# Intelligent energy management based on multi-agent approach in a hybrid vehicle

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**Summary**

Among the areas of research and development which take a big importance in the field of electrical energy production are the fuel cells and supercapacitors. In this paper, we present a multi-agent structure for energy management in a hybrid electrical vehicle. Our simulation application is conceived and developed to share, in an intelligent and instantaneous way, the demand of the electric power between a PEM fuel cell (Proton Exchanges Membrane) and a pack of supercapacitors. In our hybrid configuration, the fuel cell is the primary energy source; but the pack of supercapacitors is used to answer the demands of the strong powers during the transient regimes. The obtained results show that the multi-agent approach can remedied certain problems bound to the centralized management of hybrid energy.

***Keywords:***

*Multi-agent system, AUML, Energy management, Distributed control, Hybrid electric vehicle, Supercapacitors, Fuel cell*

## 1. Introduction

The researches of appropriate, ecological and renewable energy sources have been accelerated by the air pollution bounded to exhaust gases from thermal vehicle motor [1], the increase of the energy use and the rarefaction of fossil fuels. To decrease the use of the fossil fuels, vehicles with hybrid and electric propulsion have been realized: motorization hybridization and/or energy sources hybridization [2][3].

Generally, a hybrid vehicle is fed with at least two sources of energy: the primary and auxiliary energy sources. The latest one is a reversible energy storage (a pressure battery, a module of supercapacitors, etc)[4][5].

In this paper, we use a hybrid vehicle system which is constituted of a pack of supercapacitors and a fuel cell (figure 1). This multi-source system allows feeding the engine under a continuous bus. The adaptation of the tension levels between sources and the bus is realized by using the static converters of power [6]. Using this structure allows a vehicle to get back and store a part of the kinetic energy. This energy is used to reload the supercapacitors which save the primary energy source in a hybrid propulsion vehicle. Otherwise the kinetic energy will be lost as heat during braking or deceleration.

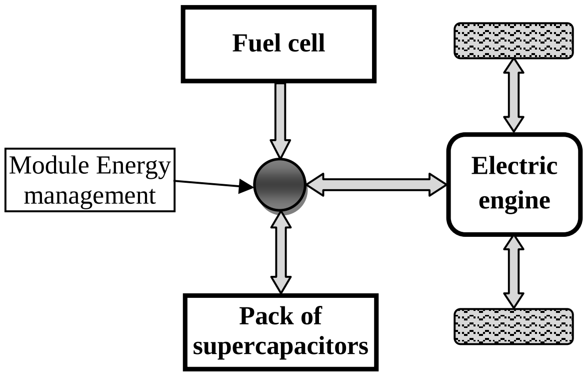


Figure 1: Structure of a hybrid vehicle

The present paper proposes new energy management architecture for a vehicle based multi-agent system. Our multi-agent structure consists in increasing vehicle fuel efficiency by managing intelligently the recovery of the braking energy and its reinjection in the traction system during the acceleration. Indeed, the simulator of energy management, leans on a multi-agent structure, allows distributing the tasks, the controls and the decision-making. The decentralized structure of this simulator optimizes the losses of energy while avoiding the degradation of the primary source. In addition, our multi-agent structure facilitates the change of configuration (addition or replacement of an element) and updating operations.

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## 2. The structure of energy management system

As we have already indicated, the electric vehicle studied is fed by two electrical energy sources: a fuel cell and a pack of supercapacitors. These two sources are connected to the continuous bus through two static converters DC-DC [7] (figure 2).

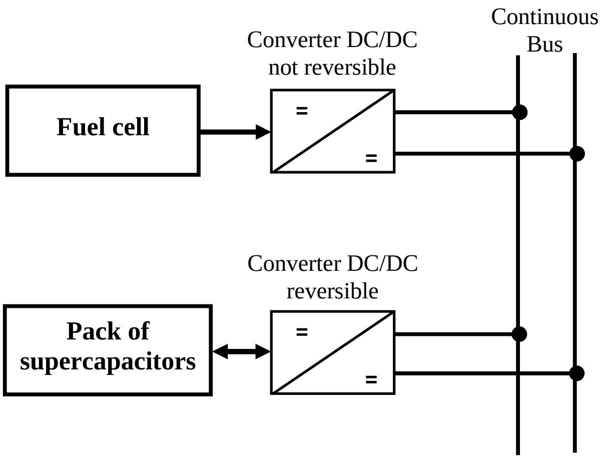


Figure 2: Supply system of the considered vehicle

### 2.1. Supercapacitor

The supercapacitor is a new component that was been the object of several researches and recent developments [8][9]. It resolves some problems related to the energy storage. The supercapacitors establish a new storage technology: a specific energy superior to the classic condensers and a specific power superior to the electrochemical accumulators (batteries). Generally, the supercapacitors are used to supply the power peaks of the energy distribution systems. Contrary to the batteries, the supercapacitors can store and restore their load with an excellent efficiency and during a very large number of charge-discharge cycles [10]. Thus, these components find their place in a several stationary and mobile industrial applications requiring energy storage (particularly in the transport field [6]) which is often reversible.

A supercapacitor is composed of two metallic collectors (usually aluminum), two porous carbon electrodes impregnated with electrolyte and a porous membrane (to assure the ionic conduction). Several models were proposed to describe its electric behavior [11]. The following figure shows the model of two branches improved by Belhachemi [9].

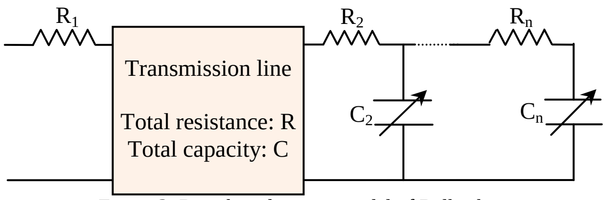


Figure 3: Distributed energy model of Belhachemi.

This model is composed of:
- A series resistance R1;
- A line of non-linear transmission for a fine description in short time,
- A few cells RC to apprehend the longest time.

### 2.2. Fuel cell

The fuel cell technology became increasingly familiar in recent decades. However, it was discovered more than 150 years ago [12].

Nowadays, the research on fuel cells is continued and successfully used in electric energy production for a wide variety of mobile and stationary applications. It converts the chemical energy (hydrogen and oxygen) directly in electrical energy [6]. This electrochemical reaction is the electrolysis of inverse water. The energy is produced when the air oxygen (oxidizer) chemically reacts with the hydrogen (reducer). The modeling of the fuel cell depends on the used equivalent circuit [13].

### 2.3. Static converters

The tension adaptation levels between energy sources (pack of supercapacitors and fuel cell) and load in the vehicle is realized by two static converters: Boost and Buck/Boost [6].

In the hybrid structure of the studied vehicle, the Boost converter is connected to the fuel cell. Generally, it allows raising the tension level of a continuous source as an alternative transformer. However, the converter Buck/Boost connected to the pack of supercapacitors is reversible. It works in boost mode when the pack of supercapacitors supplies the electrical energy on the continuous bus and in buck mode when the electrical energy is delivered to charge supercapacitors.

## 3. Energy management based multi-agent system

### 3.1. Multi-agent systems

The multi-agent approach is a subfield of the distributed artificial intelligence [14]. The multi-agent systems, set of agents interacting in a common environment to achieve their own goals, are particularly adapted to provide responsive and robust solutions to complex problems. This concept helps modeling system constituted by autonomous agents to act rationally. Multi-agent systems architecture is more suitable to simulate and solve problems for which centralized control is difficult or impossible. It possesses several advantages and benefits such as problem modeling, resolution speed, reliability, ease of maintenance and symbolic reasoning...

Generally, we distinguish two types of agents that correspond to different objectives: reagent agent and cognitive agent [15, 16].

Reagent agent: acts as a perception/action mode; i.e. when an event triggers in the system environment, the agent modifies its behavior through preconditions/actions rules. The preconditions correspond to different possible perceptions of the agent. This agent possesses only a partial perception of its environment and it is not capable to take into account its past actions.

Cognitive agent: defines behavior associated with environment changes. This agent possesses a set of explicit representations, described in a knowledge base, through which it can reasoning. Thus it makes its decision and reacts according to its knowledge, its goals and its information exchanges with the other agents. This agent can be endowed with reasoning and learning capacities allowing it to manage the unexpected situations and agents conflicts.

In a multi-agent system, the agents communicate between them to achieve the global objective. The communication is used for cooperation, coordination, negotiation and competition [17]. A communication can be defined as a form of local action of an agent towards other agents. The languages of communication between agents are generally based on the theory of the language acts. The number of languages is relatively large and somewhat homogeneous (KQML, ARCOL, KIF...). However, the FIPA (Foundation for Intelligent Physical Agents) tries to standardize the language concept by proposing the ACL (Agent Communication Language) [18].

## 3.2. Intelligent energy management

In our hybrid system (figure 2), the pack of supercapacitors is used in parallel with a fuel cell to provide the necessary power during the operating cycle NEDC (New European Driving Cycle) (figure 9). This structure consists of managing the demand of high powers during transitional regime (acceleration, deceleration and braking). The intelligent energy management allows to optimize the main source energy consumption and to ensure the good vehicle functioning. Thus, we chose the energy management based multi-agent system.

### 3.2.1. Proposed Multi-agent architecture

After the development and implementation of several architectures, we opted for the structure shown in figure 4. This structure allows intelligent distributing and sharing of electric power, required by the engine, through the two energy sources. Indeed, the developed simulator assures the energy optimization of the fuel cell and the supercapacitors pack state of charge.

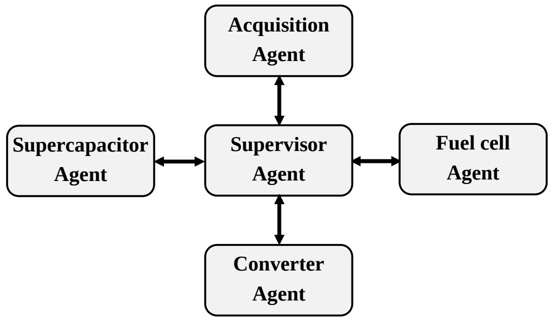


Figure 4: Multi-agent structure applied to the energy management

The star structure (figure 4) consists of five different types of agents: acquisition agent, supervisor agent, converter agent, supercapacitor agent and fuel cell agent. This architecture allowed us to reduce the communication time because the circulating information flow between agents is very important. The intelligent supervisor and supercapacitor agents are capable of learning and making the necessary decisions. However, the three other agents are of reagent agent type. According to its perceptions, they use a set of preconditions/actions rules to change its behavior.

### 3.2.2. Multi-agent architecture description

Even if the traffic of information is centralized at the level of the supervisor agent in our multi-agent structure, the control, the data, the treatments and decision making are totally distributed. Indeed, each agent keeps its autonomy of control and decision making. Furthermore it can communicate with the supervisor agent to request information or advice. In fact, the supervisor agent takes care to filter and forward the information flow within our system.

**Acquisition agent**

The acquisition agent is a reagent agent that is charged for the acquisition of different data (speed, powers and tensions). In our developed simulation, this agent gets back periodically data from text files (step=20 ms), then communicates the acquired values to the supervisor agent.

**Supervisor agent**

The supervisor agent takes charge and process the important part of data and information. It retrieves different values from each received new message of the acquisition agent (vehicle speed, power demanded, current and tension of the supercapacitors pack ...). By identifying the speed of the vehicle, this agent determines its functioning nature (constant speed, acceleration, deceleration, braking or stopping). This operation is done by comparing the new speed value with the previous ones which are hierarchy organized within the agent.

In addition, the supervisor agent sends functioning nature to the converter agent and at the same time two other messages to the supercapacitor and fuel cell agents. The message sent to the fuel cell agent is a request to supply the energy by specifying the demanded power. While the message sent to the supercapacitor agent may be a request to supply energy in the case of acceleration or a recovery request during the braking or deceleration.

The supervisor agent implements certain equations allowing it to determine instantly the power to be supplied by the fuel cell.

**Supercapacitor agent**

The supercapacitor agent is effectively designed to manage the energy stored in the supercapacitors pack. In the reception of a new message from the supervisor agent asking to supplying energy, the supercapacitor agent compares its current load with the minimum threshold (25 %) for a possible delivery of power. In case of failure, a response message is sent to the supervisor agent to take necessary decisions.

On the other hand, if the received message concerns the recovery of the energy during a braking or deceleration, this agent compares its load with the maximum threshold (95 %) and decides whether he can recover it or not. When the supercapacitors pack is loaded, it asks the supervisor agent to transform the kinetic energy into heat which will be loosened in the nature.

In certain cases, if the supercapacitors pack is not loaded after recovering the braking energy, the supercapacitor agent asks the supervisor agent to continue loading from the primary source.

Among the equations implemented in the supercapacitor agent, the following formula can instantly calculate its state of charge state (SOC):

$$SOC = \frac{E_{\max} - E}{E_{\max}} \qquad (1)$$

The energy (E) contained in the supercapacitors is expressed in terms of the Open-circuit voltage V and capacity C:

$$E = \frac{1}{2} \times C \times V^2 \qquad (2)$$

The maximum energy $E_{max}$ correspond to maximum Open-circuit voltage $V_{max}$ is given by:

$$E_{\max} = \frac{1}{2} \times C \times V_{\max}^2 \qquad (3)$$

**Converter agent**

The converter agent assures the management and the command of the three static converters DC/DC according to messages received from the supervisor agent.

This agent receives messages from the supervisor agent: one containing the functioning nature of the vehicle and another contains the powers to be supplied by both energy sources. In the ideal case, after receiving and processing these messages and starts the execution of requests to command the static converters. A response is sent to the supervisor agent in order to communicate this information to the supercapacitor and fuel cell agents.

The converter agent communicates the states of converters to an HMI (Human Machine Interface) object in order to visualize it on screen.

**Fuel cell agent**

Takes charge of fuel cell source energy management. This agent communicates with the supervisor agent to answer the energy demands during the both functioning regimes: permanent and transient. Indeed, the fuel cell supplies energy in the case of acceleration or when the speed is constant. Moreover, in some stop cases, it can continue supplying the necessary energy to reload the supercapacitors.

## 3.3. Multi-agent architecture modeling

To model the proposed multi-agent structure, we used the AUML language [19] which is an extension of UML language [20]. Generally, AUML is reserved to analysis and conception oriented agent.

The AUML language is a technology that adopts standard abstract syntax, meta-model and semantics for analysis and conception of methodologies based agents [21]. Indeed, this language allows representing several abstraction levels during the conception of class diagrams (system static view). The most used abstract levels are: the conceptual level and implementation level. The conceptual level is an abstract representation which indicates only the names of the agents (figure5). Though, the implementation level (figure 6) allows representing the details of the agents by indicating its attributes, its operations and its behaviors … [22].

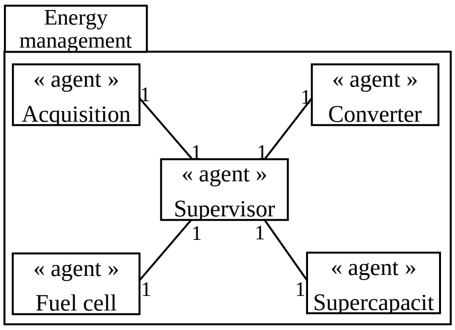


Figure 5: Class diagram: conceptual level

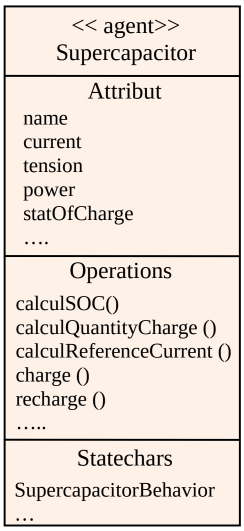


Figure 6: Implementation level of the supercapacitor agent

To model the agents behaviors, we used the state-transition AUML diagrams which are the most adapted to describe the agents behaviors. Those diagrams take into account the competitive aspect of its activities [23] (figure7). Indeed, each agent changes its behavior from a state to another according to the interactions produced between system agents and time transitions constraints [24].

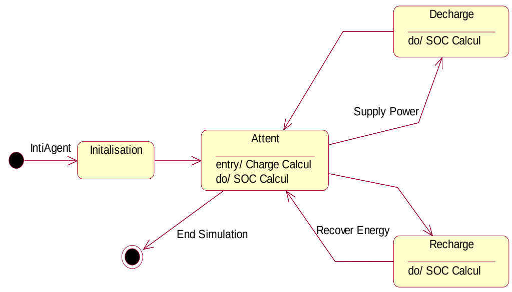


Figure 7: State-chart diagram of the Supercapacitor agent

On the other hand, to represent interactions and communications between our different system agents, we used the AUML interaction diagrams: sequence diagrams (called protocols diagrams) and collaboration diagrams [25]. The figure 8 illustrates the sequence diagram of the nominal scenario in acceleration case.

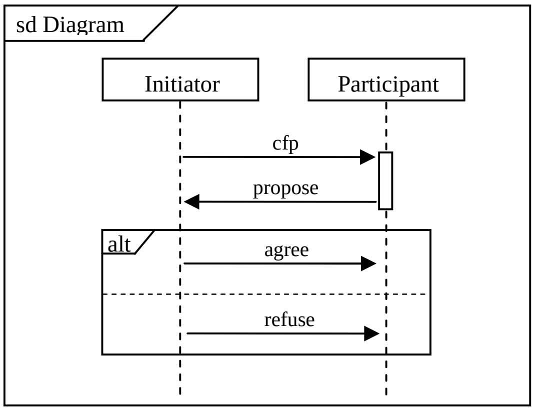


Figure 8: Example of AUML sequence diagram

## 4. Results

### 4.1. Implementation

To implement our architecture, we chose the JADE platform (Java Agent Development Framework) [26,27]. This platform is reserved for the development of the distributed multi-agents applications based on a peer to peer communication system. It includes two basic components: a set of agents FIPA compatible and a software package to create the agents using Java language.

The JADE tool possesses three main modules:

- DF «director facilitor»: supplies a yellow pages service in the platform.
- ACC «agent communication chanel»: manages the communication between the agents.
- AMS «agent management system»: controls and supervises the agents recording, its authentication, its access and uses of the system.

The communication between agents is based on sending/reception messages. The communication language is the FIPA-ACL. Each FIPA-ACL message includes several elements [28]:

- performative: communicative acts which may be primitive or compound (information demand or transmission, action completion...).
- content: message content.
- sender: sender message identification.
- receiver: recipient message identification.
- …

## 4.2. Simulation results and interpretation

The development of the conceived classes (figure 5) and the setting of the communication messages parameter between different agents, gave us the possibility of sharing intelligently the request of the power between the supercapacitor and fuel cell agents. These two agents are respectively associated to the energy sources (supercapacitors pack and fuel cell).

In fact, we calculate the state of charge (SOC) of the supercapacitors pack, during acceleration, deceleration and braking phases, to verify if this energy source is capable of continuing to supply power or to be reloaded. The figure 10 illustrates the state of charge variation of the supercapacitors pack during the functioning cycle NEDC (figure 9).

The graphic interface, associated to the supercapacitor agent, represent the supercapacitors pack supplied energy with positive values and the supercapacitors pack recovery energy with negative values on diagram (figure 12) during NEDC cycle. The supercapacitors pack supplies the energy during the accelerations and recovery it during the braking and the decelerations.

The fuel cell supplies the energy in case of acceleration and constant speed. In certain cases, this source can supply the necessary energy to reload supercapacitors. The curve of figure 11 illustrates the power supplied by the fuel cell.

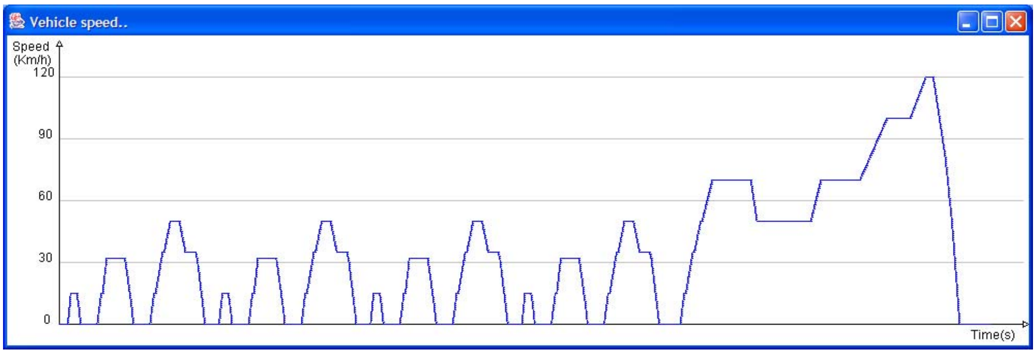


Figure 9: NEDC cycle – Vehicle speed vs. time

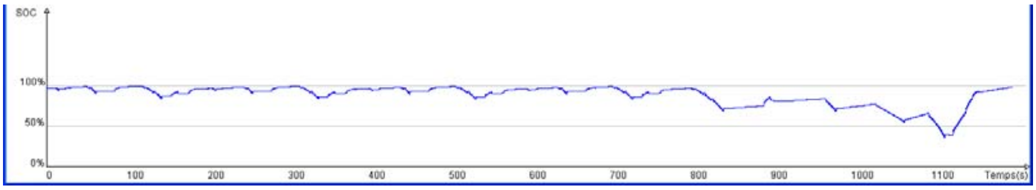


Figure 10: Supercapacitors pack state of charge.

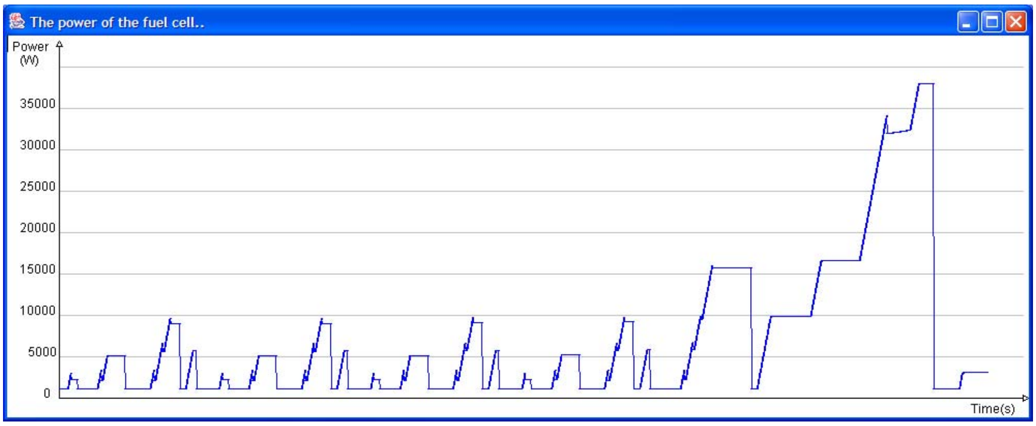


Figure 11: Supplied power by fuel cell

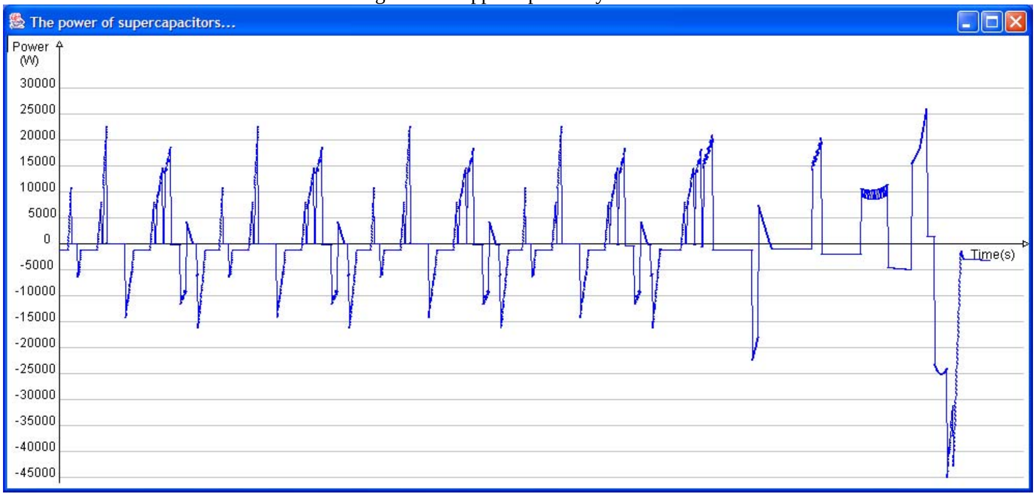


Figure 12: Power variation of supercapacitors pack

During the acceleration phases (figure 9), we notice that the supercapacitors pack and fuel cell participate together for supplying the required power (figures 11 and 12). At the same time, the supercapacitors state of charge (figure 10) decreases which means that the supercapacitors are beginning to discharge. During the acceleration phases, we also notice that the power supplied by the fuel cell increases which confirms that the supercapacitors are used to answer the high power demands.

When the speed becomes constant (permanent regime) the fuel cell continued to supply the needed energy. However, according to the SOC, the supercapacitors start to be charged in order to supply the power during a possible acceleration. In certain phases of stop (zero speed), we notice that the fuel cell provides the necessary power to reload the supercapacitors.

Generally, we notice that the supercapacitors are loaded during the decelerations phases, however the power supplied by the fuel cell is decreased. This confirms the power optimization of the main energy source due to the auxiliary source loading with the recovery energy. At the end of the functioning cycle the supercapacitors are completely reloaded and return to their initial state (figure 10).

## Conclusion and perspective

This article proposes the application of a multi-agent architecture to manage power in a hybrid vehicle during the normal functioning cycle NEDC. This proactive new structure should help in the collaborative decision-making and intelligent energy management. In addition, our approach gives us the ability to instantly know all the information concerning drive chain elements. In this architecture, each agent manages a specific type of knowledge (speed, current, tension, state of charge, power ...). Through the interactions between different agents in the system, our approach is capable of managing new situations using different learning techniques.

The purpose of our strategic energy management is to share the power demand between the fuel cell and supercapacitors pack. Thus, we conceived and developed a simulator that allowed us to implement an intelligent energy management system in a hybrid vehicle based on a multi-agents approach. The simulator enabled us to ensure the satisfaction of the global power request at the level of continuous bus, while optimizing the consumption of stored energy. The objective of our future works, on one hand, is to make this application generic and operational for any functioning cycle. On the other hand, to control and improve the reliability of the hybrid system by taking into account other factors such as vibration and temperature [29].

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