Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2019) 27: 2226 – 2242
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doi:10.3906/elk-1806-220

Automatic fault isolation and restoration of distribution system using JADE based Multi-Agents

Indhumathi CHELLASWAMY[1], **Joy Vasantha RANI SP**[2]
[1]Department of Electrical and Electronics Engineering, T. J. Institute of Technology, Chennai, India
[2]Department of Electronics Engineering, Madras Institute of Technology, Chennai, India

Received: 29.06.2018 • **Accepted/Published Online:** 06.01.2019 • **Final Version:** 15.05.2019

Abstract: This paper proposes a solution for automatic service restoration along with automatic fault location and isolation of the faulty sections in feeder in a power distribution system. A Java agent development environment-based multiagent system (MAS) is proposed to solve the problem of automatic service restoration in smart grid distribution systems. The agent-based solution development is discussed in detail and the MAS application to solve power restoration problem is elaborated in this paper. A study is done on a modified IEEE 33 bus system and the solution is implemented in the Velachery substation of the Tamilnadu electricity board. The results prove that fast and effective fault location, isolation and service restoration is achieved using the proposed solution.

Key words: Automatic service restoration, fault diagnosis, multiagent system, self-resilient power system, distribution system restoration

1. Introduction

With the increase in the size of power infrastructure, the complexity of the power distribution has increased multi fold. This is due to the inevitable increase in the demand for electric power. With the advancements of technology, the prospect for reliable power supply and swift service restoration after a fault has also increased. During a fault in a feeder, feeder sections downstream to the fault are also blacked out due to the radial nature of the distribution systems. In cases of manually controlled grids, upstream sections are restored by closing the recloser after manual detection and isolation of the faulty section. Automation of the distribution system can enable much faster restoration of supply [1,2] to downstream healthy zones by opening sectionalizes of the faulty sections and closing the tie switches from appropriate restorative backup feeders. The key points of importance are the feasible restoration configurations and the duration to achieve the reconfiguration.

In most power distribution systems, the fault identification, isolation of the faulty section, and the restorative actions for service restoration after a fault are manual and hence are considerably time-consuming than automated control. Heuristic [3], metaheuristic [4,5], expert system [6], and mathematical solutions [7] for automation offer a centralized approach of solution. However, these methods burden a central solver with huge amount of data to be handled in order to arrive at the reconfiguration solution, thus requiring enormous computational capacity. Further inclusion of time constraints increases the complexity of the problem [8,9]. Though these methods may prove relatively effective for small-scale distribution systems, implementing these approaches for larger systems and smart distribution systems that include distributed generation and renewable sources may prove challenging.

*Correspondence: indhu.cs@gmail.com

To overcome the computational challenges in the centralized approaches and to minimize the time for service restoration, multiagent system approaches have gained popularity in an effort towards achieving self-healing grids with more reliability. Reliability of a utility's distribution system is measured using indices such as System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), and Customer Average Interruption Duration Index (CAIDI) [10]. The proposed agent-based solution reduces the number of sustained outages and hence improves the reliability index of the power system.

An agent is defined as a computer system situated in an environment that is capable of autonomous action in its environment to meet its objectives [11]. A multiagent system consists of many of the distributed intelligent agents that are capable of communicating and collaborating among themselves and execute behaviors by accessing decentralized data to achieve the system goal. Multiagent systems are preferred over the centralized approaches because of their ability of decentralized data handling and processing and decision making, which makes them a much faster solution. MAS has recently been much researched for solving several power system problems such as power system restoration and monitoring [12–17], distributed energy resource (DER) management [18,19], and fault diagnosis [20] problems. Though nonhierarchical decentralized MAS approach in [12] for transmission lines and [13] avoids single point of failure, it does not guarantee an accurate solution as agents do not have complete information of the system states. Also, the number of communication between the agents is much higher and though agents in [14] have much broader information on the system, a central agent is responsible for decision making. A multiagent system for fault isolation in microgrid is discussed in [15] without the restoration operation, whereas [16] details an agent-based restorative approach for microgrid assuming fault isolation has been completed. The authors in [18] propose a multiagent system for power system facility maintenance mainly detailing the agent requirements. The proposed approach has agents in a layered architecture that have complete information of the system and decision making capabilities within the layer or in communication with one higher layer agents thereby reducing the communication and time required for optimal decision making. Also, the same set of agents are efficiently utilized for fault isolation as well as service restoration. The hybrid approach overcomes the disadvantage of the centralized architecture as the data is disseminated to agents at various layers where the processing of the data is done, hence reducing computational burden of a single centralized agent and that of decentralized architecture by the design of a single-agent layer at the upper hierarchy responsible for decision making in order to achieve a globally optimal solution.

The paper is organized as follows: Section 2 briefly describes the multiagent architecture. Section 3 explains in detail the proposed logic for fault isolation logic and Section 5 details the service restoration logic. Analysis of the results from the simulation of faults on the modified IEEE 33 bus system and the Velachery SS (substation) model and Java agent development environment (JADE) agent communication during normal and fault conditions are presented in Section 5. Section 6 presents the conclusion.

2. Multiagent architecture

This section details the architecture of the multiagent system proposed for fault location, isolation, and service restoration (FLISR).A multiagent system greatly reduces the need for human intervention as it can make autonomous and intelligent decisions based on the system variables and the agents can act to implement the decision at the physical layer level through intelligent electronic devices (IEDs) in the distribution system. Multiagent system is an extended area of distributed artificial intelligence. Application of multiagent system in the area of power system including power system protection are presented in [21–25]. Multi agent systems have also been used for solving many other power engineering problems such as power quality monitoring, demand management, microgrid automation, and market simulations [26–32]. Many commercial and open-source agent development software such as ZEUS [33], Voyager[1], and JADE [34] are presently available, among which JADE is the most prevalently used framework as it is open-source as well as Foundation of Intelligent Physical Agents (FIPA) compliant. FIPA[2] is an IEEE Computer Society standards organization that promote agent-based technology and the interoperability of its standards with other technologies. FIPA has standardized agent communications through Agent Communication Language (ACL) that has set protocols for message format, exchange, and interaction among agents. Agent communications in JADE are compliant with the FIPA ACL standards.

Three agents are proposed to be used to solve the power distribution system FLISR problem: recloser agent (RA), feeder section agent (FSA), and smart switch agent (SSA).

Each feeder will have one recloser agent, the instantaneous status of which indicates if the feeder has locked out after a fault. Each RA will also have information of the status of the neighboring RAs and the sections in its corresponding feeder. Each feeder section in a feeder has its corresponding feeder section agent. A section in feeder bound by two or more switches is a feeder section. The feeder section agents are at a level lower than the recloser agent. These agents have information of its corresponding smart switches and the IDs of its neighboring upstream and downstream feeder sections. Smart switch agents are the lower most level agents. They have communication with the physical layer and contain instantaneous RMS current and voltage information from the smart switches in a feeder section. The agents receive data at the rate of one value of instantaneous current and voltage every 0.01 s. This data is used for computation to check for fault conditions based on the measured values and calculated equivalent impedance values.

Figure 1 shows the agents architecture developed for the FLISR problem. Each RA has information of the neighboring RAs for the computations during service restoration.

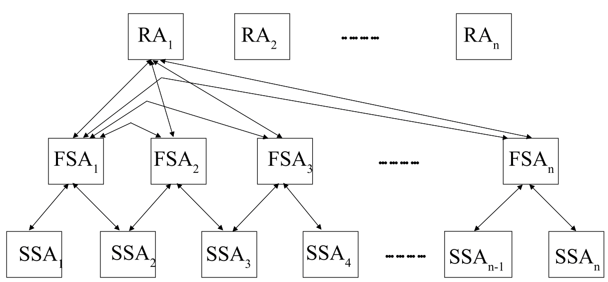

Figure 1. MAS design.

3. Fault isolation logic

Automatic fault location and isolation are imperative in developing a self-healing power distribution system. The process of service restoration can commence only after the fault has been correctly located and promptly isolated. The proposed logic makes use of the instantaneous RMS current and voltage values for fault location and isolation of faulty section.

The smart switches installed at each end of the feeder section of the monitored feeder in the physical layer capture the instantaneous values of RMS current and voltage and send it to the MAS at regular predefined

[1] Voyager (2018). [online]. Website http://www.recursionsw.com/voyager-intro/ [accessed 16 January 2019]

[2] FIPA (2018). The Foundation for Intelligent Physical Agents [online]. Website http://www.fipa.org/ [accessed 16 January 2019]

intervals. Twenty samples are transmitted per cycle of operation to the MAS agents in the proposed method. The multiagent SSA calculates the impedance value based on the received data. SSA is also responsible for comparing the current and previous steady-state values to set the fault indicators as appropriate. If the rate of change of current or voltage exceeds the predefined threshold values based on short circuit computations, the fault indicators are set.

$$I_{change_x} = (I_{RMS(inst)_x} - I_{RMS(SS)_x})/I_{RMS(SS)_x} \quad (1)$$

Here, x is the phase, $I_{RMS(SS)_x}$ is the steady-state RMS value, and $I_{RMS(inst)_x}$ is the instantaneous RMS value of the current.

The recloser agents receive instantaneous data of the status of the recloser from the physical layer and based on this, the RA alerts the corresponding FSA for fault location and isolation. RA alerts the feeder section agents to start the fault location process at the time of recloser operation and fault isolation process at the time of recloser lockout. FSA retrieves the status of its upstream and downstream switches at the time of recloser operation and lockout. The feeder section agents are responsible for fault isolation and they provide the signal to open or close a switch for isolation from the MAS layer to the physical layer.

There are three possible states of operation of the agents, i.e. normal state, recloser switching state, and recloser lockout state. Each agent has a set of behaviors that they perform at one of the three states of operation. The states of operation and the agent behavior during the three states are as below:

a. State 1 - Normal state: The agents involved are FSA and SSA and the behaviors executed are QUERY REF/getSwitchStatus and INFORM/switchData.

b. State 2 - Recloser switching: The agents involved are RA, FSA, and SSA, and the behaviors executed are REQUEST/alertSection, QUERY REF/getSwitchStatus, INFORM/switchData, and INFORM/sectionsAlerted.

c. State 3 - Recloser lockout: The agents involved are RA, FSA, and SSA, and behaviors executed are REQUEST/alertSection, QUERY REF/getSwitchStatus, INFORM/switchData, INFORM/sectionsAlerted, PROPOSE/isolateSection, ACCEPT PROPOSAL/isolatedSection.

Fault location and isolation is done performing the following steps:

i. SS agent gets the instantaneous values of current and voltage from the physical layer to calculate the change in current per phase using Eq. (1). This happens during the normal operation state or state 1

ii. Recloser agent examines the current physical status of the recloser. If a feeder fault has occurred indicated by recloser switching, RA alerts the corresponding FSAs through INFORM behavior. This is state 2 of operation, i.e. the recloser switching state

iii. FS agents send QUERY-REF message to their corresponding SSAs and SSAs respond with the fault indicator status. Based on the indicator status response from the upstream and downstream switches, the FSA calculates feeder section fault indicators. This step also occurs during state 2.

iv. Recloser agent: If the fault is temporary and autoclears during the recloser trials, RA resets the feeder status indicator to normal and sends INFORM messages to its FSAs to intimate that the fault was auto cleared and current state will return to state 1.

v. Recloser agent: If the recloser locks out, i.e. state 3, RA sends a PROPOSE signal to its FSA to start the faulty zone isolation process.

vi. FS agents: Based on the fault indicators received from SSAs in state 2, FSAs calculate zone fault indicator. If fault is identified in a particular zone, FSA sends signal to the physical layer to open the smart switches at upstream and downstream ends of the faulty zone.

vii. FS agent: The FSA of the faulty zone then sends the ACCEPT-PROPOSAL signal to RA and also to its neighboring downstream FSA connecting with the fault in its feeder section. It also sends the command to the physical layer to open the upstream and downstream switches to isolate the faulty section.

Once the fault is located and isolated, all the feeder sections in the faulty feeder are disconnected to start service restoration. This is done through signals sent to the physical layer to open the smart switches at both ends of all feeder sections in the faulty feeder.

4. Service restoration logic

The problem of service restoration aims to maximize the total restored critical loads while minimizing the total switching operations subject to the voltage and current constraints so as to ensure that they are within the limits after restoration and that the radiality of the network is not violated. The aim can be expressed as the two objective functions in Eqs. (2) and (3) and three constraints in Eqs. (4)–(6) as follows:

$$objective1 : max \sum_{i=1}^{N_{Load}} c_i P_i, \tag{2}$$

where c_i is the criticality of the load and P_i is the load to be restored.

$$objective2 : min \sum_{i=1}^{N} \left| \overline{S_i} - S_i \right|, \tag{3}$$

where $\overline{S_i}$ is status of the i_{th} switch postservice restoration and S_i is the status of the switch prior to fault.

$$Constraint1 : U_{min} \leqslant U_a \leqslant U_{max}, \tag{4}$$

where U_a is the voltage of the bus 'a' and U_{min} and U_{max} are the minimum and maximum voltage limits of the bus.

$$Constraint2 : I_k \leqslant I_{max}, \tag{5}$$

where I_k is the line current and I_{max} is the maximum permissible loading of the line.

$$Constraint3 : \sum_{i=1}^{N} N_{S(on)} \leqslant 1, \tag{6}$$

where $N_{S(on)}$ is the number of switches supplying power to a bus at any given time which must be 1, i.e. a given node will be fed by only one branch at any given instant.

The same set of three agents used for fault detection and isolation are also used for service restoration. After isolation of the fault, all the smart switches in the faulty feeder are opened. The recloser is then closed and power is restored for the upstream feeder sections one by one by closing the switches of the feeder section starting from the recloser end. The steps involved in restoring service to the feeder section downstream to the faulty section is as follows:

i. Upstream sections to fault are restored by closing the recloser and RA has information of the total load in downstream to be restored.

ii. Recloser agent sends a call for proposal (CFP) to the feeder sections downstream to the faulty section to get the information about the type of tie switch and available capacity at each of the tie switches.

iii. FS agents: Each feeder section agent through a QUERY-REF signal to its corresponding connected tie switch (SSA), gets the available restorative capacity (ARC).

iv. FS agent: Each feeder section agent then responds to the RA with a PROPOSE message indicating the type of tie switch and available capacity at the switch.

v. Recloser agent decides on the tie switch to be operated for restoration based on tie switch type and its capacity. The tie switch between the feeders of the same bus gets the first priority followed by the tie switch between feeders from different buses supplied by the same transformer, and lastly, the tie switch between the feeders fed by different buses each supplied by its own transformer.

vi. If there are multiple options for restoration by tie switch of the same type, then the deciding factor is the ARC of the tie switch.

vii. Recloser agent sends an ACCEPT-PROPOSAL to the feeder section agent corresponding to the selected tie switch, and the FSA communicates with the physical layer to effectuate the switch operation.

The tie switch with the highest preference and highest restorative capacity is the ideal selected for restoration. After the tie switch is closed, the loads are restored one by one first in the direction towards the faulty section from tie switch and then in the direction away from the faulty section.

5. Test simulations and discussions

A modified IEEE 33 bus system [35] is used to test the fault detection, isolation and service restoration algorithm. The test IEEE 33 bus model is shown in Figure 2. The nominal voltage is 12.66 KV with a total load of 3.72 MW and 2.3 MVAR. The maximum current allowed on the feeder sections under protection is 400 A and in the tie lines, the current carrying capacity is 200 A. The permissible minimum voltage is 0.92 pu and maximum permissible voltage is 1.08 pu. The feeder under consideration is from bus 3 to bus 18 and they are divided into 6 feeder sections (FS1 to FS6). The smart switches (SS1 to SS6) are placed at either ends of the feeder sections and they have information about the total load in the feeder section and the tie switches connected to the feeder section. There are four tie switches, TS1 between bus 21 and bus 8, TS2 between bus 22 and bus 12, TS3 between buses 9 and 15, and TS4 between buses 18 and 22. The tie switches are normally open (NO) and the other smart switches are normally closed (NC).

The tie switches T1 and T2 are type-2 switches between two feeders supplied by the same transformer, T3 is type-1 switch between two zones of the same feeder, and T4 is between the feeder and one of its laterals.

The IEEE 33 bus model is simulated in MATLAB[3], and Eclipse is used for java agent development. An interface 'MACSIMJX' [36] is used to implement data transfer between JADE and MATLAB environment.

For testing, a fault is assumed to occur on feeder section FS4 at Bus 10. After the recloser RC goes through three trials based on the recloser A and D curves, it eventually locks out on a permanent fault.

[3]MathWorks Inc. (2018). MATLAB [Online]. Website https://www.mathworks.com/products/matlab.html [accessed 16 January 2019]

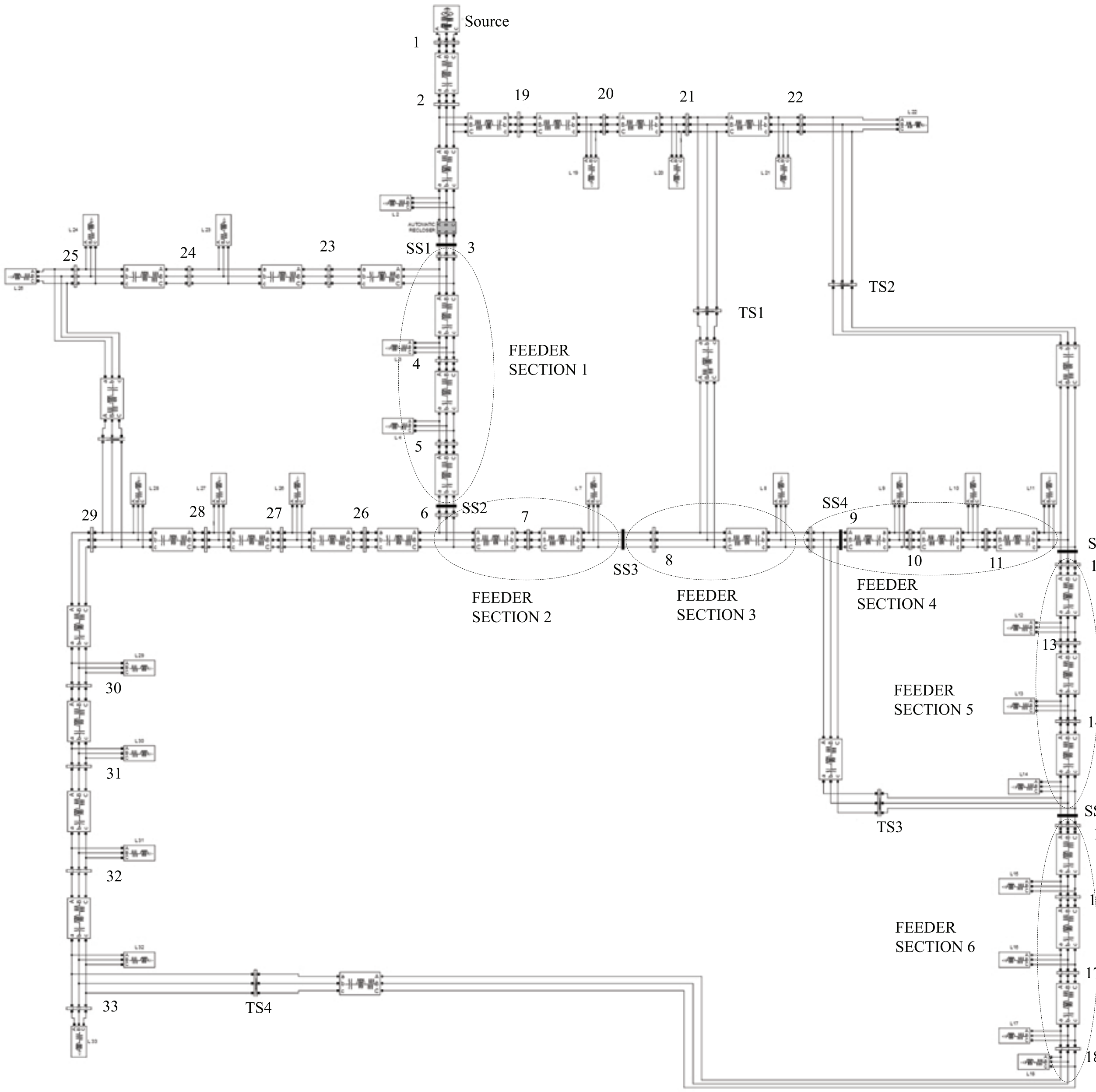

Figure 2. Modified IEEE 33 bus model.

Smart switches installed on the feeders capture the instantaneous values of current and voltage and communicate the same to their corresponding agents at regular sample intervals.

In normal state of operation or state1, the RA sends a signal to the SSAs at each sample interval in order for the SSAs to be aware of its current and voltage states. The agent communication during normal operation is shown in Figure 3.

At the time of a fault, there is a steep rise in the current along with a fast drop in voltage at the fault location. The section upstream to the fault location hence sees a rise in current value and drop in voltage values compared to the normal. As detailed in Section 3, the fault indicators will be set to 1 at switch SSA4 as the current and voltage variations at the switch are outside the predefined threshold at the corresponding switches. However, as the current in the sections downstream to the fault will be very low or zero, the downstream switch agents from SS4 will not have their fault indicator set. The voltage and current wave-forms at switch SS4 is shown in Figure 4.

Thus the FSA4 identifies that the fault is in its feeder section and sends ACCEPT_PROPOSAL message to the RA to indicate the faulty section. The agent communication during fault isolation from the JADE sniffer is depicted in Figure 5.

After the isolation of the faulty section by opening of the smart switches SS3 and SS4, the restoration operation starts with RA sending CFP messages to the possible restorative feeder section agents FSA4 to FSA6 as detailed in Section 4. Here, there are three ways in which the restoration can be effected. The first way is to close TS3 which is a tie switch between the same feeder, the second one is to close TS4 which is a switch between the feeder and its lateral, and the third option is to close the tie switch TS2 between two feeders of the same with the same transformer. By the order of preference of tie switch, TS3 is chosen for restoring the service. This is indicated via a accept proposal message from RA. Figure 6 shows the current wave-forms in the bus 10 and bus 12 (fault zone buses at either ends of the zone). Figure 7 shows the reconfigured network after isolation of the fault in feeder section 5. The current in the downstream bus 15 and upstream bus 9 are depicted in Figures 8 and 9, respectively.

The fault is simulated to occur on the system at 1.2 s and is automatically isolated at 1.55 s after recloser locks out at 1.54 s. The service restoration occurs at 1.84 s. This is shown in Figure 9. Thus, the proposed method can effectuate an automatic service restoration within 0.29 s of automatic fault section isolation.

The steady state voltages and the voltages after service restoration at the buses in the faulty sections and buses in the section connected to the restorative tie switch is presented in Table 1. It is evident that the voltages of the buses after network reconfiguration are well within the agreed voltage thresholds.

Table 1. Voltage profiles of IEEE 33 bus.

Bus number	Voltage (pu)	
	Steady state	Restoration
1	0.9999	0.9999
2	0.9979	0.998
9	0.9582	0.964
10	0.9542	0
11	0.9535	0
12	0.9523	0
13	0.9481	0.960
14	0.9468	0.962
15	0.9455	0.962
16	0.9445	0.957

The proposed method is also tested on the Velachery substation model. The single line diagram of the substation is shown in Figure 10. The model was simulated in MATLAB and MACSIMJX was used as communication interface between MATLAB and JADE for transfer of data and commands to and from the smart switches in the feeder sections. The details of feeder sections and their corresponding agents are given in Table 2.

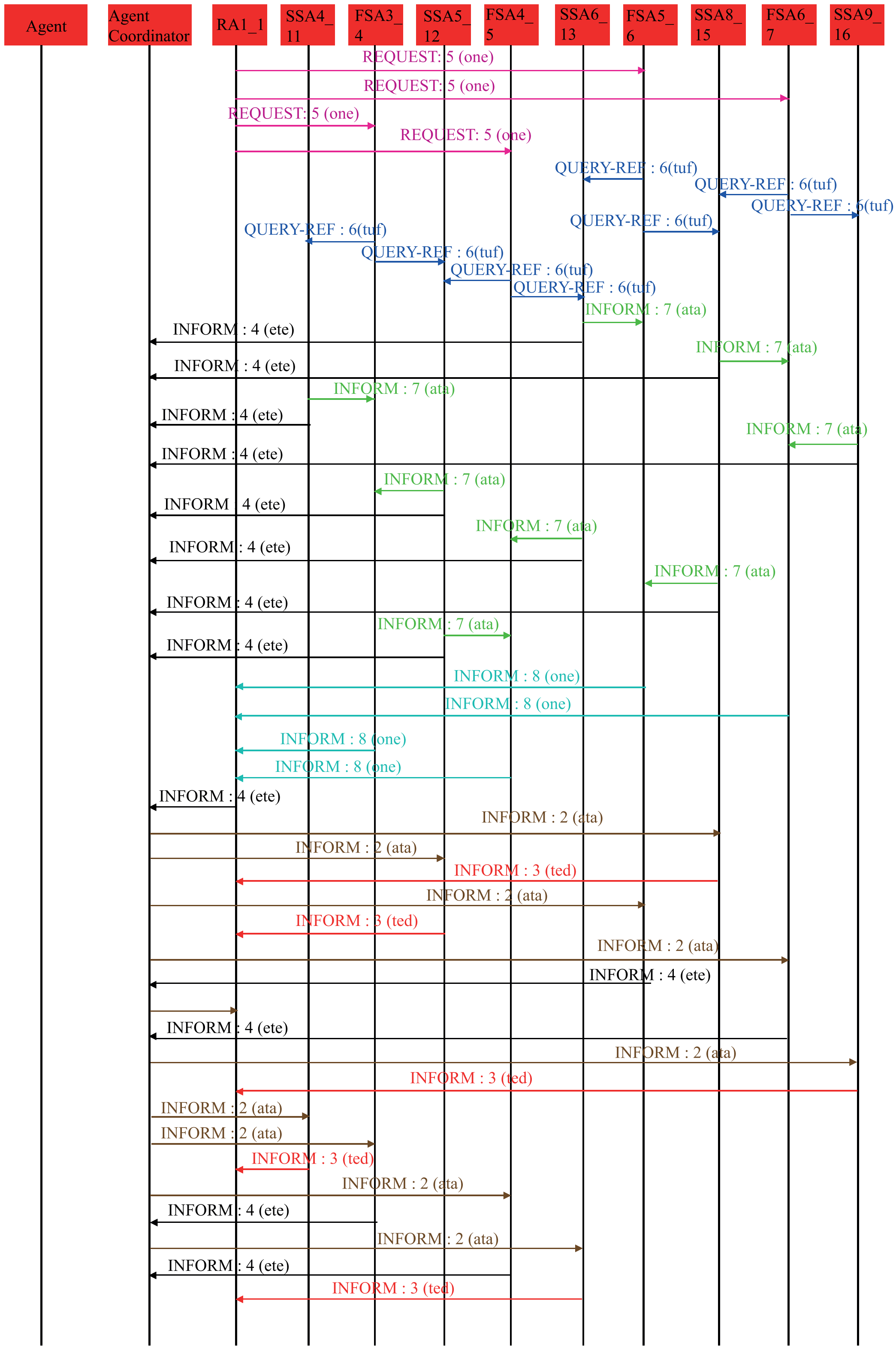

Figure 3. Agent communication during normal operation.

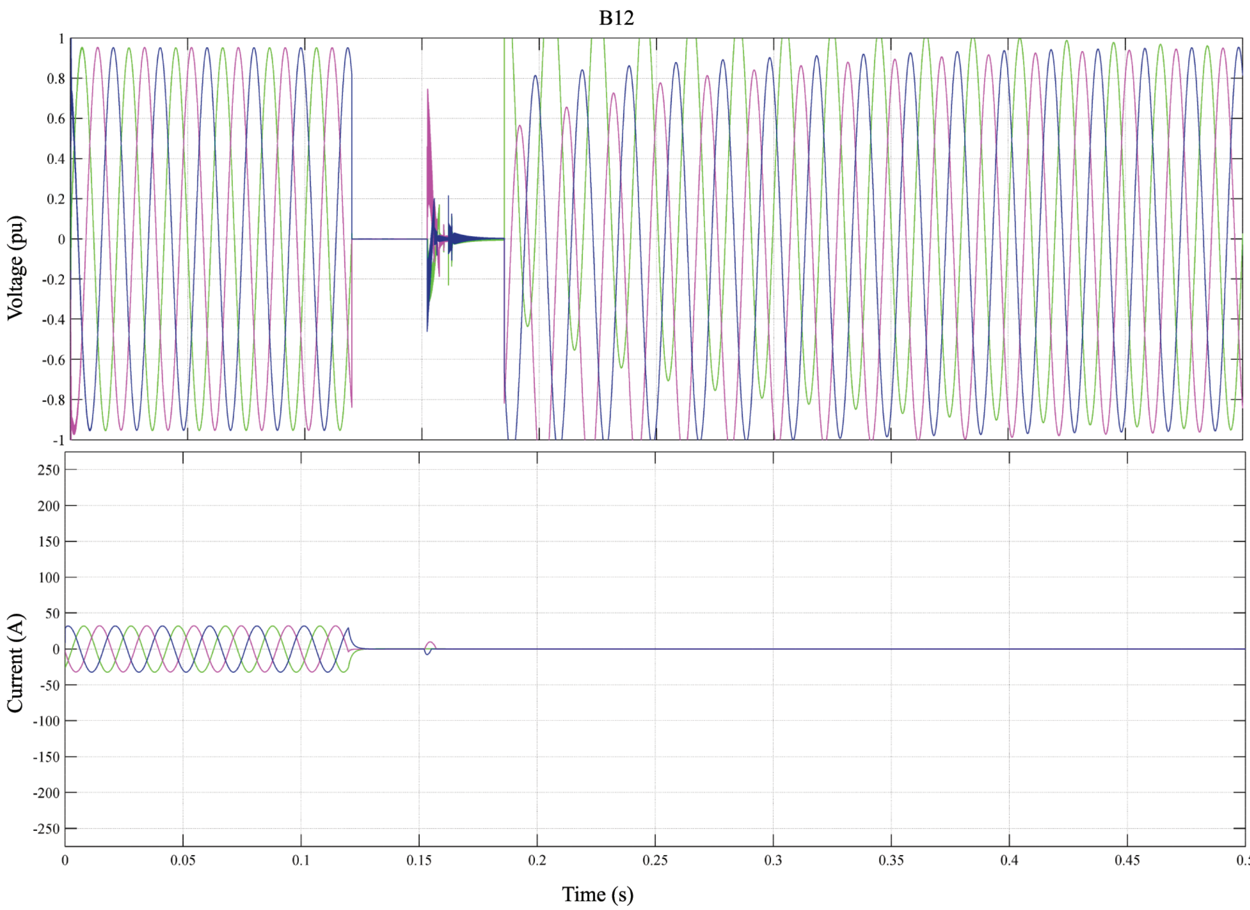

Figure 4. Fault current and voltage at switch SS4.

Multiple test scenarios were simulated to test the successful restoration both from type-2 and type-3 tie switches. As the available capacity was sufficient to meet the demands of the healthy feeders that were blacked out for restoration, no load shedding was necessary.

The tie switch is chosen as per the tie switch preference logic discussed in Section 4. Hence, the number of switching is optimized to be minimum. Further, switching operations are done in such a way that the radiality of the network is not lost during restoration. Two cases of simulation are presented here one on each feeder chosen for protection. The switching operations during both cases is shown in Table 3.

The proposed method is a hybrid multiagent approach which has the advantages of both centralized and decentralized approaches. The data handling and processing is decentralized thereby reducing the computational complexity. Thus, there is a reduction in computation time and number of communications which are much higher when a single central agent has to handle all the data. The decision making, however, is centralized, thus enabling a global optimal solution to be achieved. The data is processed by individual agents at a lower layer and the decision variables are alone passed to the central agent which generates the optimal solution based on data received from lower levels. The reduced computation time due to the hybrid design of agents ensures that the fault isolation and restoration is much faster than the other multiagent-based approaches. The service restoration is effected in 15 cycles (50 Hz) or 0.29 s as compared to the restoration approach proposed in [31] which consumes 24 cycles or 0.4 s. Also, the number of switching operation to open for isolation and close for

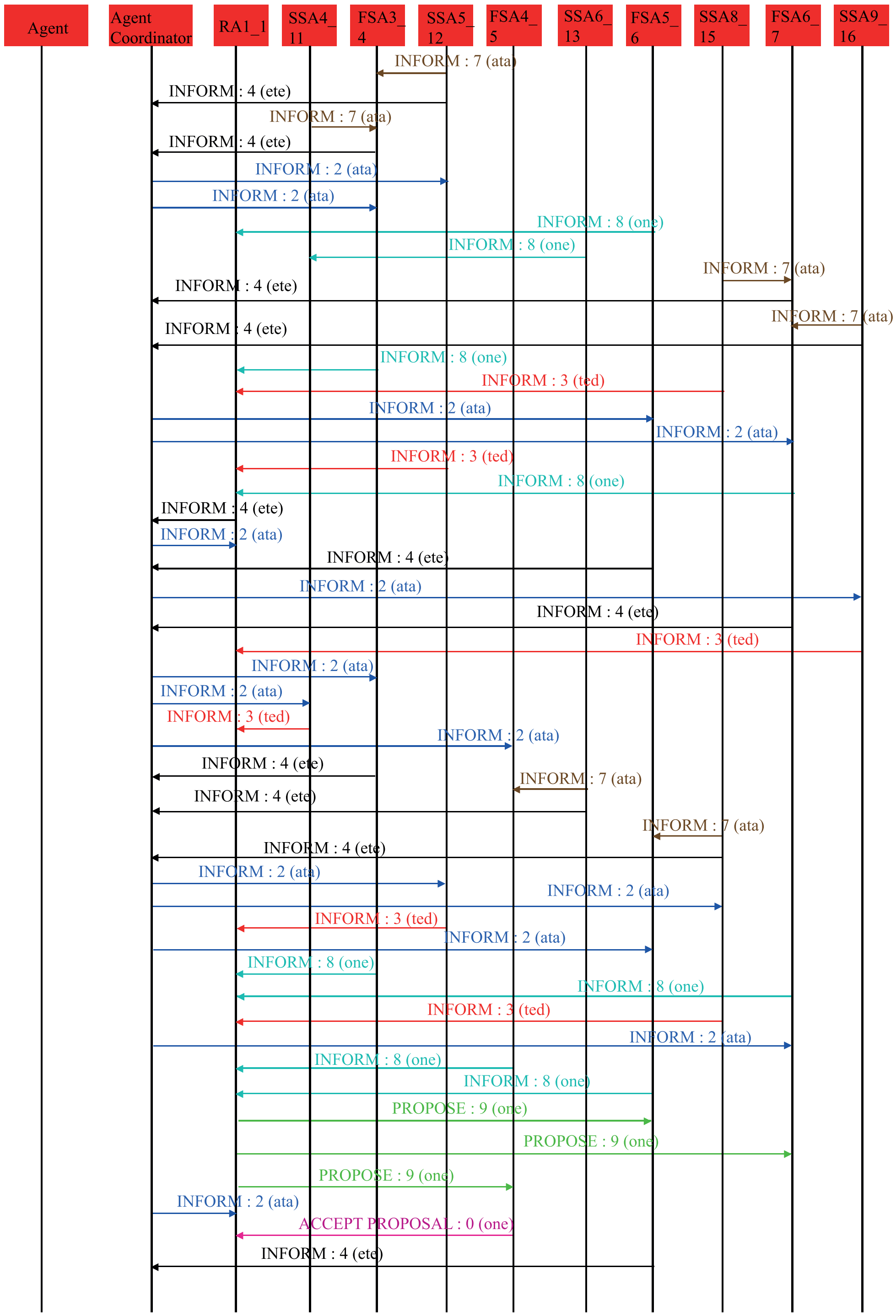

Figure 5. Agent communication during fault isolation.

restoration is optimized to be minimal by using the logic detailed in Sections 3 and 4. The fast and minimal switching leads to much quicker service restoration of the nonfaulty section of the feeder.

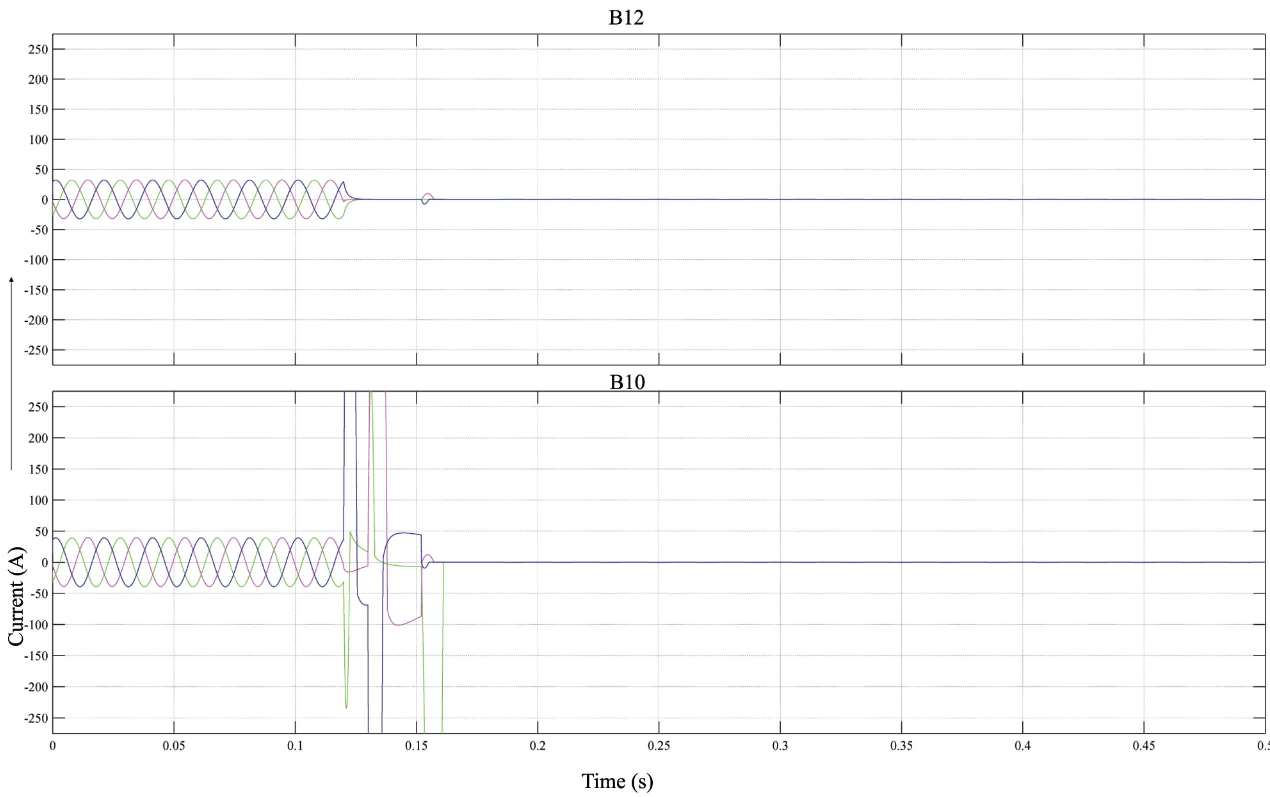

Figure 6. Current in bus 10 and bus 12.

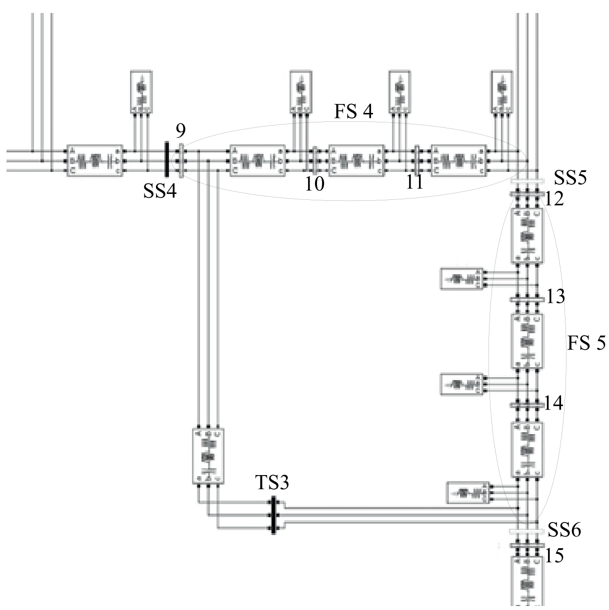

Figure 7. Reconfigured PDS after fault isolation.

6. Conclusion

The paper proposes a novel hybrid multiagent-based method for fault detection, isolation, and service restoration for a electrical distribution network. Three agents, namely recloser agent, fault section agent, and smart switch

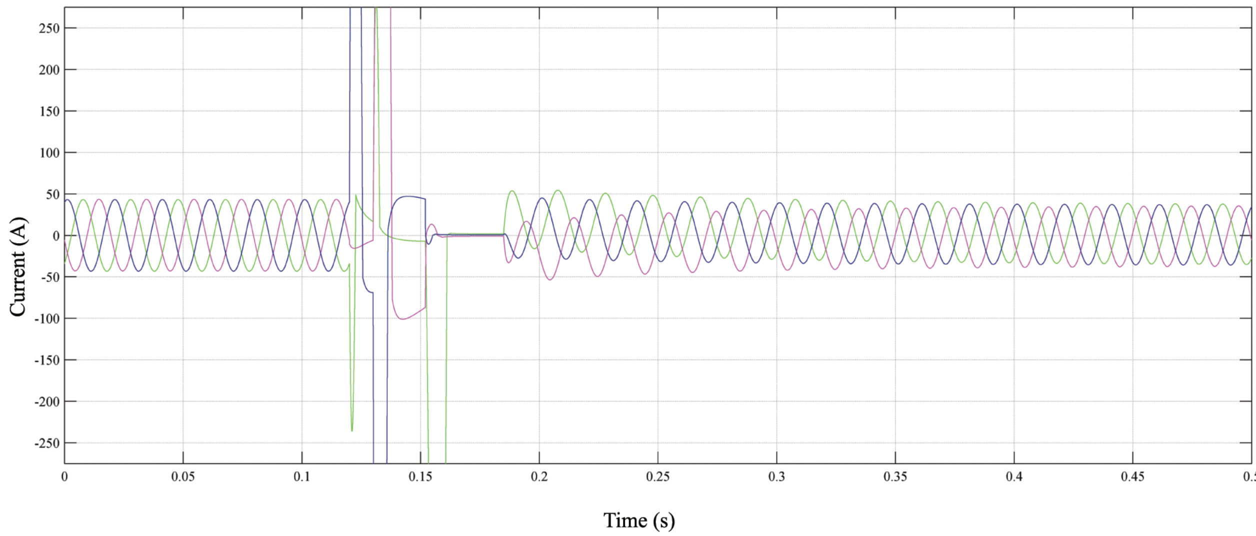

Figure 8. Current in downstream bus 15.

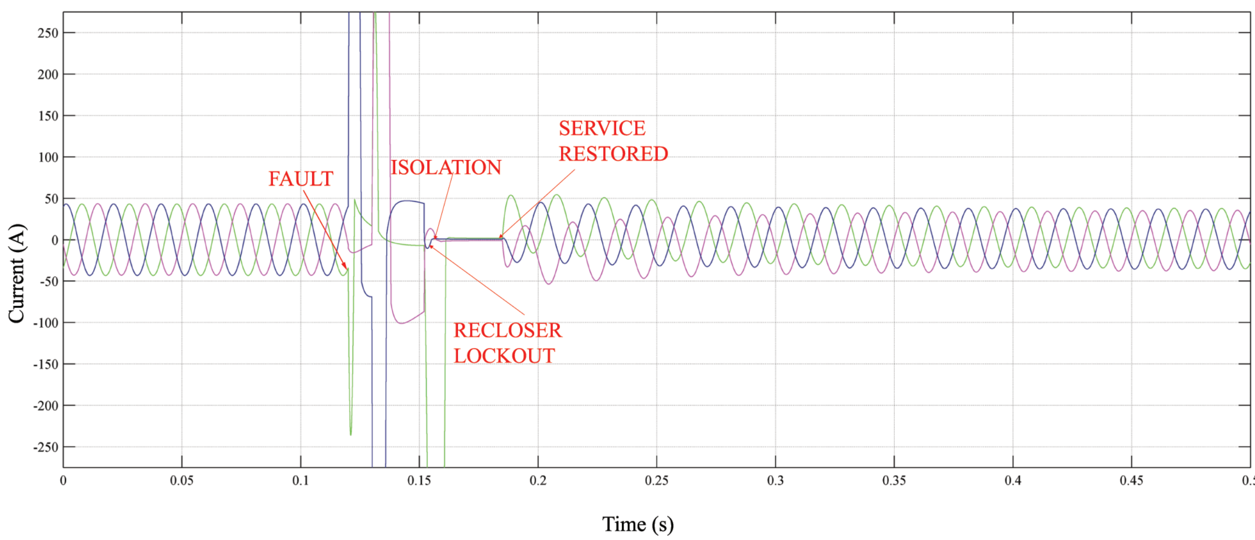

Figure 9. Current in upstream bus 9.

agent, are proposed to solve the FLISR problem. These agents communicate in an ACL compliant with IEEE FIPA standards. The proposed solution is implemented and tested on the IEEE 33 bus model and Tamilnadu Electricity Board Velachery substation model through simulation. The results prove that the proposed hybrid MAS-based solution is effective in accurately isolating the faulty section of the feeder and swiftly restoring supply to the blacked out upstream and downstream sections of the feeder with minimal switching operations. Quick restoration is possible as minimal number of agents is employed for isolation and restoration logic, thereby reducing the communication and computation time. The paper demonstrates the capability of multiagent systems as a technology for solving power distribution system problems, thus improving the reliability and resilience of the system.

As the next step to this work, the authors are working to extend the proposed MAS restoration approach to handle distribution network with distributed energy resources (DER) and varying load conditions.

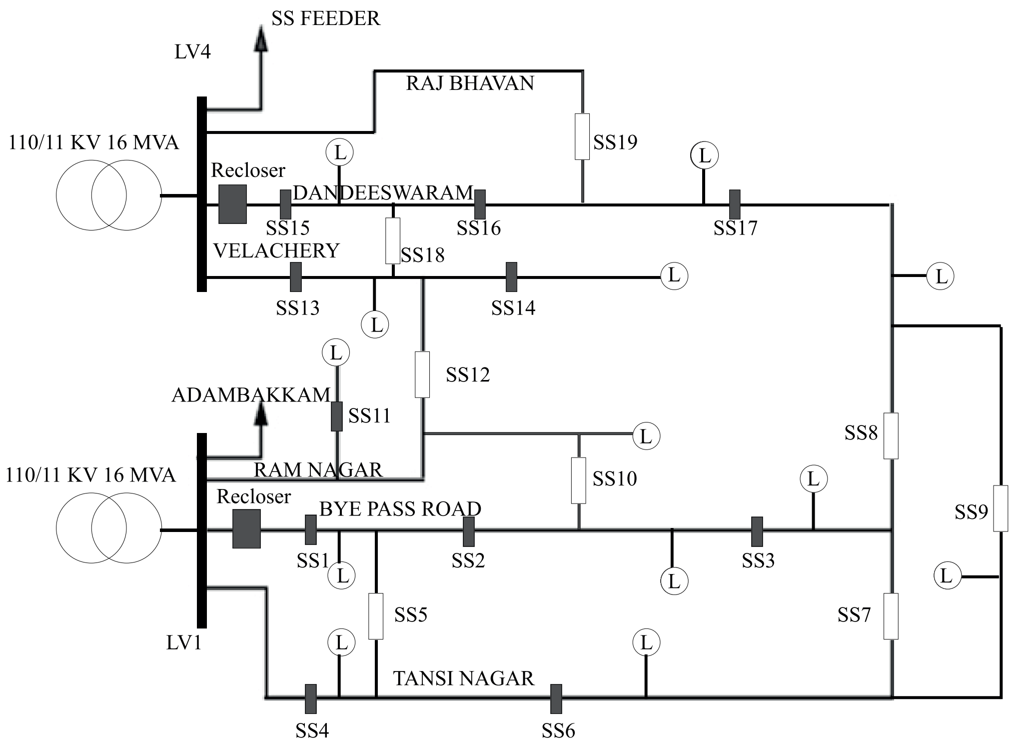

Figure 10. The Velachery substation model for simulation.

Table 2. Agents in the Velachery substation model.

Feeder	FSAs	SSAs
Bypass Road	FSA1	SSA1 SSA2 SSA3 (Type-2 tie switch)
	FSA2	SSA2 SSA3 SSA10 (Type-2 tie switch)
	FSA3	SSA3 SSA7 (Type-2 tie switch) SSA8 (Type 3 tie switch)
Dandeeswaram	FSA4	SSA15 SSA16 SSA18 (Type-2 tie switch)
	FSA5	SSA16 SSA17 SSA19 (Type-2 tie switch)
	FSA6	SSA17 SSA8 (Type-3 tie switch) SSA9 (Type-3 tie switch)

Table 3. Test results for the Velachery substation model.

Fault section	No. of switching	Switches operated	
		Isolation (NC to open)	Restoration (NO to close)
FS2 (Bypass road)	3	SS2	SS7
		SS3	
FS4 (Dandeeswaram)	3	SS15	SS19
		SS16	

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