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A multi-agent system for energy management of distributed power sources

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A R T I C L E I N F O

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A B S T R A C T

The field of energy management is an area increasingly studied. However, most solutions are based on centralized systems and barely fulfil criterion like fault tolerance or adaptability. Also, these systems are often difficult to design because of the "top–down" approach used: the designer generally knows how each component has to respond separately, but a centralized management system focuses his attention solely on the overall reaction of the system. That is why a distributed management solution based on the paradigm of Multi-Agent Systems (MASs) is proposed in this paper. In addition to a more natural conception, based on a "bottom–up" approach, this solution ensures better system reliability. After reviewing the previous works, an application of MAS to power management in a hybrid power source is presented. Then, the system is tested using a simulation model. The results show that this approach is perfectly valid and can respond to most problems of centralized energy management systems (EMSs).

1. Introduction

The steady increase in the price of fossil fuels along with concerns about emissions of greenhouse gases, presents renewable energy sources as promising solutions. Thus, the equipments that include renewable energy sources are increasingly used for stand-alone or grid-tied systems. However, even if these sources are interesting, they are intermittent and require the use of storage systems. The systems can also include different kinds of sources in order to benefit advantages from each [1,2]. Then, hybrid systems are obtained by combining several sources and means of storage.

In order to draw the best performance of such systems, a proper energy management is essential. Good management should first ensure continuous supply to the load. Thereafter, other targets may be set such as fault tolerance of an element, maximizing efficiency, reducing operating costs and so on.

Typically, energy management is ensured by a central controller in which a program is implemented. This program is based on some long series of control flow like "if else if" (e.g. "if the battery is empty then charge it"). Even if this solution achieves a constant supply of the load, it cannot fulfil easily other objectives such as fault tolerance of an element. This centralized management is also based on a "top–down" approach and requires the designer of the control system to be exhaustive in the control flow written in the program. If an event not covered by the system occurs it is unable to respond adequately. Moreover, if the configuration has to be changed (addition or removal of an element), the program must be completely redesigned [3–6].

That is why a bottom–up approach seems preferable, although little used so far for this type of problem. Indeed, the designer knows, in most cases, how each element must respond separately. For example, he knows that a battery should not be discharged too deeply to prevent its destruction. However, it is more difficult to determine the overall behaviour of the hybrid system when several storage systems and multiple sources are used. With the bottom–up approach, power management emerges from relatively simple rules established according to the constraints of each element.

This approach can be structured around the Multi-Agent Systems (MASs) paradigm that will be used and detailed in the following sections. More and more studies on energy management by MAS have been published. However, the term "energy management" is not governed by a precise definition and the problem is different depending on the scope of application. It is possible to distinguish three fields of application symbolized in Fig. 1:

- production and storage,
- distribution,
- consumption.

In the area of distribution, much work has been done, especially for naval applications or large-scale systems [7–10]. These studies seek to organize a distribution network through intelligent switches that can reconfigure the networks. In these studies, the

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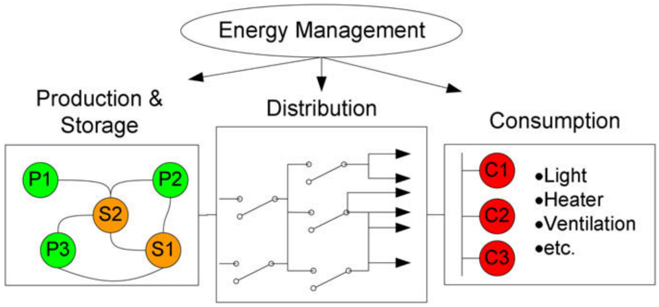

Fig. 1. Classification of areas to use energy management.

MAS allows to get a system that adapts to faults and improves performance by selecting the shortest path between sources and loads.

The first applications of MAS for energy management appear to have been used in the field of consumption [11–13]. In the end, the management of consumption is the problem of resource sharing: to control loads in order to preserve energy sources [14]. In this work, the charges are agents who will coordinate, usually through negotiations, in order to meet the load requested by the user while preserving resources. The loads are considered controllable, such as heating and air conditioning whose consumption can be controlled and possibly delayed.

Finally, the field covering the management of the sources and means of storage has not been much studied. Most studies have focused on large-scale systems, especially for reactive power compensation [15]. Other studies have invested the possibility of a contract network to coordinate the actions of sources and loads [16–18]. However, these approaches come mainly from information technology sector and their practical application is not obvious to most engineers and researchers in the electrical engineering. Thus, all these studies were confined to simulation, sometimes with a high level of abstraction.

In this article, the application of MAS for energy management is detailed, and more particularly the management of production and storage of energy in a hybrid system connected to the grid. First, the system architecture is presented before explaining the principle used for energy management. Finally, the simulation model of the system and its energy management, developed with Matlab–Simulink, are detailed and simulation results are presented and analyzed.

2. System presentation

2.1. Electrical architecture

The system in which energy management by MAS has been applied is shown Fig. 2.

The system consists of two sources:

- a 1 kW photovoltaic generator (PV) under a voltage of 65 V,
- the grid, with a voltage of 230 V (phase to phase).

The system can also store energy with two elements:

- a 200 Ah lead–acid battery bank under a voltage of 48 V,
- a super-condensator (SC) pack of 14.5 F under a nominal voltage of 60 V.

All the elements are connected to a DC bus with a rated voltage of 100 V. The bus consists of a capacitor that filters the fluctuations

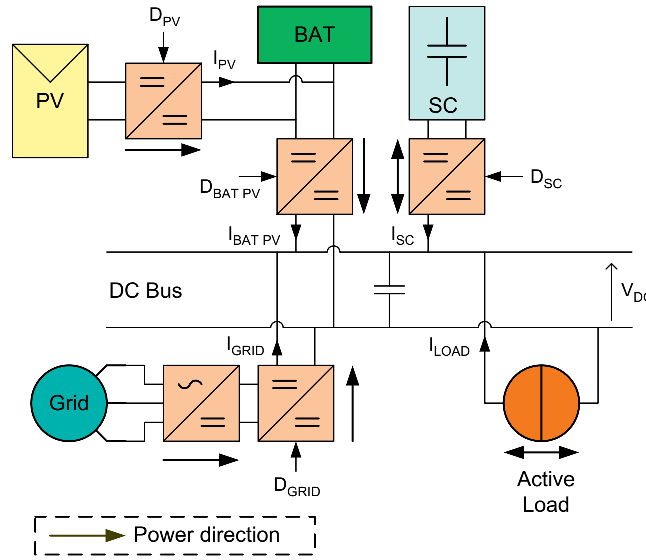

Fig. 2. Electrical diagram of the system studied.

from power converters. Only the photovoltaic generator is not directly connected to the DC bus. The converter between PV and battery is a buck–boost converter that tracks the maximum power with an MPPT algorithm. The converter connecting the battery to the bus is a boost converter. The converter linking the SC bus is a bidirectional current converter. Excluding the load, it is the only element that can remove energy from the bus. For the grid, the voltage is first rectified by a three-phase diode bridge. Then, a buck converter controls the power coming from the grid. Finally, the load represented by a current source, is active. Therefore, during certain phases, it can inject power on the DC bus.

2.2. Control architecture

Each converter connected to the bus must be current-controlled in order to manage the power of each element. This may be achieved by a classic PI controller. Two options are available for the current reference: either the reference comes from a voltage-loop or it comes from an Energy Management System (EMS).

In the proposed architecture, it is postulated that each converter on the bus DC can be either voltage-controlled or current-controlled. This selection of control mode is done symbolically by a switch as shown in Fig. 3. Like the reference I_{ref}, the choice of control returns to the EMS.

In this way, various elements can control the bus voltage. Thus, even if the element that controls voltage fails, another element can replace it.

2.3. Which energy management system?

After the introduction of the control structure, it appears that the EMS will provide at least two pieces of information to the converter's controllers: the control mode (voltage or current) and, when needed, the current reference.

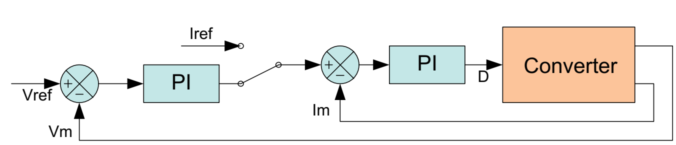

Fig. 3. Control architecture of the converters.

Before developing further the proposed approach, it is interesting to quickly summarize the operation of conventional energy management and to emphasize the limits. Conventional systems, based on a top–down approach, can be summed up by Fig. 4.

The centralized system receives information on the status of the elements (state of charge (SOC), availability, etc.). Based on this information, the system then delivers the current references to the controllers in order to manage energy according to the plans and scenarios that have been provided by the designer. It should be noted that only one element is responsible for controlling the DC bus voltage. In the case of study shown in Fig. 2, it is interesting to remark that, in most cases, the grid is chosen to control the voltage. However, if the grid becomes faulty, the system can no longer function because the DC bus voltage is not kept constant. This is a major problem in this solution. In the same way, it is interesting to note that if the central controller is in fault, the entire system cannot work.

Finally, the difficult design as well as the lack of openness of the system can also be added to the shortcomings of centralized solutions. Indeed, design can be very difficult to implement. Most of the time, a long series of rules must be thoroughly prepared in order to obtain an answer for all states of the system. If a case is omitted, the system is unable to respond adequately. The field of "soft computing" has also brought its share of solutions with neural networks and fuzzy logic [19–24]. However, the ingenuity of such solutions is equal to their difficulty of implementation. In addition, these solutions are not open, i.e. they cannot easily integrate new elements into the system. For instance, if a new storage system is inserted into the system, the centralized management system must be completely reprogrammed and new rules must be written by the designer, always with the sake of completeness.

With the many disadvantages of a centralized EMS, a solution should be proposed that presents:

- a fault tolerance of one or more elements, for more reliability,
- a distribution of the control to avoid a blackout due to the bug of only one program,
- an easier design of the system,
- openness and adaptability of the system to easily integrate new elements.

These objectives can be achieved, at least in part, through the use of MAS technology that is detailed in the next section.

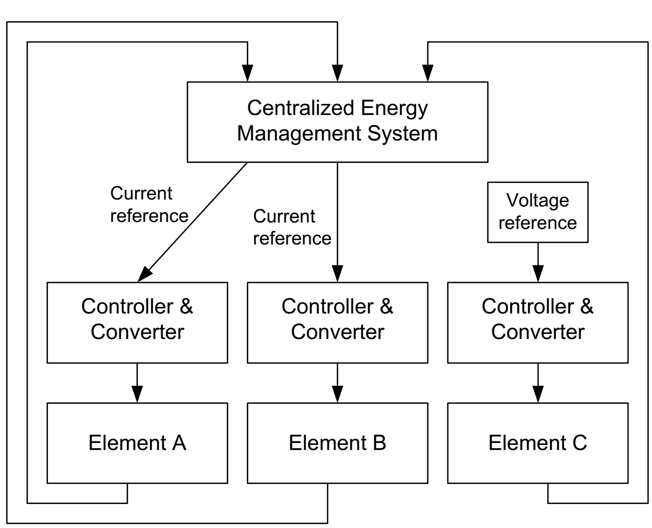

Fig. 4. Conventional energy management system.

3. Energy management using MAS

Before explaining in detail the proposed solution, it is important to show some key points of MAS because this technique is very little known in the field of electrical engineering. Indeed, for electrical engineering, the use of MAS presents certain difficulties including the very wide selection of design methodologies, the diversity of agent structures and the different strategies of implementation [25].

3.1. Agent and MAS

MAS theory is an emerging field that evolved from the distributed artificial intelligence (DAI) in the 70s and 80s. Since MAS theory represents the major stream of research in DAI, the two fields are often confused. Although MAS research is widespread, there is no precise definition about what an agent is [26,27]. Despite of the vague definition of agents, MAS theory generally specifies that an agent is an entity [28,29]:

- which is capable of acting in an environment,
- which can communicate directly with other agents,
- which is driven by a set of tendencies (in the form of individual objectives or of satisfaction/survival function which tries to optimize),
- which possesses resources of its own
- which is capable of perceiving its environment (but to a limited extent),
- which has only a partial representation of this environment (and perhaps none at all),
- which possesses skills and can offer services,
- whose behaviour tends towards satisfying its objectives, taking account of the resources and skills available to it and depending on its perception, its representations and communications.

Also according to [28], an MAS is a system composed of the following elements:

- An environment, E that is a space which generally has a volume.
- A set of objects, O. These objects are situated, that is to say, it is possible at a given moment to associate any object with a position in E. These objects are passive, that are they can be perceived, created, destroyed and modified by the agents.
- An assembly of agents, A, which are specific objects representing the active entities of the system.
- An assembly of relations, R, which link objects (and thus agents) to each other.
- An assembly of operations, Op, making it possible for the agents of A to perceive, produce, consume, transform, and manipulate objects from O.

By its nature, agent technology makes possible the implementation of scalable, flexible and distributed systems. Thus, an MAS is able to address many of the problems of energy management.

3.2. An MAS for energy management

The methodologies for designing MAS are many and varied. Here it is presented a possible method that suits the issue of hybrid power sources. Obviously, other more complex methods may be considered. However, this method has the advantage of being relatively simple to understand for neophytes in the field of MAS, while showing an application to the problem of energy management.

3.2.1. The role of agents

In the design, the role of agents has to be defined. Based on the proposed control architecture (see Section 2.2), it appears that the controllers of the converters require two inputs (the control mode — voltage or current — and the current or voltage reference). Therefore, each agent delivers both information to a controller (see Fig. 5). The agent sets himself these two pieces of information according to his own behaviour. The agent behaviour can change depending on what the agent knows on the rest of the system, through its communication with other agents, but this knowledge is not a necessity. Thus, even if other elements are in fault, the agent remains independent. This is a first response to the issue of fault tolerance.

3.2.2. Structure of the MAS

The entire structure of control by MAS is represented in Fig. 6. Each agent controls one element. Only the load ("active load") is not controlled by an agent. Indeed, the load control depends on the needs of the user and does not require a control from the management system of energy sources. However, some agents may be informed of the load current.

To ensure dialogue between agents, a communication bus is present [30]. Like a computer network, if an item is disconnected from the network, it does not prevent others from operating normally. Moreover, even if the communication bus is in fault, the elements can continue to operate independently. However, in this case there is no coordination between the agents.

3.2.3. A token for the voltage control

The agent must decide the control mode: voltage or current regulation. But only one element at a time must regulate the voltage. To avoid this conflict, a virtual token is inserted into the system. The agent who holds this token is in charge of controlling the DC bus voltage. Thereafter, the agent may give this token to another officer: he loses the voltage control but he is current-controlled. The passage of the token may be due to two phenomena:

- the agent who holds the token has requested another agent to take it and he accepted,
- another agent asked the token and the agent accepted.

For the first case, the transfer of the token can be illustrated in Fig. 7. The first question of SC agent ("Can you take the token?") is

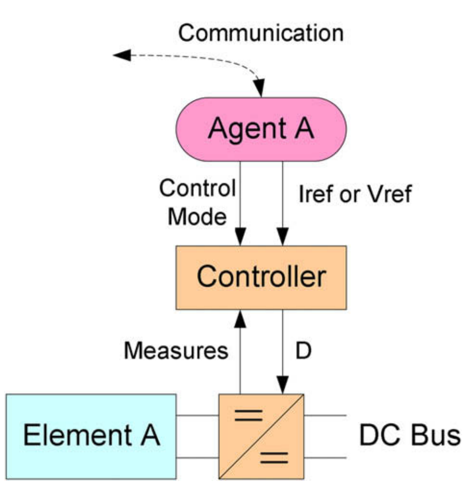

Fig. 5. An agent (agent "A") integrated in the system.

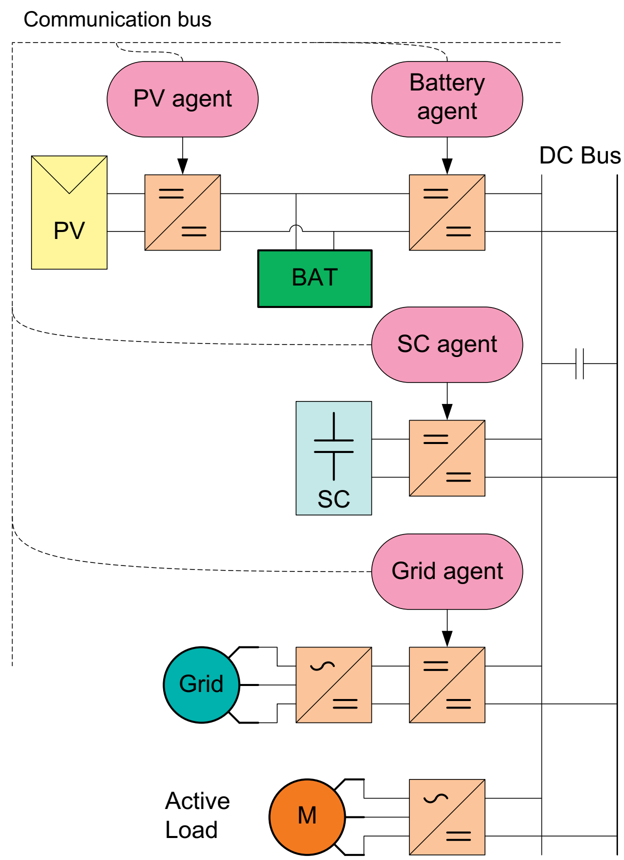

Fig. 6. Structure of the system controlled by MAS. For better readability of this scheme, the controllers between the agents and converters do not appear.

activated by the internal mechanism of this agent. This request could be motivated by an insufficient SC SOC for controlling the DC bus voltage. In the scenario, the battery agent accepts the token. However, this acceptance also depends on the internal mechanism of the battery agent. In case of refusal, the SC agent may send its request to another agent.

3.2.4. Agent's behaviours

As shown previously, the behaviour of each agent is developed individually. Only communication between agents ensures cohesion of the system. Here, the general behaviour of each agent is described and an example of this behaviour is represented by a state-flow diagram.

Like all the agents controlling an element connected to the DC bus, the SC agent has two major states: with voltage control token or without this token. When he holds the token, he keeps it while his SOC is sufficient (SC OK). Thus, if he receives a message asking to give the token, he will refuse. In addition, SC agent asks battery agent to supply a portion of the current to the bus (the battery agent can refuse or supply less power than required). When the SOC becomes critical, he will ask other agents if they can take the token. First, he asks the battery agent then, if the latter refuses, he will ask the grid agent. If the grid agent refuses SC agent is forced to keep the token. On the contrary, if an agent accepts, the SC agent goes into the state "without token". In this state, he must wait until the SC SOC reaches a higher value and that one of the other two agents accepts to give him the token. This behaviour is summarized by the state-flow diagram (Fig. 8).

The battery agent behaves similarly to the SC agent. If his SOC is sufficient, he accepts the token. Otherwise he refuses. In addition, he communicates with the PV agent asking him to stop the battery

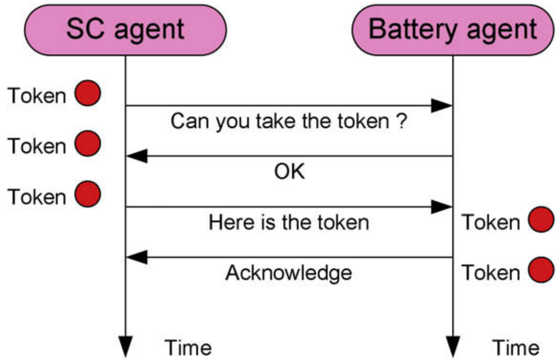

Fig. 7. Communication between two agents during the transfer of the token.

charge when it is full. Otherwise, he accepts the power generated by the PV panels.

Finally, the behaviour of grid agent was designed to minimize the power supplied by the grid. So, when the agent receives a request to take the token, he accepts. He will never try to take the token on its own initiative. Then, the grid agent will offer this token to other agents with the SC agent as a priority. The SC agent is priority because it allows better control of the DC bus voltage thanks to its greater power.

It should be noted that in the proposed design, the behaviour of agents is prepared assuming that the structure of the system is known. Therefore, the agent questions in a predefined order other agents, as it can be seen in the simplified state-flow diagram of SC agent Fig. 8. Some development prospects are presented in Section 6 to create generic agents able to be integrated into a system without changing their behaviour or their code.

4. Simulation model

4.1. The choice of Matlab–Simulink

To simulate the system and to test the validity of the proposed approach, Matlab–Simulink was chosen for several reasons. Often, object-oriented languages (including Java) are preferred to develop MAS through the approximation that can be made between objects and agents. However, these languages are really useful in the case of very large systems where communications are very advanced and, so far, the proposed solution does not require such language. Then, the behaviour of agents has been modelled by state-flow diagrams such as the one presented in Fig. 8. Simulink features a state-flow library with which it is possible to encode graphically the behaviour of an agent by drawing his state-flow diagram. Finally, the designed EMS, tested and validated in simulation, could be rapidly used on a real system through rapid prototyping solutions proposed by the dSPACE company. Indeed, this module directly builds the Simulink code and implements it in a DSP (Digital Signal Processor).

4.2. Physical model

The physical model consists of elements (batteries, SC, etc.) and converters. Equations (1) and (2) present the average models of the converters under an analytical form. They are obtained from the Kirchoff's voltage law. In these equations, *out* is for the output variables (voltage V and current I) and *in* is for the input variables. D is the duty cycle, L is the inductance value of the converter and R_L is the equivalent serial resistor. In (3), *low* represents the variables on the low voltage side and *high*, the ones on the high voltage side.

Buck converter (for the grid):

$$L\frac{\mathrm{d}I_{out}}{\mathrm{d}t} = D_{GRID}V_{in} - V_{out} - R_L I_{out} \tag{1}$$

Boost converter (for the battery):

$$L\frac{\mathrm{d}I_{out}}{\mathrm{d}t} = (D_{BAT\ PV} - 1)V_{out} + V_{in} - R_L I_{in} \tag{2}$$

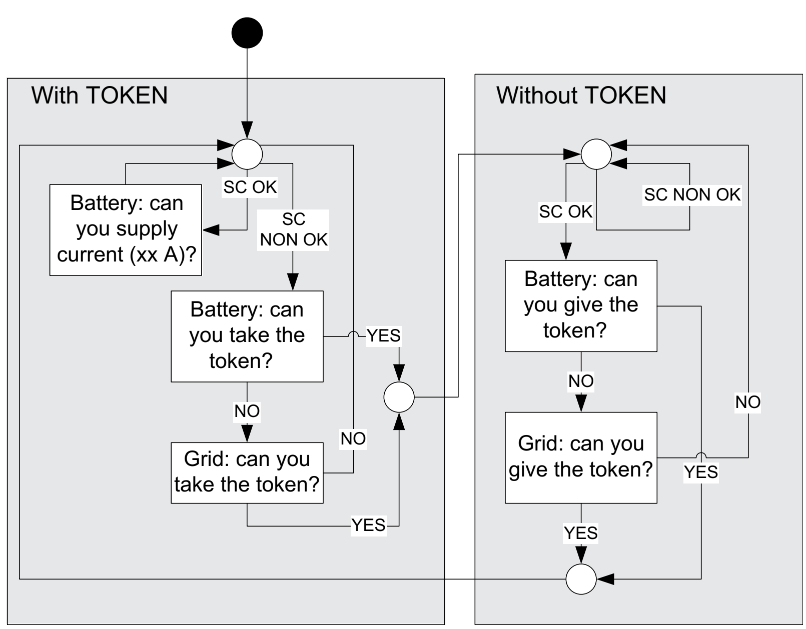

Fig. 8. Simplified state-flow diagram of SC agent.

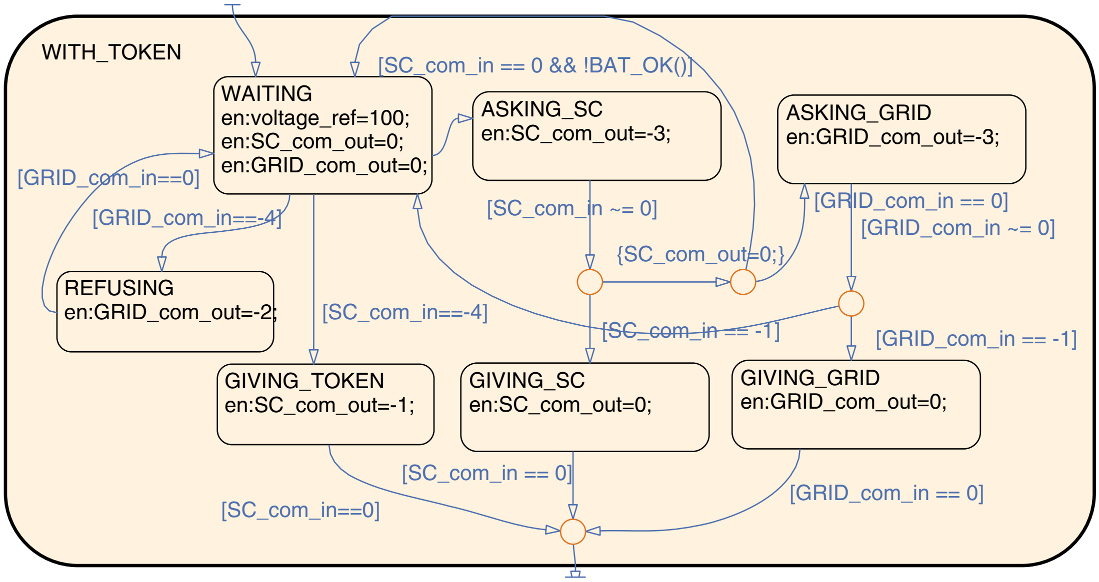

Fig. 9. Extract of the battery agent state-flow diagram.

Bidirectional converter (for the SC):

$$L\frac{dI_{low}}{dt} = V_{low} - D_{SC}V_{high} - R_L I_{low} \tag{3}$$

The DC bus voltage, V_{DC}, is obtained by integrating the sum of current injected on the bus (Kirchoff's current law) as shown in (4) where C_{DC} is the capacity connected to the DC bus.

$$V_{DC} = \frac{1}{C_{DC}}\int (I_{BAT\ PV} + I_{SC} + I_{GRID} + I_{LOAD})dt \tag{4}$$

The SC voltage, V_{SC}, and its SOC, SOC_{SC}, are obtained by (5) and (6). D_{SC} is the duty cycle of the converter linking the SC to the DC bus and $V_{SC\ nominal}$ represents the SC nominal voltage.

$$V_{SC} = \frac{1}{C_{SC}}\int\left(\frac{-I_{SC}}{D_{SC}}\right)dt \tag{5}$$

$$SOC_{SC} = \frac{V_{SC}^2}{V_{SC\ nominal}^2} \tag{6}$$

The battery voltage is assumed to be constant and its SOC, SOC_{BAT}, is obtained from (7). It is the integration of the battery current, i.e. the current supplied by PV minus the current supplied to the DC bus through the boost converter. This converter is controlled with a duty cycle $D_{BAT\ PV}$. $SOC_{BAT\ nominal}$ represents the battery nominal SOC expressed in Ah. This model does not take into account the losses caused by the storage but, in order to test the EMS, a complex model is not necessary.

$$SOC_{BAT} = \frac{\int\left(I_{PV} - \frac{I_{BAT\ PV}}{1 - D_{BAT\ PV}}\right)dt}{SOC_{BAT\ nominal}} \tag{7}$$

The buck–boost converter associated with the solar panel was not modelled so fine. For the purpose of validating the energy management, it is not necessary to consider the control of this converter. Therefore, only the current output by this converter is involved in the simulation as an arbitrary profile.

Also, the grid was not modelled in detail. Indeed, the grid operates on the bus through a three-phase rectifier and then through a buck converter. As part of the study, the rectifier need not be modelled. The presence of the grid will simply be detected through the voltage level at the buck converter input.

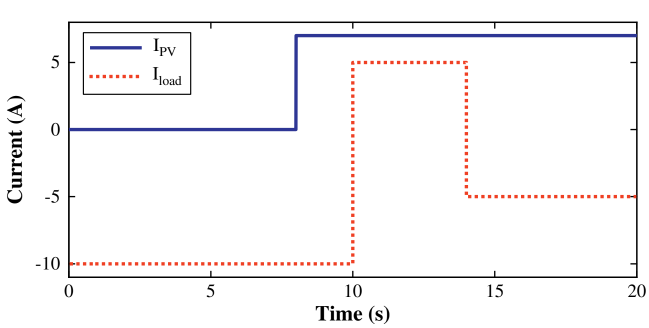

Fig. 10. Profiles of the PV panel current and the active load current.

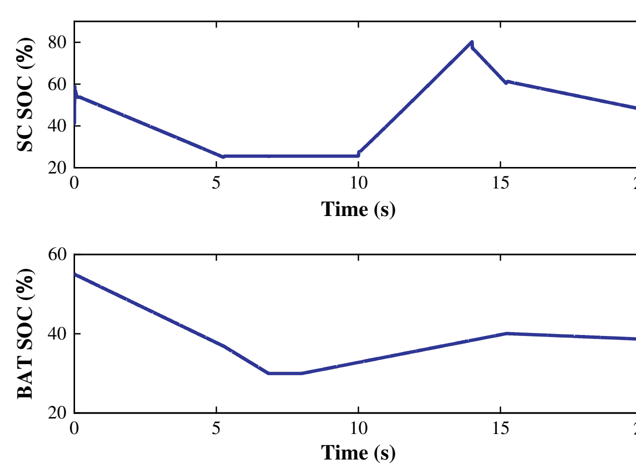

Fig. 11. SC and battery SOC evolution.

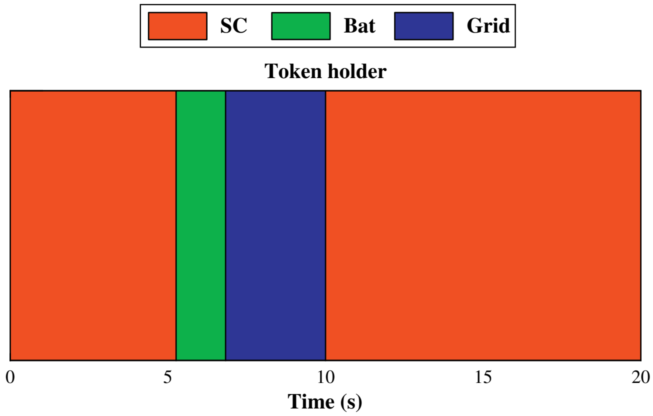

Fig. 12. Token holder.

4.3. Agent coded with a state-flow diagram

For example, Fig. 9 shows a part of implementation of the battery agent. The agent is fully described using the state-flow diagram, for both behaviour and communication.

4.4. Communication between agents

In the conducted simulation, communication between agents is cabled. For instance, the SC agent has two outputs, one for sending information to the battery agent, the other one to send information to the grid agent. In the same way, it has two inputs to receive information from these two agents.

5. Results and analysis

With the simulation model presented in the previous section, a scenario of 20 s was set up to show as clearly as possible the response of the EMS. Thus, profiles of the current generated by the solar panel (I_{PV}) and the load current (I_{LOAD}) are given in Fig. 10. The solar panel does not supply energy for the first 8 s. After, it provides 7 A to the battery. Since the load is active, the load current is sometimes negative when it consumes energy and sometimes positive when it provides energy.

Under this scenario, the SC and battery states of charge evolution are shown in Fig. 11. In the scenario, the SOC is initialized to

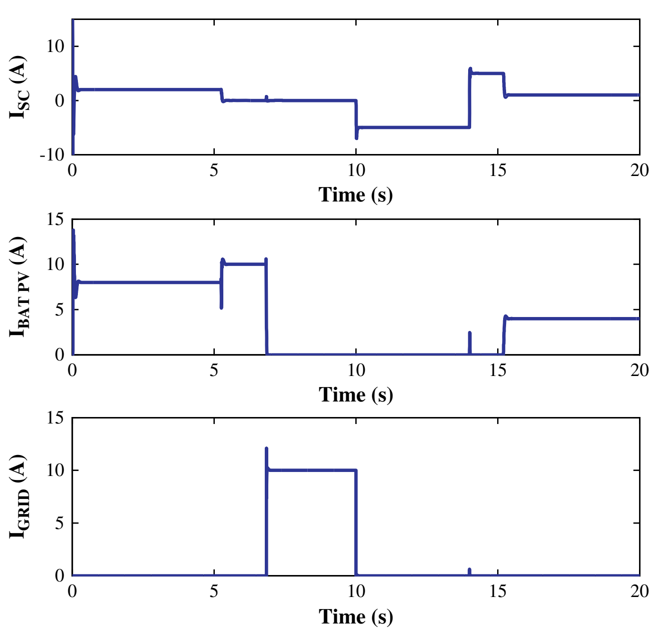

Fig. 13. Evolution of the SC, battery and grid currents.

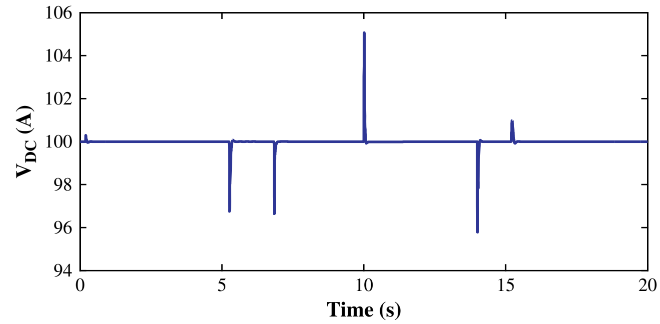

Fig. 14. DC bus voltage.

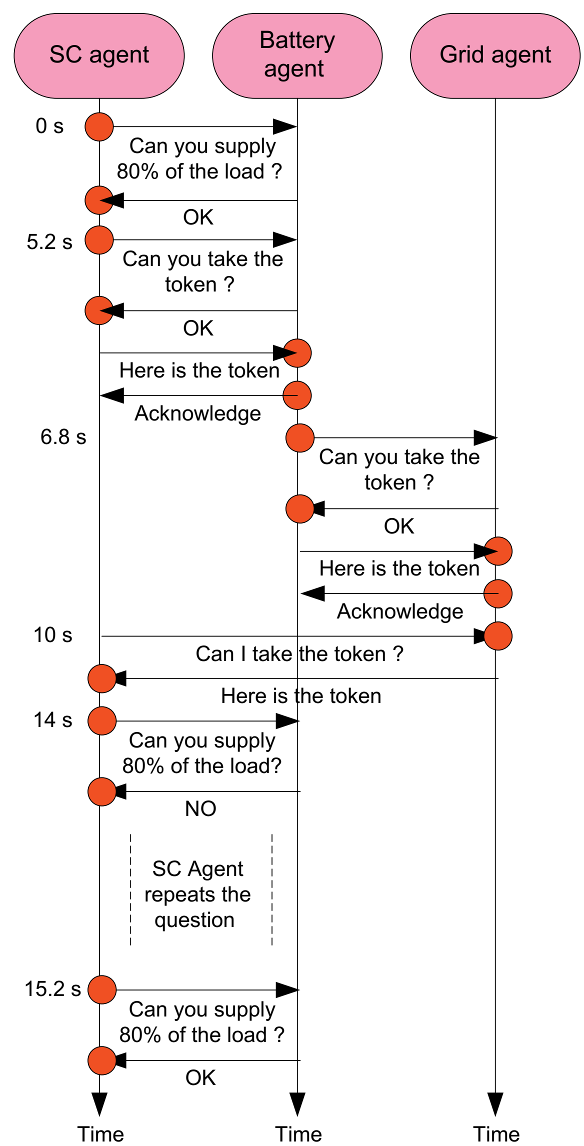

Fig. 15. Simplified communication exchange between agents during the simulation.

55%. In addition, to observe a maximum of events over a relatively short duration (20 s), the battery capacity has been reduced so that its SOC is moving more quickly.

To explain the evolution of the SOC, it is interesting to look at Fig. 12 that shows which element holds the token as well as the evolution of the currents injected on the DC bus (see Fig. 13). Thus, at the beginning, SC holds the token. Therefore, he is responsible for the voltage control and must provide the current consumed by the load to maintain a bus voltage of 100 V. At this stage, it also asks the battery to provide a part of this current in order to preserve the SC SOC (consumption of the load is assumed to be known by the SC agent). The part of current required by the SC to the battery is fixed at 80% of current consumed by the load. This part was set arbitrarily but could be variable and coming from a more complex reasoning, to be developed in future studies. The battery agrees to provide this part of current because its SOC is sufficient (over 30%). Then, just after 5 s, the SC SOC reaches a critical level (25%) and asks the battery to take the token because it is no longer able to maintain the DC bus voltage. The battery takes over until it reaches a very low SOC and calls the grid to take the token (at $t = 6.8$ s). The grid agent accepts but it should be noted that if the grid was down, he would have refused.

When the load generates energy (at $t = 10$ s), the SC asks the grid to give the token. Thus, it absorbs the energy generated by the active load. After the load has finished generating energy on the bus, the SC is charged enough to keep the token. As before, it asks the battery to provide a part of current but it refuses because it is not sufficiently charged. However, at $t = 15.2$ s, the battery was charged by the PV panel (SOC = 40%) and the battery agent accepts to provide a part of current.

Fig. 14 shows the change in DC bus voltage. There are small voltage peaks during the passage of the token, as for instance at $t = 5.2$ s. However, the amplitudes of these peaks remain very low and are less than 5% of the nominal value. In addition, peaks at 10–14 s are due to the rapid change of load current. In this case, even a classical controller, with only one element controlling the voltage, demonstrates such variations.

All communications between agents during the course of this scenario are summarized in Fig. 15.

6. Conclusion

The technique and principles of MAS, little known in electrical engineering, have been explained and illustrated through application to the problem of energy management of a hybrid system connected to the grid. Then, based on the simulation model established, the proposed approach was tested and validated. It has been shown that an alternative to centralized systems is possible. Furthermore, this solution addresses a number of issues, including fault tolerance and simplicity in the design of EMS.

This study has shown that it is also possible to create a system with a DC bus voltage which is not always controlled by the same element. This is possible thanks to the principle of dialogue and cooperation between the agents. This makes the system more reliable. Also, the bottom–up approach simplifies the design. Even though it has not been sought to develop a sophisticated behaviour for each agent, it is now possible to look in detail at the problems of each element. Thus, the designer can focus on the management of only one element without a direct confrontation with the whole problem.

The future developments of this study will focus on practical tests. First, a dSPACE card will be used to validate the principle in an experimental way. Indeed, even if this solution with the dSPACE control will remain centralized, the implemented program will be decomposed into several agents. Then, construction of a model where each agent is embedded in a microprocessor and interfaced with the others through a CAN (Control Area Network) will validate the proposed principle. In parallel to these experiments, work will be done to create generic agents able to integrate into a hybrid system without requiring the developer to reconfigure their behaviour. This will ensure greater openness of the system.

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Notations

L: inductance
C_{DC}: capacity connected to the DC bus
R_L: inductance serial resistor
$SOC_{BAT\ nominal}$: battery nominal state of charge
$V_{SC\ nominal}$: super capacitor nominal voltage
BAT: battery
$D_{BAT\ PV}$: duty cycle of the boost converter
D_{GRID}: duty cycle of the buck converter
D_{SC}: duty cycle of the bidirectional converter
I: current
$I_{BAT\ PV}$: current coming from the boost converter to the DC bus
I_{GRID}: current coming from the buck converter to the DC bus
I_{LOAD}: current coming from the load to the DC bus
I_{ref}: current reference
I_{SC}: current from the bidirectional converter to the DC bus
I_{in}: current at the input of the converter
I_{low}: current at the low voltage side of the bidirectional converter
I_{out}: current at the output of the converter
PV: photovoltaic
SC: super capacitor
SOC_{BAT}: battery state of charge
SOC_{SC}: state of charge of the super capacitor
V: voltage
V_{DC}: DC bus voltage
V_{SC}: super capacitor voltage
V_{high}: voltage at the high voltage side of the bidirectional converter
V_{in}: voltage at the input of the converter
V_{low}: voltage at the low voltage side of the bidirectional converter
V_{out}: voltage at the output of the converter