Multi-agent System for Voltage Regulation in Smart Grid

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Abstract. In this research work, a new approach of decentralized energy management for smart grid is proposed to solve the problem of distributed voltage regulation. Where, micro-grids and aggregators are used as smart agents that can communicate with each other to share information, distribute energy and control their own energy consummation. Aggregators make the link between flexible resources. Smart-agents are an emerging technology for decentralized computation and data storage, secured by a combination of cryptographic signatures and a distributed consensus mechanism. So, two types of agents: energy Generation AGent (GAG) and Bus Agent (BAG) are used to regulate the voltage levels by injecting more power at some buses using the renewable energy sources. The interaction between the two types of agents is based on communication and exchange of information about the parameters and the state of the power grid. For testing this approach, a developed tester by our laboratory has been used that gives a good result.

Keywords: Distributed energy resources · Internet of Things · Decentralized energy management system · Renewable resources · Smart grid · Multi-agent system

1 Introduction

In the literature, the energy management of smart grids (SG) is based on centralized approaches [1]. Thus, centralized SG energy management issue has been largely studied and several works have sought to improve these approaches [2, 3]. In [4] the master-slave strategy has been used for a rule-based management system applied to a microgrid composed of multiple energy resources including a PV system, a fuel cell, and a battery bank. This approach is suitable solution for energy resources near to each other. In the same context, gravitational search algorithm (GSA) method was applied in [5–8] to optimize power flow in given systems and the concept of centralized microgrid management system (MMS) was used to make decisions when information was collected in a central point, while cooperation and prioritization are achieved more easily when using a central controller [9]. Other works had addressed the problem of multi-agent power grid operation using centralized methods [10, 11]; however, the best

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results they got even near optimal, time consuming, higher control complexity or higher communication cycles to discover the information.

On the other hand, the researchers start to reshape it by using distributed energy resources (DERs). DERs are compensated for providing energy services by an aggregator or a utility: a central authority that is trusted to act fairly in scheduling generators, satisfying loads, and rendering payments [12, 13].

DERs are often remotely controlled by the Internet of Things. When they are used intelligently, these DERs can reduce cost, improve reliability, and integrate renewable resources in the electric grid—features which have led regulators to introduce policies promoting their adoption.

In this research work, a new approach of decentralized energy management for SG has been proposed. Where, micro-grids and aggregators are used as smart agents that can communicate with each other to share information, distribute energy and control their own energy consummation. Aggregators make the link between flexible resources. Multi-agents are an emerging technology for decentralized computation and data storage, secured by a combination of cryptographic signatures and a distributed consensus mechanism.

2 Distributed Energy Resources (DERS): An Overview

With SG, the planning, investment, and operation of the distribution system (DS) change dramatically. Historically, utility investment in distribution systems ensured circuit capacity was adequate to deliver power from the bulk grid to the customer. Now, customer-owned solar PV delivers power to the distribution system, and distributed resource (DR) from customers provides energy and capacity reduction at the bulk grid level. A host of other distributed resources, including fuel cells and energy storage, provide power that is injected at the low-voltage level and may create reverse power flows on the grid, moving power away from the customer. Platforms are being designed to host DERs at lower voltage levels to explicitly supply customers at the distribution level and to wholesale markets.

An immediate objective is to monetize the option value of DERs, which translates to more flexible DER uses in multiple markets. Multiple opportunities have emerged, and more will result as DER needs increase across the grid. We examine both the voltage context and future opportunities to provide greater understanding of these new resources.

Distributed resources can reduce peak demand, which can eliminate or defer new transmission and distribution capacity, and decrease total energy costs. Enhanced on-site peaking generation resources also improve the security and hence the reliability.

Moreover, with the intensifying incorporation of DER in the SG, decentralized and multi-agent approach uses become inevitable for arrangement and allocation of resources in a SG.

3 Smart Grid (SG)

Broadly defined, a SG combines electrical infrastructure with digital technologies that analyze and transmit the received information. These technologies are used at different levels of the network: production, transport, distribution and consumption. Hence, SG can be seen as the successor of the conventional electrical infrastructure which uses information and communications technology to automate the production and distribution of electricity.

SG can enhance the conventional grid in several factors such that:

- Network operators can reorient energy flows according to demand and send price signals to individuals to adapt their consumption (voluntarily or automatically); thus, maintaining real-time flow control. This can be ensured basing on the information recorded from the sensors installed through the grid and which indicate, instantly, electrical flows and consumption levels.
- By the instantaneous exchange of information, smart grids promote interoperability between the operators of the transmission network (which links the electricity production sites to the consumption areas) and those of the distribution network (which delivers electricity to end consumers).
- SG are based on an information system that allows the level of production and consumption to be predicted in the short and long term. Renewable energies which often operate intermittently and in an unpredictable way (e.g. wind power and solar energy) can thus be better managed.
- More responsible management of individual consumption: smart meters (or advanced meters, “Linky” for electricity) are the first application versions of SG. Installed at consumers, they provide information on prices, peak consumption times, quality and level of electricity consumption in the home. Consumers can then regulate their consumption themselves during the day. For their part, network operators can detect faults faster.

Therefore, the most amazing innovation of the SG is that consumers of the network can become an energy supplier as well, that is consumers can become prosumers.

4 IoT in SG

In its universal meaning, IoT (Internet of Things) depicts the notion of inter-relating the virtual world of computers with the real world of physical objects [14, 15].

Everything in IoT Smart grid is based on networking because the grids must capable of sensing (through their sensors) and reacting (through their actuators); thus, creating smart environments surround them, this can be via the integration of communication networking, the internet, sensors (PMUs), smart meters and remotely controlled switches, hardware (embedded systems) and software technologies. IoT helps SG systems to support various network functions throughout the generation, transmission, distribution and consumption of energy by providing the connectivity, automation and tracking for such devices. Figure 1 summarizes the integration of IoT in SG.

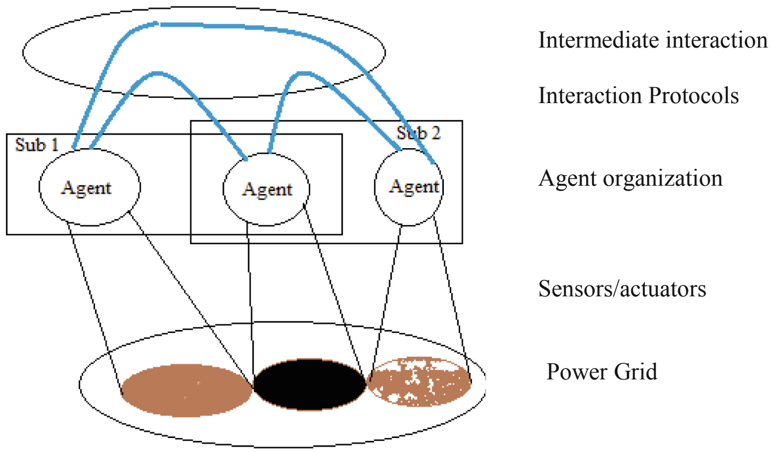

Fig. 1. Multi-agents system structure

The IoT focuses on the realization of three main concepts, namely things-oriented, Internet-oriented and semantic-oriented. The things oriented concept involves smart devices, such as RFID tags, sensors, actuators, smart meters, the Global Positioning System (GPS) and NFC. The Internet oriented concept enables communication among smart devices through various communication technologies, such as ZigBee, Wi-Fi, Bluetooth and cellular communications and connects them to the Internet. The semantic oriented concept realizes a variety of applications with the help of smart devices [14].

Connecting things to the Internet involves the devices to use an IP (Internet Protocol) address as distinctive identifier. IPv4 is definitively bushed owing to its insufficient address range against to the huge address range requirements that leads to unavoidable passage from IP v4 to IP v6 [16, 22].

5 Multi-agent System in SG

A multi-agent system (MAS or "self-organized system") is a computerized system composed of multiple interacting intelligent agents [17]. It can be divided to many different sub-systems as shown in Fig. 1. One agent can play one or more tasks. All agents coordinate with subsystems. Interactions among agents with the power grid can be ensured by the Remote Terminals Unit (RTU)s and smart actuators such as RES (Renewable Energy Source) and SVC (Static VAR Compensator) via communication network or internet as explained in previous section. The role of the smart agent determines the part of the power grid in which can receive and send the data.

Previously, conventional grids and electrical distribution systems were monitored and automated using SCADA system. SCADA stands for Supervisory Control and Data Acquisition; it is an industrial computer-based control system employed to collect and evaluate data remotely and in real-time to maintain, supervise and check technical installations in power systems for better functioning and control.

In industrial organizations, SCADA systems are required to preserve efficiency, process data for smarter decisions, coordinate and communicate system issues to help mitigate downtime. Since 2010, Ignition HMI/SCADA Software has been installed in many companies in over 100 countries. SCADA system is powerful and robust permits integrators to reach the demands of their customers, Fig. 2 summarizes the Ignition HMI/SCADA architecture which allows SCADA to gathers all system knowledge in central processor then makes the decision (remotely). However, in the micro-grid, uncertainty in SCADA systems arises when sensor data or inferred knowledge cannot be deemed accurate due to intermittent nature of renewable energy resources [18].

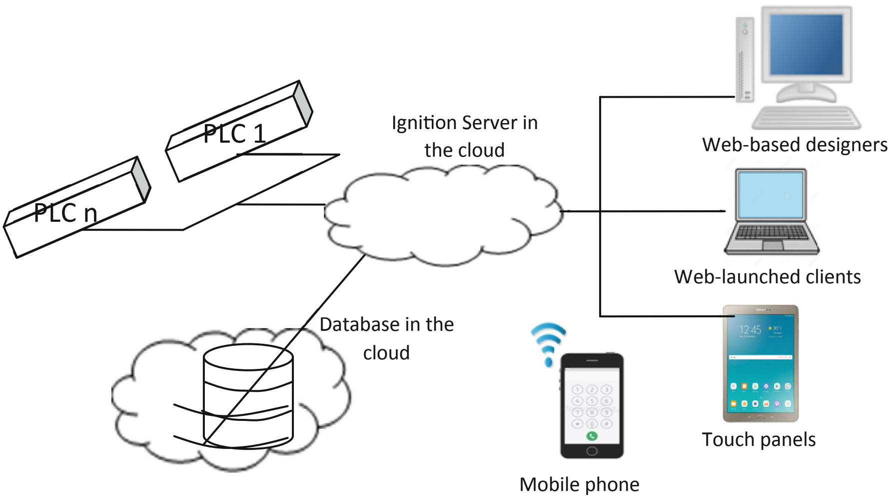

Fig. 2. Ignition SCADA standard architecture sample.

Generally, sensors information can be noisy, erroneous or uncertain; moreover, applications using multiple sources can suffer from incoherent, uncertain or divergent data; which cannot be solved even by using SCADA unless by the supervision of the human. Whereas, MAS approach for energy management does not suffer from such situations and offers better results, more energy efficiency and time reduction. MAS automates the micro-grid by associating protocols skills and communication facilities between the different agents of the micro-grid to exchange the data. Micro-grid based on MAS can replicate easily and seamlessly basing on plug and play adaptability to connect to external grids. MAS are useful for designing distributed systems requiring autonomy of their entities. MAS use new programming paradigm to implement agents, which is bringing about new programming paradigm for software engineering called Agent-Oriented-Programming AOP. MAS has the ability to add new agents (resources or loads), or dissolve them and associate them to a new environment with new resources and new abilities. Each agent in MAS can have the following utilities: communication tools, control unit, security, localization unit … Figure 3 illustrates a standard diagram of MAS for energy management.

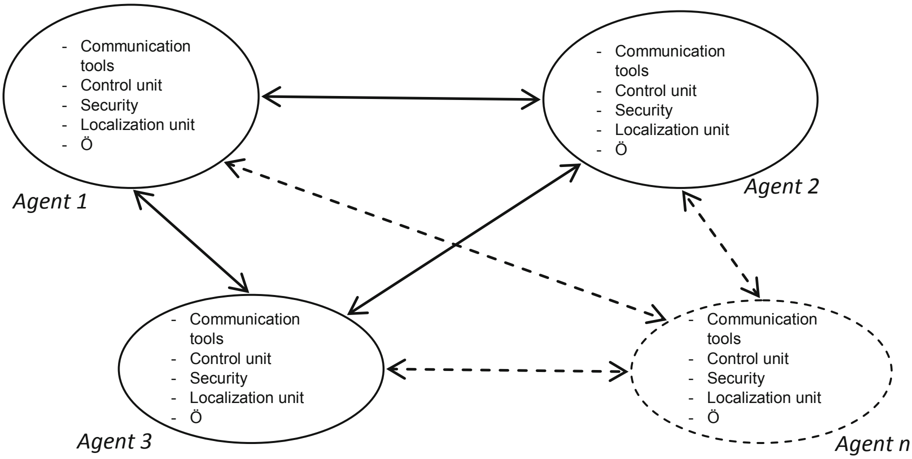

Fig. 3. Standard diagram of MAS for energy management

6 Energy Management System (EMS)

Centralized or decentralized energy management may be used in SG. However, the centralized scheme has a clear drawback; a failure in one of the control centers might result in the total collapse of the system. Moreover, the ambiguity related with renewable energy sources has made resource distribution matters even more difficult for grid users. The next smart-grid generation may combine different renewable energy sources and may have bi-directional power flow. Therefore, it is highly desirable to have enough intelligence and redundancy throughout the system to survive failures, to resource allocation problem and to permit inter-node communication and decision making. Multi-agent systems (MAS) is a promising platform to decentralize the traditional centralized resource allocation aspects of smart grid [19].

Our approach proposes a multi-agent system consists of several Bus Agent (BAGs) and power Generation Agent (GAGs) capable of regulating voltage and keeping it within the permissible limits, based on local information. This being a way of decentralizing the information, because the loss of information can lead to a cascade of overloads that can lead to voltage collapse. The decomposition of problem (P) into m sub-problems is considered, with most of the equality or inequality constraints from electric grid are expressed in terms of only few variables and local variables come from a small geographic area. Each sub-problem (assigned to one agent) contains a part of the objective of (P) and some of its constraints.

The agents will work on their sub-problems asynchronously. Agents can be used to improve the control devices, relays, Flexible AC Transmission Systems (FACTS) devices or voltage regulators. The later is treated in our case study.

The connection between software entities and automation subsystems are fixed (generally defined at design-time), but the systems should deal with unanticipated requests.

A. Voltage Regulation Based on Smart Agents

The application of smart agents to the power grid is new research field. In the power grid, the voltage level can be affected by different factors such as the load variation or the grid reconfiguration, thus, a rapid control may be needed for solving the problem that may be caused by the disturbances. At some buses, the voltage may decrease below the allowable limits. We discuss here their capability to create a coherent structure that can guarantee an efficient way to manage and control multiple distributed energy resources (DERs) [20, 21].

A.1. Agents Types

In our approach, two types of agents are used such as bus agent (BAG) and renewable energy generation agent (GAG) as shown in Fig. 4.

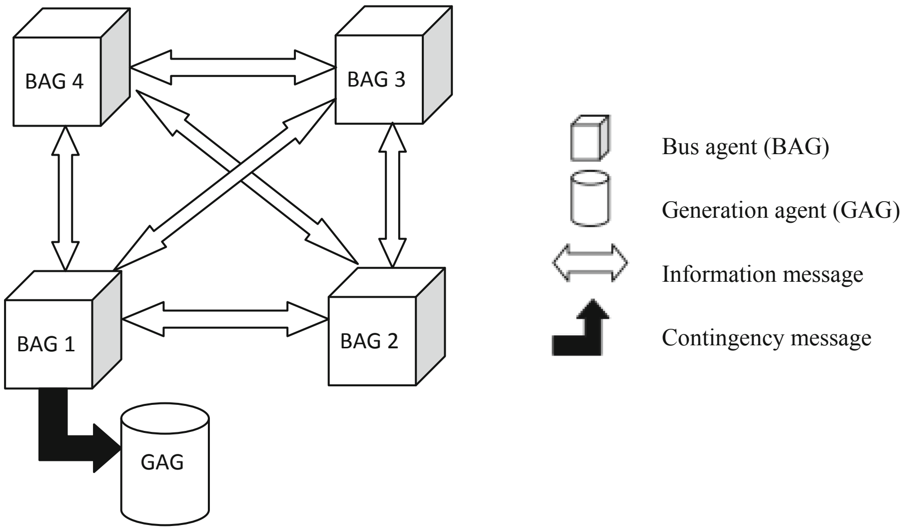

Fig. 4. Different types of agents and messages.

a) ***Bus Agent (BAG)***

Bus agent exists in each bus and respects to the following rules:

Rule 1: When BAG detects a decrease in the voltage level under the limit, a message "power demand" is sent to all neighbour agents.
Rule 2: When BAG receives a message "reject to power demand" from the first, it sends the same message to the second agent.
Rule 3: When it receives a message "generation limit" and the voltage does not attain the permitted level, BAG sends another message to the renewable energy generation agent (GAG) of the second priority.
Rule 4: When the voltage enters within the allowable limits, BAG sends a message "stop" to the agents.

b) ***Renewable energy generation agent (GAG)***

The agent GAG plays an important role in the system; it determines the stored power energy and the transmission power line thermal capacity. It acts according to the simple rules for solving the local optimization problem of generation.

Rule 1: When GAG receives a message "power demand", it will verify two constraints such as the stored power energy (generation limit) and thermal capacity of the power line. If the two constraints are verified, it will send a positive message to BAG.
Rule 2: if one of the two constraints is not satisfied, it sends a rejection message to BAG.
Rule 3: if GAG receives more than one message "power demand", all messages are classified in a vector with priority order starting by the low power amount and low price.
Rule 4: When GAG receives a message "stop", it confirms the stop.

A.2. **Message Types**

The main objective of the messages is to maintain the agents informed by the neighbour agents' conditions. Messages can be classified according to interaction and communication of agents. They are classified into two types to facilitate the distribution, control and coordination by agents.

a) *Information Messages*

These types of messages are designed for giving information exchange among agents during the normal condition. They are message state request and message state reply.

b) *Contingency Messages*

When the voltage is outside the limits, this type of information may be exchanged among the agents in order to recover the situation. These messages are: "power demand", "reject to power demand", "power generation limit", "stop", and "confirmation".

B. **Voltage Regulation by Multi-agents System**

The objective of this study is to decentralize energy management using MAS. Each BAG collects information about the grid from neighbour agents as shown in Table 1; hence, it determines during contingency the nearest energy source having the smallest electrical amount. For example, if an agent is located at bus (i, j) that is represented by:

$$AG_{ij} \quad for \quad i = 1, \ldots m \quad and \quad j = 1, \ldots n \tag{1}$$

Table 1. Agent arrangement

	j'	j	j''
i'	AG($i'j'$)	AG($i'j$)	AG($i'j''$)
i	AG(ij')	AG(ij)	AG(ij'')
i''	AG($i''j'$)	AG($i''j$)	AG($i''j''$)

Each agent has a maximum 8 neighbours, illustrated in Fig. 5, and which are defined as follows:

$$AG_{ij} = \{AG_{i'j'}, AG_{ij'}, AG_{i''j'}, AG_{i'j}, AG_{i''j''}, AG_{i''j}, AG_{ij''}, AG_{i'j''}\} \tag{2}$$

where, $\begin{cases} i' = i - 1 \\ i'' = i + 1 \end{cases}$ $and,$ $\begin{cases} j' = j - 1 \\ j'' = j + 1 \end{cases}$

Each bus can have a maximum of information about its Environment exchange among agents. Data base of agent consists of the system information that can be classified into two categories of structure arrays. One concerns the branches and other structure arrays of buses as shown in Figs. 6 and 7 respectively.

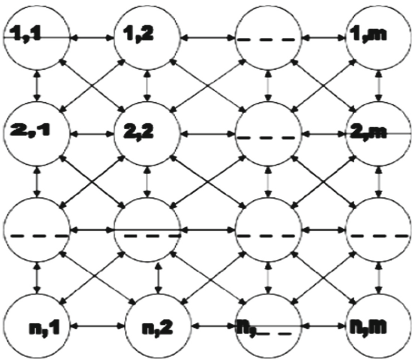

Fig. 5. Multi-agents compensation proposition

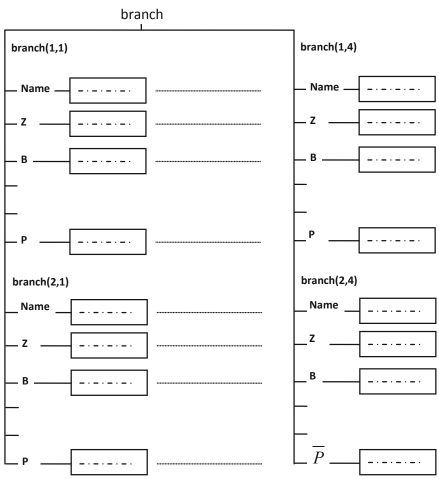

Fig. 6. Branch data structure arrays

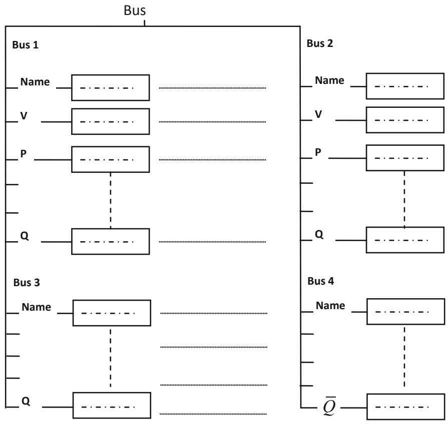

Fig. 7. Bus data structure.

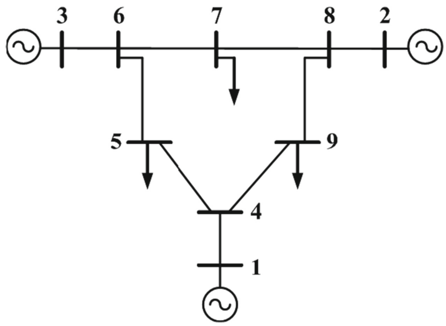

Fig. 8. IEEE 9 bus power grid.

7 Simulation Results and Discussion

A standard IEEE 9 bus shown in Fig. 8 has been implemented for testing our approach concerning multi-agents by applying the previous mentioned rules using Matlab. Bus 1 is taken as reference and the others are PQ buses. Renewable energy sources may be used to inject power at buses 4 and 7. Thus, bus 7 is considered as customer-owned solar PV. Simulink model of the test bench that has been developed in our laboratory for testing our approach is shown in Fig. 9.

The load at bus 9 has been increased from 125 MW to 425 MW, all voltage levels of buses remain within allowable limits, except bus 9 voltage level is reduced to 0.79 pu (see Fig. 10). Agent of bus 9 detects that the voltage of its bus has been reduced below the allowable limit. Then, it communicates with near neighbours which have power source. In this case, bus 4 may reply. GAG 4 verifies the two constraints which are thermal capacity of power transmission line and the stored electrical energy of the renewable source. If the two conditions have been satisfied, a positive reply may be sent to BAG 9. The obtained result is illustrated in Fig. 11.

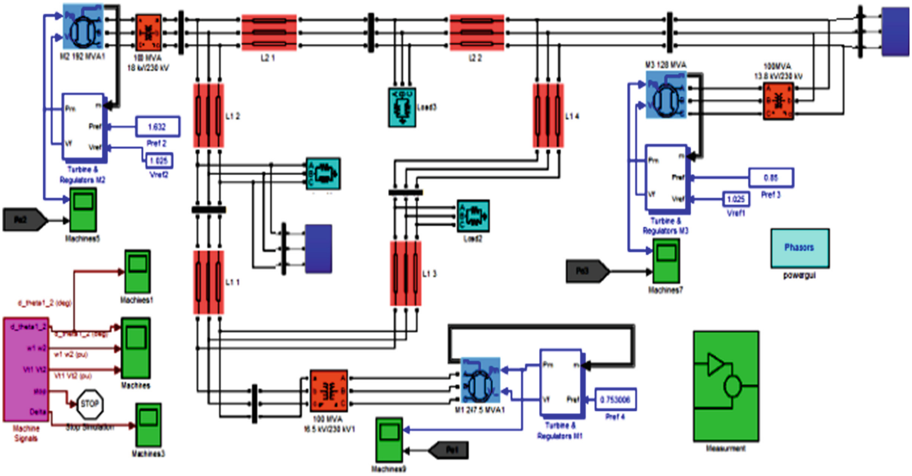

Fig. 9. IEEE 9 bus power grid Simulink model with two PV sources.

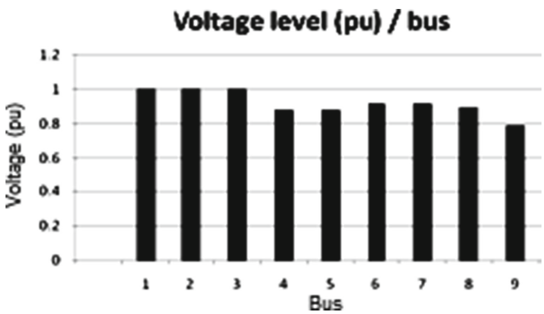

Fig. 10. Buses voltage levels during the contingency (bus 9 changes from 125 MW to 425 MW).

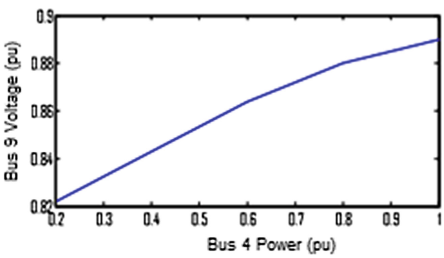

Fig. 11. Bus 9 voltage as function of power injected at bus 4.

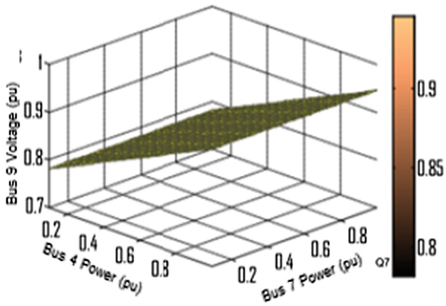

Fig. 12. Bus 9 voltage levels as function of power injected at bus 4 and bus 7.

When bus 4 attains its maximum of power energy that can be injected to the power grid, its agent will send a message "Stop" to BAG 9. If the voltage level does not return back within the limits, BAG 9 determines the next generation agent (GAG) that is in the second order which can contribute to increase its voltage level. GAG 7 may receive a message and which in turn verifies the two constraints. It can be noted that the last satisfies the conditions and inject the required energy for returning back the voltage level within the limits as shown in Fig. 12.

8 Conclusion

This paper proposed a distributed multiagent approach to mitigate the problem of voltage regulation that may be caused by the disturbances in the microgrid. In this research work, two types of agents are created the GAG and the BAG. The GAG determines the stored power energy and the transmission power line thermal capacity and BAG collects information about the grid from neighbour agents. The two kinds of agents collaborate together to regulate the voltage levels by injecting more power at some buses using the renewable energy sources. The interaction between the two types of agents is based on communication and exchange of information about the parameters and the state of the power grid. The voltage regulation can be controlled by bus agents and assured by generation agent starting by the low power generation order. Data base of each agent may contribute more in the coordination and the successful solution without conflict that may lead to time delay during the critical contingency. A coherent structure that guarantees an efficient way to manage and control multiple distributed energy resources (DERs) was created. A standard IEEE 9 bus was implemented for testing our approach; hence, simulation was used to verify the proposed approach and it was showed a satisfactory results. However, to ensure the efficiency of this approach, validation on realistic data is of must. Thus, future work will be on testing the developed approach using realistic systems with field data.

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