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Multi agent system solution to microgrid implementation

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ABSTRACT

Microgrids contain various power systems with different power capacities and generation fluctuations. An overall power management strategy is necessary to manage power flows among all interconnected elements. This paper presents a multi –agent system solution to energy management in a microgrid based on distributed hybrid renewable energy generation and distributed consumption (vital loads and non-sensitive loads). The real model of each element connected is needed, enabling microgrid modeling and control. A new architecture using multi –agent system solution is proposed, allowing making all the calculations required in Matlab Simulink and the intelligent strategy of energy management is executed by agents designed by Jade. While the communication middleware between Jade and Simulink is carried out by MacsimJX. Finally, it was justified how multi agent system can be a suitable solution to microgrid implementation requirements.

1. Introduction

Electrical energy needs are growing globally due to increased dependence on electricity for daily activities. The renewable energy sources (RES) and distributed generations (DG) are considered as a promising concept to overcome this critical issue. The RES and DG increasing incidence leads to regularities changes, also needs to improve the power system reliability and to clean power support. Therefore the development of a new power system perception commonly referred as a microgrid is required.

The microgrid is based on DG which powers a cluster of distributed loads. The power sources must then be small sized making the RES very attractive. The sources geographically distributed Rekik, Chtourou, Mitton, and Ateih (2016) in the microgrid allow the RES to be well located near the available natural deposit such as the wind, solar radiations, watercourse…etc. The distributed sources can be placed where the renewable energy is available in the case of RES or near to the load such as micro-turbines or green generators as the fuel cells. The distance between sources and loads should be limited to minimize the line losses.

In the microgrid the RES depict the total or the almost producer sources. The main drawback of RES is they are very dependent on meteorological conditions thus are hardly predictable and very unsettled. The energy storage systems are promising improvements to overcome the RES integration issue, and are able to provide or to consume the difference from generated power and the required power. On the other hand, diesel generators or fuel cells can provide ancillary services to the intermittent sources, by providing the energy necessary when the storage systems are empty. However, fuel cells remain very expensive, and diesel generators are very dependent on fossil fuels. Having regard to this, a very sophisticated energy management was presented in the literature allowing the power exchange control among different sources and storage units under different criterion such as cost minimizing, residential energy efficiency and environment protection Courtecuisse,et al., (2008), Lei, Mullane, Lightbody, and Yacamini (2006), Roche (2012).

The environment benefice of the microgrid deployment is then the integration of RES. The microgrid technical benefice is depicted in its technical implementation which requires three connecting modes: Grid-connected mode, islanded mode, or grid-on/off-grid mode. However, in the grid connected-mode, due to their intermittent, the RES are unable to participate in technical regulations such as voltage control. Also the unknown power back grid in real time could restrain the grid-connected mode development. In the microgrid islanded mode the continuous safely supply to the load is the major issue. While in the grid-on/off-grid mode the microgrid can operate in both grid-connected and in islanded mode Kroposki et al., (2008), Hatziargyriou, Asano, Iravani, and Marnay (2007). In the off-grid aspect the microgrid is autonomously feeding, while in the grid-on, the microgrid can receive energy from the utility grid and also can trade back the excess of power to the utility grid or to another microgrid Sechilariu, Locment, and Houssamo (2010).

Economically, the microgrid has the advantages of reducing losses because sources are placed nearest of the loads, that allow optimizing

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the energy routing and limiting the transmission and distribution networks invests.

The microgrid social profit offers the energy necessary to meet the fundamental energy needs evolution of a territory. However, the load growth can lead to the microgrid degradation Benetti, Caprino, Vedova, and Fachinnetti (2016); it runs well in the first years and a complete failure occurs in the following years Nelson, Starcher, Foster, Clark, and Raubenheimer, (2002).

The microgrid should meet the load changes, the technical constraints, the social changes and environment changes. Therefore, heterogeneous, intelligent, scalable, self-adaptive, autonomous, open, and dynamic, are crucial concerns for the microgrid implementation. Furthermore, an advanced energy management strategy (EMS) should be provided. The advanced EMS should first balance between the produced and the required power and maintains the voltage control simultaneously. The microgrid control was the subject of many studies Chana, Cameron, and Yoon (2017), Fattahi et al. (2016). However, as pointed out above, the microgrid should be more reliable, effective, stable, and more integrated of RES. Therefore a distributed energy management (DEM) is required. The DEM deals with the simultaneous operation of the DG, RES, storage systems and distributed loads connected to the microgrid with the respect of the multiple technologies and capacities of each element connected. Indeed the DEM in a microgrid cannot be easily implemented without a high-level energy management by means of multi-agent system (MAS).

The MAS consists of a group of entities called agents. These agents are physical or virtual entities Mevludin, (2006) able to autonomously react in the environment where are situated, can communicate with each other and perceive their environment, senses it, interact with it Ferber (1999), and act over it as shown in Fig. 1. The MAS concept, its implementation, and its design let the MAS suitable to manage complex distributed systems, where heterogeneous resources distributed in different emplacement in a dynamical fashion, and various changes can occur and the system requirements are often changed and reconfigured. However, it is noteworthy to regard the comparability between the Microgrid architecture and MAS. MAS was widely used in managing complex distributed systems such as microgrids, including grid restoration and isolation, RES integration, diagnostics, monitoring and intelligent market operations Digra and Pandey (2013), Foo Eddy, Gooi and S. Chen (2014), Khamphanchai, Pipattanasomporn, and Rahman (2012), Khamphanchai, Kuzlu and Pipattanasomporn (2013), Kouluri and Pandey (2011), Prostejovsky, Lepuschitz, Strasser, and Merdan (2012). Contrarily to the centralized control approach Dufo-Lez, Bernal-Agus, Contreras (2007), Kolen, Molitor, Wagner and Monti (2017), Mohamed (2008), Olivares, Canizares, and Kazerani (2011), Sopian et al. (2008), the DEM by MAS provides powerful communication facilities to handle a huge number of data with a certain intelligence to reduce computations and communication and perform planning action and decision-making.

Many studies regarding microgrids development by MAS such as mentioned earlier have focused in transition between the islanded and

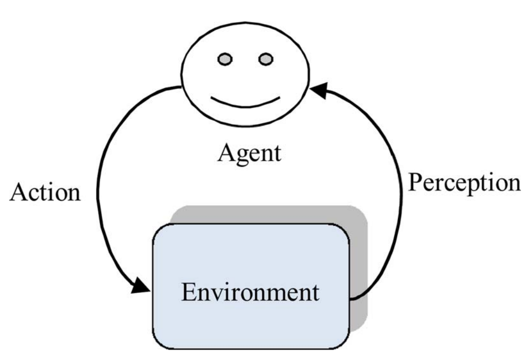

Fig. 1. Agent interaction with its environment.

grid connected mode, in restoration and isolation or detecting upstream outages and working in an island Pipattanasomporn, Feroze, and Rahman (2009), also in market operations and in energy resources scheduling and monitoring Lezama, Palominos, Ansel Rodríguez-González, Farinelli, and de Cote (2017), Logenthiran Srinivasan, and Khambadkone (2011), Logenthiran ,Srinivasan, Khambadkone, and Aung, (2010). All of these studies have proved that the MAS technology has shown the signs of future success in term of power restoration issues, energy efficiency and microgrid optimization operations Hamad and Saadany (2016). However if the microgrid contains various DGs, based on RES, therefore how to control their strong intermittent, and ensuring the stability and continuity must be of the main consideration of the studies concerning the microgrid operation. In this paper the economic, social, environmental, and technical microgrid benefits are shown. MAS is proposed to control the microgrid, it settles the microgrid bus voltage control despite to the changes in the environmental conditions by taking full advantages of the distributed RES production and DGs, and variable reconfigurations of the distributed loads to meet the load growth. The proposed control by MAS aims to meet the microgrid implementation requirements by demonstrating the following process:

Heterogeneous: when the EMS by MAS handles different components with different capacities, generation and natures.

Intelligence: agents evaluate the states of their environment where they act and react following their decisions-making.

Scalability: MAS are developed and implemented in respect of allowing making changes in the system characteristic by adding or deleting components connected

Self-adaptive: each element connected and its corresponding agent is able to making decision, acting and updating the environment following the permanent changes that occur.

Autonomous: Each agent evaluates its environment and makes decision autonomously without a need to a central controller that assigns set points.

Open: the MAS architecture lets the system more open enabling making all required load changes, social changes and environment changes without exhaustive changes in the whole control strategy system.

Dynamic: microgrid is a dynamic system integrating physical components. Thereby the control in a microgrid requires controllers for continuous systems. MAS are developed under discrete algorithm and do not allow to express all the mathematical calculation required to control dynamic systems. Therefore it is interesting to define a control using MAS dedicated to managing microgrids. A co-simulation method is introduced allowing making all the calculations required and the voltage control in Matlab Simulink and the intelligent strategy of EMS is executed by agents designed by Jade framework.

The general organization of the paper is as follows. In section 2 the microgrid studied is introduced and the distributed voltage control is presented to overcome the microgrid technical constraints mentioned earlier. Section 3 describes how the MAS approach can be a solution to microgrid implementation and introduce the microgrid agentification by detailing each agent behavior to control the microgrid voltage. Section 4 describes the proposed co-simulation enabling the junction between Matlab Simulink allowing the microgrid modeling and control and Jade the framework where agent implemented and developed in order to perform planning action and decision-making. Section 5 shows the economic, social, environmental, and technical microgrid benefits and demonstrates the feasibility of the EMS by MAS in the reorganization settling control process enabling the microgrid implementation. Section 6 concludes the paper.

2. Microgrid presentation and control

The studied microgrid is a power system that combines multiple distributed sources and loads. It is a heterogeneous system which each

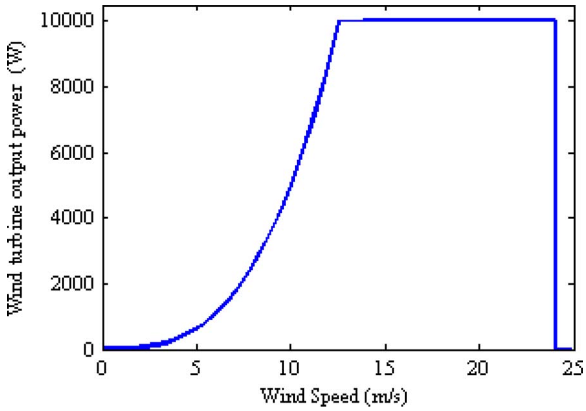

Fig. 2. Wind turbine output power characteristic vs wind speed.

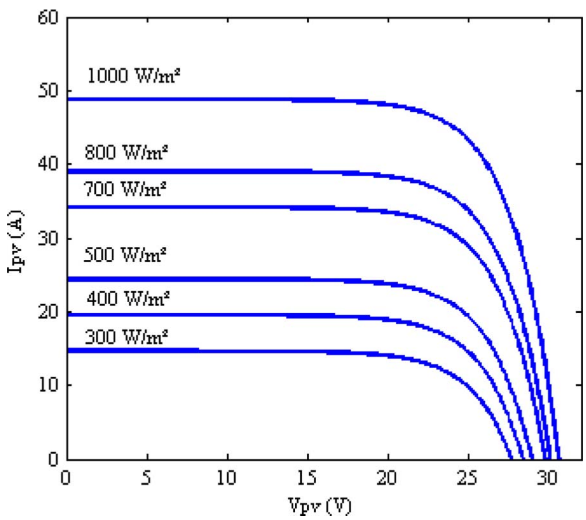

Fig. 3. I–V characteristic curves of the PV modules at different irradiances.

element has its own output characteristic which is distinguishable from the others. Four buses are considered. The wind/PV hybrid systems are typical DG units and are highly dependent in climate conditions. As depicted in Figs. 2 and 3, the RES are controlled in a way to generate their maximum power Sholapur, Mohan, and Narsimhegowda (2014). 6 kW wind generation system is connected to bus 1 and 5 kW PV array is located at bus 3. 8 kW battery is connected to bus 4 while the non-sensitive loads are located at bus 2 as shown in Fig. 4.

2.1. Microgrid components modeling

The details of modeling of each component are given hereafter.

2.1.1. Wind turbine model

In order to model a wind generator, it is necessary to go through the wind modeling, the turbine and the corresponding generator and finally the whole generator-rectifier if the wind turbine is connected to a DC bus. In this study the electrical power generated from the wind variation that it is injected in the DC bus is needed. Therefore the wind generator chain modeling is not necessary. In this paper the power delivered by the wind generator is modeled by respecting the intervals of operation of the wind turbine according to the wind speeds as presented in (1). The characteristic of the wind is based on three areas of operation as shown in Fig. 2. The power generated by the wind turbine is expressed in Eq. (1). Numerical approximation has been developed to calculate Cp for given values of λ and β Duc-Hoan TRAN (2010).

Eq. (2) is given in order to model the electric power directly injected in the DC bus. With ηt and ηgen are the turbine and the generator efficiencies. The microgrid DC bus voltage is always constant and equal to the reference voltage. Therefore, the current delivered by the wind generator and injected to the DC bus is expressed by (3).

$$\begin{cases} 0 < V < V_{start-up} P = 0 \\ V_{start-up} < V < V_{rated} P = \frac{1}{2}\rho\pi R C_P(\lambda, \beta) V^3 \\ V_{rated} < V < V_{\max} P = P_{\max} \\ V > V_{\max} P = 0 \end{cases} \tag{1}$$

Where:

P Power generated by the wind(W)
ρ Air density (Kg/m2)
R Blades radius (m)
C_P Power coefficient
λ Tip speed ratio
β Pitch angles of the rotor blades(degree)
V Wind speed (m/s)

$$P_{electric} = \eta_t \eta_{gen} \frac{1}{2}\rho\pi R C_P V^3 \tag{2}$$

$$i_{w\ dc} = \frac{P_{electric}}{v_{dc}} \tag{3}$$

2.1.2. PV model

To model the PV generator, two models are considered which are the ideal model and the real model. The ideal model expressed in (4) is represented by an electric current generator, which the behavior is equivalent to a current source in parallel with a diode Weidong. Dunford, and Capel (2004), Yusof, Sayuti, Abdul Latif, and Wanik (2004).

The current-voltage characteristic (I–V) of a real cell is given by Equ. (5). Pandiarajan and Muthu (2011), Ramos Hernanz et al. (2012). Fig. 3 shows the relationship between the output voltage V_{PV} and the PV current I_{PV} under different irradiances at 25 °C.

For Ns cell connected in series, the model of the photovoltaic module is given by Eq. (6). Whereas for a module composed of Np cells connected in parallel, the model can be expressed by (7).

$$\begin{aligned} i &= i_{pv,cell} - i_d \\ i_d &= i_{0,cell}\left[\exp\left(\frac{q v_{pv}}{aKT}\right) - 1\right] \end{aligned} \tag{4}$$

$$i = i_{pv,cell} - i_{0,cell}\left[\exp\left(\frac{q(v_{pv} + R_S \cdot i)}{KTa}\right) - 1\right] - \frac{v_{pv} + R_S \cdot i}{R_p} \tag{5}$$

$$i = i_{pv} - i_0\left[\exp\left(\frac{q(v_{pv} + R_S \cdot i)}{N_s KTa}\right) - 1\right] - \frac{v_{pv} + R_S \cdot i}{R_p} \tag{6}$$

$$\begin{aligned} i_{pv} &= i_{pv,cell} \cdot N_p \\ i_0 &= i_{0,cell} \cdot N_p \end{aligned} \tag{7}$$

$i_{PV,cell}$ The light generated current in a PV module (A)
i_d Diode current, given by the Shockley equation (A)
$i_{0,cell}$ The PV module saturation current (A)
q Electron charge 1,60217646.10–19 (C)
K Boltzmann constant 1,3806503.10^{-23} J.K^{-1},
T Operating température (K),
a Ideality diode factor
i_r Current delivered by the parallel resistance (shunt) (Ω)
R_S Equivalent resistance series of the photocell (Ω)
R_P Equivalent parallel resistance (Ω)

As the PV generator characteristic (I–V) is nonlinear. The reason why for the same illumination, the power delivered will be different according to the required DC bus power. To meet this problem, the MPPT (maximum point power tracking) controller can therefore control

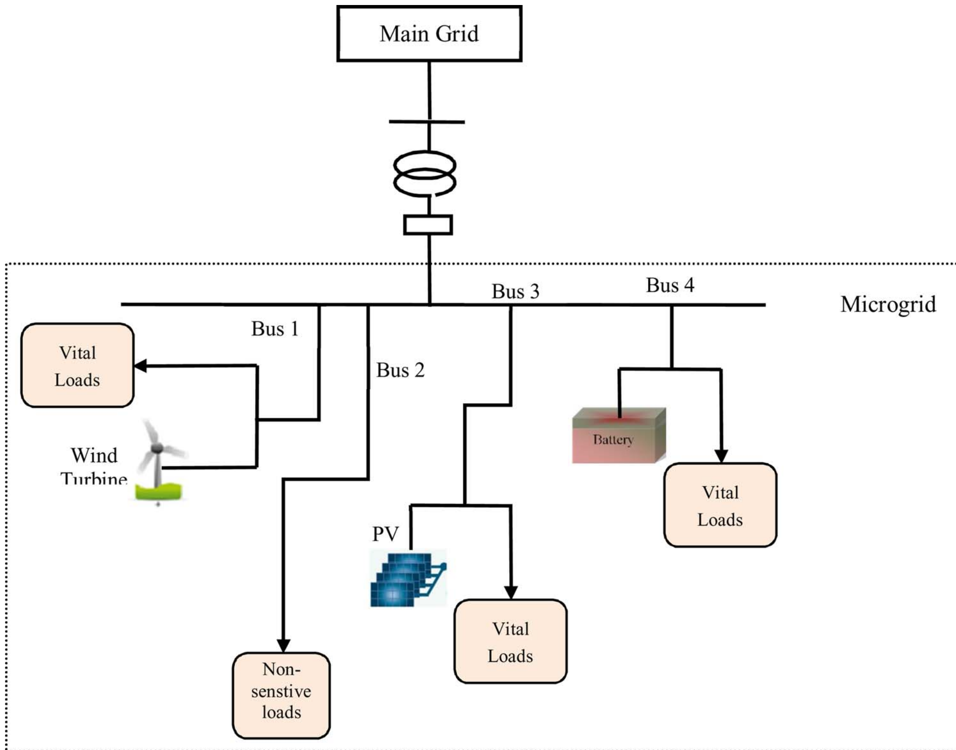

Fig. 4. Microgrid architecture.

the Boost converter connecting the PV generator to the DC bus, in order to continuously provide maximum power to the DC bus. MPPT is a kind of controller that will force the generator to provide its maximum power (MPP).

2.1.3. DC-DC converters model

The average model of the converters is adequate to describe the process and simplify the system-modelling. The average model of the battery and PV converters are expressed by (8)–(9) respectively Gaiceanu (2012), Paire (2010). The PV is associated to the Boost converter as mentioned above and the battery is associated to a Buck-Boost converter allowing its charge and discharge. I_{LPV} and I_{LB} are the PV and battery corresponding converters inputs currents. D_{PV} and D_B are the duty cycles, while v_B and v_{PV} depict the battery and the PV voltage, while v_{dc} expresses the DC bus voltage.

$$L_B\frac{di_{L\ B}}{dt} = v_B - (1 - D_B)v_{dc} \tag{8}$$

$$L_{PV}\frac{di_{L\ PV}}{dt} = v_{PV} - (1 - D_{PV})v_{dc} \tag{9}$$

2.1.4. Battery model

The battery model sought does not require an advanced model. The model chosen is, therefore, an electrical equivalent model as shown in Fig. 5. It is composed of a voltage source in series with resistance R_B (the battery internal resistance) and a C_B capacitance (battery internal capacity). E_0 represents the idle voltage of the battery; i_B and v_B are the battery current and voltage respectively.

The output voltage is then governed by the classical meshes equation. It is deduced directly from the no-load battery voltage and the drop voltage due to the RC dipole as expressed in (10). Thus the transfer function modeling the battery dynamics is given in (11).

$$\begin{aligned} v_B &= E_{0\ B} + Z_B{\cdot}i_B \\ Z_B &= R_B + \frac{1}{jC_B\omega} \end{aligned} \tag{10}$$

$$\begin{aligned} v_B &= E_{0B} + \left(\frac{jR_BC_B\omega + 1}{jC_B\omega}\right){\cdot}i_B \\ v_B &= \frac{R_B \times C_B \times 3600s + 1}{C_B \times 3600}i_B + E_{0B} \end{aligned} \tag{11}$$

The battery pack modeling is shown in Fig. 6. This is the association of a battery cells in serie. The battery under load voltage becomes (12). The equivalent internal battery pack resistance becomes R_{Beq} expressed in (13) and the equivalent internal capacity becomes C_{Beq} expressed in (14).

$$v_B = n{\cdot}E_{0B} + R_Beq{\cdot}i_B + C_Beq{\cdot}i_B \tag{12}$$

$$R_Beq = n{\cdot}R_B \tag{13}$$

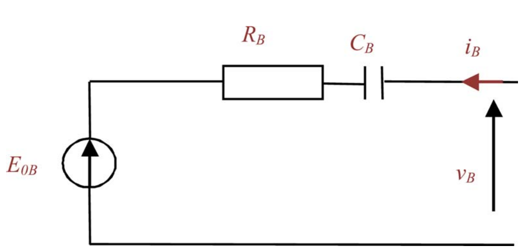

Fig. 5. The proposed battery model.

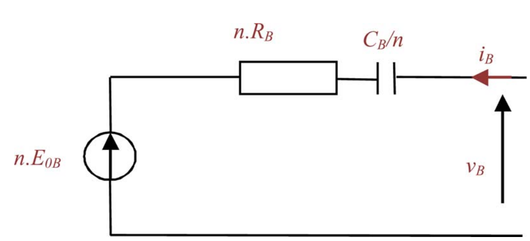

Fig. 6. The battery model of n cell.

$$\frac{1}{C_B eq} = \frac{n}{C_B}$$
$$C_B eq = \frac{C_B}{n} \tag{14}$$

The battery is a complex electrochemical system; the battery state of charge (SOC) cannot be measured directly by a sensor. So, it must be estimated. The SOC estimation methods available in the literature are limited and cannot be generalized for configurations of unknown battery dynamics and are therefore not generic. In Boudoudouh and Maâroufi (2017a), the SOC estimation has been proposed for real-time applications and for all battery technologies according to its external conditions of use.

The battery SOC function is expressed by (15) Singo (2010). Q_{Bn} is the battery maximal capacity, and SOC_B (0) is the initial SOC value. To conserve a long life cycle of the battery, the SOC should be limited between two values, it does not absorb current when the SOC exceeds 80% and it should not supply current when it is fewer than 30%.

$$SOC_{B(t)} = \frac{\int i_{B_{dc}} dt}{Q_{B_n}} + SOC_{B(0)} \tag{15}$$

The bus voltage control is the main consideration to ensure the stability and continuity within a microgrid. Contrarily to Jun, Junfeng, Jie, and Ngan (2010), this paper proposes a distributed DC bus voltage control in a microgrid in which no element is used to control the DC bus or to represent the voltage reference. However, all connected elements able to control the DC bus are concerned thanks to the corresponding converters. Two control strategies are used which are the voltage control and the current control. In the first one the IrefDC is calculated thanks to a classical proportional-integral (PI) controller which designates the amount of current that should be transferred to the corresponding converters thanks to PI controller in the current control phase to compensate the lack or the excess of energy through the microgrid DC bus due to the RES intermittent generation and the variable load demand.

The vital loads are passive DC loads, therefore the combination between the RES maximum power and the vital passive DC loads can be viewed as a reversible source, able to absorb or to supply power when the RES production do not meet the vital loads demand or when they exceed the RES generation respectively. The non-sensitive loads are involved when it is needed to consume the extra energy through the DC bus and their consumption does not lead to a need of energy instead of excess of energy that means the non-sensitive loads should be integrated in the microgrid when their consumption does not exceed the RES generation. In the other side, the battery should be adequately charged and discharged depending on the storage unit restriction which is the SOC evolution function. Therefore according to the uncertain RES generation, sudden demand changes, vital loads uninterrupted supply, storage unit restriction, microgrid voltage control and the non-sensitive loads plug-in cut-off operations, an energy management unit for each entity is needed and should be autonomous and have a certain degree of intelligence to handle the simultaneous changes of each entity by evaluating its state following its' environment update and making decision. To meet all these microgrid implementation requirements a MAS approach is proposed and detailed in the following section.

3. MAS & microgrid implementation

The microgrid studied contains different components with different capacities, generations, and natures. Two different RES such as; the wind turbine that produces alternative current thanks to the wind kinetic energy, and the PV which produces a DC current thanks to the sunlight reflections inside the panels. These RES will power two kinds of loads; uninterrupted loads and non-sensitive loads, depending on the RES production sufficiency and the uninterrupted load consumption. The battery compensates the need or the excess of energy. This heterogeneous feature of the microgrid is managed by the microgrid controller agent. It receives from Simulink the difference between the RES production and the uninterrupted loads' consumption signal. Then it evaluates the signal sign, if it is negative it asks agents eligible to provide energy to control the lack of energy in the microgrid by sending the request. On the other hand if the signal sign is positive, the agents able to consume the excess of energy are concerned. Fig. 7 depicts the microgrid controller agent request. It is shown that the request is classified by services which two services are defined; 'supply' service and 'absorb' service. Each agent has to register its services in the yellow pages Boudoudouh, Ouassaid, and Maâroufi (2014), Fabio Bell feminine, (2007), which can provide throughout the agent life, for being easily found by other agents. When an action requires being performed, agents try to find which service can be provided to execute this action. Therefore agents registered in this service, decide together which agent will take over the action required. That means to execute an action; it does not depend directly on the agent but on the service. Therefore when the supply action is detected by the microgrid controller agent, it asks agents registered as 'supply' service to perform the request. Currently this agent is the battery agent. In the other hand when the absorb action detected by the microgrid controller agent, it asks agents registered as 'absorb' service to perform the request which are currently the battery agent and the non-sensitive loads agent. By this way adding new elements to the microgrid or withdrawing from it, is allowed. For example when a new element is added, the corresponding agent should belong at least to one service, and when the service is concerned, this agent will receive the request even if it has just been added. However, when the element is withdrawn the corresponding agent will not receive the request when the service where it is registered is concerned, because the agent died. Consequently the microgrid scalability is shown; also the adding/deleting process does not require any exhaustive changes in the whole system therefore the microgrid can be open. Fig. 8 shows the battery agent registration services which it is registered in 'supply' service and 'absorb' service.

Microgrid Controller Agent Code Snippet

```
// Find agents that are interested in
this agent's data.
agentIDs =
getAgentIDsOfService(thisAgent,
"supply");

agentIDs =
getAgentIDsOfService(thisAgent,
"absorb");
```

Fig. 7. Microgrid controller Agent request.

The battery agent receives the SOC value from Simulink which is permanently updated in real time. Also it receives the proposal to provide or to consume energy from the microgrid controller agent. Then it processes the SOC and the proposal data in order to make autonomously its decision which concerns if the battery will contribute or not in the microgrid voltage control by providing the needed energy or removing the excess of energy to or from the microgid DC bus as described earlier in Section 2. Therefore the battery agent is self-adaptive because it is able to inject in and absorb from the microgrid bus without a need to a central controller.

The non-sensitive loads agent is registered as 'absorb' service, it receives the microgrid controller agent' proposal when an excess of

Battery Agent Code Snippet

```
String[] services1 = {"supply",
"absorb", "Agent"};
registerAgent(thisAgent, services1,
services1);
```

Fig. 8. Battery Agent registration services.

energy should be removed from the microgrid DC bus to control the bus voltage. When there is an excess of energy and the non-sensitive loads are integrated, it can occur that the RES production cannot meet the uninterrupted loads and the non-sensitive loads simultaneously and therefore instead of having an excess of energy, the lack of energy can happen. However, the non-sensitive loads agent is intelligent self-adaptive and autonomous, it receives from Simulink the difference between the RES signals, the uninterrupted loads consumption signal and the non-sensitive loads consumption signal. If the difference is positive that means that the RES is widely sufficient to power the uninterrupted loads and the non-sensitive loads and therefore decides to start consuming the excess of energy alone or simultaneously with the battery (if the SOC allow it). If the difference is negative that means the RES cannot meet the uninterrupted loads and the non-sensitive loads, therefore it decides to cut-off the non-sensitive loads letting the battery consuming alone the excess of energy caused by the uninterrupted loads' lower consumption level. This is very important when it comes to meet the load growth and also can encourage the RES intensive integration because, despite the number of the RES implemented and the forthcoming increased loads, the non-sensitive loads' agent makes the decision following the difference sign and therefore the loads and RES sizes can vary. Table 1 summarize the tasks of each agent actually available in the studied micrgrid.

4. Co-simulation Matlab-Simulink and Jade

To control the power flow through a DC bus in a microgrid, a real model of each device is required. Therefore complex mathematical equations are used. Each entity in the microgrid studied is modeled under Matlab Simulink that enables the execution, of all the mathematical computations. While the EMS is done by the MAS developed under Jade. (Java Agent DEvelopment Framework). JADE, is a software framework for the development of agent, implemented in Java. The communication between Matlab Simulink and Jade is established by MacsimJX. It is a tool for enabling models of systems created in Simulink to exchange data with MAS created using Jade. The junction of the two architectures is reported in Robinson, Mendham, and Clarke (2010). MAS are implemented in computer simulations, stepping the system through discrete 'time steps'. In the other side real model of each element connected is required enabling real time microgrid distributed control. Boudoudouh and Maâroufi (2017b) shows the distributed system modeling and control by MAS. This paper proposes the microgrid implementation by taking full advantages of real models of each entity and enables performing the continuous control by Matlab Simulink while the discrete decision making is made by agents developed under Jade.

There are three agents' input and output signals. The input signals express the data that each agent must know to react at any reaction required, in order to achieve the objectives and to meet all the challenges of the environment where the agents react. As depicted in Fig. 9, the SOC function is the battery agent input signal, the difference from generated power and the required power is the microgrid controller agent input signal and the difference between the RES signals, the uninterrupted (vital) loads consumption signal and the non-sensitive loads consumption signal is the non-sensitive loads agent input signal. These signals are sent from Matlab Simulink to agents developed under Jade thanks to Macsim JX for processing. Once the agents are finished processing this data, the results that depict the outputs signals are sent from agents to elements modeled under Matlab Simulink. These results express which elements will take over the bus control allowing the microgrid reorganization.

Other devices or services, therefore other agents can be added depending on the flexibility desired in the microgrid. The control strategy of the system when applying the MAS approach is resumed in the algorithm in Fig. 10, this flowchart can be a generalization of the operation of the energy management in a microgrid; it takes into account all the required operations despite of devices quantity connected to the DC bus. What is important is that they constitute the base of a microgrid basically involving DGs, RES, loads and energy storage systems. This is the highlight of a control using MAS technology.

5. Results and discussion

To validate the microgrid implementation requirements, two configurations are studied. The first one aims to show the economical and environment benefits of the RES integration in the microgrid implementation. To take full advantages of the distributed and intelligent energy management in order to overcome the social, environment and technical issue, the second configuration that validates the strategy of EMS proposed is studied by the following.

Figs. 11–13, show the considered first configuration. The distance between loads is equal to 8 kM. The total loads consumption is about 10 kW. The line resistance is equal to 0.015 Ω/kM (the reactive power calculation is not considered).

Fig. 11 depicts the power routing in the line before integrating the DG. The power flows are unidirectional and are provided from the utility grid.

The wind generator is connected to node D as illustrated in Fig. 12. The power flow no more follows one direction but it becomes bidirectional. The energy provided from the wind generator do not supply only the load connected to the same bus but it is exported to the nearest loads in the microgrid. The losses in the line are reduced, also the energy provided from the main grid.

The PV generator is connected to node B as shown in Fig. 13. The losses are becoming lower than the previous case when one DG is integrated. There is energy excess that it is exported to the main grid. The reversibility with the main network should be controlled also the energy flow coming from each direction. In the studied microgrid a storage units such as the battery is considered. It can consume the energy excess in the microgrid. Therefore the battery and the main grid depict two elements with different capacity and nature that are available to provide the consumption service. The grid code, the SOC constraints

Table 1
Microgrid Agents' tasks.

Agents	Tasks
Microgrid controller agent	• Receives from Simulink the difference signal between the RES production and the uninterrupted loads' consumption. • Evaluates the signal sign and determines if there is a need to supply or to consume energy in the microgrid • Sends a request to the concerning agents following their services depending on the required action (supply/consume)
Battery Agent	• Receives the SOC value from Simulink • Receives the proposal to provide or to consume energy from the microgrid controller agent. • Processes the SOC and the proposal data • makes autonomously the decision concerning the bus voltage control (supply or consume energy)
Non-sensitive load Agent	• Rreceives from Simulink the difference between the RES signals, the uninterrupted loads consumption signal and the non-sensitive loads consumption signal and the microcrgrid controller Agent proposal • Evaluates the signal sign and decides to plug –in or cut off the non-sensitive load

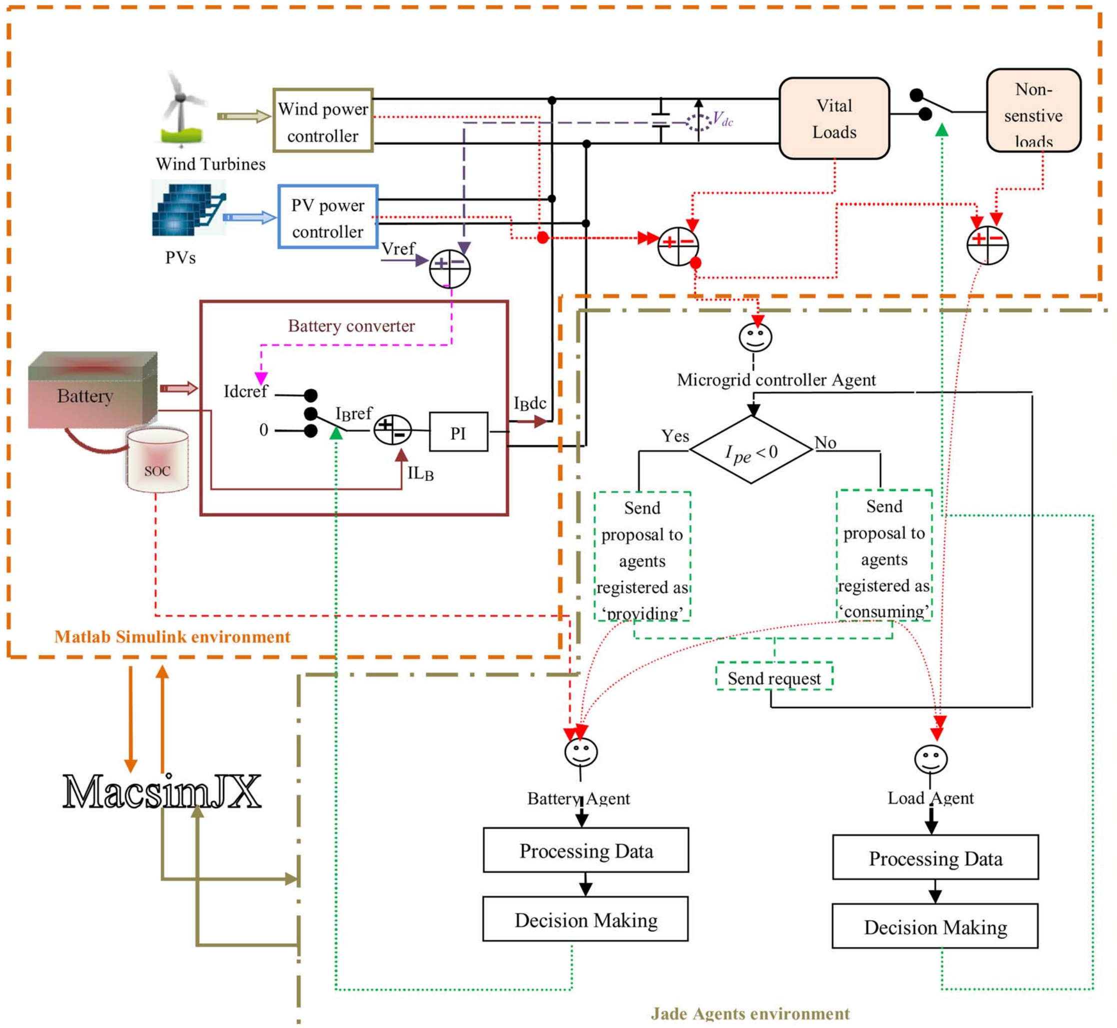

Fig. 9. Microgrid control by MAS.

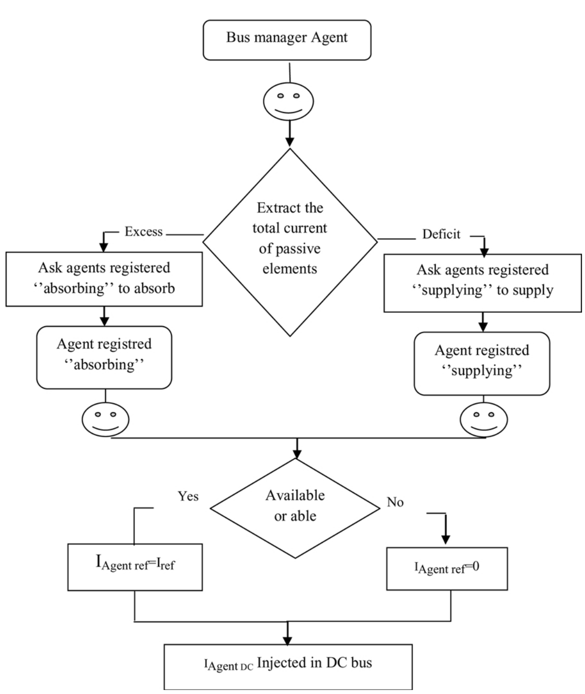

Fig. 10. General algorithm of EMS in a microgrid using MAS.

and the materials characteristics are determinant point to ensure stability to the microgrid. Also in the previous case illustrated in Fig. 12, the battery can provide the missing energy without a need to the main grid. However, the SOC limit should be verified. Consequently, distributed and intelligent energy management it is needed. It takes into account the reversibility issue, the SOC limits and materials characteristics. These constraints are dealt with the EMS executed by agents and detailed in the second configuration described by the following.

Fig. 14a shows the battery agent input signal that depicts the SOC function evolution during the simulation time. The difference from generated power and the required power is the microgrid controller agent input signal which is shown in Fig. 14b, it takes different signs positive or negative depending on the resultant current from the RES generated power and consumed power by the vital loads. The difference between the RES signals (I_{RES}), the uninterrupted loads consumption signal (vital loads I_{VL}) and the non-sensitive loads consumption signal (I_{NSL}) is the non-sensitive loads agent input signal, expressed in (16) and shown in Fig. 14c while the non-sensitive loads signal is depicted in Fig. 15b.

$$I_{RES} - I_{NSL} - I_{VL} = >\text{Non Sensitive Loads Agent Input Signal} \quad (16)$$

It is shown in Figs. 14c, 15b, and 16(a,b) that the non-sensitive loads are consumed when the non-sensitive loads agent detects that it is still needed to remove the excess of energy through the microgrid DC bus even if the non-sensitive loads consumption is involved because the non-sensitive loads agent input signal is positive, that means the RES

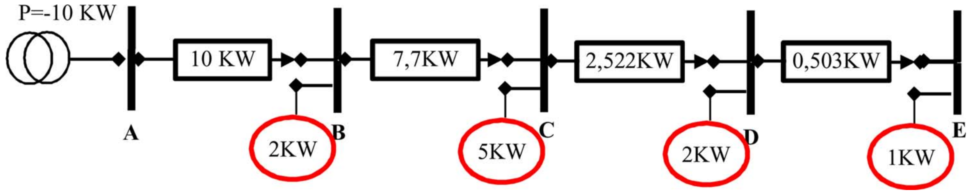

Fig. 11. The transit power in the line without DG.

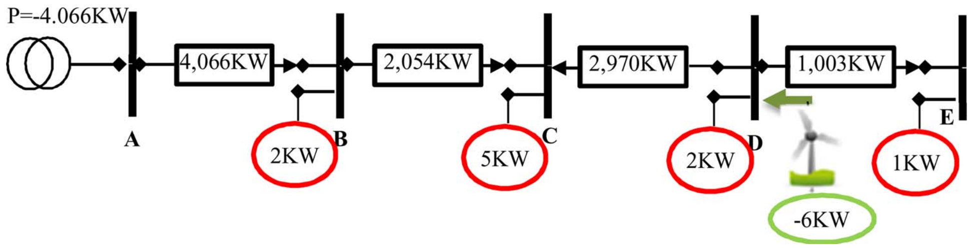

Fig. 12. The transit power with one DG (P_W = 6KW).

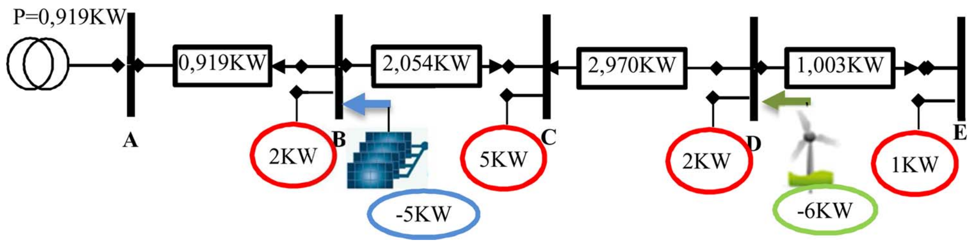

Fig. 13. The transit power with one DG (P_W = 6KW, P_{PV} = 5KW).

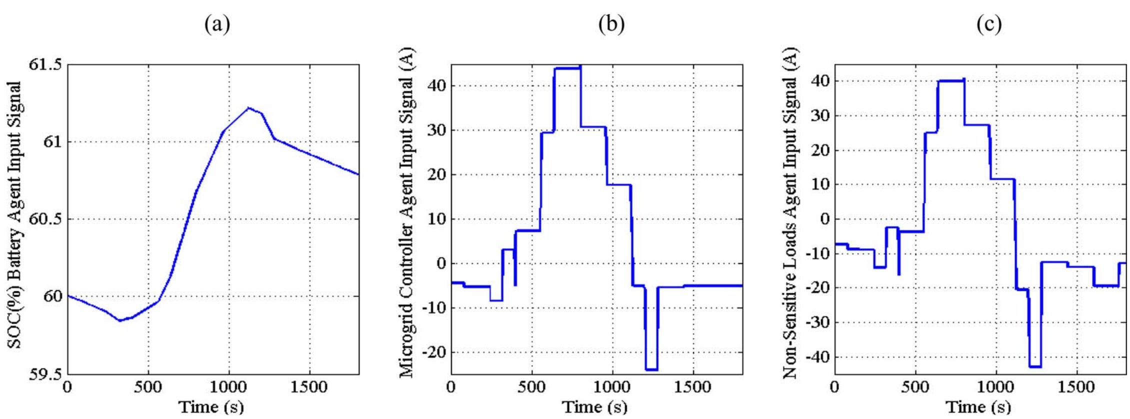

Fig. 14. (a) battery Agent input signal, (b) Microgrid controller Agent inputs signal, (c) Non-sensitive loads Agent input signal.

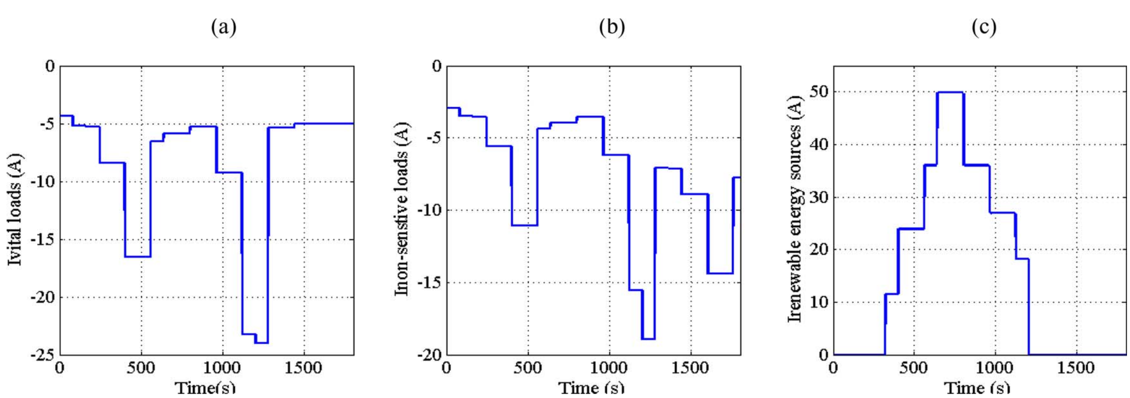

Fig. 15. (a) Vital loads consumption, (b) Non sensitive loads consumption (c) RES production.

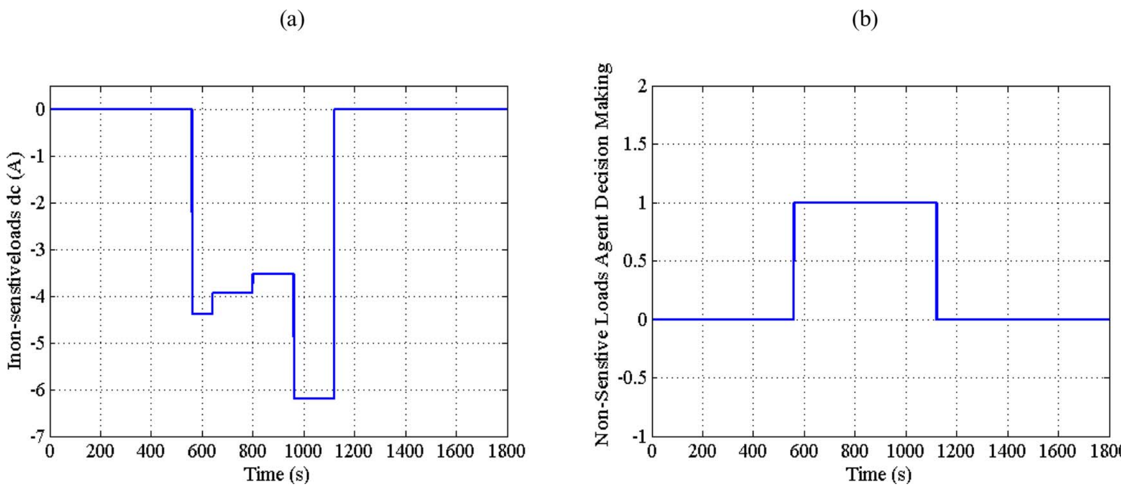

Fig. 16. (a) Non-sensitive loads Agent reaction in the DC bus, (b) Non-sensitive loads Agent decision making.

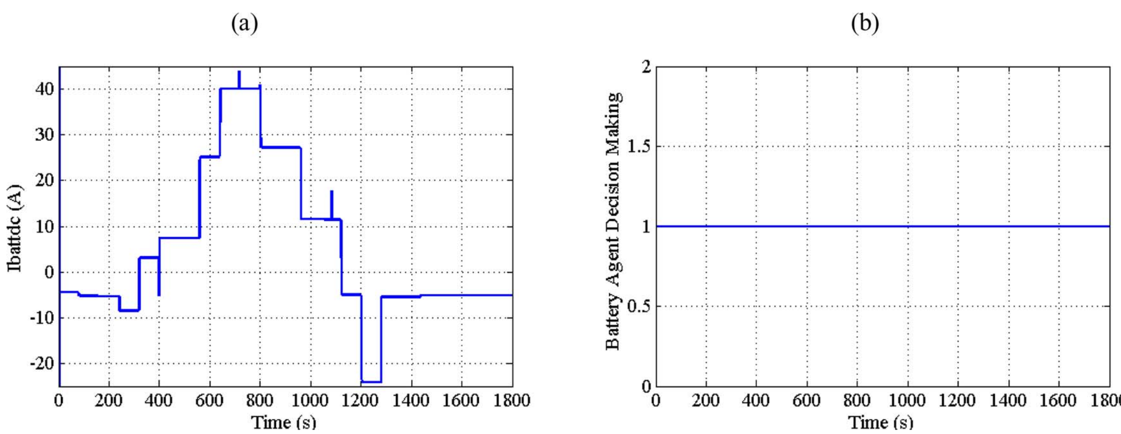

Fig. 17. Battery Agent reaction.

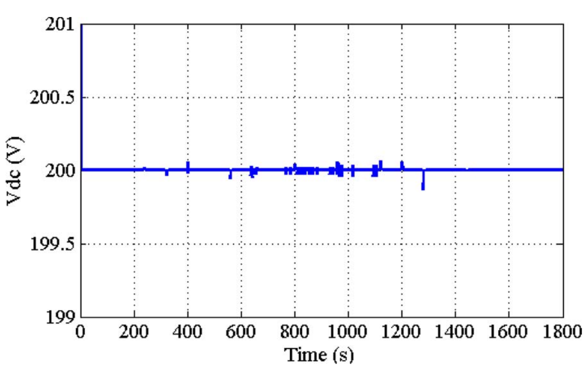

Fig. 18. Microgrid DC bus voltage during simulation.

generation can meet the vital loads and the non-sensitive loads simultaneously. It is shown in Fig. 16a that the microgrid is reorganized and the non-sensitive loads are integrated from 560 s to 1120 s. In this period the battery takes over the DC bus control by consuming the excess of energy through the DC bus coming from the RES generation, the vital loads and the non-sensitive loads consumptions.

The microgrid controller agent detects from 320 s to 560 s that an excess of energy is occurred through the DC bus, however, while sending the proposals, only the battery agent who accepts to consume the extra energy because the non-sensitive loads agent finds that when integrating the non-sensitive loads consumption, the energy excess disappears because the RES do not suffice to power the vital loads and the non-sensitive loads simultaneously and therefore the resultant difference of the three signals which is the non-sensitive loads agent input signal is negative. Therefore, the non-sensitive loads are not involved as shown in Figs. 14c, 15b, 16(a, b) and 17(a, b) , the battery consume the total excess of energy coming from the difference between the RES generation and the vital loads demand.

In the other side, when it is needed to provide energy through the DC bus, the battery agent receives the proposal from the microgrid controller agent because it finds that the difference coming from the RES generation and the vital loads consumption is negative as shown in Fig. 17a. The no-sensitive loads agent is not concerned by this proposal because it is registered as ‘absorb’ service and therefore it does not receive this proposal. It is shown in 16a and 17a that the non-sensitive loads are not involved when it is needed to provide energy and the battery takes over the DC bus control by injecting in the DC bus the required amount of current thanks to the associated DC-DC converter.

The battery charge and discharge follow the microgrid DC bus reference current calculated thanks to PI controller as explained earlier. When it is negative the battery converter output current is negative and therefore the battery is in discharging mode, consequently the SOC is decreased as shown in 14a and 17a. However, when it is positive the battery converter output current I_{battdc} is positive and the battery is in charging mode. Then the SOC is increased as shown in Fig. 14a.

The battery agent and the non-sensitive loads agent send their decision-making from Jade environment to Matlab Simulink environment as ‘1′ or ‘0′ to express their agreement or disagreement respectively and therefore setting the battery converter and deciding about the microgrid reorganization by integrating or not the non-sensitive loads. It is shown in 14a and 17(a, b) that the battery agent decision making is correlated with the battery converter output current and the SOC evolution. While 14a and 16(a, b) show that the non-sensitive loads agent decision making follows the microgrid reorganization and therefore the non-sensitive loads integration.

Finally, Fig. 18 shows the microgrid DC bus voltage evolution during simulation time. It is shown that it follows the reference voltage allowing the microgrid stability and continuity and overcoming the microgrid technical constraints.

6. Conclusion

The considered microgrid is an autonomous power system interconnecting, RES and energy storage system which supply vital loads and non-sensitive loads. The real model of each device was employed. The variation of the load demand and RES production matches generally with real variation, that allows to fully validate in extreme cases, the proposed strategy using MAS technology. Two configurations are studied. The first one aims to show the economical and environment benefits of the RES integration in the microgrid implementation. The reliability of the proposed control was validated in the second configurations by meeting the following microgrid implementation requirements; heterogeneous, intelligent, scalable, self-adaptive, autonomous, open and dynamic, by showing the social and the technical benefits provided by the microgrid.

The communication middleware between Matlab Simulink and Jade which is MacsimJX has facilitated the implementation of the system, and enabled making all the calculations required in Matlab Simulink. This junction was very useful to validate the control in a microgrid using MAS. The reaction of each element in various conditions has proved the capacity of agents to react and to execute together the appropriate actions and therefore MAS can be a suitable solution to microgrid implementation.

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