Autonomous Energy Management System with Self-Healing Capabilities for green buildings (Microgrids)

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Abstract

Nowadays, distributed energy resources are widely used to supply demand in micro grids specially in green buildings. These resources are usually connected by using power electronic converters, which act as actuators, to the system and make it possible to inject desired active and reactive power, as determined by smart controllers. The overall performance of a converter in such system depends on the stability and robustness of the control techniques. This paper presents a smart control and energy management of a DC microgrid that split the demand among several generators. In this research, an energy management system (EMS) based on multi-agent system (MAS) controllers is developed to manage energy, control the voltage and create balance between supply and demand in the system with the aim of supporting the reliability characteristic. In the proposed approach, a reconfigurated hierarchical algorithm is implemented to control interaction of agents, where a CAN bus is used to provide communication among them. This framework has ability to control system, even if a failure appears into decision unit. Theoretical analysis and simulation results for a practical model demonstrate that the proposed technique provides a

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robust and stable control of a microgrid.

Keywords: Energy management system, multi-agent system, self-healing, subsumption architecture, microgrid, green building.

Nomenclature

Acronyms

CANopen	controller Area Network-open
CEMS	centralized energy management system
DEMS	distributed energy management system
EMS	energy management system
ESS	energy storage system
MAS	multi-agent system
PV	photovoltaic
RES	renewable energy system
SC	super-capacitor

Parameters

Δt	Total delay in the system
ΔV	maximum oscillation voltage at the DC bus
C_{bus}	Capacitor of DC bus
i_{Bat}	injected current of battery
$i_{batchar}$, $i_{batdchar}$	charging/ discharging current of battery
i_{grid}, i_{pv}, i_{sc}	Injected current of grid/ PV/ SC
i_{scchar}, $i_{scdchar}$	Charging/ Discharging current of SC
i_{total}	total injected current to the DC bus
L	inductance
m	Binary variable, m=1 boostmode, m=0 Buck mode
P_{Bat}, P_{grid}, P_{pv}, P_{SC}	injected Power of battery/ grid/ PV/ SC

R	resistance
t_c	controller's delay
t_d	the time delay for the power electronic devices
t_m	delay in communication port
t_p	delay in processing of agent
t_s	delay in measurement sensor
U	duty cycle
V_{Bat}, V_{dc}, V_{grid}, V_{pv}, V_{sc}	Output voltage of battery/ DC bus/ grid/ PV/ SC
η	efficiency

1. Introduction

Utilization of renewable energy systems (RES) such as wind and solar power is increasing due to their environmental friendly and cost-effective operation. However, intermittent generation from RES and unpredictable changes in demand profiles cause concerns regarding supply-demand balance and the stability and reliability of power systems. For example, in a building with engaged renewable energy resources, voltage stability and reliability of system could be significant as well as supporting supply-demand balance [1, 2]. Energy Storage systems (ESSs) could be used in such system to guarantee these features [3]. However, by aggregating ESS (usually of small scale) in a micro-grid, power control and energy management become more challenging. MASs are introduced to solve such control problems in EMSs, where individual system components are distributed and control is decentralized and autonomous [4–7]. Each component acts as an agent and operates in a dynamic environment, where it has the freedom to either join or leave the system whenever required. The agents in MASs are able to perceive environmental changes and decide based on their own decision structure and change the environment with proper actions [8]. Consequently, the overall challenge and objective in the EMS is divided into a set of small tasks that could be controlled either integrated or distributed [9]. It is important to mention that, by autonomous and decentralized control, the response time and control delays are minimized, thus increasing the reliability of grid connected RES [10].

The energy management system for distributed energy sources can be divided into centralized energy management system (CEMS) and distributed energy management system (DEMS) [11–13]. In both cases, the aim is to achieve a balance between supply and demand; the difference lies in the control architecture and decision type [14–18]. In CEMSs, associated controllable devices are directly connected to a central control unit, so that it efficiently monitors the whole system taking into consideration the various factors such as the energy balance and cost functions [19–24]. The control unit receives measured variable and sends suitable control signals based on certain restrictions and set points [25–28]. The DEMS, on the other hand, works on small networks and use distributed processing and control units for regulating the entire system [29]. Each part in the DEMS has its own decision unit and based on a specific predefined control structure, it participates in the process of EMS [30–32]. In order to implement the DEMS, the MAS can be used to provide maximum independence to the individual energy systems. In fact, each decision part, acting as an agent, communicates and offers a robust control over the distributed energy sources [33]. This type of control presents many benefits as compared to the CEMS, such as, the scalability and redundancy [34]. The following shortcomings have been recognized in previous studies relating to energy management:

- The utilities of offline optimum tools for minimizing cost function and maximum benefits to the whole power system were not investigated [35, 36].
- The failure in smart control units, which is critical in microgrids, has not been considered in previous literatures [37, 38].
- In the online smart control of microgrids by using MAS, communication could be used to avoid collapse in faced with failure in decision parts and increases reliability and stability of system but it was ignored [39–41].

In this paper, an active load is supplied by multi-type distributed generators that are connected to the grid. Battery and super-capacitor (SC) are considered as ESSs to store extra energy in the microgrid. In order to control and management energy in the microgrid, MAS will be implemented over the system wherein any generator will be considered as an agent which can make its own decision based on different conditions. In this study, a hierarchical algorithm which is modified Subsumption architecture is used as a framework to control and allocate tasks among agents in the system. In designed framework, any agent will be located separately into layers and operates based on system's situation by taking into account its own constrains. Lower layer has high priority and can dismiss priority of its higher layer. In order to have cooperation in the system, agents have to interact through a CAN bus.

In this research, the aim is to fix the voltage of DC bus and supply demand. At any time, only one agent controls the voltage in system and shares current based on its own constrains. This request is applied by a signal shared through the communication port. In most previous research (mentioned earlier), the objective is to enable energy management in a system without considering any fault in the management unit [37, 38]. This may threaten the reliability and stability of smart grids. In this paper, a new energy management system is developed and applied to a system similar to that presented in [42, 43] and results are compared especially when decision part is under fault. Results show that the proposed approach is more fault tolerant as compared to the method presented in [42, 43], where the whole system would collapse if CEMS faced a failure or agent carries token fails, respectively. In the proposed mechanism, when the agent is in normal operation, sets in a layer of Subsumption architecture and with sending 5 bits signal via the communication bus clarifies its cooperation in the system. When that agent faces failure, its signal will not be received by others and hierarchical algorithm reconfigures itself. In general, the main contributions of this research are:

- An online smart energy management framework is proposed to support supply-demand balance in a DC microgrid. The framework is easy to implement in a large-scale system due to simple behavioural if-then rules.
- A multi-agent based energy management scheme is proposed to monitor generators interaction. The proposed solution has high reliability and is easy to implement.

- A low bandwidth communication is used engage agents in order to transmit their operating conditions and status in the smart system. By implementing it on the smart system, characteristic of fault tolerance will be added to the system.

The rest of paper is organized as follows. In section 2, the structure of the proposed system and control are explained. The energy management and communication mechanisms are discussed in section 3. Finally, results of simulation and conclusions are presented in section 4 and 5, respectively.

2. Description, modelling and control structure of the micro-grid

This section presents the description and details for the micro-grid model considered for our study.

2.1. Electrical Network

A simple model of DC micro-grid is depicted in Figure 1, which is similar to the system in [42, 43]. This electrical system contains a Photovoltaic (PV), battery, SC and gird those are supplying a DC active load through a DC bus.

2.2. Mathematical Model

The mathematical formulation of the system is presented in this subsection. Equations (1)-(4) describe the average model of converters which is obtained by applying the Kirchhoff rules on circuit shown in Figure 2 [44].

$$di_{sc}/dt = 1/L_1 * (V_{sc} - U_{12}V_{dc} - R_1 i_{sc}) \tag{1}$$

$$di_2/dt = 1/L_2 * (U_{43}V_{Bat} - V_{dc} - R_2 i_2) \tag{2}$$

$$di_3/dt = 1/L_3 * (U_5 V_{PV} - V_{dc} - R_3 i_3) \tag{3}$$

$$di_4/dt = 1/L_4 * (U_5 V_{grid} - V_{dc} - R_4 i_4) \tag{4}$$

where, R and L are resistance and inductance of converters, respectively. U is the duty cycle, where as U_{12} and U_{34} are defined in Eq.(5) and (7), respectively.

$$U_{12} = m(1 - U_1) + (1 - m)U_2 \tag{5}$$

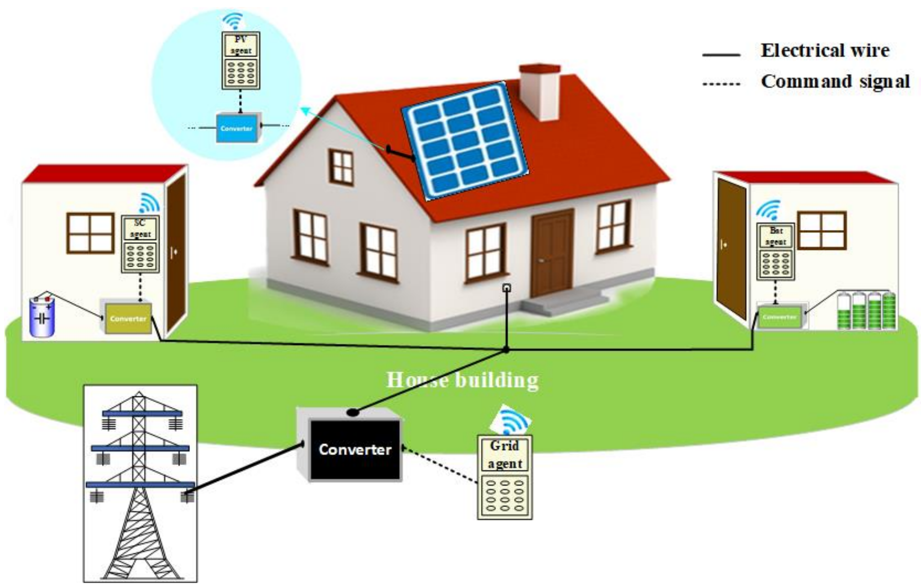

Figure 1: simplified Model of a DC green building (microgrid)

$$U_{43} = m(1 - U_4) + (1 - m)U_3 \tag{6}$$

where, m is binary variable defined as following:

$$U_{43} = m(1 - U_4) + (1 - m)U_3 \tag{7}$$

$$m = \begin{cases} 1 & \text{if Boostmode} \\ 0 & \text{if Buckmode} \end{cases} \tag{8}$$

The voltage at DC bus is equal to the sum of injected currents to the DC bus and is given by Eq.(9.

$$V_{bus}(t) = 1/C_{bus} \int i_{total} dt + V_{bus}(t_0) \tag{9}$$

where, C_{bus} is the capacity of capacitor connected to the bus. Equation (9) can be rewritten as Eq. (10).

$$V_{bus}(t) - V_{bus}(t_0) = 1/C_{bus} \int i_{total} dt \tag{10}$$

The total injected current i_{total} to the DC bus can be calculated by Eq. (11.

$$i_{total} = \sum i = i_{1_{dchar}} - i_{1_{char}} + i_{2_{dchar}} - i_{2_{char}} + i_3 + i_4 \tag{11}$$

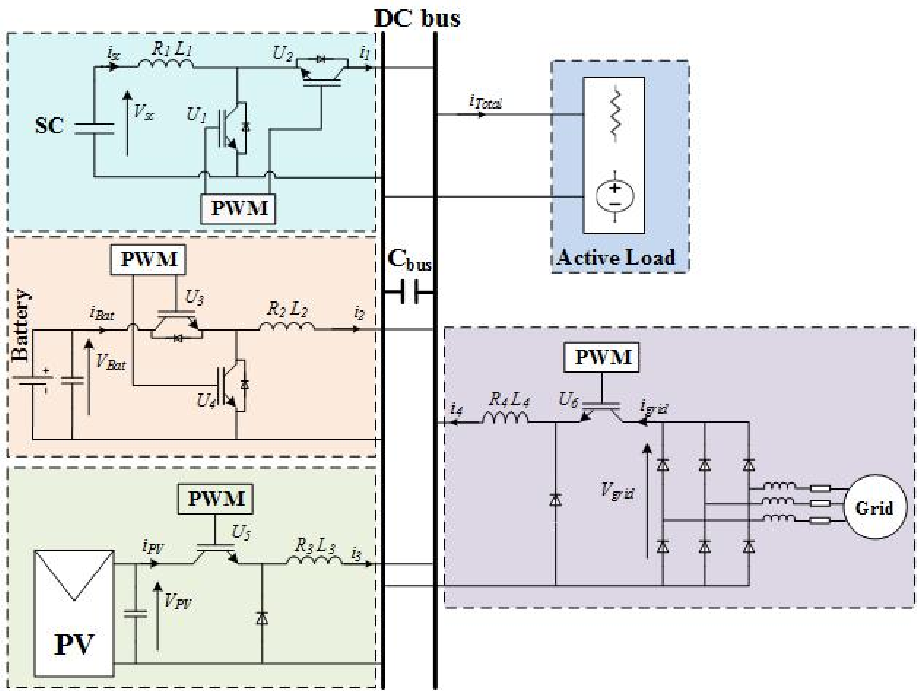

Figure 2: Realisation mode of Microgrid

where, $\sum i$ is the sum of injected current to the DC bus by individual converters and it can be calculated by Eq. (12.

$$i_{total} = \sum \begin{cases} i_{1_{dchar}} = \eta_1 P_{sc}/V_{bus} = \eta_1 V_{sc} i_{sc}/V_{bus} \\ i_{1_{char}} = V_{sc} i_{sc}/\eta_1 V_{bus} \\ i_{2_{dchar}} = \eta_2 P_{Bat}/V_{bus} = \eta_2 V_{Bat} i_{Bat}/V_{bus} \\ i_{2_{char}} = V_{Bat} i_{Bat}/\eta_2 V_{bus} \\ i_3 = \eta_3 P_{pv}/V_{bus} = \eta_3 V_{PV} i_{PV}/V_{bus} \\ i_4 = \eta_4 P_{grid}/V_{bus} = \eta_4 V_{grid} i_{grid}/V_{bus} \end{cases} \tag{12}$$

where, η is efficiency of converter, and i_1,i_2,i_3 and i_4 respectively represent the currents for super-capacitor, battery, PV and grid. Consequently, the total injected current in Eq. (11) can be expressed as Eq. (13).

$$\begin{aligned} i_{total}(t) = 1/V_{bus}\Big(&\eta_1 V_{sc} i_{sc}(t) - V_{sc} i_{sc}(t)/\eta_1 + \eta_2 V_{Bat} i_{Bat}(t) \\ &-V_{Bat} i_{Bat}(t)/\eta_2 + \eta_3 V_{PV} i_{PV}(t) + \eta_4 V_{grid} i_{grid}(t)\Big) \end{aligned} \tag{13}$$

By substituting Eq. (13) in Eq. (10), it can be rewritten.

$$\begin{aligned} V - bus(t) - V_{bus}(t_o) = 1/C_{bus} V_{bus} \int \Big(&\eta_1 V_{sc} i_{sc}(t) - V_{sc} i_{sc}(t)/\eta_1 \\ &+\eta_2 V_{Bat} i_{Bat}(t) - V_{Bat} i_{Bat}(t)/\eta_2 \\ &+\eta_3 V_{PV} i_{PV}(t) + \eta_4 V_{grid} i_{grid}(t)\Big) dt \end{aligned} \tag{14}$$

Equation (14) shows voltage oscillation on the DC side, thus, a proper control strategy is needed to avoid voltage fluctuations at the DC bus. The corresponding control strategy is applied to the system by transmitting set points through the individual agents. In order to calculate capacity of capacitance, in DC bus, the following voltage constraint can be assumed:

$$V_{nom} - \Delta V \leqslant V_{bus} \leqslant V_{nom} + \Delta V \tag{15}$$

where V_{nom} is the nominal voltage and ΔV signifies the maximum oscillation voltage at the DC bus that can be controlled by the DC bus capacitor. Equation (16) shows the relationship between the current and voltage of capacitor.

$$dV(t) = 1/C_{bus} * i_{total}(t)dt \tag{16}$$

Equation (16) can further be modified to find the optimal value of capacitance for a certain value of Δ, as

$$C_{bus} = I_{total}\Delta t/\Delta V \tag{17}$$

The T in Eq. (17) represents the total time delay in the system and calculated by Eq. (18).

$$\Delta t = t_d + t_p + t_m + t_s + t_c \tag{18}$$

where t_d is the time delay for the power electronic devices such as the delay in switching of converters, t_p is related to the delay involved in the processing of individual agent, t_m indicates the delay in sending and receiving messages on a communication port, t_s represents the measurement delay caused by sensors and t_c is time delay associated with the controllers. For instance, in the system with 0.2 ms as a total time delay and 20 A as total current; if 2% voltage oscillation is desired, a capacitor with 2mF should be used.

2.3. Control structure

Figure 3 shows the control structure of converters which are used to control the voltage and current [45]. Each element in this topology is controlled by an agent. In this control structure, agent based on measured value that could be output voltage of PV panel or SOC of SC or battery, and also communication signal that comes from other agents, generates suitable set points. These set points include mode selector, voltage and current reference. Mode selector is used to determine that a converter is in voltage mode or in current mode. Voltage mode is considered to maintain output voltage of converter in constant value, consequently, voltage of DC bus will be preserved in desired value. Current mode is expected to supply shared current by other agents. It is clear that one agent can be used to regulate the voltage and others just participate in the current control. In order to enable a smooth

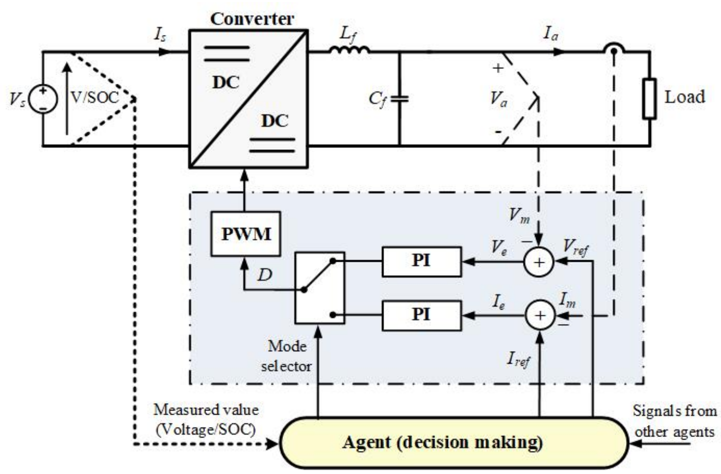

Figure 3: The control structure for a dc-dc converter

switching, to maximise the optimum use of resources and to help protecting storage devices, agents share current in the system. In this control structure, error signal that is difference between Voltage/currnt reference, V_{ref} (or I_{ref}), and measured voltage/current, V_m (or I_m), applied to the P.I control. The out put of the P.I control is applied to the pulse width modulation (PWM) in order to generate proper signal for switching Masfet in the converter.

3. The proposed Energy Management System

3.1. Decision algorithm

As it was mentioned that there are two decision-making structures in order to control the agents in multi-agent systems; the CEMS and the DEMS. In this study, the DEMS is used to manage and control the energy among various available sources, where each energy source is controlled through an agent. The first step for the agents is to check the available power from the generator. Subsequently, based on the hierarchal algorithm given in Figure 4, agents will choose the control mode that is either voltage mode or current mode. If the voltage control mode is chosen, agent will control DC bus voltage and can share current based on its current sharing layer

(Section 3.4). In this case, shared current is supplied by another one (as will be discussed in Section 3.2).

3.2. Priority mechanism

In order to manage and control MASs, it is essential to utilize a robust intelligent algorithm to allocate tasks between agents. Subsumption architecture is proposed as a reactive structure to organize and define principle among agents. In this architecture, any agent has priority in the system. Each agent takes place in one layer and the lowest layer has the highest priority. Brooks developed this algorithm in 1986 to control robot's behaviours, wherein any behaviour is organized in a layered architecture based on a priority as shown in Figure 5 [46]. For example, layer 1 has priority over layer 2 and 3 but if layer 0 is activated, it can be disregarded. With this approach, the main challenge of energy management in a system is divided into a set of simple challenges which can be implemented by some simple if and then rules.

Subsumption architecture designed by Brooks includes a hierarchy of competence for layers. Accordingly, a layer without any communication can override the remaining of its higher layers at any time and control the system as long as it is necessary [47]. It means that there is a rigid separation among the layers and it is impossible for an agent to disregard this hierarchy any time even if a failure exists in the decision part. Thus, when a fault occurs in a decision layer, the entire system collapses. In order to have a robust control on the system, in this study, a mechanism similar to the classic Subsumption will be implemented but there is a communication between agents that enables it to change priorities. This architecture is developed to control the voltage of DC bus.

As the main objective of energy management is to reduce the use of conventional energy sources, thus, the external grid is located in the highest layer. Despite an active load in the system, SC is considered in the lowest layer in order to store energy when the load is in generation mode and supply power as soon as the load turns to demand mode. Hence, SC has given the highest priority in suggested architecture by allocating it the lowest layer. PV is next agent that has high priority to make

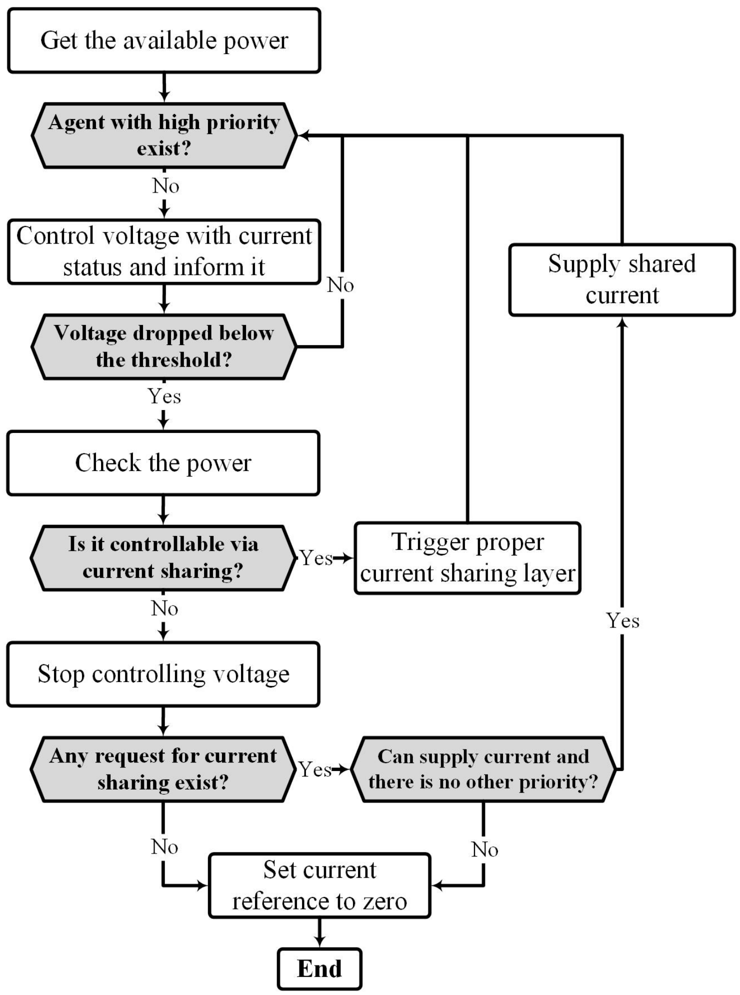

Figure 4: The flowchart of agent's decision

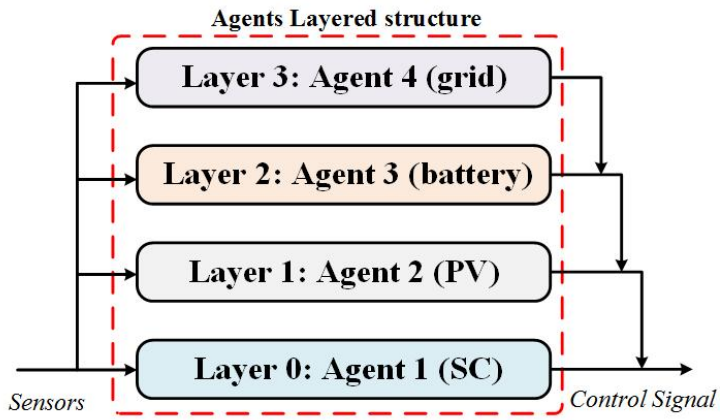

Figure 5: Brooks's Subsumption architecture for our case study

room for energy saving and maximum exploitation of its energy. Finally, battery is located in layer 2 and when SC and PV are unable to control the voltage, it could be controlled by the battery. As it is obvious, grid has the lowest priority and when SC, PV, and battery could not control the voltage of DC bus, the grid will be switched in for maintaining the system operation.

In the proposed approach, there is a distributed decision unit where agents make their own decisions and carry out tasks independently, and in comparison with ref. [42], communication between agents makes system robust. In order to better understand, assume in [42], agent A is in voltage mode, if a fault occurs in the central unit, the entire system will collapse, because all the set points are appointed by the central unit. However, in the proposed mechanism, when an agent collapses, system is reconfigured and rest of system controls and manages energy.

3.3. Communication mechanism

To have proper reaction in the system, status of agent is transferred by a communication link. Consequently, the communication between agents is explained.

3.3.1. Communication protocol

In order to use multi-agent systems, especially in DEMSs as depicted in Figure 6, it is essential to have frequent communication among the agents. For this purpose, Controller Area Network-open (CANopen) can be used as a communication protocol to transmit instructions between the agents [48]. The CAN bus is a fast field bus control system having the possibility to transmit instructions in 0.2ms between various CAN stations and is used for decentralization, intelligence and network control [49, 50]. Despite of CANbus does not need to support high data traffic in this application; it has been selected due to its wide availability and comparatively low price.

3.3.2. Digital message

In the proposed approach, agents communicate through CAN bus and transmit 5 bits to clarify their states. By using this data, each agent can have appropriate reaction in the system. This data as status signal is defined as follows:

Bit 2^0 shows current control mode of agents. If it is 1, that means agent just supplies shared current. For example, in Figure 6, agent 2 supplies requested current by agent 1. Bit 2^1 shows voltage control mode and when its value is 1, it means agent is involved in controlling the voltage of DC bus. For instance, agent 1 in Figure 6 is in voltage control mode. Bit 2^2 and 2^3 show the level of current sharing (refer to Table 1). When bit 2^2 is 1, it means that agent shares current as defined by level 1, and when bit 2^3 is 1 it implies that level 2 of the current sharing is activated. Further, when bit 2^2 and 2^3 is activated simultaneously, it means that current is shared based on level 3. For example, in Figure 6, agent 1 shares layer 2 of its Subsumption architecture with others. In next subsection, Subsumption architecture for current sharing will be explained.

Bit 2^4 shows failure status of the agent. If it is 1, agent is in normal performance and when it is 0, agent is under fault. For example, in Figure 6, agent 3 is collapsed and others are operating in normal state.

3.4. Current sharing mechanism

For optimal use of RESs and to eliminate voltage ripple on the switching, Brooks' Subsumption mechanism is implemented to share current between the available sources. Thus, when agent wants to share current, it sends a binary code through

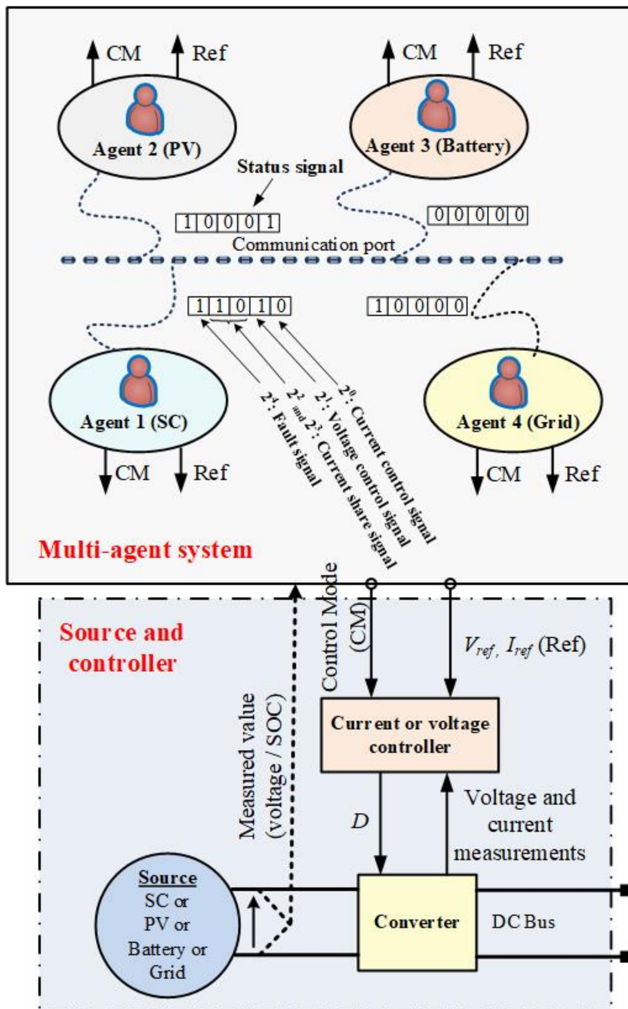

Figure 6: Structure of communication between agents

the CAN bus wherein agent clarifies about the shared current. Based on priority and capability, other agents can reply to the request. In order to decrease transmitted data in sharing, maximum three levels for each agent are considered. In this case only the agent that is on voltage control mode can make the request. The complete mechanism of current sharing is explained below.

3.4.1. Current sharing in SC

Assume SC is in voltage control mode, therefore, it can share current based on its charge according to Subsumption architecture shown in Figure 7 (a). The following set of instructions will be passed over the layers.

1. Layer 0: SC will set bit 22 if its SOC is in level 1.
2. Layer 1: When its charge reaches to level 2, it triggers the bit 2^3.
3. Layer 2: SC activates bit 2^2 and 2_3 when its SOC is in level 3.

3.4.2. Current sharing in PV

Similar to SC, current sharing in PV is carried out by a hierarchy approach. As it is shown in figure 7(b), when PV agent controls voltage of DC bus; it shares current in two states.

1. Layer 0: When terminal voltage of PV is nominal, it activates bit 2^2.
2. Layer 1: When terminal voltage of PV is dropped from nominal value, bit 2^3 is set by PV agent until it loses the voltage control.

3.4.3. Current sharing in battery

According to hierarchy algorithm, battery controls voltage when SC and PV are out of service. In this case, if battery has enough stored charge, it will supply to fulfil the demand and share current in three levels with grid as shown in Figure 7 (c).

1. Layer 0: When SOC of battery is level 1, battery agent triggers bit 2^2.

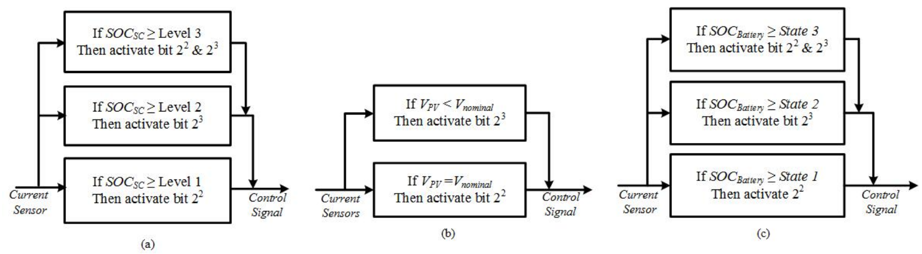

Figure 7: The Subsumption architecture for current sharing by (a) the SC agent, (b) the PV agent and (c) by the battery agent

2. Layer 1: Battery agent sets bit 2^3 when its charge is in level 2.

3. Layer 2: When its charge drops to level 3, before moving out of the voltage control, battery agent activates bits 2^2 and 2^3.

When an agent is unable to supply shared current, it informs the other by activating bits 2^0 and 2^1.

4. Results and Discussion

The system as shown in figure 1, includes an active load and a grid connected PV with two storage devices. The details are:

- 1 kW PV generator with a voltage of 190 V
- The electrical grid with a voltage of 380 V (phase to phase)
- SC with a capacity of 10 F having a nominal voltage of 75 V
- Two batteries each having a voltage of 144 V and a capacity of 60 AH

All the elements are connected to an active load through a 100 V DC bus. The active load can be operated as a motor or generator. A current rectifier and 230/100 V buck converter is used to connect the grid to the DC bus. The SC and batteries are connected to the load through bidirectional converter and buck converter, respectively.

At first, the proposed EMS is implemented on a simulation model with a scenario of 30 s while all the converters act with real behaviour. The converters are modelled to present real behaviour and not just as a voltage source converter. For this reason, inevitable oscillation appears in profiles. In the second case, a scenario of 10 s is set up to consider operation of EMS when a failure occurs in a decision part.

4.1. Result of Energy Management

To implement the proposed mechanism on the system, some parameters have been defined as shown in Table 1. In order to have a suitable comparison, these parameters are obtained from [42]. Initially, it is assumed that SC and battery is fully charged and all the agents are in normal mode, and therefore, bit 24 for all of them is set to 1.

Table 1: The level of constraints for agents and respective shared currents.

Agent	Level of constraints	Constraints	Shared current (A)
SC	Level 1	$85\% < SOC_{SC}$	0
	Level 2	$70 < SOC_{sc} \leqslant 85\%$	6
	Level 3	$55\% < SOC_{SC} \leqslant 70\%$	12
PV	Level 1	$V_{PVnom} \geqslant 190$	0
	Level 2	$V_{PVnom}<190$	15
Battery	Level 1	$13\% \leqslant SOC_{Bat}$	0
	Level 2	$10\% \leqslant SOC_{Bat}<13\%$	8
	Level 3	$7\%<SOC_{Bat}<10$	16

Control voltage by SC: In the start, all the agents check for the available power and based on Subsumption architecture, SC agent overrides all requests and takes control of DC bus and supplies the energy demand. Consequently, it sets bit 2^1 and, sends [10110] as signal to the communication port. It means that SC agent is in normal mode and shares current with level 1 of its current constraint as shown in figure 8. At t=1.3s, its charge is dropped to 85% (Figure 9) and SC enters to second level of current constrain, so activates 2^3 bit, [11010], to request for sharing current. Based on section 3.4, PV has high priority to share current with SC. Subsequently, PV agent accepts to supply shared current, by activating bit 20 ([10001]). The PV

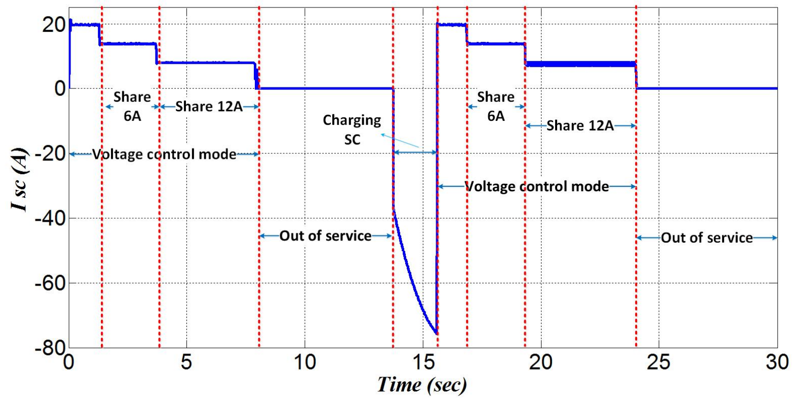

Figure 8: The injected current by SC under different time periods of decision making

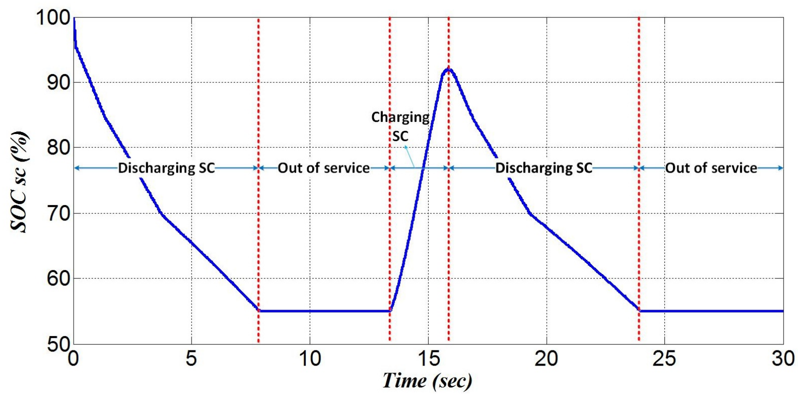

Figure 9: The state of charge of SC

supplies 6A of demand as shown in Figure 10. At t=3.7s, as the SOC of SC drops below 70%. PV increase the share to 12 A. Therefore, the communication signal by SC is changed to [11110], and PV supplies a total of 12 A. If PV cannot supply shared current, battery and grid can do it based on their priority.

Control voltage by battery: When charge of SC drops to 55% (t=7.9 s), SC agent based on its voltage constraint in Subsumption architecture cannot deliver to fulfil the demand. So, the voltage control transferred completely to the agent placed in the next layer (which was supposed to be PV). However, at t=7.9 s, terminal voltage of PV is also dropped such that it is out of service (Figure 11). Thus, based

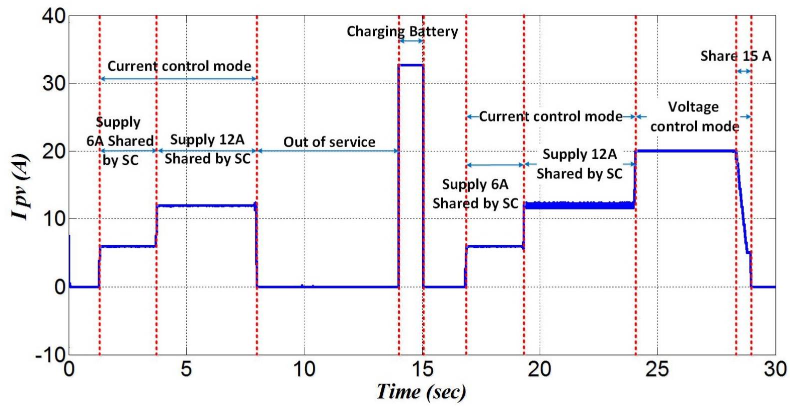

Figure 10: The injected currents by PV under different time sections of the decision making

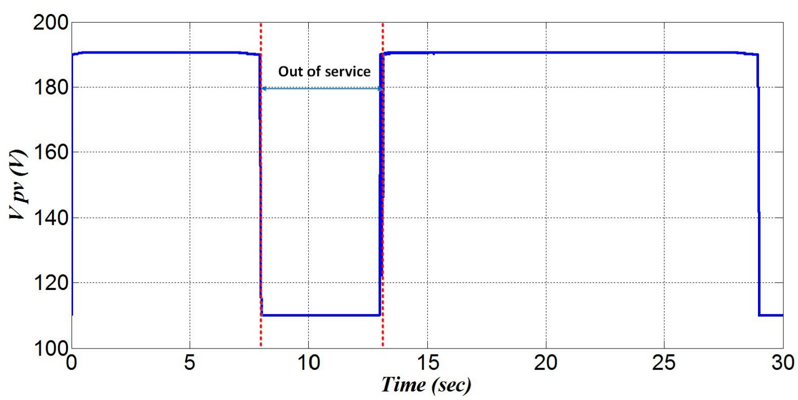

Figure 11: The evolution of the PV output voltage

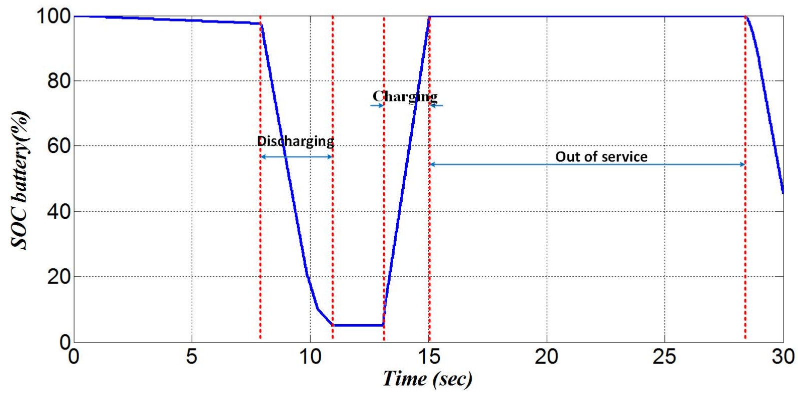

Figure 12: The state of charge of battery

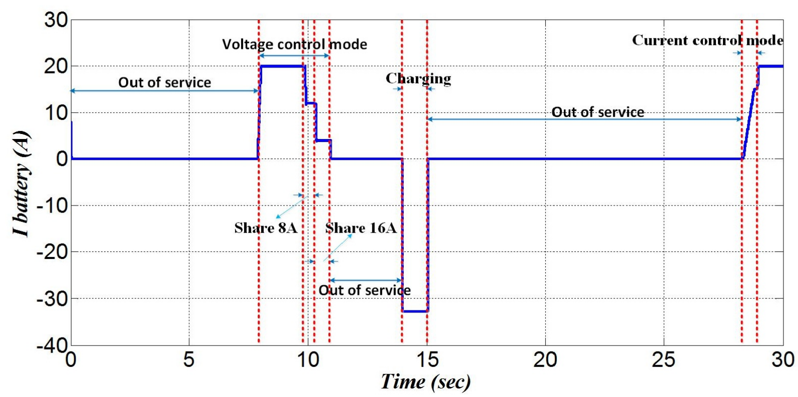

Figure 13: The injected current by battery under different time span of decision making

on figure 12, battery has enough charge to supply the requested demand, and by sending [10110] as a data signal, it controls the DC bus. Further, based on the SOC of battery, the battery agent shares current in three levels with the grid agent, as shown in Figure 13 and Figure 14.

Control voltage by grid: After cooperating in three levels of current share by battery as shown in figure 14, at t=11 s the grid takes the control of voltage at DC bus by sending [10010] over the communication port. If any agent with high priority exists with sufficient power to share, it can override the grid's request. However, the grid has the ability to keep it for a long time without sharing current until one

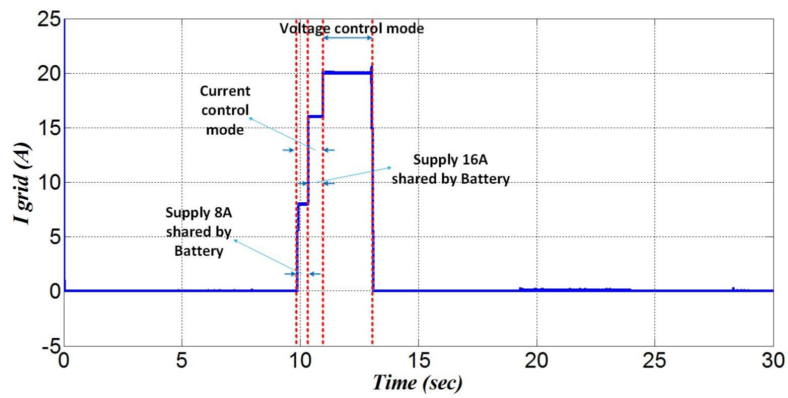

Figure 14: The injected current by grid under different time section of decision making

of the agents with high priority overrides its precedence.

As there is an active load in the system and thus, it can provide energy in generator mode (see Figure 15). At t=13 s, load generates power and SC stores it. Therefore, SC takes voltage control until t=15.6s. During this time, the terminal voltage of PV is also increased. The energy generated by PV is absorbed by the battery since it is already discharged. When the SOC of battery is reached to 100%, it is disconnected from the PV. Once the load finished generating energy, the SC is charged enough to keep the control of DC bus by sending request [10110]. The other agents cannot override its competence because it is in the lowest layer with high priority.

The SC agent during voltage control of DC bus shares current with PV in two steps by sending signals [11010] and [11110] over the communication network. After the SOC of SC drops to a critical percentage, the PV with high priority based on hierarchical algorithm takes voltage control of DC bus. It is obvious that when PV controls the voltage of DC bus, others can just participate in sharing the current. It is worth mentioning that only the agent with high priority (here SC) can take voltage control back. The PV agent will supply load until there is sunshine. To conclude, all the interactions among the agents are assigned by a communication signal. Agents just by reading the 5 bits signal can sense variations in the system and take a proper control action. Figure 16 shows how agents control DC bus without

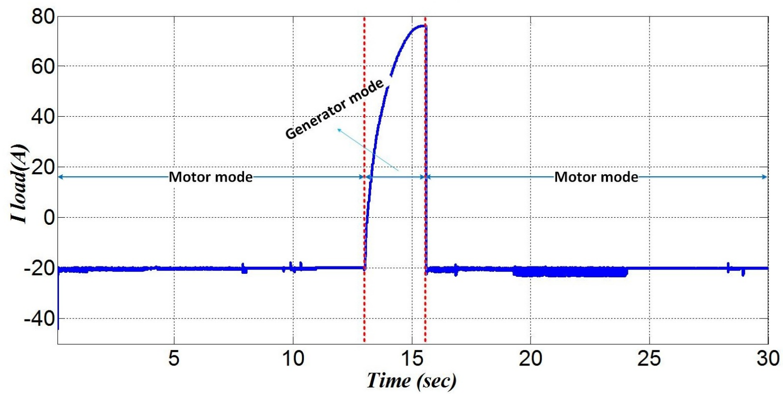

Figure 15: The waveform for the load current variation

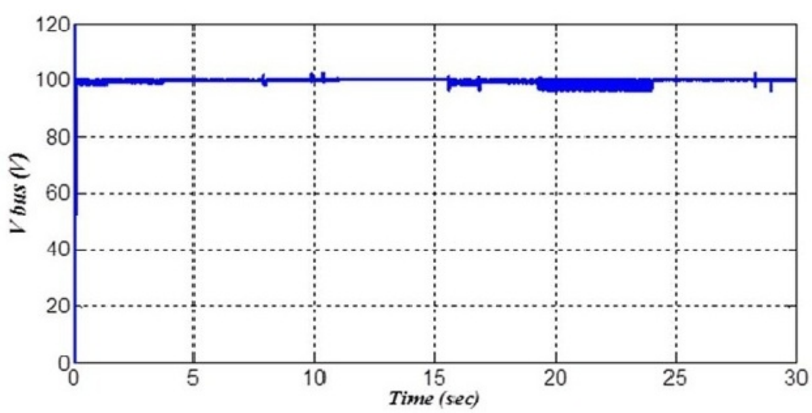

Figure 16: The voltage at the DC bus

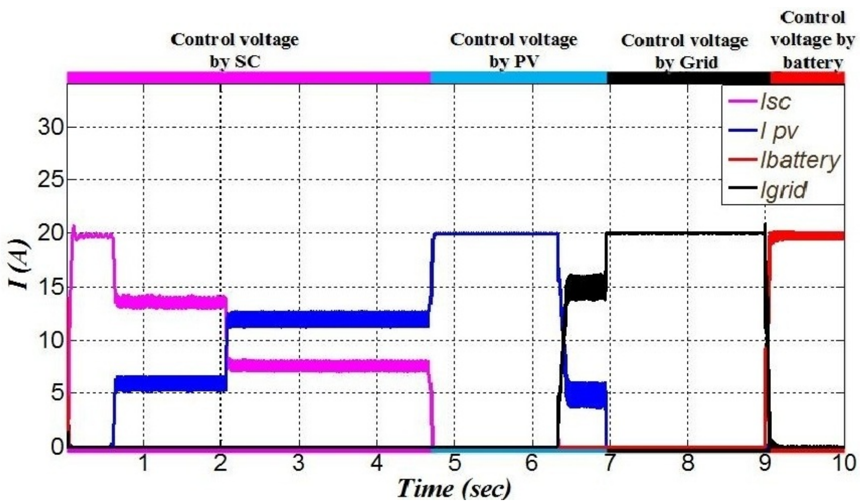

Figure 17: The injected current of SC, PV, battery and grid under different time periods of fault tolerance test

any fluctuation in switching.

4.2. Result of Fault Tolerance

In this section, the system is simulated for 10s in order to evaluate the operation of EMS in a fault-facing at the decision part. As mentioned in Section 4.1, agents transfer 5 bits to the communication port wherein bit 2^4 describes about the failure status of an agent. Assuming at the beginning that the battery agent (decision part of battery) suffered from a breakdown. Subsequently, the signal from the battery over the data bus will be [00000]. In this case, hierarchy in layers is reconfigured only with sub-behaviours of SC, PV, and grid agents without considering the battery agent. This is one of the main advantages of MASs known as fault tolerance and high reliability. It enables a system to continue its operation while even some parts stop working.

At first, SC agent completely controls the voltage and after sharing 6 A and 12 A by sending [11010] and [11110] to the data bus, respectively, PV agent takes the control of DC bus voltage, as shown in figure 17. The PV supplies demand until t=6.3 s, this time it shares current by sending signal [11011] to the data bus.

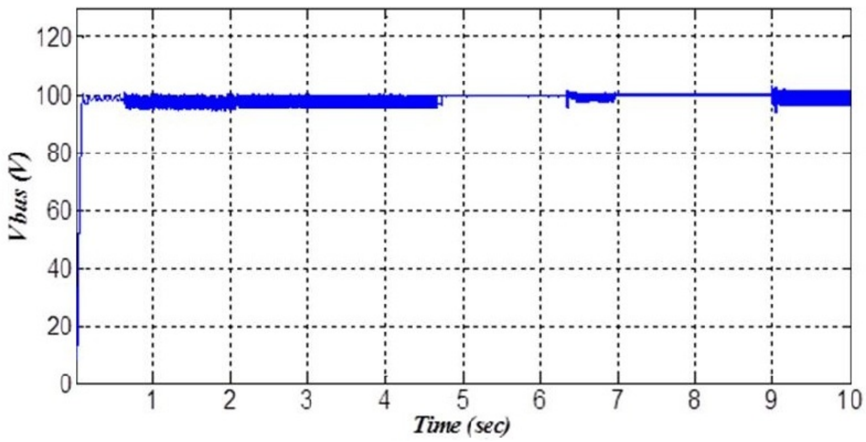

Figure 18: The voltage of the DC bus during fault tolerance test

Although battery has high the priority rather than the grid, however, the detected signal from battery on the communication port is [00000], due to its fault. Consequently, the grid agent supplies the shared current. At t=6.9 s, the grid controls voltage of DC bus by sending [10010] signal. This situation stays until one of the agents is able to supply the demand.

The battery failure is resolved at t=9 s, so it sets 2^4 bit to 1. By this signal, the configuration among the agents is changed to 4 agents and the voltage control of DC bus is handed over to the battery agent. Figure 18 shows the changes in the DC bus voltage. It is obvious that despite of failure in battery agent, there is no oscillation in the voltage profile and energy management is carried out smoothly among the generators.

5. Conclusions

In this paper, a multi-agent based distributed energy management system with a low bandwidth communication bus is proposed to control the voltage of DC bus and supply-demand balance in a micro-grid. In the proposed system, any agent can control the voltage and current through the set points using Subsumption architecture and is supported by a communication link. The proposed architecture provides flexibility, high speed in decision-making, adaptability after redevelopment and fault tolerance. The fault ride through capability enables smooth and reliable operation of the entire system if local controllers develop faults. To achieve these objectives, agents in this framework cooperates through a communication link wherein allocated tasks such as voltage and current control are conveyed. The communication between agents improves the reliability of the system, especially in mitigating the failure state by reconfiguring the sequence of agents. The proposed control for voltage and power is validated for normal operation and in failure state. Overall, the proposed framework presents the following advantages:

1. Online smart control of microgrids
2. Flexible and easy implementation, even for large-scale systems
3. Require low communication bandwidth and low sized transmission data (5 bits)
4. High reliability and fault tolerance
5. Easy redevelopment by reassigning the priorities

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References

[1] S. Khemakhem, M. Rekik, L. Krichen, A collaborative energy management among plug-in electric vehicle, smart homes and neighbors' interaction for residential power load profile smoothing, Journal of Building Engineering 27 (2020) 100976.

[2] V. Aryanpur, M. S. Atabaki, M. Marzband, P. Siano, K. Ghayoumi, An overview of energy planning in iran and transition pathways towards sustainable electricity supply sector, Renewable and Sustainable Energy Reviews 112 (2019) 58–74.

[3] S. Aznavi, P. Fajri, R. Sabzehgar, A. Asrari, Optimal management of residential energy storage systems in presence of intermittencies, Journal of Building Engineering 29 (2020) 101149.

[4] H. R. Gholinejad, A. Loni, J. Adabi, M. Marzband, A hierarchical energy management system for multiple home energy hubs in neighborhood grids, Journal of Building Engineering 28 (2020) 101028.

[5] P. Chen, Y. Wu, L. Zou, Distributive pv trading market in china: A design of multi-agent-based model and its forecast analysis, Energy 185 (2019) 423–436.

[6] R. K. Chauhan, K. Chauhan, Building automation system for grid-connected home to optimize energy consumption and electricity bill, Journal of Building Engineering 21 (2019) 409–420.

[7] L. Ju, Q. Zhang, Z. Tan, W. Wang, H. Xin, Z. Zhang, Multi-agent-system-based coupling control optimization model for micro-grid group intelligent scheduling considering autonomy-cooperative operation strategy, Energy 157 (2018) 1035–1052.

[8] J. Ferber, G. Weiss, Multi-agent systems: an introduction to distributed artificial intelligence, Vol. 1, Addison-Wesley Reading, 1999.

[9] J. B. Almada, R. P. S. Leão, R. F. Sampaio, G. C. Barroso, A centralized and heuristic approach for energy management of an ac microgrid, Renewable and Sustainable Energy 60 (2016) 2884–2894.

[10] T. Wang, D. O'Neill, H. Kamath, Dynamic control and optimization of distributed energy resources in a microgrid, *IEEE Transactions on Smart Grid*, 6 (6) (2015) 2884–2894.

[11] M. S. S. Danish, T. Senjyu, A. M. Ibrahimi, M. Ahmadi, A. M. Howlader, A managed framework for energy-efficient building, Journal of Building Engineering 21 (2019) 120–128.

[12] H. Zhou, T. Bhattacharya, D. Tran, Composite energy storage system involving battery and ultracapacitor with dynamic energy management in microgrid applications, IEEE Transactions on Power Electronics 26 (3) (2011) 923–930.

[13] M. Latif, A. Nasir, Decentralized stochastic control for building energy and comfort management, Journal of Building Engineering 24 (2019) 100739.

[14] B. Li, R. Roche, D. Paire, A. Miraoui, A price decision approach for multiple multi-energy-supply microgrids considering demand response, Energy 167 (2019) 117–135.

[15] M. Nazari-Heris, M. A. Mirzaei, B. Mohammadi-Ivatloo, M. Marzband, S. Asadi, Economic-environmental effect of power to gas technology in coupled electricity and gas systems with price-responsive shiftable loads, Journal of Cleaner Production 244 (2020) 118769.

[16] A. Q. Santos, R. M. Monaro, D. V. Coury, M. Oleskovicz, A new real-time multi-agent system for under frequency load shedding in a smart grid context, Electric Power Systems Research 174 (2019) 105851.

[17] D. Stimoniaris, T. Kollatou, D. Tsiamitros, M. Zehir, A. Batman, M. Bagriyanik, A. Ozdemir, E. Dialynas, Demand-side management by integrating bus communication technologies into smart grids, Electric Power Systems Research 136 (2016) 251–261.

[18] M. Marzband, E. Yousefnejad, A. Sumper, J. L. Domínguez-García, Real time experimental implementation of optimum energy management system in standalone microgrid by using multi-layer ant colony optimization, International Journal of Electrical Power & Energy Systems 75 (2016) 265–274.

[19] D. E. Olivares, C. A. Cañizares, M. Kazerani, A centralized energy management system for isolated microgrids, IEEE Transactions on smart grid 5 (4) (2014) 1864–1875.

[20] M. Marzband, M. Ghadimi, A. Sumper, J. L. Domínguez-García, Experimental validation of a real-time energy management system using multi-period gravitational search algorithm for microgrids in islanded mode, Applied energy 128 (2014) 164–174.

[21] M. Jadidbonab, B. Mohammadi-Ivatloo, M. Marzband, P. Siano, Short-term self-scheduling of virtual energy hub plant within thermal energy market, IEEE Transactions on Industrial Electronics (2020) 1–1.

[22] M. A. Mirzaei, A. Sadeghi-Yazdankhah, B. Mohammadi-Ivatloo, M. Marzband, M. Shafie-khah, J. ao P.S. Catalão, Integration of emerging resources in igdt-based robust scheduling of combined power and natural gas systems considering flexible ramping products, Energy 189 (2019) 116195.

[23] M. Pourakbari-Kasmaei, M. Lehtonen, M. Fotuhi-Firuzabad, M. Marzband, J. R. S. Mantovani, Optimal power flow problem considering multiple-fuel options and disjoint operating zones: A solver-friendly MINLP model, International Journal of Electrical Power Energy Systems 113 (2019) 45–55.

[24] N. Gholizadeh, G. Gharehpetian, M. Abedi, H. Nafisi, M. Marzband, An innovative energy management framework for cooperative operation management of electricity and natural gas demands, Energy Conversion and Management 200 (2019) 112069.

[25] C. Wang, Y. Liu, X. Li, L. Guo, L. Qiao, H. Lu, Energy management system for stand-alone diesel-wind-biomass microgrid with energy storage system, Energy 97 (2016) 90–104.

[26] R. Das, Y. Wang, G. Putrus, R. Kotter, M. Marzband, B. Herteleer, J. Warmerdam, Multi-objective techno-economic-environmental optimisation of electric vehicle for energy services, Applied Energy 257 (2020) 113965.

[27] M. Hong, X. Yu, N.-P. Yu, K. A. Loparo, An energy scheduling algorithm supporting power quality management in commercial building microgrids, IEEE Transactions on Smart Grid 7 (2) (2014) 1044–1056.

[28] A. Mondal, S. Misra, M. S. Obaidat, Distributed home energy management system with storage in smart grid using game theory, IEEE Systems Journal 11 (3) (2015) 1857–1866.

[29] Y. Xu, W. Zhang, G. Hug, S. Kar, Z. Li, Cooperative control of distributed energy storage systems in a microgrid, IEEE Transactions on smart grid 6 (1) (2014) 238–248.

[30] B. M. Radhakrishnan, D. Srinivasan, A multi-agent based distributed energy management scheme for smart grid applications, Energy 103 (2016) 192–204.

[31] Q. Shafiee, J. M. Guerrero, J. C. Vasquez, Distributed secondary control for islanded microgrids—a novel approach, IEEE Transactions on power electronics 29 (2) (2013) 1018–1031.

[32] Y. F. Eddy, H. B. Gooi, S. X. Chen, Multi-agent system for distributed management of microgrids, IEEE Transactions on power systems 30 (1) (2014) 24–34.

[33] A. Kulmala, M. Alonso, S. Repo, H. Amaris, A. Moreno, J. Mehmedalic, Z. Al-Jassim, Hierarchical and distributed control concept for distribution network congestion management, IET Generation, Transmission & Distribution 11 (3) (2017) 665–675.

[34] I.-Y. Chung, S.-J. O. Cheol-HeeYoo, Distributed intelligent microgrid control using mul-ti-agent systems, Engineering 5 (01) (2013) 1.

[35] H. J. Monfared, A. Ghasemi, A. Loni, M. Marzband, A hybrid price-based demand response program for the residential micro-grid, Energy 185 (2019) 274–285.

[36] M. Marzband, S. S. Ghazimirsaeid, H. Uppal, T. Fernando, A real-time evaluation of energy management systems for smart hybrid home microgrids, Electric Power Systems Research 143 (2017) 624–633.

[37] T. Logenthiran, R. T. Naayagi, W. L. Woo, V.-T. Phan, K. Abidi, Intelligent control system for microgrids using multiagent system, IEEE Journal of Emerging and Selected Topics in Power Electronics 3 (4) (2015) 1036–1045.

[38] G. Artale, A. Cataliotti, V. Cosentino, D. Di Cara, S. Guaiana, N. Panzavecchia, G. Tinè, Real-time power flow monitoring and control system for microgrids integration in islanded scenarios, IEEE Transactions on Industry Applications 55 (6) (2019) 7186–7197.

[39] H. Fallahzadeh-Abarghouei, S. Hasanvand, A. Nikoobakht, M. Doostizadeh, Decentralized and hierarchical voltage management of renewable energy resources in distribution smart grid, International Journal of Electrical Power & Energy Systems 100 (2018) 117–128.

[40] M. S. Golsorkhi, D. J. Hill, H. R. Karshenas, Distributed voltage control and power management of networked microgrids, IEEE Journal of Emerging and Selected Topics in Power Electronics 6 (4) (2017) 1892–1902.

[41] M. R. B. Khan, R. Jidin, J. Pasupuleti, Multi-agent based distributed control architecture for microgrid energy management and optimization, Energy Conversion and Management 112 (2016) 288–307.

[42] M. Selseleh Jonban, A. Akbarimajd, J. Javidan, Intelligent fault tolerant energy management system with layered architecture for a photovoltaic power plant, Journal of Solar Energy Engineering 137 (1) (2015).

[43] J. Lagorse, D. Paire, A. Miraoui, A multi-agent system for energy management of distributed power sources, Renewable energy 35 (1) (2010) 174–82.

[44] A. Tahri, H. El Fadil, F. Belhaj, K. Gaouzi, A. Rachid, F. Giri, F. Chaoui, Management of fuel cell power and supercapacitor state-of-charge for electric vehicles, Electric Power Systems Research 160 (2018) 89–98.

[45] R. Teodorescu, M. Liserre, P. Rodriguez, Grid converters for photovoltaic and wind power systems, Vol. 29, John Wiley & Sons, 2011.

[46] R. Brooks, A robust layered control system for a mobile robot, IEEE journal on robotics and automation 2 (1) (1986) 14–23.

[47] G. Schouten, J. Steckel, A biomimetic radar system for autonomous navigation, IEEE Transactions on Robotics 35 (3) (2019) 539–548.

[48] H. Boterenbrood, Canopen high-level protocol for can-bus, Nikhef, Amsterdam 20 (2000).

[49] M. Esro, A. A. Basari, S. Kumar, M. Sadhiqin, Z. Syariff, Controller area network (can) application in security system, World Academy of Science, Engineering and Technology 35 (2009).

[50] Y. Zhu, F. Zhuo, L. Xiong, Communication platform for energy management system in a master-slave control structure microgrid, in: Proceedings of The 7th International Power Electronics and Motion Control Conference, Vol. 1, IEEE, 2012, pp. 141–145.