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Intelligent energy management system of a smart microgrid using multiagent systems

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Abstract: The smart grid concept is predicated upon the pervasive use of advanced digital communication, information techniques, and artificial intelligence for the current power system, to be more characteristics of the real-time monitoring and controlling of the supply/demand. Microgrids are modern types of power systems used for distributed energy resource (DER) integration. However, the microgrid energy management, the control, and protection of microgrid components (energy sources, loads, and local storage units) is an important challenge. In this paper, the distributed energy management algorithm and control strategy of a smart microgrid is proposed using an intelligent multi-agent system (MAS) approach to achieve multiple objectives in real-time. The MAS proposed is developed with co-simulation tools, which the microgrid model, simulated using MATLAB/Simulink, and the MAS algorithm implemented in JADE through a middleware MACSimJX. The main study is to develop a new approach, able to communicate a multi-task environment such as MAS inside the S-function block of Simulink, to achieve the optimal energy management objectives.

Key words: artificial intelligence, fault detection, microgrid, multi-agent system (MAS), power distribution, smart grid

1. Introduction

The scares of conventional energy resources and the increase of CO2 emissions impact of these sources are accelerating the technologies for new renewable energy (RE) environment-friendly energy options, the smart grid and smart microgrid are becoming increasingly important [1].

A smart grid is a modern system based on new information and communication technologies (ICTs), represents a transformation towards an intelligent and digital technology that is utilized to supply the electrical power to consumers via two-way communication [2]. A microgrid is an important block of a smart grid system and it plays an important role in the adoption of a renewable energy source. A microgrid (MG) is a new type of power system, a low voltage network system, normally located at the consumer's side, wich consists of a storage system, distributed generators (including wind power, solar, fuel cells, micro-turbines, and hydroelectric), and control units for energy management [3]. An MG locates the downstream of a distribution substation through a point of common coupling (PCC). An MG can operate either in grid-connected mode or in island mode [4], and normally requires an energy management system to ensure the interaction between the controllable units for achieving stability and balanced operation. Economically, the microgrid has the benefits of decreasing losses because the energy sources are located nearest to the consumers, that allows optimizing the energy routing and limiting the transmission and distribution networks investments.

However, the intermittent nature of renewable energy sources creates new challenges and issues when integrating into the grid power and impacts the stability of the micro-grid [5]. To meet these challenges, the microgrid should integrate the control strategies to achieve a balance between production and consumers. Distributed energy management and control in real time are required for the injection of new renewable energy sources into the microgrid. Early power services used for dispatch operators are equipped with supervisory control and data acquisition (SCADA) [6] systems to manage and control, transmission switching, protective relaying, and communication protocols. In traditional SCADA deployments, the human supervisor takes the role of encapsulating and handling inherent uncertainties arising from incompleteness and inconsistencies. Intelligent multi-agent systems need to perform this role autonomously. The research on a multi-agent system (MAS), particularly on their use in smart grid and microgrid control and management have been developed over the last ten years [4].

The use of multi-agent systems to increase the performance of distributed control capabilities and energy management in microgrid applications offers various advantages over traditional SCADA systems [7]. The SCADA systems offer timely and precise monitoring of traditional network resources, the raw data produced usually contains only implicit information. Additional analysis by engineers using multiple data sources is often required to obtain explicit information about power system operations. Such manual analysis of data can be time-consuming. MASs are composed of multiple intelligent agents that are combined to resolve problems that may be behind the capacities of each specific agent in a short time [8]. A multi-agent control system provides a necessary degree of efficiency and reliability which works in real-time and a fully distributed system, where each agent can be connected to other agents at the same or different layers.

A multi-agent system (MAS) is a computer software architecture, largely used in current years. It is naturally efficient to solve the challenges in a distributed environment, uses a highly distributed topology which is compatible with the new electrical network structure [9]. The communication between agents can be designed in such a way that the MAS achieves a global goal for management and control. Current research indicates that the MAS approach has been proposed for protection, automation, and control tools in power distribution networks [10]. DIMEAS *et al.* [11], presents the capacities of MAS technology in microgrid operation and the importance of the distributed control and autonomy of the microgrid. The development and implementation of a multi-agent system that provides intelligent, real-time supervision and MAS application in smart grid systems are discussed by Warodom *et al*. [12]. In [13], an autonomous control algorithm based on an MAS algorithm for fault analysis, fault control, and power restoration solution in the distribution network is proposed. The distribution management and control of microgrid energy, the major issues, and challenges of microgrid control are presented in [14]. The integration of renewable energy sources into grid creates new challenges, Boudoudouh *et al*. [15] proposed a real-time distributed system modeling and management of amicrogrid that combined a photovoltaic source, fuel cell, and electrolyzer system by MAS technology, using the MACSimJX platform. In [6], a microgrid model, using MATLAB/Simulink software and an MAS in the JADE platform for intelligent autonomous, is developed for distributed energy management of a smart microgrid. The design and implementation of the MAS for the intelligent distributed power system to optimal load scheduling, using JADE and MACSimJX, have been reported [16].

In [17], a multiagent system (MAS) for the real-time operation of microgrid energy management in islanding mode, using real-time digital simulator (RTDS) and JADE, is proposed. The development and implementation of a hardware-in-the-loop simulation (HILS) system for a distributed intelligent energy management system for microgrids is also proposed. The HILS system, intelligent agents are developed using microcontrollers and ZigBee wireless communication protocol using the Opal-RT simulator [18].

This paper focuses on proposing a multi-agent system to control and manage the microgrid distribution system. The energy management strategies are introduced autonomously and implement smart grid features using the MACSimJX platform. Thereafter, a multi-agent system based coordinated control strategy for distributed loads is developed for the microgrid in island mode. The advanced approach is developed upon a co-simulation platform for a hybrid microgrid, modeled in MATLAB/Simulink, and managed by the actions of an MAS implemented in JADE.

This paper is organized as follows: Section 2 presents the Simulink model of a microgrid, in Section 3, we present a multi-agent framework for the microgrid coordinated control strategy and implementation of energy management using MACSimJX, the simulation and results discussions of the control strategy are shown in Section 4, finally, Section 5 presents conclusions.

2. Simulink model of the microgrid

The studied microgrid system combines many distributed energy resources (DERs), critical loads, the energy storage system (ESS), and non-critical loads. The energy storage systems prove the increases of the RES integration into the grid challenge and are capable to provide or to store the difference between production power and the consumption power. An MG can be connected to the main grid power via PCC or can run in island mode. In this paper, the microgrid model consists of a distribution network of 20 kV that connects three DERs, including a photovoltaic (PV) generator with the maximum power point tracking (MPPT) control that allows the PV to operate at the voltage corresponding to the maximum power extracted, wind turbines, diesel generator, three loads (including two 500 kW non-critical loads (NCLs) and one critical load with a variable load profile that achieves a peak of 3 MW, whose power must be supplied reliably), the distributed storage system that increases the quality of a microgrid by damping peak surges and surplus in electricity demand. The microgrid AC bus is connected to both the DC source and storage assets (using an inverter) and the utility grid through a PCC breaker. The maximum production power of an MG achieves 3.6 MW and the peak of consumption achieves 4 MW. The parameters of the MG components are summarized in Table 1. Our goal in this paper is to propose an intelligent multi-agent system in the main grid and smart management of energy in island mode to protect microgrid components when a fault occurs.

Table 1. Microgrid components

MG components	Size
PV	100 KW
Wind	1.5 MW
Diesel	2 MW
NCL-1	500 KW
NCL-2	500 KW
Critical load	Variable with a peak load of 3 MW
ESS	500 KW

2.1. Wind turbines

The wind turbines generate electrical power in the same way as all other sources of production technologies. The wind energy is produced according to the linear relationship with the wind speed. The wind turbine will generate a nominal power when the wind speed has a nominal state [19, 20]. The wind turbine model is described as:

$$P_{\text{wind}}(v) = \begin{cases} \dfrac{P_{\text{nom}}(v - v_{ci})}{(v_r - v_{ci})} & (v_{ic} \le v \le v_r) \\ P_{\text{nom}} & (v_r \le v \le v_{co}) \\ 0 & (v \le v_{ci} \quad \text{or} \quad v_{co} \le v) \end{cases}, \tag{1}$$

where P_{wind} is the wind power (kW), P_{nom} is the nominal power (kW) of a wind turbine, v_{ci}, v_{co} and v_r are cut-in, cut-off and rated wind speeds, respectively, and v is the wind speed (m/s). Final output $P_{\text{out}} \le P_{\text{wind}}(\vartheta)$ is due to losses. The output power of a wind turbine can always be adjusted to match the load demand.

2.2. Photovoltaic model

Photovoltaic solar energy is reliable, free, provides long-lasting supply and high energy security. The solar energy is converted into electrical energy by PV cells. This phenomenon occurs in materials which have the characteristic of sensor photon and release electrons. The photovoltaic panel is characterized by the equation [21]:

$$I = I_{ph} - I_s \left(e^{\frac{(V + I R_s)q}{akT N_s}} - 1 \right) - \frac{(V + I R_s)}{R_{sh}}, \tag{2}$$

where N_s represents the cell's number in series, I_{ph} is the current generated by the photoelectric sensor, I_s is the reverse current of saturation. R_{sh} and R_s are inherent resistances in parallel and series connected with the cell. k is Boltzmann's constant, q is the electron charge and a is the modified ideality factor.

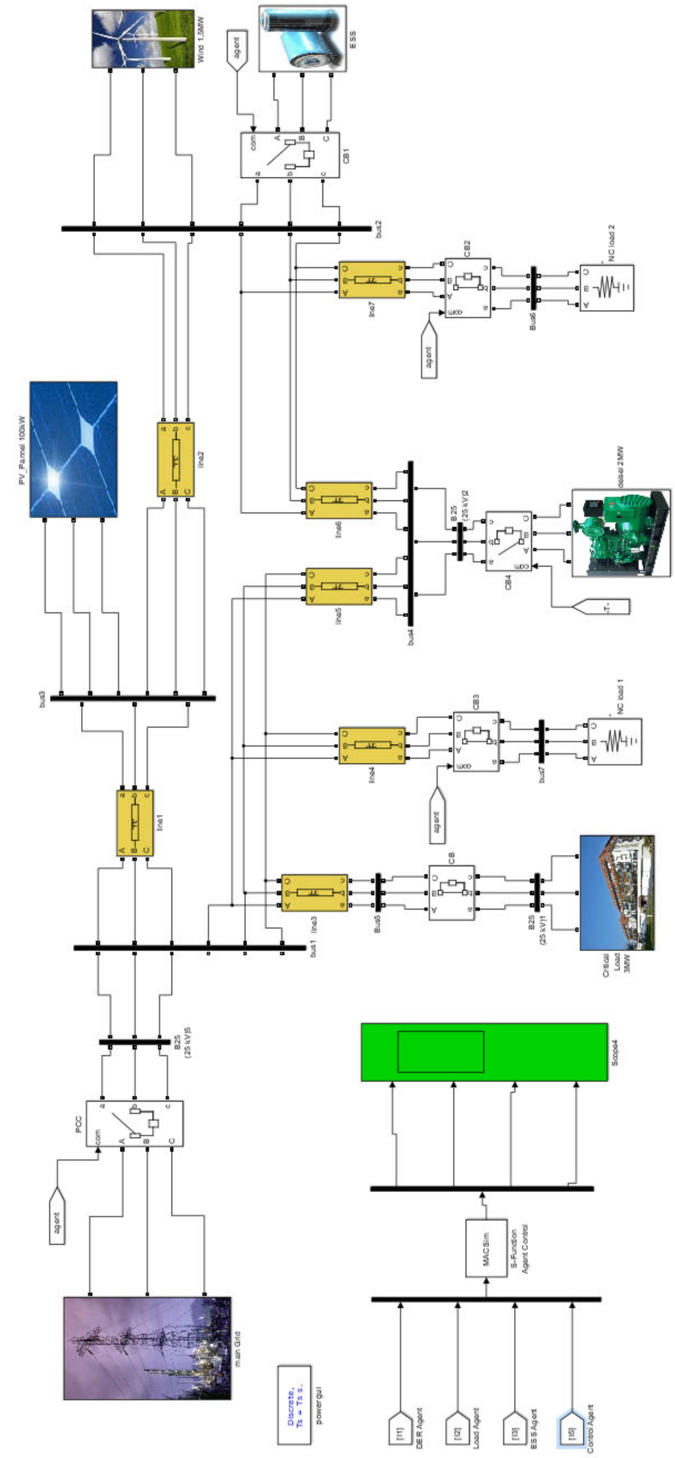


Fig. 1. Microgrid Simulink model

2.3. Battery storage system

The increase of renewable energy development, especially with the variability of power production like PV and wind energy, leads to requiring a difference in storage technologies to decrease the intermittency problems of renewable energy sources. The battery storage system stores the surplus of energy production and provides energy when there is a power deficiency of renewable energy source systems. The batteries' simple dynamics are modeled as follows [22]:

$$\mathrm{SOC_{batt}} = 100\left[1 - \left(\frac{1}{Q_{\mathrm{batt}}}\int_0^t i_{\mathrm{batt}}(t)\,\mathrm{d}t\right)\right], \tag{3}$$

where $\mathrm{SOC_{batt}}$ is the battery state of charge (%), i_{batt} is the battery current and Q_{batt} is the maximum battery capacity (Ah).

The microgrid model proposed consists of distributed generation systems simulated, developed, and tested using Matlab/Simulink. The Simulink model of the microgrid is shown in Fig. 1, consists of five components: a diesel generator, wind farm (DFIG), PV system, battery storage system and load. The microgrid model is simulated using SimPowerSystem's discrete mode in order to achieve a faster simulation time for a 10 s scenario.

3. Multi-agent framework for microgrid control

The design for microgrid organized control and energy management is presented in Fig. 2. There are four types of agents: Load Agent, control Agent, DER Agent, and ESS Agent. Each agent has its particular functions, characters, and provides several services. Each agent communicats with other agents and controls its assigned asset according to specified goals (Table 2).

Table 2. Microgrid agents' tasks

Agent	Tasks
Control Agent	a) Responsibility for the protection of microgrid operation modes, monitoring, and controlling all agents in the microgrid. b) Supervising the state of the microgrid, connection and disconnection of the MG to the main grid in PCC. c) Receiving data from Simulink (DER production and the consumption of loads).
DER Agent	d) Assembling the data associated with the energy source such the power produced in real time and its availability.
Load Agent	e) Obtaining critical and non-critical load consumption data from the Simulink-model. f) Assembling the information such as load power, current, and voltage. g) Responsibility for the control and protection of a load and varying power consumption.
ESS Agent	h) Obtaining recommendations from the control agent to provide or to store energy. i) Collection of the state of charge of the storage unit from Simulink.

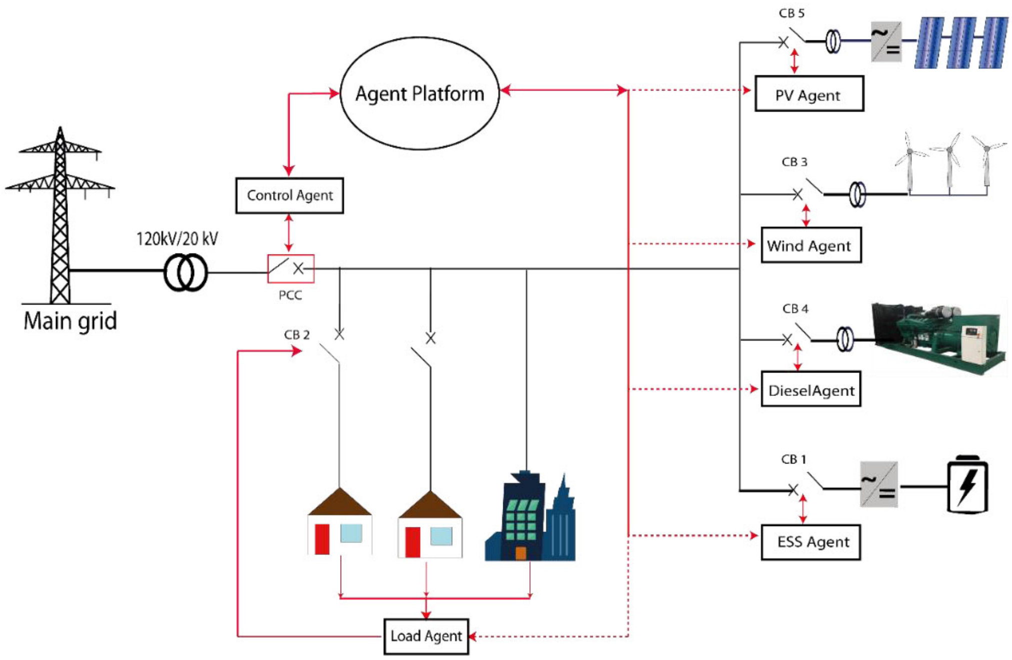


Fig. 2. Structure of the microgrid with different control agents

In this paper, the MAS is developed using the JADE (Java Agent Development Framework) environment and the distribution microgrid is created and simulated using MATLAB/Simulink. The JADE and MATLAB/Simulink tools are run on the same machine to allow the agents in the MAS layer to gather, to command and control (open/close command) the circuit breakers (CBs) in the Simulink process layer.

The communication middleware for transmitting the MAS data (send/receive) to/from the microgrid model in the Simulink required the co-simulation platform between both simulators (JADE and Simulink). These two simulation platforms are connected together through the MAC-SimJX or the Multi-Agent Control for the Simulink program [23] middleware to facilitate the interaction of the electrical power system and its integrated multi-agent communication layer as shown in Fig. 3. The MACSimJX platform is based on smart grid communication protocols using Pipes under Windows to provide data exchanging between the multi-agent system in JADE and microgrid simulation model in Simulink.

Due to the intermittency of the renewable energy source capacities, the power supply demands of all loads in a microgrid may not be able to be met simultaneously in island mode. However, it is important and necessary to ensure that some critical loads can be operating reliably and safely in island mode, if production power is lower than the power required from loads. The ESS Agent verifies the state of charge (SOC) of the storage system and switches the CB1 to provide energy to the microgrid. If the SOC is fully drained (20%), therefore, the non-critical loads are being removed via Load Agent to secure stable operation of the microgrid and to supply the critical load. If more energy is required the Control Agent provides the control signal to close the

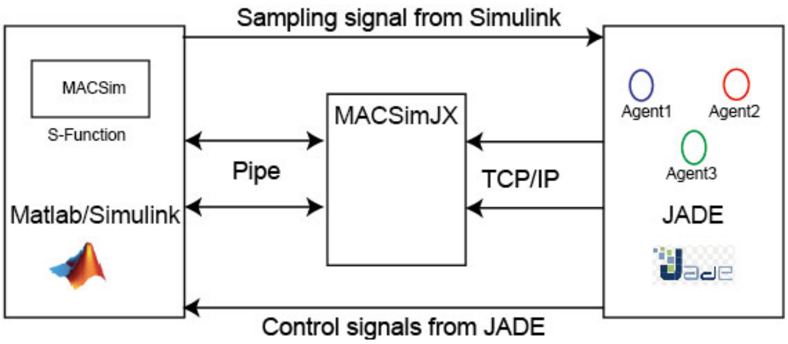


Fig. 3. Simulink and JADE co-simulation

circuit breaker (PCC) to connect to the main grid. In the case when DER power is higher than the power required from loads, the ESS Agent switches CB1 to store energy from the microgrid, if the ESS is not fully charged yet. When the ESS is fully charged (SOC = 100%), the Control Agent closes the circuit breaker (CB) to provide energy to the main grid. Microgrid components must be protected during a fault in the main grid. When Control Agent detects a voltage dip or an overvoltage fault occurs near the main grid, an MG disconnects and runs in island mode. The control strategy presented in this paper, to use the smart grid characteristics in a microgrid, is shown in Fig. 4.

The agent platform represents the communication network between agents, each agent executes a set of behaviors that are arranged by the designer based on the agent's goal. The agent that consists of a message handling layer is responsible for the sending and receiving of messages from other agents, as well as implementing the relevant agent communication language (ACL) and ontology.

In a microgrid, DER power, loads, an ESS level, and NCL are controlled continuously and based on the randomness of a load consumption profile and RE intermittency. The MAS proposed estimates all logical decisions and chooses the best reasonable action for optimal energy management. The overall procedure is as follows:

i. Initially, in island mode of a microgrid, the Load Agent communicates with the DER Agent through an ACL message. If the DER power is not sufficient to satisfy the load energy consumption, it looks into the storage unit. The ESS supplies the full amount required until it gets drained, at each instant ESS agent checks the SOC of the ESS.
ii. Moreover, after taking from the ESS, if power is still needed, the Load Agent disconnects the NCL and follows demand-side management strategies. Even after NCL shedding, if the critical load requires power, the Control Agent closes the PCC breaker to connect with the grid.
iii. If the excess of energy is available in the microgrid after satisfying consumers, the ESS Agent checks the SOC to charge and store the surplus power in the ESS till it is full, then if there still is surplus energy, the energy is delivered to the grid by the Control Agent.
iv. Each agent is processed according to the associated switching procedure to decide on a reflexive action. These switching commands are sent to Simulink by the MAC-SimJX

interface for dynamic and real-time simulation. These action commands are applied to circuit breakers for switching and controlling the microgrid.

v. If the grid power is not needed or if a fault occurs near the main grid, the Control Agent commands the PCC breaker and microgrid to run in island mode. Every hour the algorithm based on the load necessary and availability of DER power, gives an agent the logic possible decision in a distributed environment.

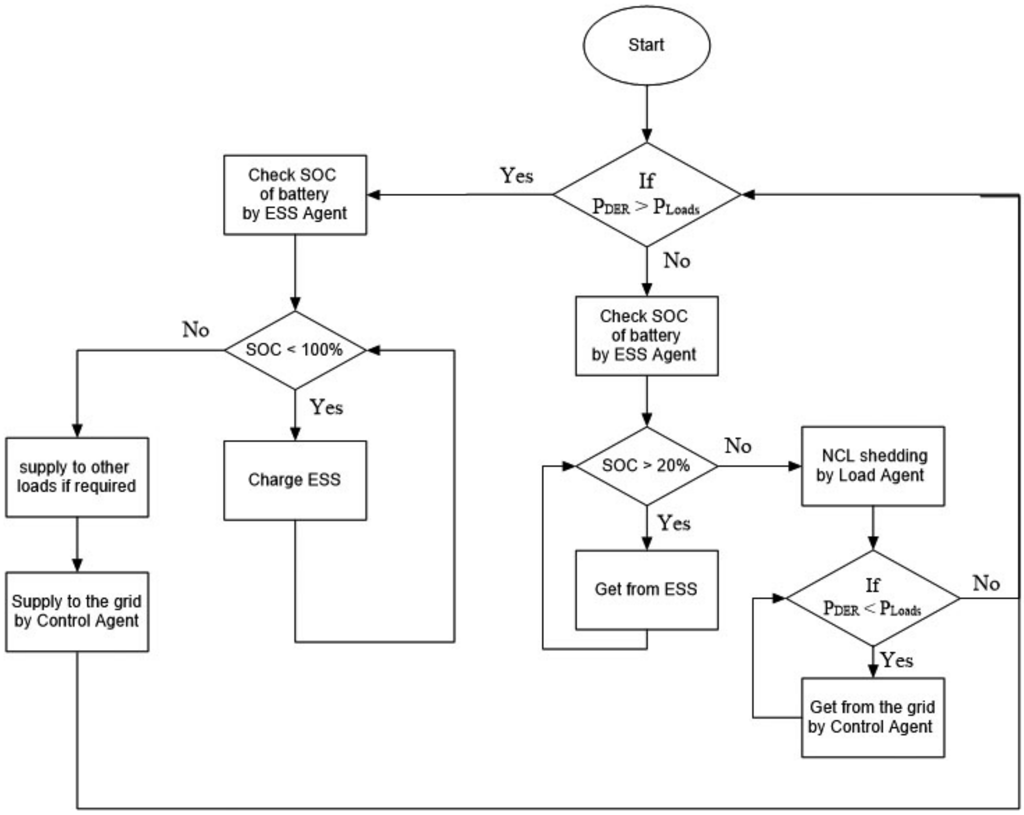
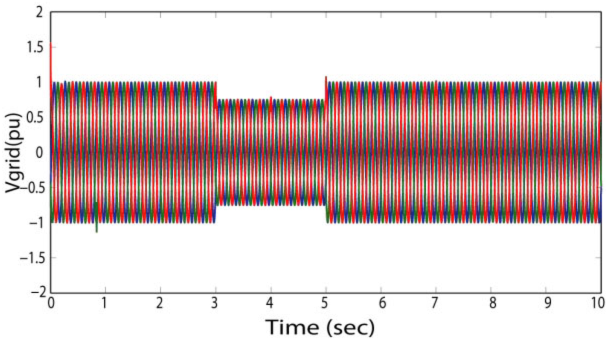


Fig. 4. Flowchart of the control strategy

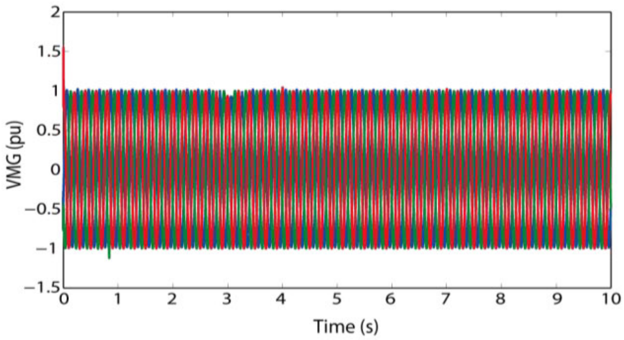
4. Simulation and discussions

4.1. The result of the occurrence of a three-phase fault

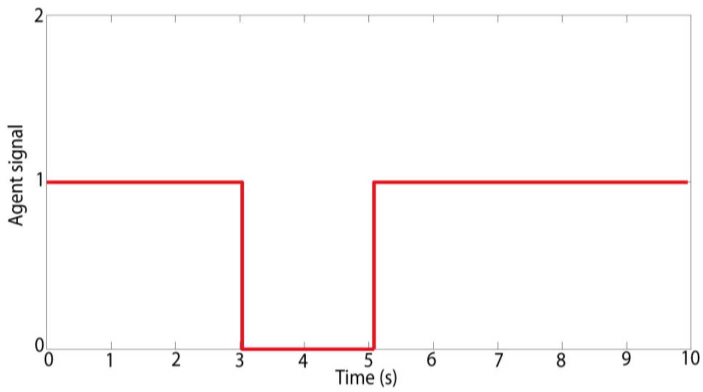
First of all, when Simulink starts, the voltage and frequency of a microgrid must be controlled and follow the frequency (50 Hz) and voltage (1 per unit) of the main grid. When a three-phase fault happens near the main grid (Fig. 5(a)), the Control Agent detects that ($VG < 0.9$ pu) and sends a control signal to the PCC breaker for isolating the MG during a fault, ths securing all the components. After the Control Agent sends a signal (Fig. 5(b)) to switch the microgrid in island mode, it requests the power production and consumption from the DER and Load Agent. Fig. 5(c) shows the MG voltage after the isolation and its grid current, respectively, the multiagent system controls the voltage when a fault occurs in the grid. After the restoration, the MG connects itself to the grid.



(a)



(b)



(c)

Fig. 5. Grid's voltage (a), microgrid's voltage (b), Load Agent's decision-making (c)

4.2. In island mode

In island mode, we consider that: $P_{\text{wind\_max}} = 1.5$ MW, $P_{\text{pv\_max}} = 100$ KW, $P_{\text{diesel}} = 2$ MW, $P_{\text{critical}} = 1$ MW, the ESS is fully drained and critical load is operating online at 2 MW and the NCL at 1 MW. In this case, $P_{\text{DER}} \approx P_{\text{Loads}}$, at the instant 7 s, the critical load consumption increases by 1 MW and needs an electricity supply which shows that the total consumption becomes 4 MW (Fig. 6). The Load Agent queries the DER Agents and SOC from the ESS Agent for running state information on power production. Then the Control Agent sends the request of shedding the non-critical loads to the Load Agent during this period as shown in Fig. 7.

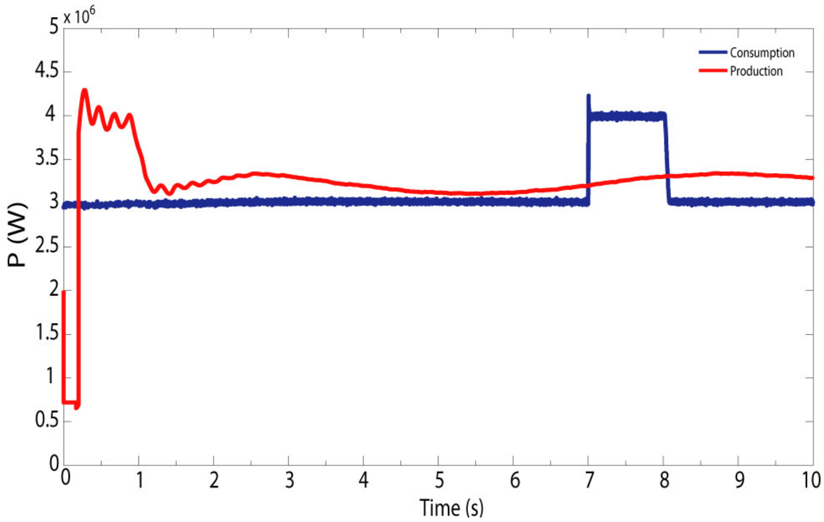


Fig. 6. DER and loads' power

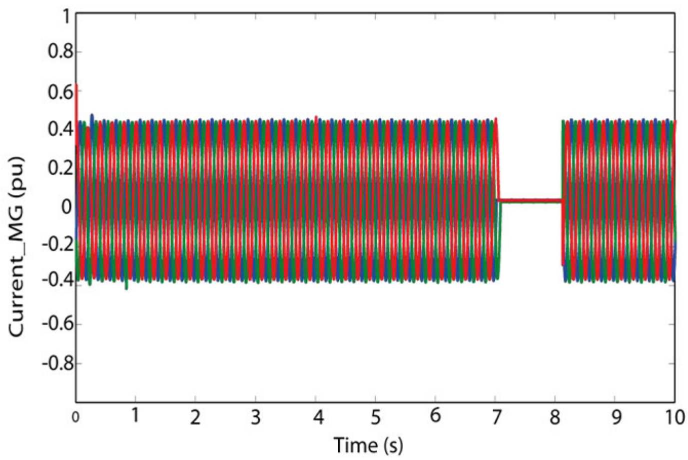


Fig. 7. The non-critical load current

In the case when the ESS is fully charged (SOC = 100%), the ESS takes over control by providing the energy without a need for the main grid to supply the non-critical load consumption during the period that the production is lower than the consumption. The Control Agent sends to the ESS Agent a request to close CB 1 at 7 to 8 second. Fig. 8 presents the SOC decreasing in the storage system during this period. After taking power from the ESS, if power is still required, the Control Agent checks if it is necessary to remove non-critical loads at this period and follows demand-side management strategies.

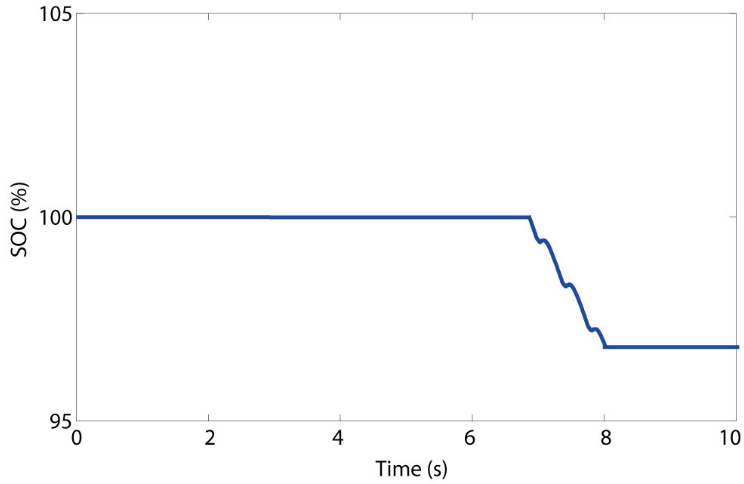


Fig. 8. ESS state of charge

In the case: P_{wind_max} = 1.5 MW, P_{pv_max} = 100 KW, P_{diesel} = 2 MW, $P_{critical}$ = 1 MW, and SOC = 20%. The Control Agent detects at 0 to 4 s that a surplus of energy has occurred $P_{DER} > P_{Loads}$ (Fig. 9), the remaining energy is used for charging the ESS. The ESS Agent

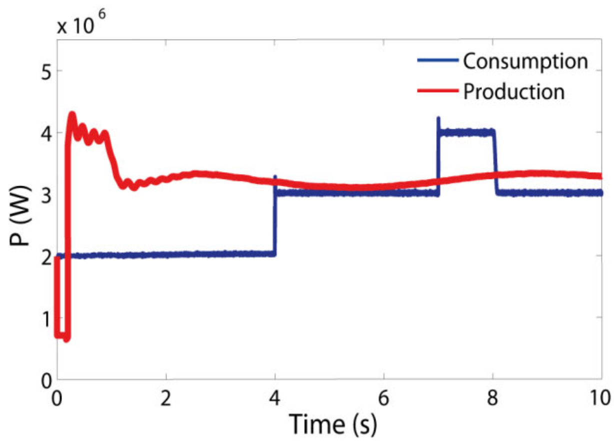


Fig. 9. DER production and loads consumption

receives the command from the microgrid Control Agent to close the breaker (CB1) for consuming the surplus energy. If the ESS is fully charged and power is still in excess, the Control Agent sends signal to connect to the grid from the JADE environment. Between 4 and 7 sec, the consumption critical load increases to 3 MW, almost equal power production, and a microgrid's voltage as well as frequency in the normal range. The ESS Agent sends a control signal to open CB1.

At the instant $t = 7$ s, the maximum power consumption increases to 4 MW and the Control Agent queries the DER Agents and ESS Agent for running state information. Then the Control Agent will request the ESS Agent to control storage breaker to provide energy and secure the electricity supply that has the right properties to serve the balancing of electricity generation and demand. Fig. 10 shows the SOC of the ESS evolution during the simulation time, the ESS stores the energy during the peak production when output is in an over-supply state, to bridge the gap when the renewable energy is intermittent.

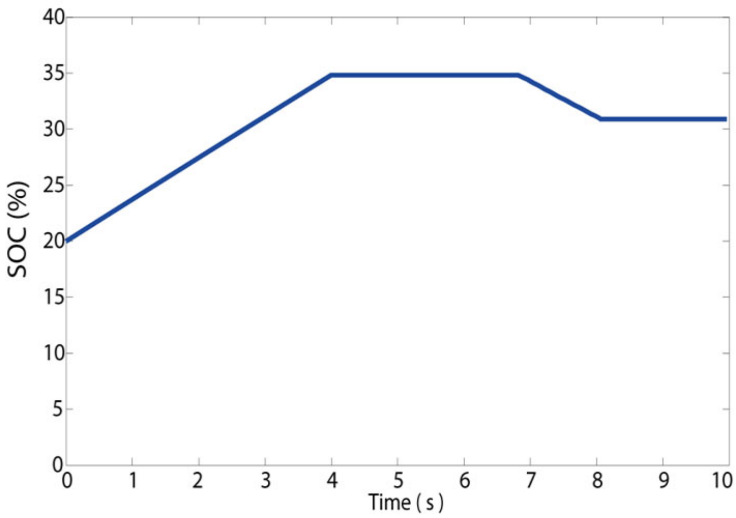


Fig. 10. Battery state of charge

The above simulation results show the advancement and efficiency of the multi-agent approach strategy that we proposed using the co-simulation between the Simulink and JADE environment. It is proved that this algorithm can assure the balance between supply and demand and the control of the microgrid voltage, frequency, and components. This control and energy management strategy can be used also in all the smart grid specialties such as fault location, modularity, flexibility, fault recovery and diagnostic.

The communication flow diagram of all agents for this case study is shown in Fig. 11, in which it can be seen that the Control Agent communicates with all Agents via different message schemes. All the agents have performed their tasks properly in terms of fault detection, energy management, and system control.

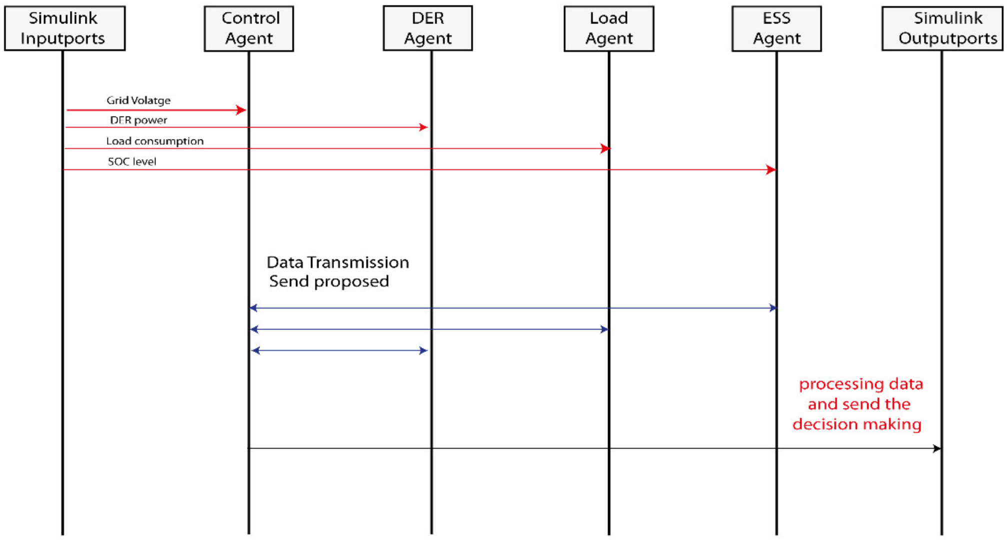


Fig. 11. Multi-agent communication flow diagram

5. Conclusion

The multi-agent systems consist of many smart agents that are combined to resolve the complex problems. For several years, the MAS designs and applications have been used in power systems and power engineering applications such as the integration of distributed energy resources in a microgrid, renewable energy challenges because of their intermittency, and energy management. In this paper, a multi-agent approach control strategy and real-time energy management are proposed for power loads in the microgrid. The MAS-based control design is developed using the JADE simulator and microgrid model simulated in MATLAB/SIMULINK with the MACSimJX interface to share data with each other. The simulation results prove the capability of the multi-agent system to effectively work in island mode in the case of the up-stream fault in the main grid and secure the supply for critical loads. For the proposed strategy the response time to making a decision in a short time and operational efficiency are improved by contribution to the conventional methods.

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