This paper presents a new control algorithm for utilizing PEM fuel cell and supercapacitors for automotive system. A PEM fuel cell is operated as a directional main power source connected to 42 V dc bus (PowerNet) by boost converter, and supercapacitors is controlled as a fast bidirectional auxiliary power source connected to dc bus by a 2-quadrant dc/dc converter. The system employs a 500 W PEM fuel cell and a supercapacitive storage device, composed of six components (3,500 F, 2.5 V, 400 A) associated in series. The system control structure is realized by analogical for current loop at high dynamics and digital control (dSPACE) for voltage loop and algorithm. The proposed control, illustrated by experimental results, avoids speedy transition of fuel cell current and is based on the power sharing demanded at the dc bus between the main and auxiliary sources.

Index Terms— Automotive, Fuel Cell, Hybrid Electrical System, Polymer Electrolyte Membrane, Supercapacitors

I. INTRODUCTION

For the moment, automotive hybrid electrical system has been developed for drastically cleaner and more economical vehicles. Hybrid electrical cars, such as the Honda Insight and Toyota Prius, were especially tested by U.S. Department of Energy (DOE) and showed the fuel saving [1]. Fuel cell has been manifestly developed to become the main source in many applications. The fuel cell transit bus, which has been designed and developed by DOE, has been acknowledged as a zero emission vehicle. Its only emission is in fact water vapour [2].

One of the main weak points of fuel cell is its slow dynamics [3-5]. In fact, the dynamics of fuel cell is limited by the hydrogen delivery system, which contains pumps and valves, and in some cases a reforming process. In particular, a step electrical load will imply vast variation of the voltage of 42 V dc automotive distribution bus, because the main source has slow dynamic response.

Moreover, the automotive system has problem when starting electrical motor, which demands from the dc bus high energy in short time.

To solve these problems, the system must have a fast auxiliary source, to supply high transient energy. The new high current supercapacitor technology has been developed for this purpose [6]. Then the very fast power response of supercapacitors can be used to complement the slower power output of the fuel cell to produce the compatibility and performance characteristics needed by hybrid automotive system as shown in Fig. 1.

Compared with batteries, supercapacitors have at least two orders of magnitude higher specific powers, and much longer lifetime. Because they are capable of millions cycles, they are virtually free of maintenance. Their great rated currents enable fast discharges and fast charges as well. Their quite low specific energy, compared to batteries, is in most cases the factor that determines the feasibility of their use in a particular high power application [7].

By nature, fuel cell has slow dynamics. If it is operated in nearly steady state condition in order to avoid high dynamics, the key advantage is that the mechanical stretch of fuel cell is prevented, and therefore the fuel cell stack damage will not happen.

This paper presents automotive system having a PEM (Polymer Electrolyte Membrane) fuel cell as main source and supercapacitors as auxiliary source. It especially details the new control algorithm.

The experimental results are composed of two parts; the first one shows PEM fuel cell characteristics when connecting with converter to dc bus; the second one shows hybrid characteristics for different situations at dc bus in order to authenticate system operation.
II. HYBRID SYSTEM STRUCTURE

A. Fuel Cell Converter

Fuel cell operates at a directional current, and at low voltage. Thereby, the fuel cell converter, presented in Fig. 2, is selected as a boost converter used to adapt the low dc voltage delivered by fuel cell, which is around 12.5 V at rated power, to the 42 V standard automotive dc bus.

The fuel cell converter is composed of a high frequency inductor L1 (72 μH), an output filtering capacitor C1 (0.702 F), a diode D1 and a main switch S1. Switch S2 is a shutdown device for test bench security to prevent the fuel cells stack from short circuit in case of accidental destruction of S1, or of faulty operation of the regulator. Taking into account the low voltage, we choose power MOSFETs for S1 and S2 [8].

B. 2-Quadrant Supercapacitors Converter

The supercapacitors are connected to the dc bus by means of a 2-quadrant dc/dc converter, as shown in Fig. 3. L2 represents the inductor used for energy transfer and filtering. The inductor size is classically defined by switching frequency and current ripple.

Supercapacitors size is defined by dc bus energy requirements deduced from hybrid power profile. The supercapacitor current, which flows across the storage device, can be positive or negative, allowing energy to be transferred in both directions.

Finally, the converter is driven by means of complementary pulses, applied on the gates of the two MOSFET S3 and S4.

steady state conditions, and supercapacitors are functioning during lacking energy from main source, transient energy delivery or transient energy recovery.

The control principle of the hybrid system is presented in Fig. 4. The main point of this control is to regulate dc bus voltage \( V_{bus} \) with the following constraints: fuel cell electrical power must be kept within an interval \( [P_{FCMin}, P_{FCMax}] \), supercapacitive storage device voltage must be kept within an interval \( [V_{SuperCMin}, V_{SuperCMax}] \), and fuel cell current slope must be limited to a maximum absolute value. In previous work [9], one has tried in hybrid system built with battery as a main source and supercapacitors as an auxiliary source to control currents in the different parts of the system (battery, supercapacitors and load).

One of the problems, which appear in such a control, is the presence of dead time operation while the system changes of operating mode (from steady state to a sudden recovery state, for example). For new conception, the hybrid system control presents \( V_{bus} \) regulation through the power delivered by the fuel cell and the supercapacitors [10], and the current references are a consequence of the power demand. More precisely, the dc bus voltage controller (PI controller) generates a power reference, called \( P_{busREF} \) as delineated in Fig. 4. This signal is limited in level and rate of change (slopped limitation), to create fuel cell power reference \( P_{FCREF} \) and then it obtains fuel cell current reference \( i_{FCREF} \).

The difference between the two previous power references gives supercapacitors power reference \( P_{SuperCREF} \) and one of the three supercapacitors current references, that is to say \( i_{SuperC} \).

This signal defines supercapacitors modes of operation: normal (charge from fuel cell) if \( i_{SuperC} \) is zero, recovery (charge from dc bus) if it is positive, and discharge if it is negative. The two other supercapacitors current references, \( i_{SuperC1} \) and \( i_{SuperC2} \), are generated by fuel cell current controller2 (I controller) and supercapacitors voltage controller (P controller), respectively. The hybrid control algorithm as explained hereafter does the choice among these three references.

Firstly, during normal operation, when \( i_{SuperC} \) is zero, supercapacitors are charged by the fuel cell up to the voltage level \( V_{SuperCNormal} \), which is within the previously defined interval \( [V_{SuperCMin}, V_{SuperCMax}] \). To meet this target, fuel cell current controller2 is supplied with fuel cell rated current as reference, \( I_{FCRated} \) corresponding to fuel cell rated power. Supercapacitors voltage controller is supplied with \( V_{SuperCNormal} \) as reference. The hybrid control algorithm leads to select the minimum value between \( i_{SuperC1} \) and \( i_{SuperC2} \) if supercapacitors voltage is less than \( V_{SuperCNormal} \) (that is to say if \( i_{SuperC2} \) is positive), zero otherwise.

Note that during this operation, charging current has to be limited in rate of change, in order to avoid instability due to a too fast increasing current, which would be seen as a peak load by the system.

Note also that each transition in the normal mode begins with the initialisation of the integrator of fuel cell current controller2.
Secondly, when one of the two limitations (rate of change, and level) on fuel cell power reference is working, a non-zero $i_{SuperC3}$ signal is generated, which can be positive or negative, depending on power condition at dc bus. Therefore, in the case of discharge mode, characterised by a fast transient increasing load, or by a power load greater than $P_{FCMax}$, the current reference $i_{SuperC3}$ become negative in order to transfer the lacking energy to the dc bus. Supercapacitors voltage controller is supplied with $v_{SuperCMin}$ as reference, and the hybrid control algorithm leads to select the maximum value between $i_{SuperC3}$ and $i_{SuperC2}$ if supercapacitors voltage is greater than $v_{SuperCMin}$ zero otherwise.

On the other hand, in the case of recovery mode (transient fast decreasing load, or power load less than $P_{FCMin}$), the current reference $i_{SuperC3}$ become positive. Supercapacitors voltage controller is supplied with $v_{SuperCMax}$ as reference, and the hybrid control algorithm leads to select the minimum value between $i_{SuperC3}$ and $i_{SuperC2}$ if supercapacitors voltage is less than $v_{SuperCMax}$ zero otherwise.

In the two cases ($i_{SuperC3}$ is positive or negative), the reference and integrator of fuel cell current controller2 are set to zero for prevision of the next normal operation as shown in Fig. 4 by named Control Signal.

Finally, note that $i_{SuperC3}$, which is sensitive to dc bus disturbance (noise immunity), has to be filtered before sending to hysteresis switch in order to define hybrid system modes of operation.

III. HYBRID SYSTEM IMPLEMENTATION

In addition, Fig. 5 presents hybrid system implementation in Matlab/Simulink block diagram for dSPACE interfacing card. The hybrid system communicates with operator by ControlDesk from computer screen, and contacts with converter ($v_{Bus}$, $i_{FCREF}$, and so on) by DAC and ADC of dSPACE interfacing card.

Note that motor controller is realized for becoming load at dc bus. It does not relate with the hybrid control algorithm, which is independent from load current.

![Figure 4. Hybrid system control structure.](image-url)

![Figure 5. Hybrid system context diagram.](image-url)
IV. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 6 shows the simplified diagram of the PEM fuel cell system used for this research. Constructed by the Zentrum für Sonnenenergie und Wasserstoff-Forschung (ZSW), Ulm, Germany, the fuel cell stack is composed of 23 cells of 100 cm². It is supplied with pure hydrogen (stored under pressure in bottles) and air from a compressor. Additionally, the hardware test bench system structure is presented in Fig. 7.

A. Fuel Cell Converter Testing with an Ideal Power Supply

Extensive testing is performed using an ideal 12.5V power supply, which has the same rated voltage as the fuel cell, in order to confirm that the boost converter can operate correctly and to compare fuel cell characteristics with ideal power supply.

Fig. 8 shows the input current response with a stepped current command. It shows that current response has high dynamics with optimum response by current controller (PID). Moreover, Fig. 9 presents the voltage loop test with a load disturbance. This result shows that the regulation of the fuel cell converter correctly works.

B. Fuel Cell Converter Testing with a PEM Fuel Cell

When fuel cell is operated, its fuel flow is controlled by fuel cell processor, which receives current demand from current reference as shown in Fig. 4. To present the fuel cell characteristics, the test bench is operated in two different ways. Firstly, fuel cell works at constant fuel flow corresponding to the maximum available current of 50 A. In this case, the fuel cell has enough hydrogen and oxygen. Secondly, the fuel flow varies depending on current reference.

As shown in Fig. 10, it can be seen that dynamic response of fuel cell current is different from Fig. 8. There are two ways to explain this phenomenon. Firstly, by electrical way, the electrical fuel cell model is different from an ideal power supply. Secondly, by physical way, the phenomenon is due to the slowness of its thermodynamic operation.

Fig. 11 shows the effect of mechanical problems. It can be seen from fuel cell voltage that it drops lower than on Fig. 10. This means that its fuel supply and delivered electrical current do not coincide. Fuel flow is not enough for converter current. This condition of operating is hazardous for the fuel cell stack.

These tests clearly confirm the slowness and complex model of the fuel cell system [12].
Voltage loop test without slopped limitation is presented on Fig. 12. Compared with the current response of Fig. 9, it also shows the slowness of the fuel cell response. The fuel cell current points out high overshoot and delay time.

C. Hybrid System Test Bench

As storage device, hybrid system utilizes six SAFT supercapacitors (capacitance: 3500 F, rated voltage: 2.5 V, rated current: 400 A, series resistance: 0.8 mΩ) connected in series. The technical specifications are as follows:

- \( P_{FC_{\text{Rated}}} = 500 \text{ W} \),
- \( P_{FC_{\text{Min}}} = 50 \text{ W} \),
- \( P_{FC_{\text{Max}}} = 530 \text{ W} \),
- \( i_{FC_{\text{Rated}}} = 40 \text{ A} \),
- \( v_{\text{SuperCNormal}} = 13 \text{ V} \),
- \( v_{\text{SuperCMin}} = 8 \text{ V} \),
- \( v_{\text{SuperCMax}} = 15 \text{ V} \).

Power slope of fuel cell is 500 W.s\(^{-1}\) (around 8.5 A.s\(^{-1}\)) while current slope of fuel cell for charging supercapacitors is limited to 4 A.s\(^{-1}\).

While operating with the supercapacitors, the fuel flow is not anymore fixed to a 50 A current but adapted to the value of the delivered current to improve the efficiency of the system.

Fig. 13 shows transient responses to a stepped load which corresponds nearly to 10-40 A step of the fuel cell current. One can observe that the dc bus voltage is well regulated, and that fuel cell current smoothly increases with a slope of 8.5 A.s\(^{-1}\). Furthermore, during transient state, supercapacitors transfer energy back to the dc bus in order to compensate the energy, which is not supplied by the main source.
Fig. 13 presents hybrid responses to a stepped load. At the beginning of charge at $t = 3$ s, $i_{\text{SuperCREF}} = i_{\text{SuperC}1}$. It can be observed that fuel cell current slope is approximately $4$ A.s$^{-1}$, which is lower than the previous $8.5$ A.s$^{-1}$, necessary condition for stability. Furthermore, during the charging process the fuel cell delivered its rated current. Besides, the transition of $i_{\text{SuperCREF}}$ from $i_{\text{SuperC}1}$ to $i_{\text{SuperC}2}$ occurs (end of charge) at time $t = 25$ s, for a supercapacitors voltage of nearly $13$ V, because of the use of a high proportional gain (200) for supercapacitors voltage controller.

Fig. 14 presents hybrid characteristics during normal operating mode, through supercapacitors charge from $12$ V to $13$ V. The dc bus has a constant load of about $10$ A delivered by the main source. At the beginning of charge at $t = 3$ s, $i_{\text{SuperCREF}} = i_{\text{SuperC}1}$. It can be observed that fuel cell current slope is approximately $4$ A.s$^{-1}$, which is lower than the previous $8.5$ A.s$^{-1}$, necessary condition for stability. Furthermore, during the charging process the fuel cell delivered its rated current. Besides, the transition of $i_{\text{SuperCREF}}$ from $i_{\text{SuperC}1}$ to $i_{\text{SuperC}2}$ occurs (end of charge) at time $t = 25$ s, for a supercapacitors voltage of nearly $13$ V, because of the use of a high proportional gain (200) for supercapacitors voltage controller.

Fig. 15 presents transient responses of the hybrid system to an excessive load. Before this test, supercapacitors voltage is equal to $V_{\text{SuperCNormal}} = 13$ V. The supercapacitors compensate the main source during both transient state and steady state, because of fuel cell current slope and fuel cell power limitations. During the first interval, beginning at $t = 4$ s, the current delivered by the main source slowly increases (with a controlled slope) up to its maximum value, the lacking energy being delivered by supercapacitors during $t = 7.8$ s to $18$ s. Then, the sudden decrease of the power load at $t = 18$ s leads to a recovery mode for supercapacitors, in order to allow a slow controlled decrease of the fuel cell current.

Fig. 16 corresponds to a sudden recovery of energy on the dc bus. This energy is recovered by the supercapacitors while a slow decreasing of the main source current is performed. In this example, fuel cell never delivered less than $50$ W in order to maintain fuel cell converter operating in continuous current mode.

V. CONCLUSION

The main objective of this work is to propose a new method of controlling an automotive dc bus supplied by a hybrid source using supercapacitors as auxiliary source, in association with a PEM fuel cell as main source, knowing that this kind of electrical source is not able to supply energy during fast transitions of load because of current slope limitation, during peak loads because of power limitation, and during recovery because of only positive current delivering.

The experimental results with a $500$ W PEM fuel cell confirm the slow dynamic response of the system, due to both thermodynamic and mechanical phenomena. Results carried out by means of a hybrid system test bench, which uses a storage device composed of six SAFT $3500$ F supercapacitors connected in series, have shown the possibility to improve the transient performance of the system and validate the proposed control principle.
Figure 15. Hybrid system response when overloading.

Figure 16. Hybrid system response when recovering.

REFERENCES


