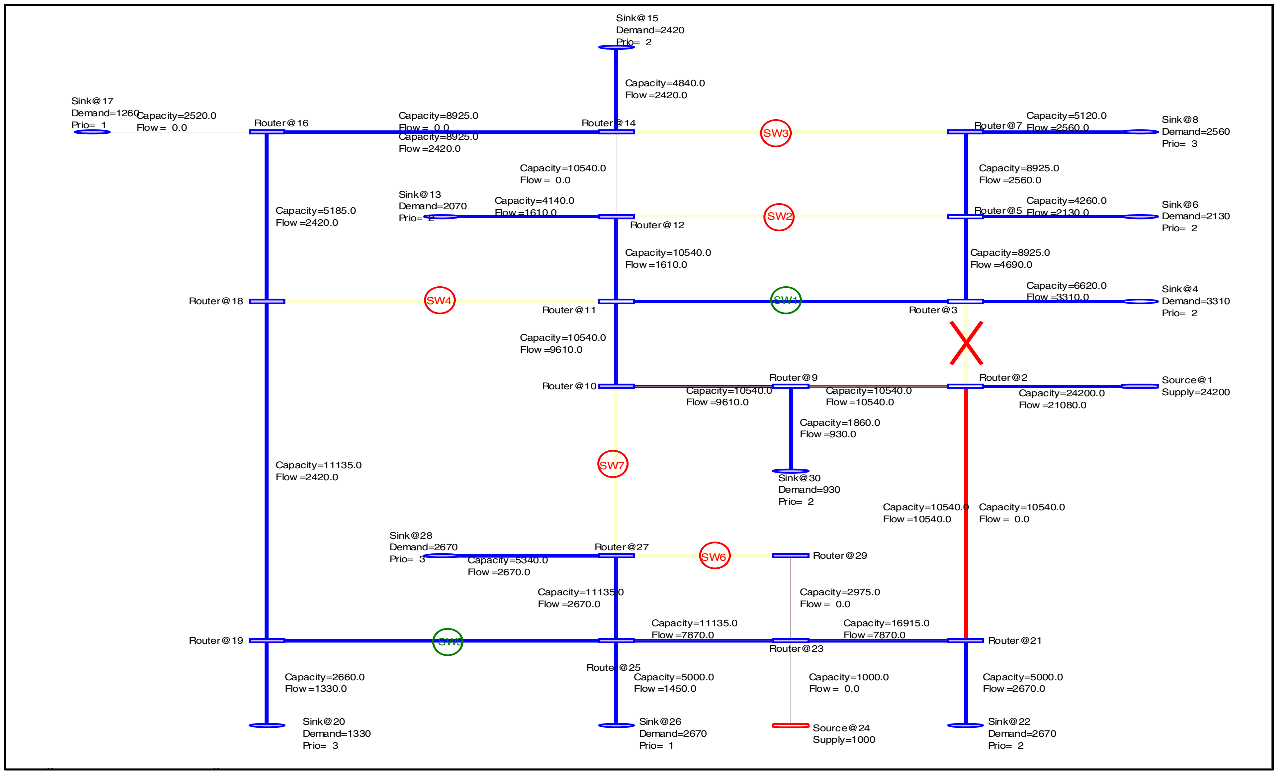

Fig. 6. Reconfigured system after the line fault.

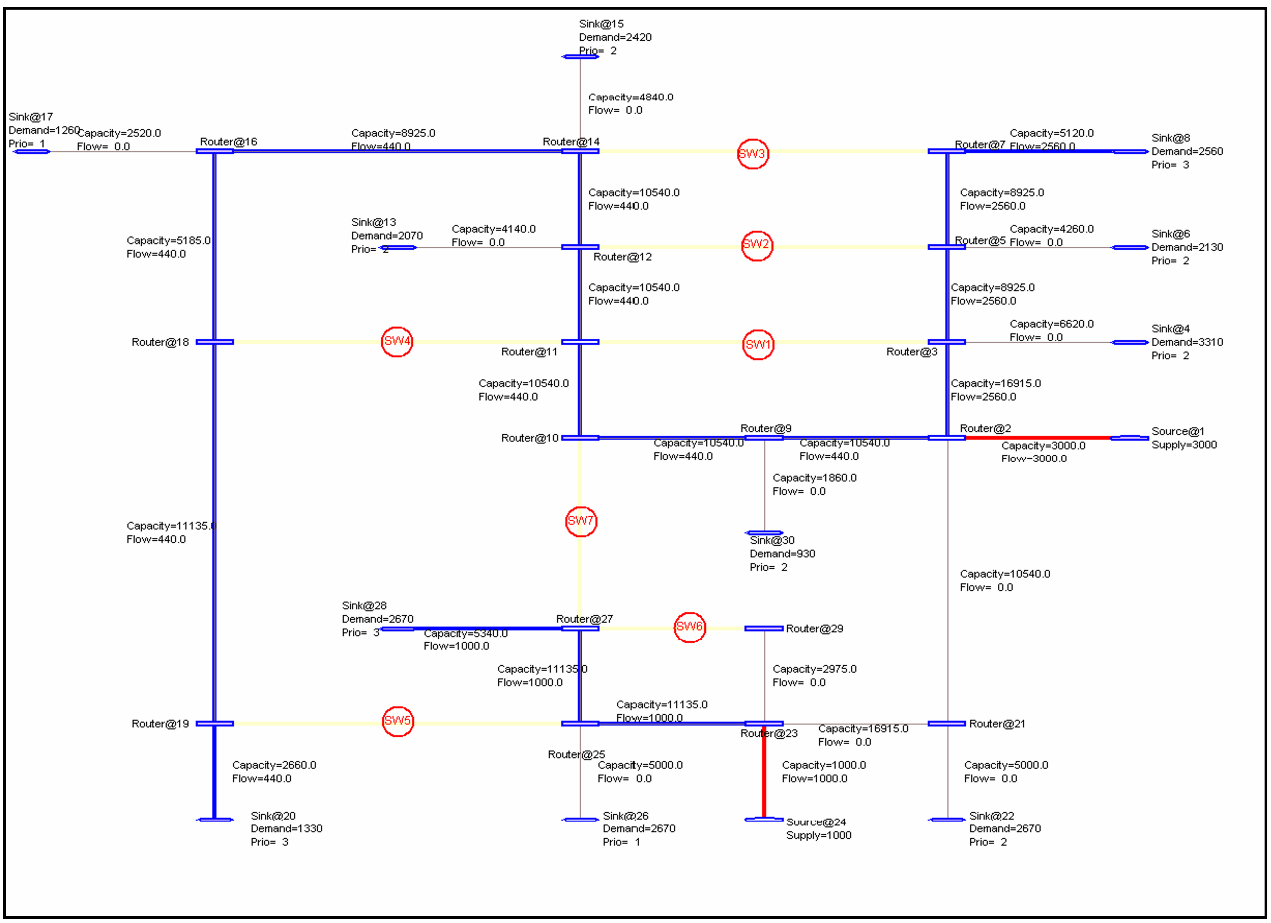

Fig. 7. Reconfigured System after a shortage in source capacity.

It has to be noted that the average execution times calculated are for the proto type circuit simulated in this work. But in reality, the execution time will be higher than the software simulation durations given in this section. This is due to the time taken for interfacing the software with the hardware and also due to the actual time delay in communication links that are used for message transportation.

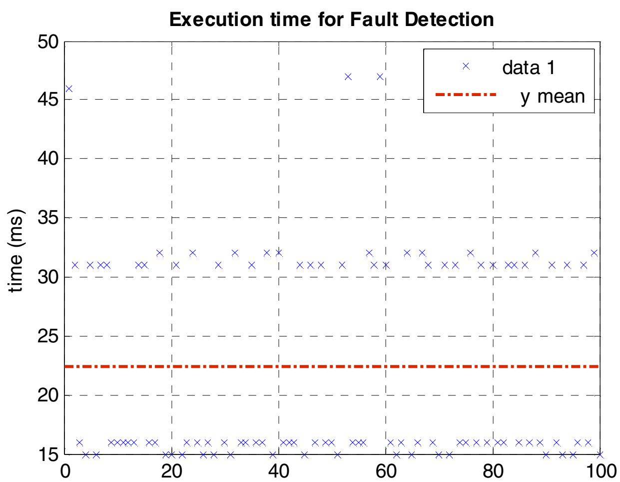

Fig. 8. Plot of Execution Time for Fault Detection Algorithm.

Fig. 9. Plot of Execution Time for Reconfiguration Algorithm.

D. Voltage Profile

It is important to test the voltage profile of the reconfigured system to check whether the customer voltages are maintained within the tolerance limit. Hence the original system and the Test Case 3 were simulated in DEW to analyze the voltage profile in Figure 10 and Figure 11 respectively.

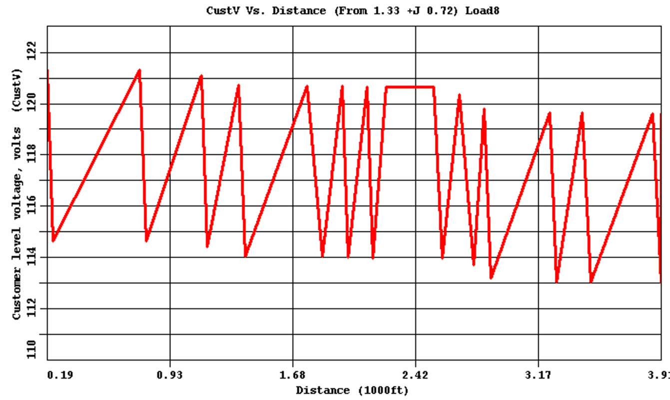

Fig. 10: Voltage profile of the CoF under normal operations.

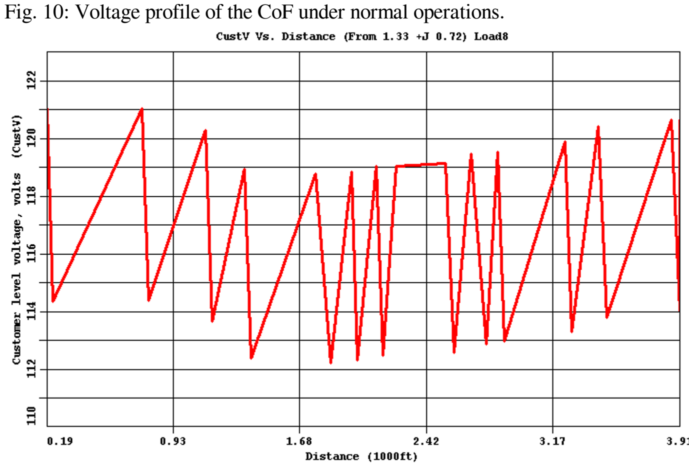

Fig. 11: Voltage profile of the CoF under the faulty situation in Test Case 3.

From the above graphs, it is shown that by reconfiguring the system, the system voltages are maintained within its limits of ±10% tolerance.

The reason for the voltage peaks and dips observed in the graphs above are due to the capacitance of the distribution cables in the system.

V. Conclusion

Multi-agent system models for fault detection and reconfiguration applications for a proto-type circuit are presented in this paper. The model was developed based on graph theory. The circuit concerned is the Circuit of the Future, a power distribution system that has three main feeders, several loads and switches.

All possible fault scenarios were tested in both the models. The results obtained are promising and it shows a very good start in the direction of MAS application in power distribution system.

The simulations reveal that the critical line fault that can occur is in the very beginning of the first feeder, which causes 12.24% of the total unsupplied demand. This harms the system reliability and can be avoided if the distribution line capacity can be increased.

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VII. BIOGRAPHIES

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