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Multi-agent Systems Applied to Topological Reconfiguration of Smart Power Distribution Systems

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***Abstract*—One of the various features expected for a smart power distribution system - a smart grid in the power distribution level - is the possibility of the fully automated operation for certain control actions. Although this is very expected, it requires various logic, sensor and actuator technologies in a system which, historically, has a low level of automation. One of the most analyzed problems for the distribution system is the topology reconfiguration. The reconfiguration has been applied to various objectives: minimization of power losses, voltage regulation, load balancing, to name a few. The solution method in most cases is centralized and its application is not in real-time. From the new perspectives of advanced distribution systems, fast and adaptive response of the control actions are required, specially in the presence of alternative generation sources and electrical vehicles. In this context, the multi-agent system, which embeds the necessary control actions and decision making is proposed for the topology reconfiguration aiming the loss reduction. The concept of multi-agent system for distribution system is proposed and two case studies with 11-Bus and 16-Bus system are presented.**

I. Introduction

THE minimization of losses in distribution systems has been one of the classical power distribution system problems. The problem consists in changing the topology by changing the open/closed states of the switches to transfer loads from one feeder to another, in order to optimize a specific system performance [1].

The problem has a combinatorial nature, since the number of possibilities depend on the combination of the switch statuses. In reconfiguration problem, each topology is associated with a specific system performance, such as losses, voltage unbalance, load unbalance. The changes on the topology must satisfy various conditions and constraints, such as radial topology, voltage constraints, current limits and it is common to be modeled as an optimization problem, in which the aim is for the optimal topology which can be attained from specific switching actions. The new trend in this problem, is to consider a more advanced infrastructure with sensors and data communication between the components. A device with sensors and data communication such as modern reclosures can be used as part of a specialist system to detect, identify and execute actions to mitigate faults or even to improve the system performance.

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Therefore, it is possible to advance on new solution methods based on distributed computation and decision making. One more important issue on the current reconfiguration methods is the fact that they are based on a unidiretional power flow from the substation to loads. This behavior has been changing with the appearance of distributed generation, therefore, methods deviced to take into account known scenarios or slowly changing scenarios should be adapted to the new fast changing and more unpredictable situations.

The objective of this study is to propose the modeling and development of a multi-agent systems for topological reconfiguration for an advanced distribution system. In this study, key components of the system will be considered as existing, such as computation, communication and sensing capability, so that each unit can be considered as an agent that can perform calculations, data exchange and switching opening/closing operation.

The main contribution of this paper is the development of topological reconfiguration method to power distribution system in smart grid scenario taking into account the communication capable devices that can perform actions based on knowledge based decision making in distributed computing logic.

This paper is organized as follows. Section II present the state-of-art of distribution system reconfiguration. Section III describes the theory of multi-agent systems and its adaptation to the smart grid infrastructure. The multi-agent method for topological reconfiguration is presented in Section IV. Section V shows the results of the method to a power distribution system test case and, finally, in Section VI the conclusions are presented.

II. Topological Reconfiguration in Power Distribution Systems

Topological reconfiguration in power distribution systems has wide applications. For example, it can be used to reduce electrical losses [1], to improve the voltage stability profile [2], load balancing [3], system restoration [4], to name a few.

Specifically on the minimization of electrical losses, there are many papers using different approaches, and one of its seminal application has been presented in [5]. In [1], the authors presented a branch exchange heuristic method for the problem. Following, in [6] shows a improvement of the method presented in [1] by using an approximation of power flow expressions.

The ealier papers show the classical mathematical methods or constructive heuristic algorithms to solve the problem. More

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ellaborate algorithms that resorts to artificial intelligence can be found in [7], where genetic algorithm is employed, and in [8], an ant colony optimization algorithm is proposed. In [9], a hybrid method that combines evolutionary programming and ant colony optimization is proposed.

Few papers using distributed computation can be found on this topic. The paper [10] proposes a multi-agent system for minimization of electrical loss, and in [11], a hybrid multi-agent system and heuristic method.

In the next section, the concept of multi-agent systems and its use as a tool for modeling of smart grids will be shown in detail.

III. Multi-agent Systems and Smart Grids

The Agent is a concept related with an entity (this entity can be a software like a bot or a hardware like a robot) that perceives the environment around and can acts in order to achieve some objective or reproduce some behavior [12]. Agents are autonomous (they operates without human intervention), are reactive (they acts after verifying change in the environment), and pro-active (they are able to take the initiative to achieve goal).

Some problems can be modeled to operate with a set of agents instead of a single agent. For those problems which require more than one agent, the main issue is to deal with more than one expertise with differents tasks. The objective is the coordination of the agents that will result in the solution of the problem.

Multi-agent systems is in a multidisciplinary area, which utilizes theories and concepts from many areas such as computer science, artificial intelligence, distributed systems, social sciences, economics, organization and management and so on. It is also part of distributed artificial inteligente [13], because the use of multi-agent systems supposes the existence of a distributed environment where the agents are present.

In electric power systems, the application of multi-agent systems has been seen recently and interesting studies can be found in [14], [15]. However, researches in this area to the simulation and deployment on advanced power systems is still recent [10], [11], [16], [17].

As previously mentioned, smart grid is composed by many different devices which are responsible for monitoring the grid state, by collecting and sending the measurement data, and finally executing actions. Each device take specific actions (for example, smart meters, capacitor banks, switches) and thus an effective coordination among different devices is needed.

For example, for real-time loss minimization, the device which is in the substation requires the data measured and transmitted by smart meters allocated in loads dispersed along the grid in order to take an action to achieve your goal. It can be considered as an distributed information system, because it is intrinsically distributed with the sensors, actuators, and decision system spread in the grid. As a conclusion, the multi-agent systems is a natural approach for studies, modeling and simulation of smart grids. Multi-agent systems allows the smart grid devices to be modeled as agents, which allows simulating monitoring behaviors, data exchange, and decision making in a distributed way because it is a common characteristic of multi-agent systems. In the next section the proposal for topology management method using multi-agent systems, is presented.

IV. Multi-agent Based System for Reconfiguration of Distribution System

In this multiagent system, three types of agents are defined: the "Substation Agents" (SuA), which monitor the substation and the power flow from the loads; "Switch Agents" (SwA), which monitor the switches and the "Load Agents" (LoA) and they are responsible for verifying the load demand. Figure 1 illustrates the operations of SuA; Figure 2 presents the LoA actions; and Figure 3 shows the operations of SwA.

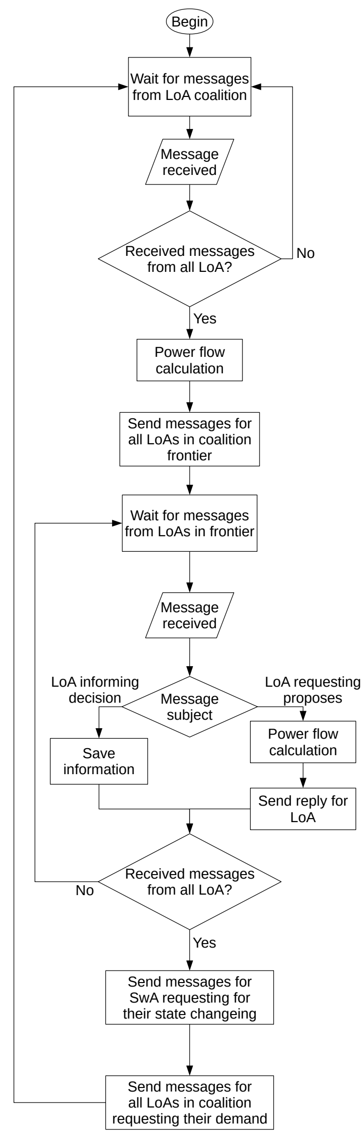

Fig. 1. Substation Agent flowchart

The interactions between the agents are the key characteristic of the method, which defines the success of the application.

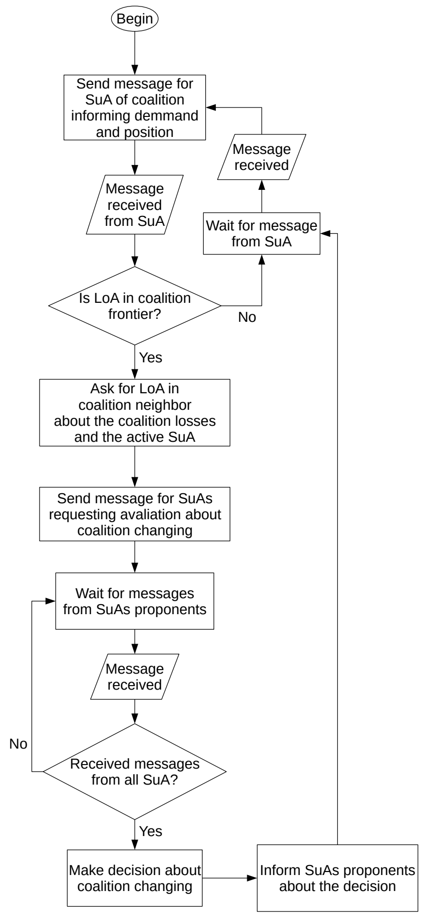

Fig. 2. Loader Agent flowchart

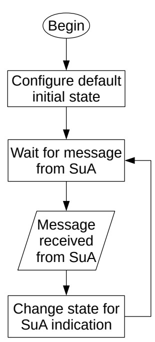

Fig. 3. Switch Agent flowchart

Figure 4 shows a sequence diagram that shows the interactions between the agents of the system.

The following actions illustrate the working of the multi-agent system. The processing starts with an initial feasible solution. In this solution a set of LoA receives the electrical energy from a specific SuA, which represents a coalition (or active system) in the grid. The corresponding SwA are configured to allow the loads being supplied.

In the beginning, each LoA sends a message to the corresponding SuA informing its demand. After receiving the messages from the LoA, SuA calculates the power flow using a forward-backward sweep method [18] to calculate the electrical losses.

After the calculation of the the electrical losses, the SuA agent identifies the set of LoAs allocated in the frontier of the coalition. This frontier indicates the existence of a power distribution line and an open state SwA agent between the LoA of the coalition and another LoA of another active system.

Then, SuA sends messages for LoAs in the coalition frontier informing about the losses of the active system and enables these agents to communicate with LoAs from another coalitions to verify for changes. SuA sends messages to another LoAs allocated in non-frontier region just for warning it about the end of calculation of losses.

Now, LoAs in the frontier regions send messages to other LoAs from another coalition neighbor to the frontier. This message asks the active SuA in that coalition and its electrical losses. After receiving the inquiry, LoA reply it immediately.

With the SuA resposible for the coalition neighbor and their electical losses, LoA send messages to its SuA requesting an assessment about the increment of coalition losses if the LoA agent moves to its active system. LoA also sends a message to the SuA responsible for its coalition, requesting for an evaluation about the decrements in coalition losses in case of the agent not becoming part of the current active system. All LoA in active system frontier regions will perform this test.

When SuA from LoA coalition receives the message, it removes the respective LoA from the active system and calculates the power flow using the fast forward-backward sweep method, calculating the electrical losses of the coalition without that LoA. After this phase of calculation, SuA sends a reply to the LoA informing this result.

In the case of SuA from another coalition, when it receives the message from LoA, the LoA is added to the current system and a power flow calculation is performed, which will provide the losses of the coalition with that LoA. Then SuA sends a reply to the LoA informing the result.

After receiving the replies from all SuA, now LoA has enough information to decide wether it continues in the current coalition or it would change to another coalition. This decision is made by selecting the combination that provides the minimum sum between the loss from the current coalition plus the neighboring coalition and the loss with LoA being removed from the current coalition plus the loss if LoA is added to the neighboring coalition.

The LoA decides in which coalition it will get into. Therefore, the LoA sends message to the SuA informing its decision. If the LoA remains in the current coalition, then there will be no change in the system. However, if the LoA changes to another coalition, the SuA responsible for this LoA sends message to the SwA in the line that connects to the LoA to disconnect by changing the switch status to open. The new SuA sends message to the SwA which is in the line between the LoA and its new coalition to connect by changing the switch to closed. This action connects the LoA with the new coalition.

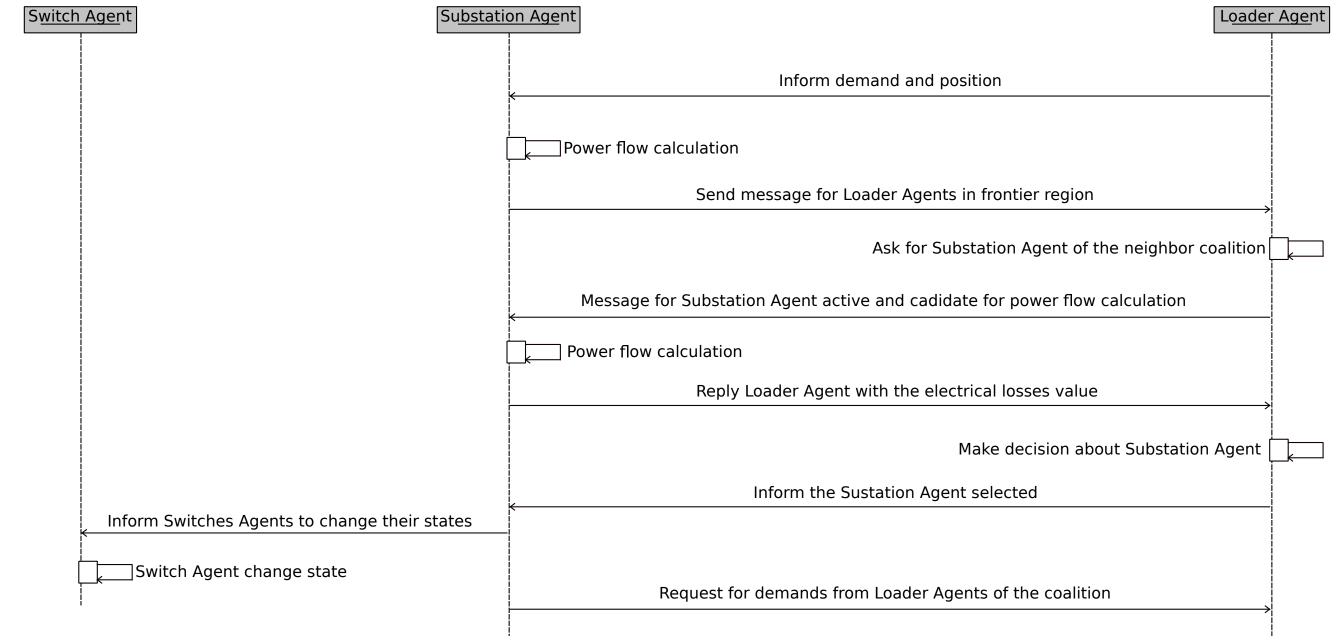

Fig. 4. Sequence diagram

Each SuA awaits for all LoA in the coalition frontier to perform the actions described above. After this, SuA sends messages for all LoA in their coalition requesting for the current load demand. Then, the process restarts.

The next section will show some test cases with the proposed multi-agent system with systems of the technical literature.

V. Test Case

The multi-agent system was implemented in Java using Jade framework [19]. This framework enables a simple API to multi-agent system development using multithreading programming, computer network access, messages passing and control.

Two systems have been used for tests. The power distribution system with 11 buses, and the 16 buses system are both from [1]. In this test, each substation are assumed to have a SuA allocated, as well as all each load has a LoA. All distribution feeders in the systems have a SwA too.

Figure 5 present the 11-bus system topology and devices: the "□" represents the switches (SwA), "•" represents the loads (LoA). Nodes 0 and 1 are the substations (SuA). Table I shows the active and reactive power in the loads, and Table II shows the resistance and reactance of the feeders when the respective switch is closed.

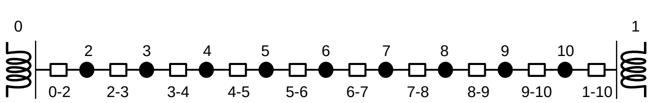

Fig. 5. 11-Bus Test System

TABLE I
11-Bus System - Power Demand

Load	Active (kW)	Reactive (kvar)
2	1840	460
3	980	340
4	1790	446
5	1598	1840
6	1610	600
7	780	110
8	1150	60
9	980	130
10	1640	200

TABLE II
11-Bus System - Feeder Parameters

Power Line	Resistance (Ω)	Reactance (Ω)
0-2	0.1233	0.4127
2-3	0.0140	0.6051
3-4	0.7463	1.2050
4-5	0.6984	0.6084
7-6	1.9831	1.7276
8-7	0.9053	0.7886
9-8	2.0552	1.1640
10-9	4.7953	2.7160
1-10	5.3434	3.0264
5-6	0.9053	0.7886

Three scenarios representing three different initial states for the problem has been defined. Table III presents the scenarios and its characteristics. Figure 6 shows the coalitions, loads and substations, and the state of switches is: open when "□", and closed when "■".

Table IV present the losses for each coalition for each initial scenarios and the total electrical losses for each scenario.

TABLE III
SCENARIOS FOR 11-BUS SYSTEM

Scenario	Coalitions
1	Substation: 0; Loads: 2, 3, 4, 5 Substation: 1; Loads: 6, 7, 8, 9, 10
2	Substation: 0; Loads: 2, 3, 4, 5, 6, 7, 8, 9 Substation: 1; Loads: 10
3	Substation: 0; Loads: 2 Substation: 1; Loads: 3, 4, 5, 6, 7, 8, 9, 10

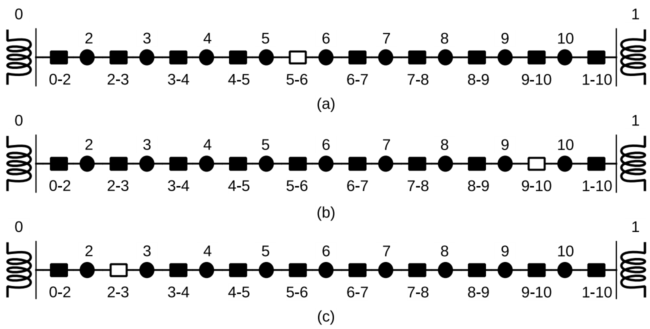

Fig. 6. 11-Bus system topology scenarios: (a) Topology for scenario 1; (b) topology for scenario 2; (c) topology for scenario 3

TABLE IV
11-BUS SYSTEM - LOSSES IN INITIAL SCENARIOS FOR EACH COALITION

Scenario	Losses by Coalition (kW)	Losses by Scenario (kW)
1	Coalition 0: 117.1872 Coalition 1: 1043.8731	1161.0603
2	Coalition 0: 604.3742 Coalition 1: 31.7786	636.1529
3	Coalition 0: 2.0692 Coalition 1: 2269.7291	2271.7983

After the application of the method and processing of the initial solutions, all the scenarios converges to the topology presented in Figure 7. In this topology, coalition where the substation is node 0 has the LoAs in nodes 2, 3, 4, 5, 6, 7, and 8, while coalition where the substation is node 1 has LoAs 9 and 10. Table V presents the number of iterations of each initial scenario that converges to the final topology.

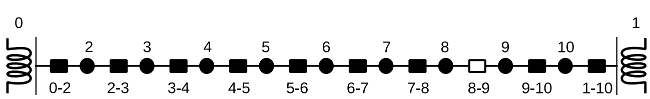

Fig. 7. 11-Bus system final topology

In the final topology, the electrical losses of the entire system is 533.3422 kW. The losses of coalition 0 is 438.4089 kW, while losses of coalition 1 is 94.9333 kW. This result represent a decrease in electrical losses of 54.06% for Scenario 1, 16.16% for Scenario 2, and 76.52% for Scenario 3.

TABLE V
11-BUS SYSTEM - ITERATIONS FOR CONVERGENCE

Scenario	Number of Iterations
1	3
2	1
3	6

Figure 8 present the electrical losses along the iterations for the Scenario 3. The vertical axis is the magnitude (complex modulus) of the sum of electrical losses from the complete system.

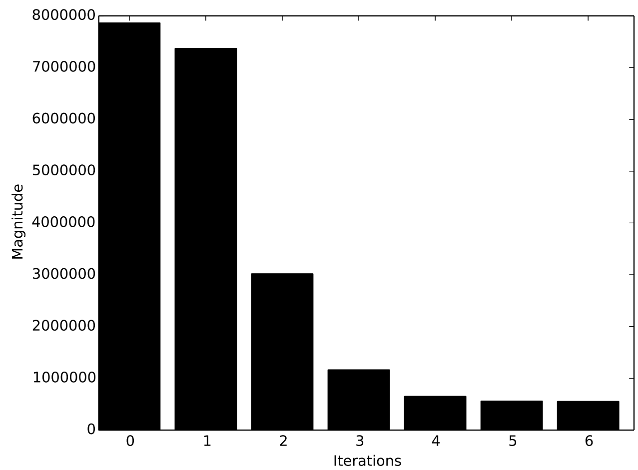

Fig. 8. Electrical losses decrements for 11-Bus system, scenario 3

The application of the proposed method to the 16-bus test system results in the following results. Figure 9 presents the topology for this system, where "☐" represents the switches, "•" represents the loads. Nodes 0, 1, and 2 are the substations. Table VI shows the active and reactive power in the loads, and Table VII shows the resistance and reactance of lines in the case of switch state is closed.

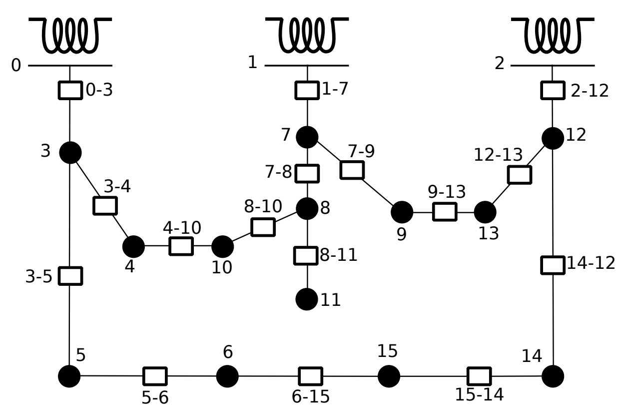

Fig. 9. 16-Bus Test System

TABLE VI
16-BUS SYSTEM - POWER DEMAND

Load	Active (kW)	Reactive (kvar)
3	2000	1600
4	3000	1500
5	2000	800
6	1500	1200
7	4000	2700
8	5000	3000
9	1000	900
10	600	100
11	4500	2000
12	1000	900
13	1000	700
14	1000	900
15	2100	1000

TABLE VII
16-BUS SYSTEM - FEEDER PARAMETERS

Power Line	Resistance (Ω)	Reactance (Ω)
0-3	0.075	0.1
3-4	0.08	0.11
3-5	0.09	0.18
5-6	0.04	0.04
1-7	0.11	0.11
7-8	0.08	0.11
7-9	0.11	0.11
8-10	0.11	0.11
8-11	0.08	0.11
2-12	0.11	0.11
12-13	0.09	0.12
12-14	0.08	0.11
14-15	0.04	0.04
4-10	0.04	0.04
9-13	0.04	0.04
6-15	0.12	0.12

For the simulation with the 16-bus system, four initial scenarios have been defined. They are described in Table VIII. Figure 10 shows the coalitions, loads, substations, and switches status to all scenarios.

TABLE VIII
SCENARIOS FOR 16-BUS SYSTEM

Scenario	Coalitions
1	Substation: 0: Loads: 3, 4, 5, 6
	Substation: 1; Loads: 7, 8, 9, 10, 11
	Substation: 2; Loads: 12, 13, 14, 15
2	Substation: 0; Loads: 3, 4, 10
	Substation: 1; Loads: 7, 8, 11
	Substation: 2; Loads: 5, 6 9, 12, 13, 14, 15
3	Substation: 0; Loads: 3
	Substation: 1; Loads: 4, 7, 8, 9, 10, 11, 13
	Substation: 2; Loads: 5, 6, 12, 14, 15
4	Substation: 0; Loads: 3, 5, 6, 14, 15
	Substation: 1; Loads: 4, 7, 8, 9, 10, 11, 13
	Substation: 2; Loads: 12

The electrical losses for each coalition and for each scenario is presented in Table IX.

TABLE IX
16-BUS SYSTEM - LOSSES IN INITIAL SCENARIOS FOR EACH COALITION

Scenario	Losses by Coalition (kW)	Losses by Scenario (kW)
1	Coalition 0: 32.5318 Coalition 1: 127.7250 Coalition 2: 14.6902	174.947
2	Coalition 0: 13.8293 Coalition 1: 106.0017 Coalition 2: 63.5121	183.3431
3	Coalition 0: 1.4154 Coalition 1: 210.6075 Coalition 2: 47.6515	259.6744
4	Coalition 0: 54.1886 Coalition 1: 210.6075 Coalition 2: 0.4141	265.2102

The electrical losses of the system for the final topology, as presented in Figure 11, is 163.3019 kW. The losses of coalition 0 (LoAs 3, 4, 5, 6, and 10) is 36.5325 kW, the coalition 1 (LoAs 7, 8, and 11) is 106.0017 kW, and the coalition 2 (LoAs 9, 12, 13, 14, and 15) is 20.7677 kW. This result represent a decrease in electrical losses of 6.65% for Scenario 1, 10.93% for Scenario 2, 37.11% for Scenario 3, and 38.42% for Scenario 4.

All scenarios need two iterations for the convergence to the final topology, as presented in Table X.

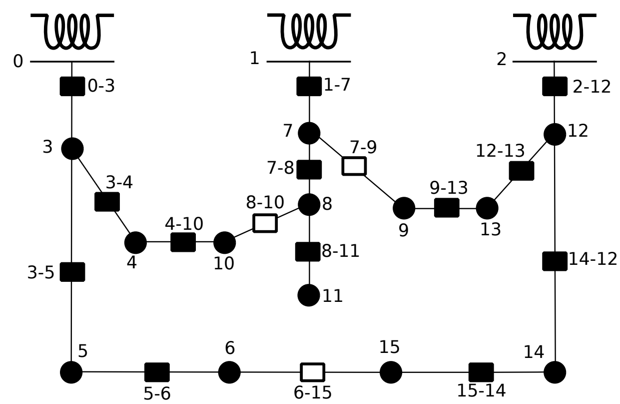

Fig. 11. 16-Bus system final topology

TABLE X
16 BUS SYSTEM - ITERATIONS FOR CONVERGENCE

Scenario	Number of Iterations
1	2
2	2
3	2
4	2

Figure 12 presents the electrical losses along the iterations for the scenario 4. In Figure 8, the of the sum of electrical losses (complex modulus) (vertical axis) and the number of iterations (horizontal axis) are presented.

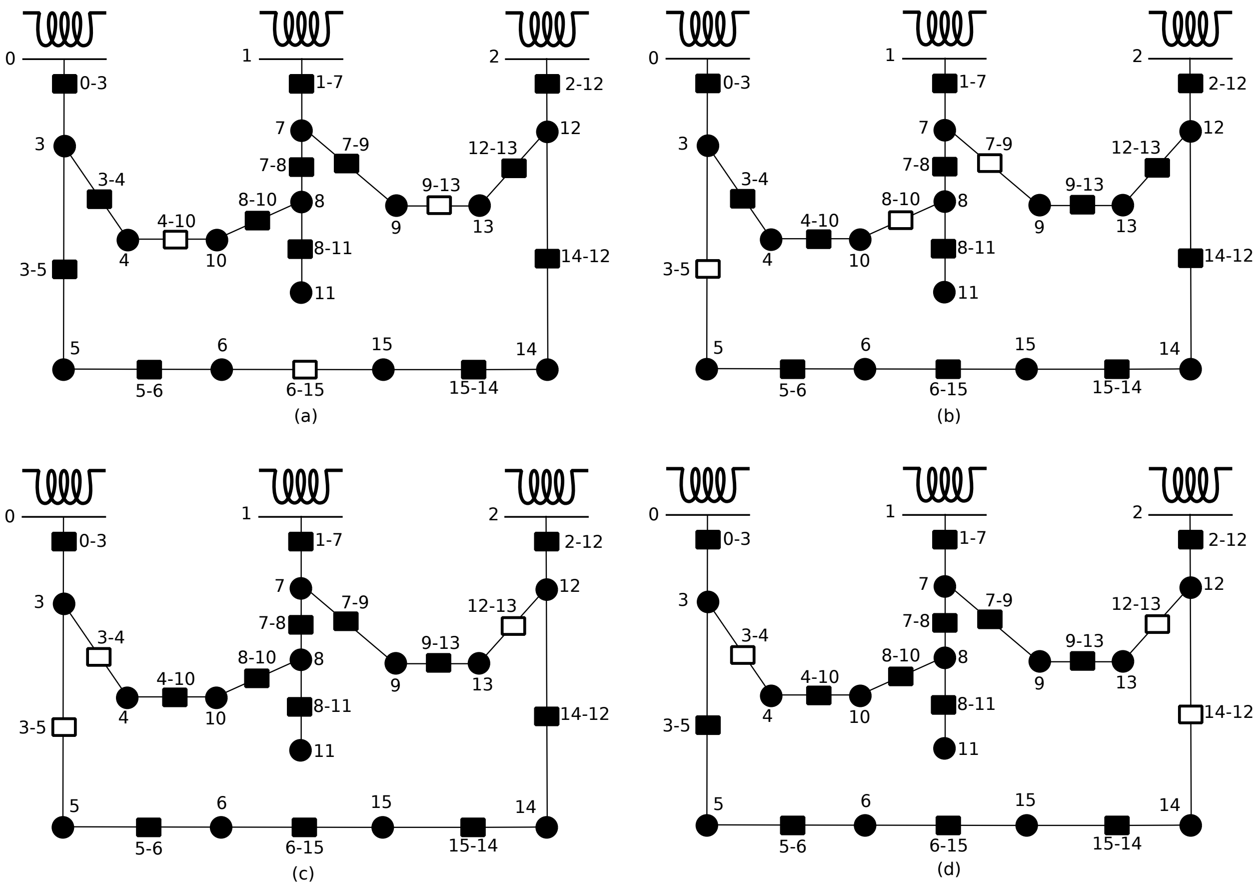

Fig. 10. 16-Bus system topology scenarios: (a) topology for scenario 1; (b) topology for scenario 2; (c) topology for scenario 3; (d) topology for scenario 4

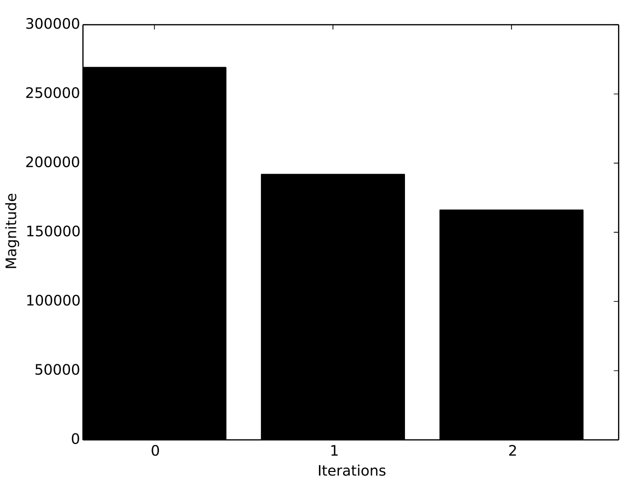

Fig. 12. Electrical losses decrements for 16-Bus system, scenario 4

VI. Conclusions and Future Works

The application of intelligent methods for distribution system automation is possible from the use of specialist systems and with the presence of the communication layer, which connects the devices along the grid. Therefore, the proposed method relies on such advanced infrastructure to achieve a more precise and decentralized control of distribution systems.

This paper presented the application of multi-agent systems to the topological reconfiguration of distribution systems. The methodology, the agents modeling, and the multi-agents interaction have been the main topic in this research work. The method has been applied to two test systems, which reveiled the complex nature of the problem. The proposed method have shown good performance and provided good quality configurations. It is important to highlight the method was developed for distributed environments, as required for the smart grid environment. The data collecting, calculation, and decision making are performed by different agents immersed in this distributed environment. The decisions are local, but the consequences are global as can be seen by the total losses which decreases along the iterations.

Future work includes further tests with different strategies in a multi-objective formulation. The interest in multiobjective formulation is due to the fact that some of the benefits present conflicting actions or objectives such as minimization of losses and minimization of switching actions.

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