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MODELING AND IMPLEMENTATION OF A MULTI-AGENT ARCHITECTURE FOR INTELLIGENT ENERGY MANAGEMENT IN AN ELECTRIC VEHICLE

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ABSTRACT

Hybrid vehicles and energy management is now a fertile area of research and development. The aim of this paper is to contribute to the tools development for energy management and collaborative decision-making in hybrid electrical vehicles. We propose a multi-agent system for intelligent energy management. To test the designed and developed system, we have used a vehicle powered by a hydrogen fuel cell and a pack of supercapacitors. This system is based on the state of charge of supercapacitors to share optimally and instantaneously the power demand between these sources. Thus, the system's role is to improve the vehicle autonomy and longevity of the components of its supply system.

Keywords: *Multi-Agent System, Language AUML, JADE, Intelligent Energy Management, Hybrid Electric Vehicle, Super Capacitors, Fuel Cell.*

1. INTRODUCTION

Environmental concerns, depletion of fossil resources and the growing energy needs are behind the continuous development of means of transport [1]. In this issue, integrates hybrid vehicles including hybrid electrical vehicles constituting an intermediate step towards an "all electric".

Hybrid vehicles with fuel cell combine on the one hand a fuel cell to produce electricity board and the other hand an element of storage of electrical energy [2]. These vehicles have the advantages of electric cars on a particular zero emissions and total independence from oil and on the other the benefit of a conventional vehicle to find a better autonomy.

In this work, the vehicle in question is powered by an electric motor. Its power system consists of fuel cell PEM hydrogen [3][4] as the main source of energy, and a pack of supercapacitors as an auxiliary source [5][6]. This system feeds the engine under a continuous bus. The adaptation of voltage levels between these sources and the continuous bus is achieved using static converters DC-DC [7] (Fig. 1).

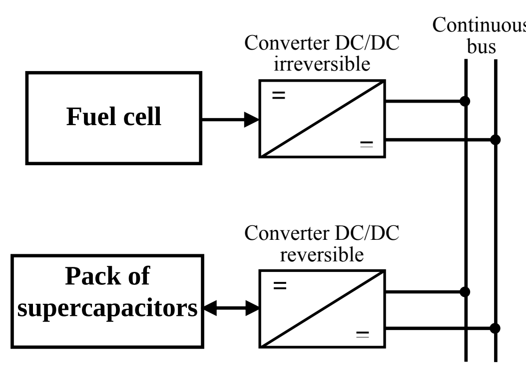

Fig. 1 Supply system of the considered vehicle

In this type of vehicle, the power source is hybrid and motorization is fully electric. Energy sources are arranged in parallel to ensure the necessary propulsive power. The auxiliary energy source plays the following roles [8] [9]:

- Assist the fuel cell power: the supercapacitors module provides power during peak high power

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(acceleration) or when the fuel cell reaches its maximum power.

- Kinetic energy recovery: the recovery of kinetic energy during braking phases and deceleration can increase the vehicle autonomy.
- Introduce a degree of freedom in the distribution of powers: the hybridization is to distribute the power demand between the fuel cell and supercapacitors. By using appropriate control strategies, it can maximize the use of hydrogen.

We propose in this paper a new architecture of intelligent energy management in a hybrid electrical vehicle based agents. The proposed architecture is an improved variant of what is presented in a previous paper [10]. Indeed, the new multi-agent structure has the following advantages:

- The decision making is rapid and collaborative: the developed structure enables the decentralization of data handling division. Each agent controls a system component and collaborates with agents to direct the behavior of the system entirely.
- Adaptability: the system-based agent functions according to a predefined cycle, but it can override this cycle by adapting to real operating conditions.
- The control of the designer: it can follow, at any time, the status of each component via its agent. So, component reliability can be assured at all times. In addition, our system owns like other advantages flexibility and ease of maintenance.
-

2. PRINCIPLE OF SYSTEM POWER MANAGEMENT

Energy management simulator, we have developed, enables control of static converters binding energy sources (a pack of supercapacitors and fuel cell PEM) with the load (charge). Our system main inputs are the vehicle speed, current and voltage of the supercapacitors. The role of this system is the determination of the reference current of the two energy sources during the functioning regimes: transient and permanent. The following diagram described the conceived control structure (Fig. 2) [11].

The role of the developed energy management system is to control the converters, in an intelligent manner, during the standard operating cycle NEDC (New European Driving Cycle). Indeed, it allows share the high powers demand during the acceleration and recharge the supercapacitors during braking and/or deceleration.

3. ENERGY MANAGEMENT ARCHITECTURE: MULTI-AGENT APPROACH

3.1. Multi-agent system

The multi-agent systems have several advantages and benefits such as problems modularity, resolution speed, reliability, maintenance ease and symbolic reasoning [12]. These systems can be classified according to several criteria such as number of agents, types of communication, the representation of the environment and other agents, the capacity for cooperation and learning agents, etc [13]. Thus, we have chosen to develop our approach to agent simulator so as to improve energy management performance, such as decisions and accelerating treatments and controls.

The agents communicate with each other in order to achieve the universal objective. In a multi-agent system, we distinguish between two communication modes [14]: Indirect communication via the environment and direct communication through sending a message. The languages of communication between agents are generally based on the theory of speech acts. The foundation FIPA (Foundation for Intelligent Physical Agents) [15] however, attempts to standardize the notion of language by proposing the ACL (Agent Communication Language) [16].

3.2. Proposed multi-agent architecture

We introduce in this part of the multi-agent proposed structure for the energy management in the vehicle under investigation (Fig. 1).

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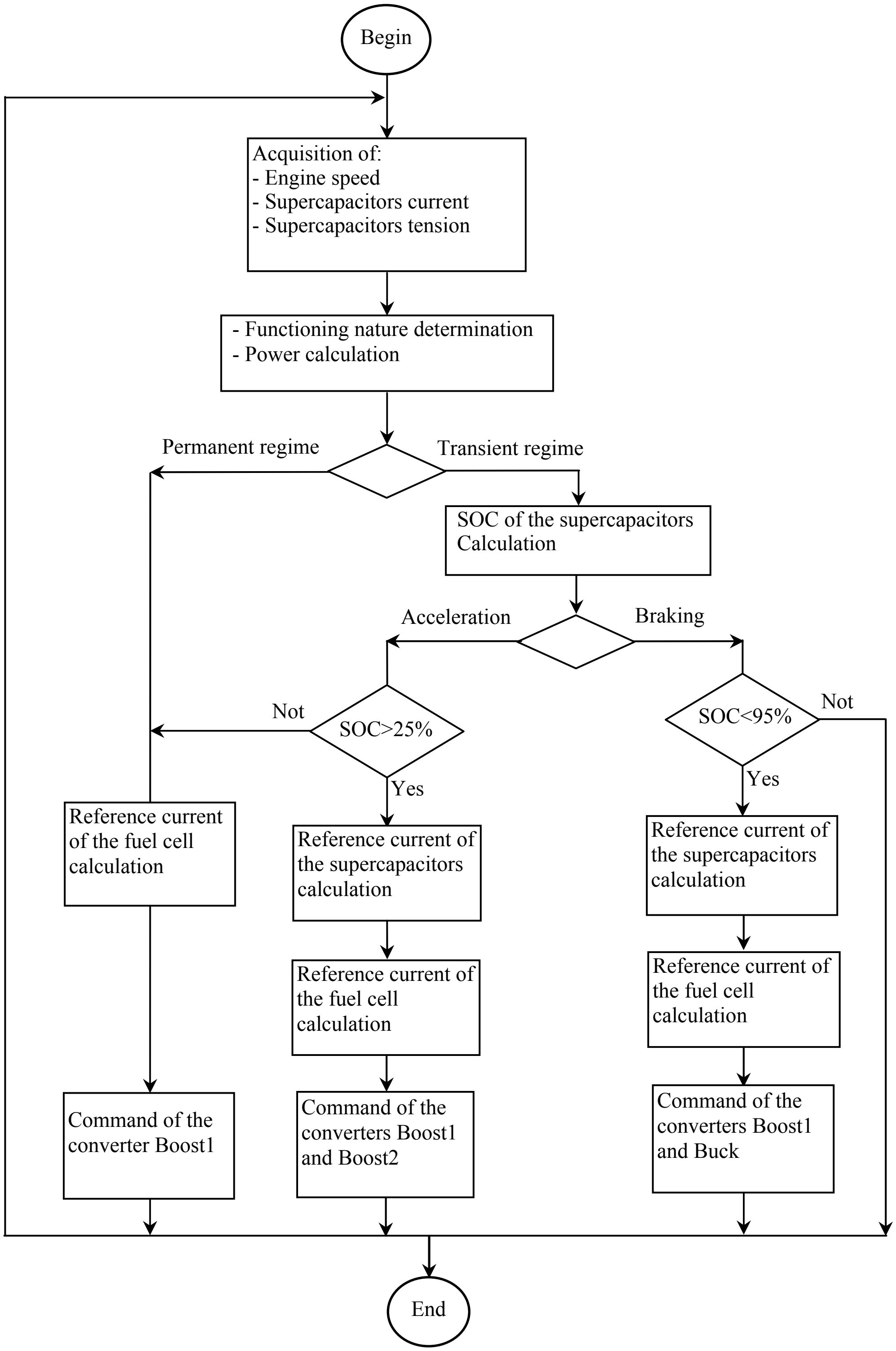

Figure 2: Diagram of energy management

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Our architecture power management, agent-based, allows optimum energy management during the standard cycle NEDC. It shares an intelligent demand of electric power through the two energy sources, while ensuring both the good functioning of vehicle and optimization of energy consumption of the fuel cell. Figure 3 presents the proposed architecture [11].

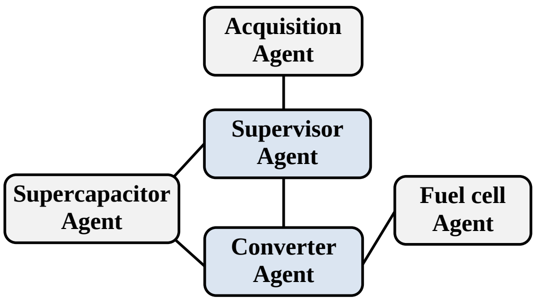

Figure 3: Proposed multi-agent structure

It is a hierarchical structure composed of five agents: an acquisition agent, a supervisor agent, converter agent, a supercapacitor agent and a fuel cell agent. The system agents retain their autonomy and control over decision they can communicate to achieve the global objective. The supervisor agent and the converter agent are cognitive. These two agents can make learning and take the necessary decisions. Other agents are reactive and simple. Each reactive agent is based on a set of rules preconditions/actions type which allow to modify its behavior based on their perceptions.

3.3. Description of architecture

Acquisition agent: allows acquisition of system data that is: vehicle speed, voltage and current of supercapacitors module. In the application of developed simulation, the acquisition agent periodically collects data from text files, and then it communicates the values acquired to the supervisor agent of system.

Supervisor agent: Upon receiving a new message from the acquisition agent, the supervisor agent retrieves different sent values: vehicle speed, current and voltage supercapacitors.

To determine the nature of operation (constant speed, acceleration, braking or deceleration), this agent compares the received new speed with the previous one. Different speed values are stored in a linked list. The agent allows also complete the unadjusted or poorly received data.

The supervisor agent calculates the power required from the speed using the mechanical characteristics of the vehicle (Formula 1) [17].

$$P_{ch} = 1.33\left[\frac{1}{2}\rho_{air}V_t^2SC_x + MgC_r + M\frac{dV_t}{dt}\right]V_t \quad (1)$$

- M: the vehicle mass;
- Vt: the vehicle speed;
- S: the frontal vehicle surface;
- Cx: the penetration coefficient in the air;
- ρair: the air density;
- Cr: the coefficient of vehicle movement;
- g: the acceleration due to the gravity;

After determining the nature of the operation, the power load and the total current, the supervisor agent sends a message to the converter agent whose content is the power, mode of operation and the total current. In parallel, another message containing operation mode, the voltage and current of supercapacitors is sent to the supercapacitor agent.

Converter agent: provides command and control of static converters. This agent receives a message from the supervisor agent containing the nature of functioning, power and total current. According to the content of this message, the converter agent sends two messages one to the supercapacitor agent and the other to the fuel cell agent to provide or not provide the necessary energy. For example in the case of acceleration, the converter agent sends a message to the supercapacitor agent asking him to provide energy with power precision (the reference current) applied, in parallel it sends another message to the fuel cell agent so as to ask him to continue also to provide energy.

To calculate the reference current to be supplied by the supercapacitor, this agent implements certain equations.

Example: the equation 2 is used to calculate without constraints the reference current to provide by super capacitors.

$$I_{SC_{ref}} = \frac{Q_{sc}}{C_{sc}}\sqrt{\left(\frac{Q_{sc}}{C_{sc}}\right)^2 - 3{,}8\left(P_{ch} - P_{fc_{\max}}\right)R_{sc}} \quad (2)$$

With: Q_{sc}, C_{sc} and R_{sc} are respectively the charge quantity, the supercapacitors capacity and resistance. P_{fcmax}: the maximal power of the fuel cell.

In order to control the static converters binding the two sources of energy in continuous bus, the

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converter agent uses other formula to determine the reference current to be supplied by the fuel cell. States converters are provided to a HCI object for viewing on screen.

Converter Agent uses the HCI objects to display on screen the powers and the reference currents of the two energy sources.

Supercapacitor agent: manages power supercapacitors. The model of the pack of supercapacitors used is that of Zubieta (Fig. 4) [17].

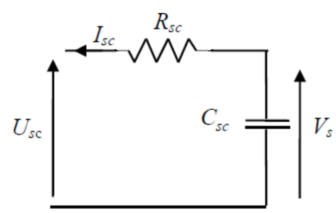

Figure 4: Model used of the supercapacitors

Upon receiving a new message from the supervisor agent, the Supercapacitor agent calculates the quantity of charging of supercapacitors, by implementing the following formula:

Then, this agent calculates the state of charge (SOC) of supercapacitors through the implementation of the following formula:

$$SOC = \frac{E_{max} - E}{E_{max}} \qquad (3)$$

After receiving a message asking to provide energy for the benefit of the agent converter, Supercapacitor agent compares the current load with the minimum 25% (SOC> 25%) for a possible power delivery. In case of failure, a response message is sent to the converter agent to take the adequate decisions. On the other hand, if the received message relates to the recovery of energy during braking or deceleration, this agent compared with the SOC calculated maximum threshold (95%) and decides if he can recover it or not. In case the supercapacitors pack is loaded, it requests the supervisor agent to transform kinetic energy into heat which will be subsequently released into the air. In some cases, if the pack of supercapacitors is not loaded, after recovering the braking energy, the agent asks the agent supercapacitor converter to continue to load from the fuel cell.

Fuel cell agent: this agent communicates only with the converter agent in order to meet energy demands during the two operating modes: permanent and transient. The fuel cell provides the energy in the case of acceleration or if the speed is constant. In addition, in some cases of stopping, it can continue to provide the energy needed to recharge the supercapacitors.

4. ARCHITECTURE MODELING

We have used the language Agent-UML (AUML) to model proposed multi-agent structure. AUML is an extension of UML including the agent specifications [18][19]. This language, graphical modeling, is to analyze and design systems oriented agents. Indeed, AUML offers several types of representations describing the system and its components until interactions [20][21].

AUML language enables to represent several levels of abstraction in the design class diagrams (static view of system) [22]. Levels of abstraction commonly used are: the conceptual level and implementation level. The conceptual level is the abstract representation that indicates only the names of agents (Fig. 5). While the implementation level (Fig. 6) gives in detail the contents of the agents, indicating all the information necessary to understand the system structure: attributes, operations, roles, behaviors...

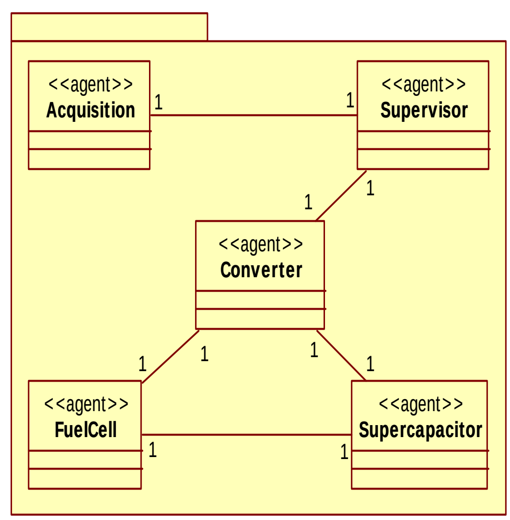

Figure 5: Class diagram: conceptual level

Figure 6 shows the class diagram of the Supercapacitor agent:

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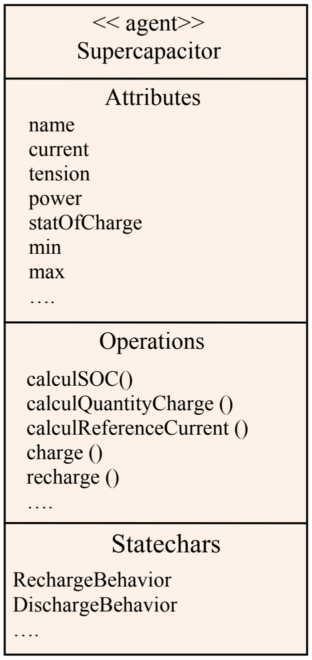

Figure 6: Implementation level of the Supercapacitor agent

Interactions and communication protocols between agents must be well studied. Thus, we chose to use AUML interaction diagrams (also known as sequence diagrams or protocols) [19][20][23] to represent the interactions and communications between the various agents in our system. Figure 7 shows the AUML sequence diagram representing interactions between agents in our system during acceleration. The diagram shows the messages exchanged between agents to provide the required power while taking into account the cases/states of energy sources.

To model the behavior of agents, we have used the state-chart diagrams AUML [24] that seem most appropriate to describe the behavior of agents. This type of diagram allows taking into account the competitive aspect of their activities (Fig. 8) [25]. The agents move from one state to another based on actions occurring in the environment or to the messages received. Each agent changes its behavior from one state to another and this, according to the interactions produced between the system agents or as a function of time response constraints associated with transitions.

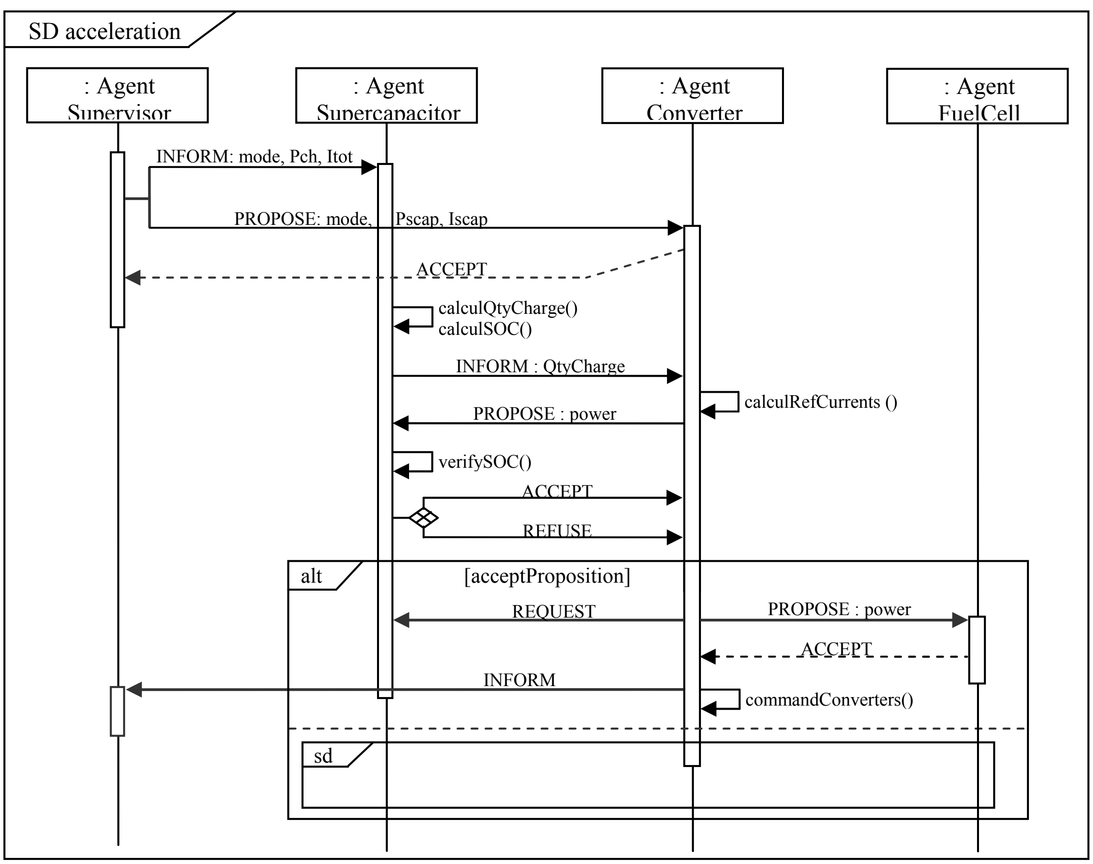

Figure 7: AUML sequence diagram for the case of acceleration

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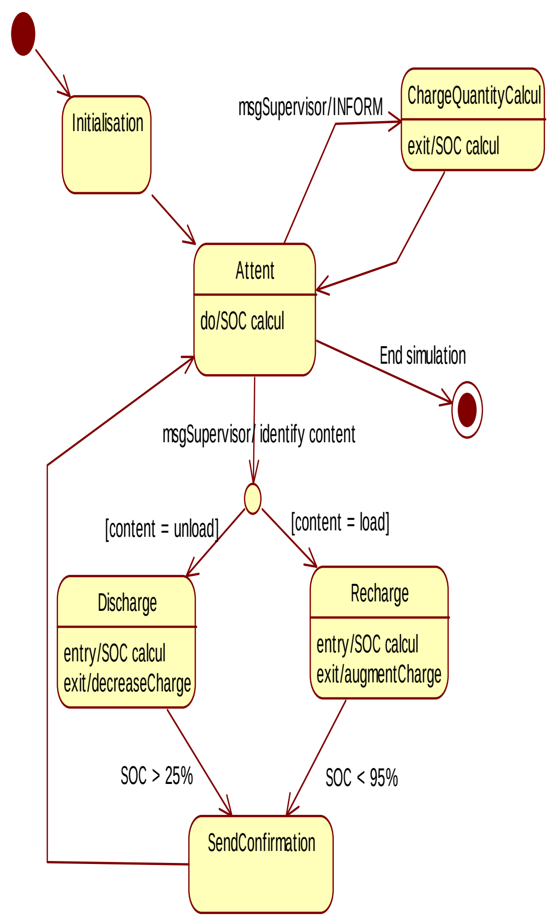

Figure 8: State-chart diagram of the Supercapacitor agent

5. IMPLEMENTATION AND RESULTS

We chose the platform JADE (Java Agent Development Framework) [26] to implement our architecture. This platform is dedicated to the development of multi-agent systems, it provides two basic components: a basic set of agents and a FIPA compliant software package to the development agents in Java.

The interaction and coordination of actions between agents are based on sending / receiving messages asynchronously. The language used for communication is language FIPA-ACL. Each FIPA-ACL message consists of several elements (performative, content, sender, receiver ...) [27].

5.1. Simulation and results

The system we have designed and developed based on the state of charge supercapacitors to make the right decisions. Supercapacitors are charged during the phases of deceleration/braking until the state of charge (SOC) reaches 95%. During phases of acceleration, the supercapacitors continue to provide the power required until the SOC reaches 25%. By working within this range of use, permit the boost of the longevity of these modules by increasing the number of charge/discharge cycles.

To test our simulation system, we used a speed profile that matches the operating cycle NEDC (New European Driving Cycle). The final time of operation is 1200 seconds and the maximum speed is 100 km/h (Fig. 9).

As indicated above, the system calculates the current and power required from the speed profile followed by the vehicle studied based on its mechanical characteristics. We represent in figure 10 the result of calculating the total current by the supervisor agent for the cycle of operation considered.

The state of charge of the pack of supercapacitors, calculated by the supercapacitor agent, allows verifying the ability of supercapacitors to provide power during the acceleration phase, or to recover it for the other phases. Figure 11 illustrates the variety state of charge of supercapacitors during the operating cycle NEDC.

The GUI (Fig. 12) associated with the Supercapacitor agent represents, as a diagram, the reference current of supercapacitors that optimizes the power supplied by the fuel cell. Positive values mean the current supplied and negative ones represent the collected current by the pack of supercapacitors.

Figure 13 shows the curve of the reference current of the fuel cell during the functioning cycle.

Converter Agent visualizes various calculated power in a graphical interface. Figure 14 shows the power of the load in green, the power delivered or picked up by the pack of supercapacitors in blue and in red the power supplied by the fuel cell.

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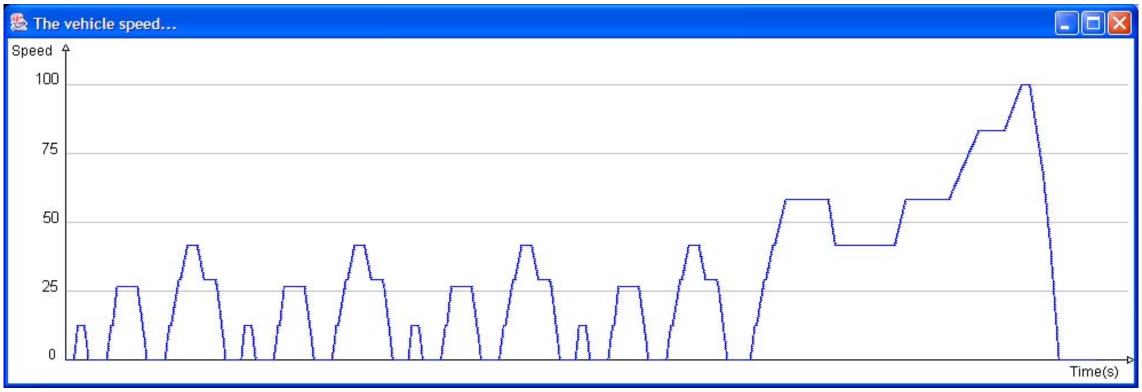

Figure 9: Cycle NEDC - Vehicle speed vs. time

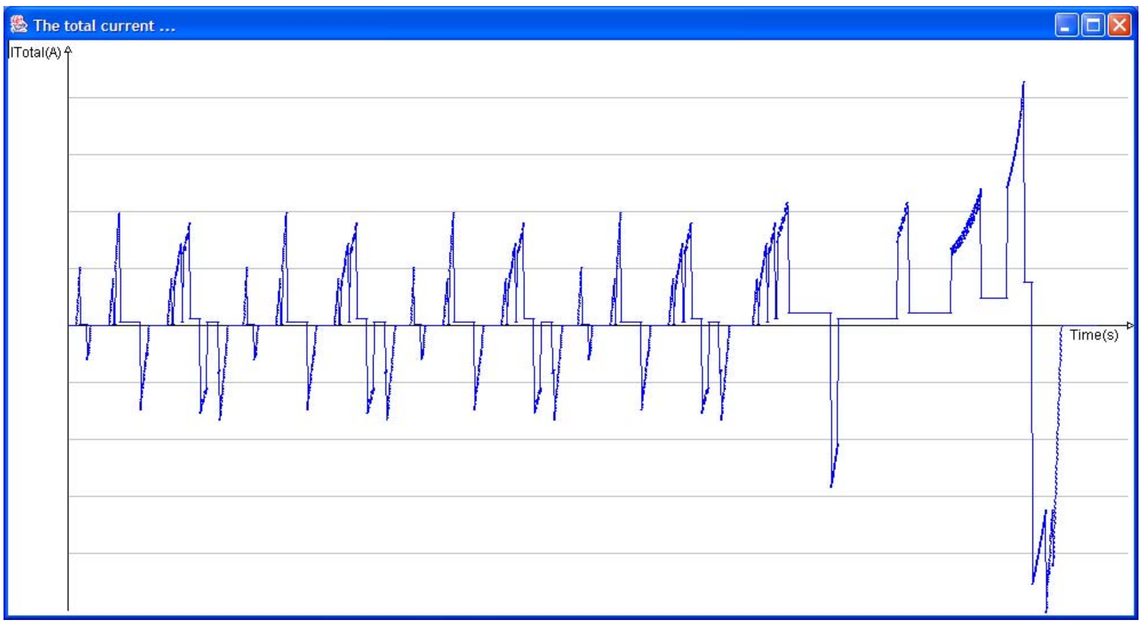

Figure 10: the total current of the continuous bus

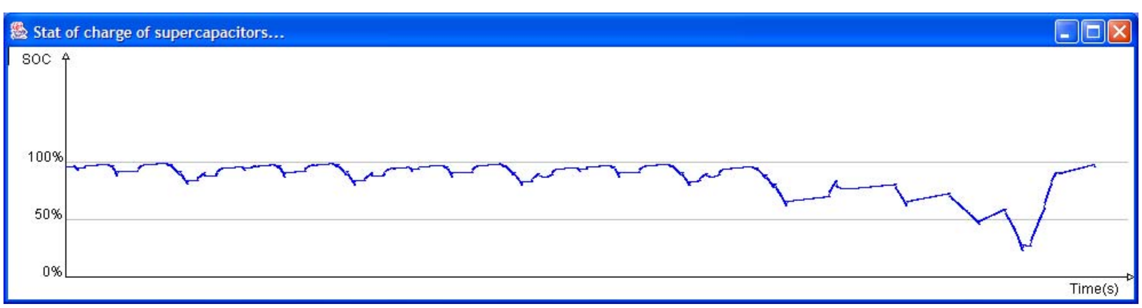

Figure 11: state of charge of the pack of supercapacitors

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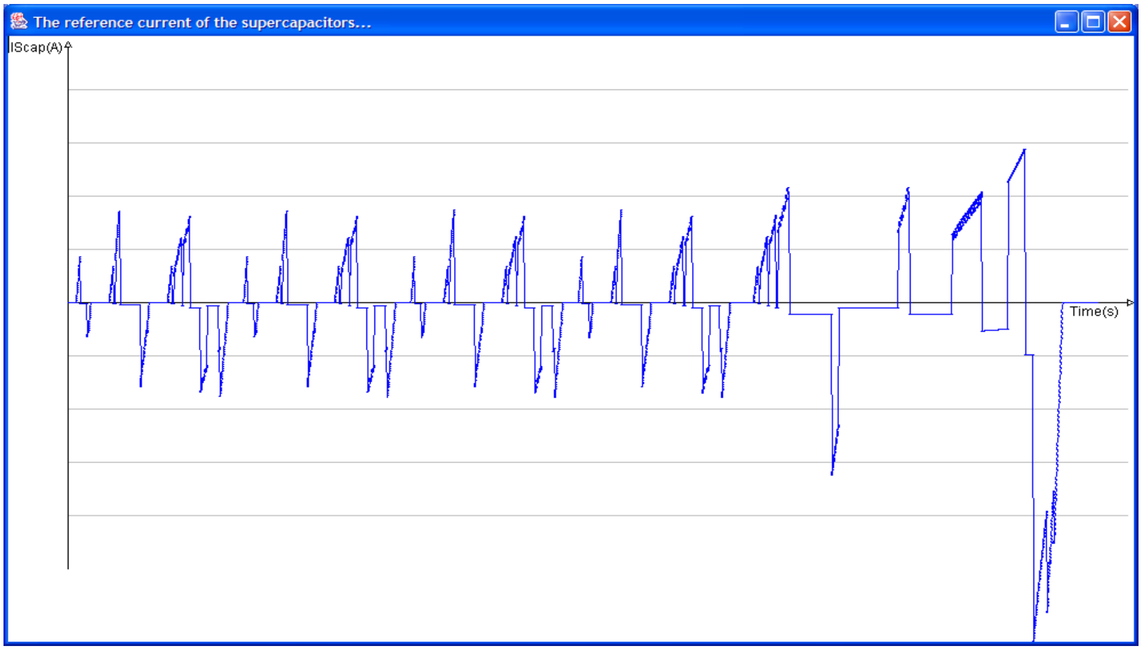

Figure 12: The reference current of the pack of supercapacitors

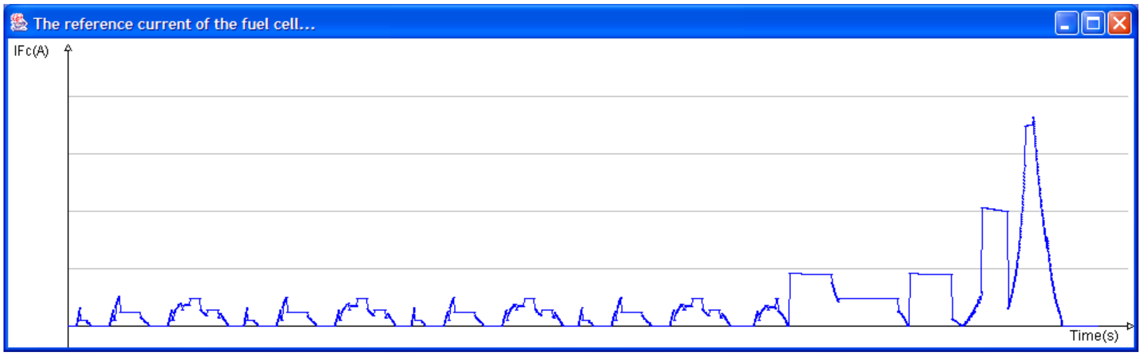

Figure 13: the reference current of the fuel cell

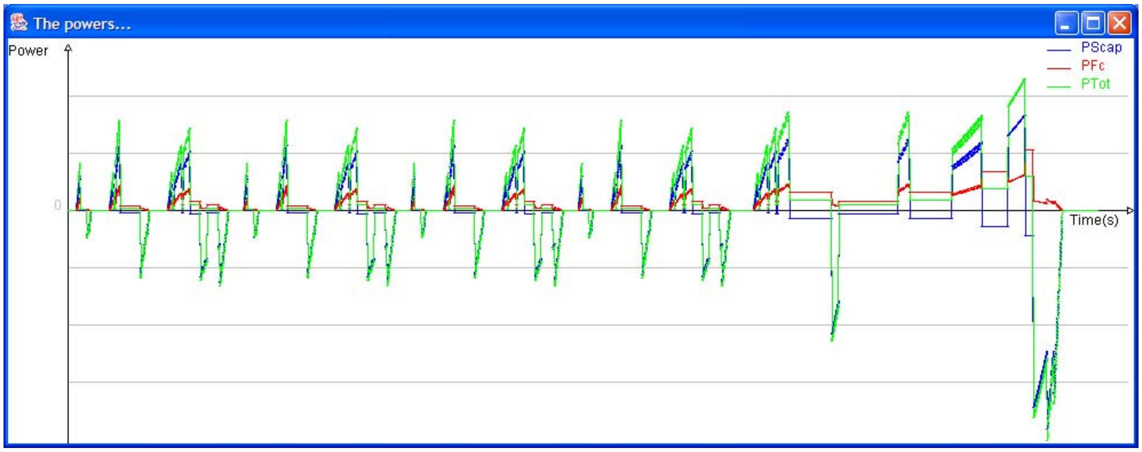

Figure 14: variation of the powers

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5.2. Discussion

It is observed during acceleration (Fig. 9) that the total current of the continuous bus increases (Fig. 10). Meanwhile, the reference current of supercapacitors also increases (Fig. 12), which means they are involved in providing power during transients. During the phases of accelerations, we also note that the reference current of the fuel cell increases (Fig. 13) which confirms that the supercapacitors are used solely to meet the demands of high power.

When the speed becomes constant (permanent state), the fuel cell continues to provide energy, however, and according to the state of charge, supercapacitors are starting to charge to be able to provide power during possible acceleration. During certain stop phases (zero speed), we see that the fuel cell provided the power needed to recharge the supercapacitors.

It is seen that supercapacitors recharge well (negative current) during phases of deceleration, while the reference current of the fuel cell decreases. This confirms that the optimization of the power of the main source of energy is due to the loading of the auxiliary source by the recovered energy.

At the end of the operating cycle, we note that supercapacitors recharge completely and return to their initial state (Fig. 11).

6. CONCLUSION

This paper proposes the application of a multi-agent architecture for intelligent management of electrical energy in a hybrid vehicle. The system structure is composed of different types of agents; each is responsible for managing a specific type of knowledge. The system agents can use different techniques to manage new situations.

The operating principle of the system is to take into account three variables: the vehicle speed, current and voltage of the pack of supercapacitors. Thus, this system controls the two power sources in an intelligent way to meet power demand. It reacts instantly and adequately to changes in speed according to the operation cycle NEDC: it shares the power demand between the two energy sources while respecting the energy characteristics of each.

The results obtained by simulation are very promising. Thus, later we will intentionally develop, the experimental system designed to validate the algorithm for power management and multi-agent structure, to develop a testing ground (prototype). However, the estimated success of our simulation requires a comparison of results obtained by other methods of power management using the same hardware.

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