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# Energy Management Algorithm of Fuel Cell/Supercapacitor System with a Floating Interleaved for Electrical Vehicle

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**Abstract**— The main objective of this work is to apply a method of energy management between two sources and a load using two interleaved floating DC/DC converters dedicated to vehicular applications; the first is a two-way converter, the second is a one-way converter. These two converters are combined to interface the hybrid power which consists of a fuel cell as the main source for the vehicle and a storage system (supercapacitor) as a secondary source.

This article provides a modelling of the two proposed DC-DC converters as well as a control strategy for each of them.

However, the studied system being powered by two sources, it is essential to apply an energy management algorithm which must ensure the distribution of the energy flows between the sources and the load in order to satisfy the required power. A rule based algorithm is applied as well to generate source power references considering state-of-charge limitation to avoid overcharging and deep discharging in order to decrease the lifetime of the supercapacitor.

To evaluate the performance of the studied converters, simulation results of the hybrid system with the energy management algorithm are presented.

## I. INTRODUCTION

In recent years the number of cars has shown a very significant increase which leads to a huge growth in the consumption of fossil fuels, thus, stimulating environmental pollution on a larger scale.

For these reasons, the demand for vehicles that provide more or less fuel economy and less polluting solutions has increased. The use of clean and renewable energies in electrical systems becomes a necessity. Fuel cell (FC) can be considered, so, as a good solution which allows to reduce gases emissions, and consequently, environment pollution. We talk so about Fuel cell electric vehicle (FCEV) which is an electric vehicle. For a FC hybrid vehicle, it uses, in addition to the fuel cell, a secondary source of electrical energy which is reversible in power as storage systems (Super-capacitors and Batteries) [1].

In order to satisfy the FCEV requirements in terms of step-up ratio, FC current ripple and fault tolerance [1] Li [2] and

Pang [3], the traditional boost converter is not a good solution because the converter with single switch has no fault tolerance and the voltage gain is limited. Compared to this topology, the Floating Interleaved Boost Converter (FIBC) is particularly suitable for fuel cell applications, due to the interleaving architecture of this topology that allows the converter to operate without any interruption in presence of open circuit fault (OCFs) occurred on one or two switches and the respective shift between the phases that allows reducing the input current ripple [4] [5]. Furthermore, Ref [5,6] has demonstrated that the 4phase FIBC is the best selection through discussing between the 2-phase, 4-phase and 6-phase FIBC from the different aspects (e.g. the input current ripple, efficiency, the volume of the inductors and fault tolerance).

It is to mention, also, that for a hybrid vehicle which is powered by more than one source, a method of energy management between sources is necessary in order to evaluate the contribution of the hybridization of the source intended for the power supply of an electric vehicle compared to a traditional vehicle and its effect on fuel economy and reduction of pollutant emissions [7]. There are several management methods that we can use. Among these methods, there rule-based energy management strategy has been frequently used for the simplicity of its implementation. Rules-based strategy can be, typically, applied on specific vehicle operation and states such: start, brake, accelerate, decelerate, climb and grade.

In the energy management of FCHEVs, the operating modes mainly depend on the input parameters, such as the charging power, the vehicle speed or the state of charge of the storage system. A clear and beneficial explanation can be found in the previous research work [7], who are among the researchers who applied the rule-based strategy for FCHEV. The paper is structured as follows: A thorough vehicle structure is executed in Section II. Section III is consecrated to develop modeling of DC/DC converters and present the propose control loops. Then, a rule-based energy management algorithm is developed in section IV. Then the numerical simulation results are given in Section V.

## II. VEHICLE STRUCTURE

The energy chain of the studied hybrid electric vehicle is shown in figure 1. This chain is made up of:

- A fuel cell which is a unidirectional source: It plays the role of main source. This source consists on the heart cell associated with all auxiliaries which are necessary to the operation of a fuel cell for an embedded application.

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- Supercapacitor is a bidirectional source: used as a storage system that presents the secondary source.
- A unidirectional floating interlaced DC/DC converter with four legs, its role is the interface between the main source and the DC bus.
- A bidirectional floating interleaved converter with four branches allowing to connect the storage system to the DC link while ensuring the transfer of energy between this device and the DC bus in both directions.
- An inverter whose role is to interface between the DC link and the propulsion motor.

In this work, we will limit ourselves only to the part before the DC link (from the sources to the DC link).

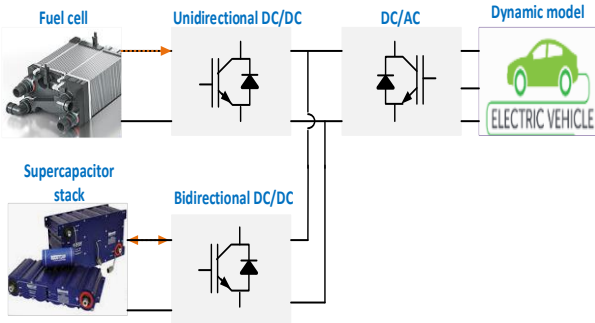


Figure 1. Energy chain of electric hybrid vehicle

### III. VEHICLE STRUCTURE DC/DC CONVERTERS

The combination of two or more interleaved floating amplification architectures thus improves the voltage gain compared to the conventional amplification topology. Moreover, the presence of a non-floating and floating bus in the interleaved floating DC/DC boost converter nevertheless has a strong point of being fault-tolerant due to the presence of static redundancy [8].

Applying a Floating Interleaved Boost Converter at the source output can guarantee several advantages, the most important are:

- o Constant voltage at the output of the converter.
- o Equal leg currents.
- o Constant frequency for phase shift.

It should be mentioned that it is necessary to apply the adequate control to the proposed converter topology. This control must keep the output DC bus voltage constant to prevent load damage. However, the currents in all four legs must be equal in order to increase the efficiency of the converter and to avoid overloading any of the modules when energizing heavy loads.

Furthermore, it is necessary to keep the intake current ripple low, as this latter can reduce the lifetime of the source [9].

Indeed, phases interleaving technology can be considered as an effective method to reduce input current ripple.

#### A. Bidirectional Floating Interleaved Converter Topology

The figure below shows the chosen bidirectional floating interleaved converter.

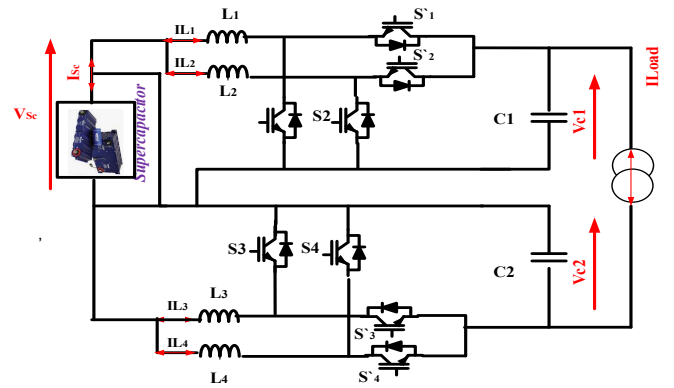


Figure 2. 4-leg Floating Interleaved buck-Boost Converter

The concept of interleaving, used in the proposed topology is ensured by the paralleling of a non-floating version and a floating version of the DC/DC boost converter at the input. Thus, a delay between the control signals for the switches  $S_1, S_2, S_3$  and  $S_4$  must be made. Interleaving two or more converter legs can reduce the input current ripple [9]. Moreover, this topology makes it possible to reduce the electrical constraints on the power semiconductors.

The number of phases of a floating DC/DC interlaced converter must always be even in order to maintain a balance between the non-floating part (i.e. the upper part) and the floating part (i.e. say the lower part). Moreover, in term of reliability, this architecture is more robust compared to the two-phase one [10].

It should also be noted that the loss of phase of a part (i.e. floating or non-floating part) for a 4-phase converter can be compensated by the other phase located on the defective part. However, by maintaining the balance of the converter, this leads to an excess of one phase, thus creating additional electrical stresses, in particular on the magnetic components.

All passive components are ideal elements without the parasitic parameters and they are also equal.

$$C_1 = C_2 = C \quad \& \quad L_1 = L_2 = L_3 = L_4 = L \quad (1)$$

Regarding the duty cycle, we will build models and according to these models we will make control.

Each leg is controlled by its proper Duty Cycle ( $d_1, d_2, d_3, d_4$ )

#### A. Average model

The representation of the state space system is shown by the equation system (2).

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases} \quad (2)$$

U is the control or input vector, Y is the output, and X is the vector of state variables.

$$\begin{cases} x = [I_{L1}, I_{L2}, I_{L3}, I_{L4}, V_{c1}, V_{c2}]^T \\ y = [V_{SC}, I_{Load}]^T \\ u = V_{DC}(t) \end{cases} \quad (3)$$

$$\dot{X} = \begin{pmatrix} \frac{dI_{L1}}{dt} & \frac{dI_{L2}}{dt} & \frac{dI_{L3}}{dt} & \frac{dI_{L4}}{dt} & \frac{dV_{C1}}{dt} & \frac{dV_{C2}}{dt} \end{pmatrix}^T \quad (4)$$

During mode alternation, the operating mode of the FIBDC is forced conduction mode (FCM), and the FIBDC model contains both charging and discharging mode. These two models have a unified form, which means that the unified model (5) is also suitable for the alternating mode.

### Discharging Mode

During high power demand or for high SOC cases, the FIBDC will operate in boost mode, and the Fuel cell will be dump. For the time being, the operating mode of the FIBDC will be in continuous conduction mode (CCM) or critical conduction mode (CRM). On the assumption that  $U_i$  ( $i=1,2,3,4$ ) is the power switch control signal  $S_1, S_2, S_3$  and  $S_4$

During the power switch state  $S_{1,2,3,4}$  are on  $U_i = 1$ , and  $S'_{1,2,3,4}$  are off, the inductors store the energy of battery banks and capacitors release DC bus energy. During the power switch state  $S_{1,2,3,4}$  are off ( $U_i = 0$ ), and  $S'_{1,2,3,4}$  are on, the inductors release energy to the capacities and the DC bus. Consequently, energy is transformed from the Supercapacitor side to the DC bus side so the FIBDC operates in boost mode.

The representation of the state space system on discharging mode is shown by the equation system (5).

$$\begin{pmatrix} \frac{dI_{L1}}{dt} \\ \frac{dI_{L2}}{dt} \\ \frac{dI_{L3}}{dt} \\ \frac{dI_{L4}}{dt} \\ \frac{dV_{C1}}{dt} \\ \frac{dV_{C2}}{dt} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & \frac{d_1-1}{L} & 0 \\ 0 & 0 & 0 & 0 & \frac{d_2-1}{L} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{d_3-1}{L} \\ 0 & 0 & 0 & 0 & 0 & \frac{d_4-1}{L} \\ \frac{1-d_1}{C} & \frac{1-d_2}{C} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1-d_3}{C} & \frac{1-d_4}{C} & 0 & 0 \end{pmatrix} \begin{pmatrix} I_{L1} \\ I_{L2} \\ I_{L3} \\ I_{L4} \\ V_{C1} \\ V_{C2} \end{pmatrix} + \begin{pmatrix} \frac{1}{L} & 0 \\ \frac{1}{L} & 0 \\ \frac{1}{L} & 0 \\ \frac{1}{L} & 0 \\ 0 & -\frac{1}{C} \\ 0 & -\frac{1}{C} \end{pmatrix} \begin{pmatrix} V_{Sc} \\ I_{Load} \end{pmatrix}$$

$$B = \begin{bmatrix} 1/L & 0; & 1/L & 0; & 1/L & 0; & 1/L & 0; & 0 & -1/C; & 0 & -1/C \end{bmatrix}$$

$$C = [1 \ 1 \ 1 \ 1 \ 0 \ 0]$$

### B. Control in Discharging Mode

This type of controller is used for interleaved boost topologies (2), (3), (4), (5), (6), and it makes it possible, in fact, to distribute the instantaneous currents between different phases.

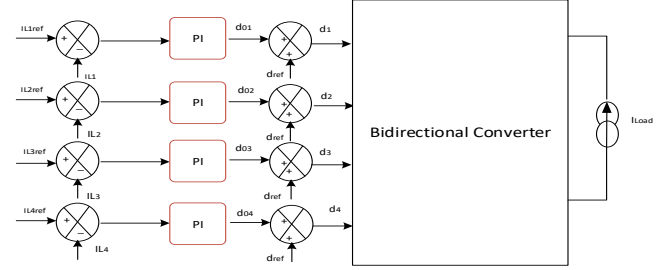


Figure 3. Control model

### Charging Mode

As shown in Fig.2, the converter consists of two modules, when the load power demand is low or for low SOC case, the FIBDC will work in buck mode and the Supercapacitor must be loaded. At that moment, the mode of operation of the FIBDC was still CCM or CRM. Supposing that  $U'_i$  ( $i=1,2,3,4$ ) is the signal control of the power switch  $S'_{1,2,3,4}$

During the power state the switch  $S'_{1,2,3,4}$  is on  $U'_i = 1$  and  $S_{1,2,3,4}$  is off, the inductors store the DC bus energy, and the capacitors release the energy to the battery banks. During the state of the power switch  $S'_{1,2,3,4}$  turn off ( $U'_i = 0$ ) and  $S_{1,2,3,4}$  turn on, the inductors release energy to the Supercapacitor. Energy is transformed from the DC bus on the Supercapacitor side so the FIBDC is in buck mode.

All math done for the charging mode, it can be modeled as follows:

$$\begin{pmatrix} \frac{dI_{L1}}{dt} \\ \frac{dI_{L2}}{dt} \\ \frac{dI_{L3}}{dt} \\ \frac{dI_{L4}}{dt} \\ \frac{dV_{C1}}{dt} \\ \frac{dV_{C2}}{dt} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & -\frac{d'_1}{L} & 0 \\ 0 & 0 & 0 & 0 & -\frac{d'_2}{L} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{d'_3}{L} \\ 0 & 0 & 0 & 0 & 0 & -\frac{d'_4}{L} \\ \frac{d'_1}{C} & \frac{d'_2}{C} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{d'_3}{C} & \frac{d'_4}{C} & 0 & 0 \end{pmatrix} \begin{pmatrix} I_{L1} \\ I_{L2} \\ I_{L3} \\ I_{L4} \\ V_{C1} \\ V_{C2} \end{pmatrix} + \begin{pmatrix} \frac{1}{L} & 0 \\ \frac{1}{L} & 0 \\ \frac{1}{L} & 0 \\ \frac{1}{L} & 0 \\ 0 & -\frac{1}{C} \\ 0 & -\frac{1}{C} \end{pmatrix} \begin{pmatrix} V_{Sc} \\ I_{Load} \end{pmatrix} \quad (7)$$

Since the FIBDC is driven by complementary PWM, it is:

$$U'_i = 1 - U_i (i = 1, 2, 3, 4) \quad (8)$$

Substitute (8) to (7), the same pattern can be obtained as (5), which proves that the two models of boost and buck actually have the unified form.

### Control Model in Charging Mode

This type of controller is used for interleaved topologies, and it makes it possible to actually distribute the instantaneous currents between different phases.

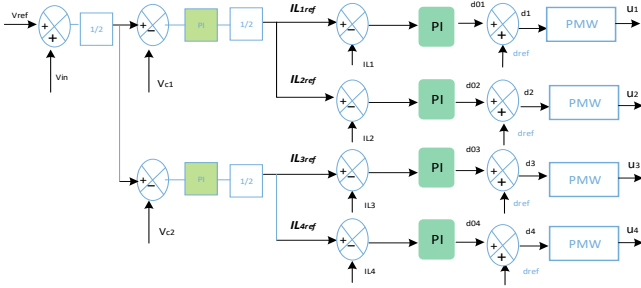


Figure 4. Control model

The control loops shown in Fig. 4 are applied, in this part, to the proposed 4-phase FIBC. In order to test the behavior of our system in this case, the same conditions (NEDC), used to test the performance of a single voltage regulation loop, and apply a regulation loop for each phase for the current.

### B. Floating Interleaved Converter Topology (unidirectional)

A Bidirectional Converter circuit combines elements of a buck converter and a boost converter.

Fig. 5 presents a 4-phase floating interleaved DC/DC Boost converter (Discharging mode on bidirectional)

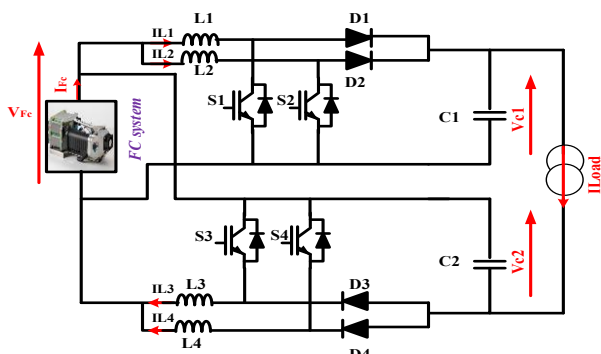


Figure 5. 4-leg Floating Interleaved Boost Converter topology

As it is mentioned above, we can notice that the unidirectional floating interleaved boost converter has the same operation as the bidirectional in discharge mode, hence the same modeling and the same control

### IV. ENERGY MANAGEMENT ALGORITHM

Since the vehicle is powered by more than one source, it is necessary to apply an energy management strategy which can distribute the power required by the motor traction between the two sources. Fig.6 presents the energy management algorithm proposed to ensure the power sharing between fuel cell and supercapacitor. This algorithm

allows to generate the reference of the fuel cell bower based on tests on the load power. So, the rules on which are based the algorithm, take into consideration the SOC of the supercapacitor and the power of the fuel cell. Rules guarantee, also, to keep these variables between their limit values [7].

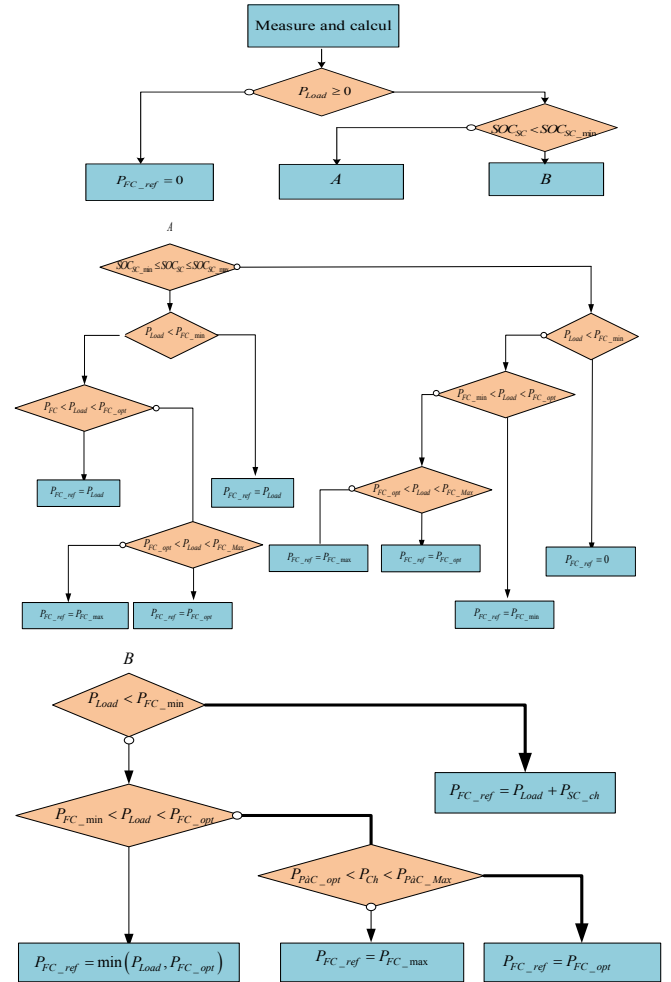


Figure 6. Rule-based energy management algorithm

### V. SIMULATION RESULTS

In order to evaluate the behavior of the studied system, the chosen converters and the proposed energy management strategy, we used the speed profile (NEDC), presented in Fig.7

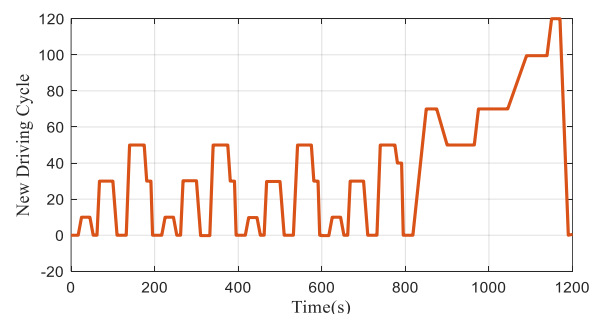


Figure 7. New European Driving Cycle (NEDC)

Fig. 8 presents the evolution of different powers in the system (Load power, Fuel cell power and supercapacitor power). It can be seen that source powers satisfy the power required by the vehicle. The proposed energy management algorithm, allows to distribute the load power between the source elements respecting the limitation on the fuel cell power.

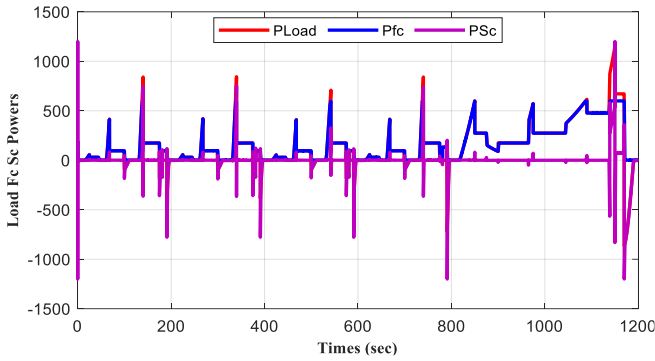


Figure 8. Powers of load, Fuel cell and supercapacitor

It can be seen on Fig. 9, that the sum of the source currents is equal to the load current. Indeed, the currents evolution is the same seen on the powers evolution.

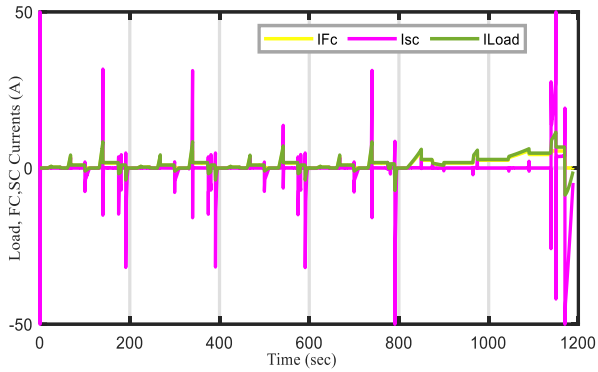


Figure 9. Supercapacitor Fuel Cell Load Current

From Fig. 10, we can see that the fuel cell voltage presents important drops when its power increases. As well for the supercapacitor voltage, this variable increases or decreases according to the operating mode (charging or discharging). For the SOC of the supercapacitor Fig.11, its evolution present the same variations seen on the voltage of the same device. Thus it kept between the maximal and the minimal values imposed by the energy management algorithm.

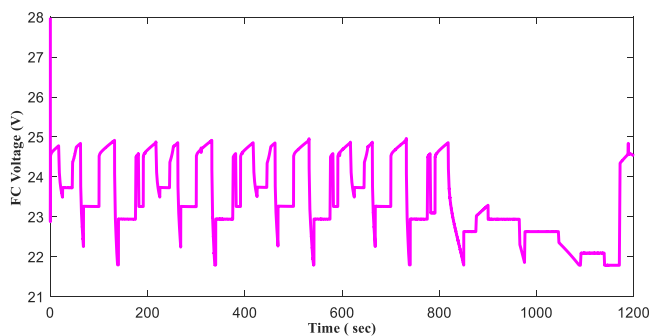


Figure 10. FC Voltage

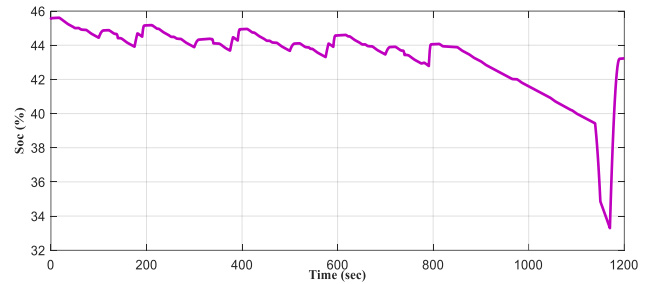


Figure 11. SOC of the Supercapacitor

It can be proved from Fig.12, Fig.13 and Fig.14 that the regulators used in these work present good performances. Indeed, the inductor currents and the capacitor voltages show perfectly their references obeying to the control loops presented in Fig.4 and Fig.3

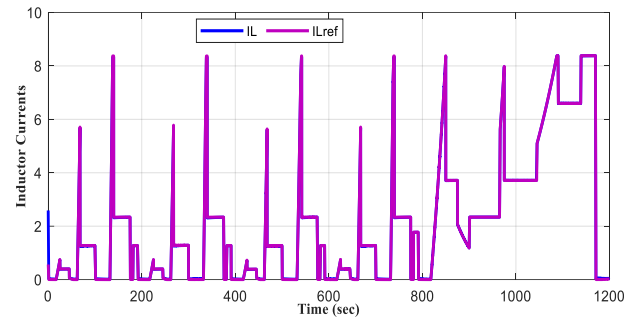


Figure 12. Ref and inductor Current (Unidirectional converter)

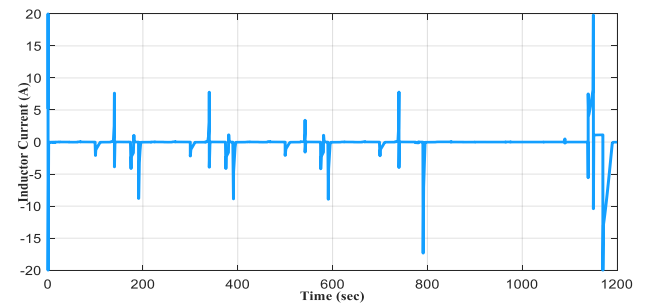


Figure 13. Inductor Current (bidirectional converter)

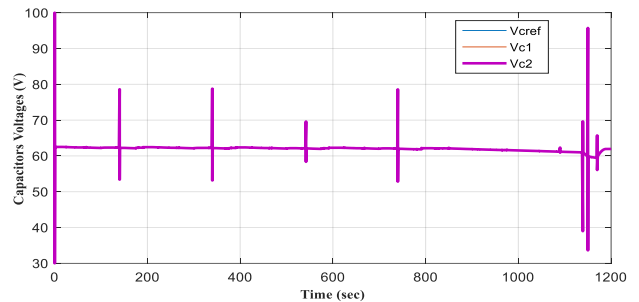


Figure 14. Capacitor voltages

The waveform of the DC bus voltage is given by Fig.15. It is clear that it is kept equal to its reference value (100V) which proves good performances of the DC bus voltage

control loop which allows to provide the super-capacitor current reference ensuring the compensation of the bus voltage fluctuations due to load variations.

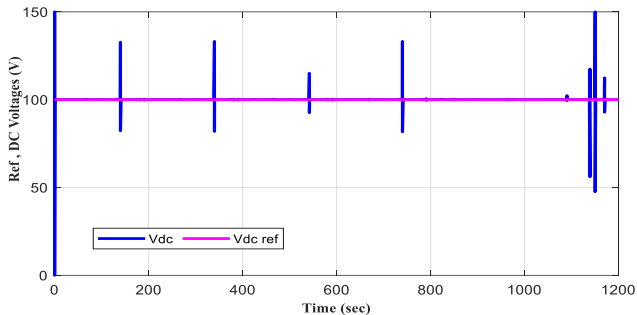


Figure 15. DC link voltage

From the simulation results presented above, the major advantage of the strategy proposed in this paper is that it ensures stable operation of the fuel cell during long intervals as well as a limitation of the state of charge of the super-capacitor pack, which makes it possible to avoid the deep discharge of this storage device and, also, its overcharge.

## VI. CONCLUSION

In this work, a rule-based power sharing strategy was developed and applied for a electrical vehicle supplied by a dual source power system which was consisting of a fuel cell, interfaced by a floating interleaved boost converter, and a supercapacitor connected to a floating interleaved bidirectional converter. The proposed converter topology and the energy management strategy were tested for the NEDC driving cycle. The adopted strategy was found to be effective in sharing the power flow between the main and the secondary source in order to satisfy the power required by the propulsion system taking into account constraints on the source powers and the supercapacitor SOC. The major advantage of the proposed converters topology in this paper, is that allows to reduce the input current ripple, increase efficiency, minimize the volume of the inductors and ensures operating in degraded mode.

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