Energy Management of Stand-Alone Power Systems with Renewable Energy Sources

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Abstract. The paper deals with storage and generation systems with renewable energy sources. A stand-alone combined system with electrochemical batteries, supercapacitors and fuel cells is considered.
The power flow among the different storage devices is controlled in order to optimise the energetic efficiency and avoid irregular working conditions. A proper control strategy is proposed to keep constant the fuel cell power and limit the charge/discharge batteries current. The control strategy is implemented by means of two hierarchical algorithms on the power converters that interconnect storage devices and generation sources.
Experimental tests done on electrical drives to validate the algorithm are illustrated and the results are discussed.

Keywords

Stand-alone systems, fuel cells, supercapacitors

1. Introduction

Power availability of renewable energy sources, as wind turbines and photovoltaic arrays, is not regular in the time nor continuous. The stochastic nature of the exploitable primary power and the power required by the load implies that stand-alone generation systems with renewable sources need to be supported by suitable storage devices and/or auxiliary generation systems. At the state-of-the-art, different storage devices, e.g. electrochemical batteries, supercapacitors and hydrogen storage systems, are available. These technologies have different performance characteristics, as energy density and power density, and each device can effectively deliver electrical power only with a specific rate. Therefore, compound storage systems make it possible to combine their intrinsic advantages and to achieve performance better than those deriving from the single device. In stand-alone power generation systems, a combined storage system is definitely an effective and useful solution for balancing the mismatch between the available energy supplied by the sources and the power required by the load. Benefits connected to the combined use of different storage devices is though subordinated to their synergic action and their complementary use. Specifically, both the power flows into and from each storage device have to be designed accurately and controlled according to a global energy management strategy. This has to be designed with the aim of optimising the energetic efficiency and of avoiding that irregular working conditions could reduce the life of the components.
Control of power flows can be easily obtained by interconnecting storage devices and generation sources by means of power electronic converters. Control algorithms have to be implemented on power converters according to local operative constraints. Control algorithms have to adapt controlling actions in order to satisfy many constraints and critical conditions (low state of charge, overvoltages, overcurrents) with an assigned priority order. Previous specifications can be effectively satisfied with a control algorithm with a hierarchical structure. An innovative control strategy for a combined system including electrochemical batteries, supercapacitors and fuel cells is proposed in the paper. This strategy is based on two independent control algorithms with a hierarchical structure. The former algorithm drives the power electronic converter that operate as interface between fuel cells and electrochemical batteries; the latter, implemented on another converter, manages the power flows between supercapacitors and batteries. The control strategy has been programmed on real converters and has been validated with experimental tests on a sample system configuration. Some relevant results are reported in the paper and commented.

2. Control strategy

In a stand-alone generation system with renewable energy sources, the combined system of energy storage and auxiliary generation has to compensate the difference between the primary source power P_G and the load power P_L. The control strategy of the power flows through the supply network has to share the power P_A (difference between P_G and P_L) among the different devices of the combined system. If reference is made to a system with electrochemical batteries, supercapacitors and fuel cells, whose configuration is represented in fig.1, the aim of the control system is the evaluation of the output powers of each device. However, these three powers are not independent one on the others, but they have to satisfy an algebraic equation, because their summation is equal to the power P_A. A combined system like this represented in fig.1 is therefore a physical system with two degrees of freedom. For this reason, it is possible to select two auxiliary conditions and it is convenient that these conditions involve optimised operations for the combined system. The auxiliary condition set defines, hence, also the control algorithm.

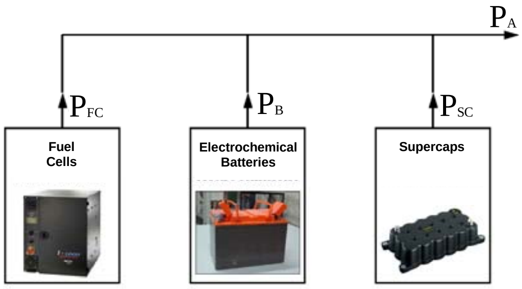

Fig.1 – Block diagram of the combined system with electrochemical batteries, supercapacitors and fuel cells

The system configuration suggests, as a useful auxiliary condition, that the fuel cells operate with constant output power:

$$P_{FC} = P_{FCM} \quad (1)$$

The reference power P_{FCM} can be supposed to be equal to the rated power of fuel cells or to the power corresponding to the maximum conversion efficiency. Both the references involve operating advantages. If the reference power is equal to the rated fuel cell power, the fuel cell size is reduced and then also its weight, volume and cost. If conversely the reference power is set in the point of the maximum efficiency, the energetic efficiency is preferred and the losses are minimised. Moreover, the operating condition with constant power avoids that repetitive transients, among different power levels, could reduce the life of the cells.

The second auxiliary condition can be set for optimising the working operations of electrochemical batteries. This can be achieved if both the discharge and recharge currents of batteries are limited. The technical literature has dealt with the life reduction of batteries connected to the peak currents supplied. At present, the common opinion is that peak currents involve a gradual deterioration of the active materials inside the battery and, consequently, a reduction of performances and also of the life. Therefore, the control algorithm has to limit the battery current to values lower then the reference current I_{BL}:

$$|I_B| \leq I_{BL} \quad (2)$$

The electrochemical supercapacitors can be effectively used as auxiliary energy storage system for supporting the battery pack. They can be used for supplying the short power peaks that the batteries, driven with the current limitation, could not supply.

The management of power flows can be realised connecting both the devices by means of power electronics converters. The converters regulate the output power of each device changing their output voltages; in addition, they harmonise the operating voltages of each device. A quite common solution is that the electrochemical batteries are connected in parallel to the dc-bus of a VSI-inverter supplying the load; the fuel cells and the supercapacitors are connected to the dc-bus by means of dc-dc converters (fig.2).

In particular, the fuel cell requires a single quadrant dc-dc converter; the supercapacitors require instead a bi-directional dc-dc converter, because they need to be both charged and discharged.

The control strategy of power flows has to be implemented on the drives of the converters by means of two different control algorithm. The first one controls the power flows between the supercapacitors and the batteries, whereas the second controls the power flows between the fuel cells and the batteries.

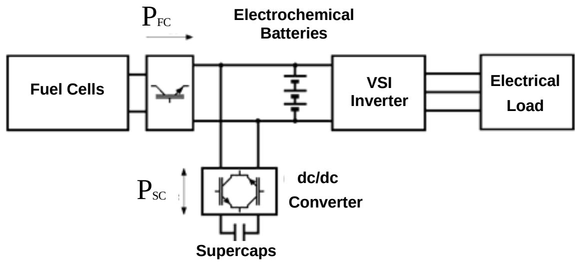

Fig.2 – Block scheme of a compound storage system

A. Control algorithm for supercapacitors

In the suggested control strategy, supercapacitors have to support storage units for limiting discharge currents of electrochemical batteries, I_B, during power peaks of short duration. They should be discharged when the current requested by load from the storage system I_A is higher than the reference limit current for electrochemical battery discharge I_{BL}. The supercapacitors current I_{SC} contributes to balance the difference between I_A and I_{BL}. When the power requested by load decreases, the control system has to reestablish the maximum state of charge of supercapacitors so that they will have energy enough for the next supporting action.

The limitation of the output current of electrochemical batteries represents an optimal operative condition in order to preserve electrochemical batteries from long term damages and the reduction of their operating life. However, it should be subordinated to the condition of some physical parameters (current and voltage of supercapacitors, voltage of electrochemical batteries) that can generate critical conditions or damages. The control system has to adapt its action to specific constraint imposed on these quantities with a predefined sequence of priority.

- With first level of priority, the control system has to guarantee that the output current of supercapacitors I_{SC}, is lower than the maximum allowable current $I_{SC,Max}$ indicated by manufacturer (both during charge and discharge):

$$|I_{SC}|<I_{SC,Max} \quad (3)$$

Overcurrents occur when the output current requested by load is too high and/or supercapacitors are quite discharged. The control algorithm has to commutate from a control of the electrochemical batteries current to a control of supercapacitors current with a reference equal to $I_{SC,Max}$.

- With a second level of priority, the control algorithm has to impose that the voltage on supercapacitors V_{SC} is maintained into a predetermined range delimited by the upper voltage limit $V_{SC,Max}$ and the lower limit $V_{SC,Min}$.

$$V_{SC,Min}<V_{SC}<V_{SC,Max} \quad (4)$$

The higher voltage limit is specified by the manufacturer while the lower voltage limit has to be chosen with reference both to the maximum elevation ratio of the converter (4-5 for standard converter) and with consideration on energy efficiency. For a discharge with constant current the efficiency of supercapacitors decreases when the voltage decrease because the output current and, consequently, ohmic losses are increased. If operative voltages are too low, charge-discharge efficiency could became unsatisfactory. The existence of a lower limit reduces partially the energy available for discharge; however, since the energy available depends on the square of the voltage, the residual energy that cannot be discharged is negligible compared to the whole capacity. When the voltage V_{SC} reaches its limits, the control algorithm disconnects temporarily the supercapacitors from the dc bus. In particular, if $V_{SC}=V_{SC,Min}$, supercapacitors can be reconnected and recharged when the power requested by load becomes low enough and the supercaps can be recharged. Conversely, if $V_{SC}=V_{SC,Max}$, supercapacitors can be reconnected only when the power requested by load is high enough that they have to be discharged.

In order to accomplish the imposed constraints, it can be adopted a control algorithm with a hierarchical internal structure implemented with a finite state machine. Control algorithm can be configured as a system with four states, where each state corresponds to a specific control action. The functional diagram of the states is reported in fig. 3.

The first state corresponds to the control of the current of electrochemical batteries (CB). Current of electrochemical batteries is controlled by regulating the output voltage of the dc/dc bidirectional converter. The control has been implemented by a proportional integral regulator with a feedback on the battery current both during charge and discharge. The error signal is processed by a PI block, whose output signal represents the reference duty cycle of the converter.

A second state implements an analogue control with a feedback of the current of supercapacitors (CSC). The control has been realized with a PI regulator. The transition from the control on the battery current to the control of electrochemical capacitors current occurs when the output current of supercapacitors becomes higher than their maximum admissible current:

$$|I_{SC}|>I_{SC,Max}$$

The reverse transition occurs when the load is reduced and the current becomes lower than the limit current:

$$|I_{SC}|<I_{SC,Max}$$

In order to avoid that natural fluctuations on the current I_{SC}, could produce an instable behavior, with permanent oscillations of the control between the states CB and CSC, both the transitions occur for two threshold limits slightly different; more specifically, the first transition (from CB to CSC) has to occur for a current value slightly higher than $I_{SC,Max}$ ($I_{SC,Max}^{+}$) while the second transition (from CSC to CB) for a value slightly lower ($I_{SC,Max}^{-}$).

The two remaining states (VU, VD) implement the control of voltage on supercapacitors. Both of them disconnect supercapacitors from the dc bus in order to avoid that the voltage can assume values out of the predefined voltage range. The transition from the control of battery current to the state VU occurs when the voltage on supercapacitors V_{SC} equals the higher threshold $V_{SC,Max}$. The transition from the state CB to the state VD occurs when the voltage V_{SC} equals the lower threshold $V_{SC,Min}$. The reverse transitions are decided with reference to the values assumed by the battery current. In particular, the transition from VU to CB has to be executed when electrochemical capacitors have to be discharged and, then, when the battery current became higher than the reference ($I_B>I_{BL}$). The transition from VD to CB have to be executed when electrochemical batteries can recharge electrochemical capacitors that is when the battery current becomes lower than the reference ($I_B<I_{BL}$).

If electrochemical capacitors remain disconnected for a time interval sufficiently long, natural self discharge phenomena can reduce the available energy. Control algorithm has to recharge them when the voltage V_{SC} reaches a predetermined limit $V_{SC,Max}^{-}$. The transition between the states VU e CB has to occur also when:

$$V_{SC} < V_{SC,Max}^{-} \quad (5)$$

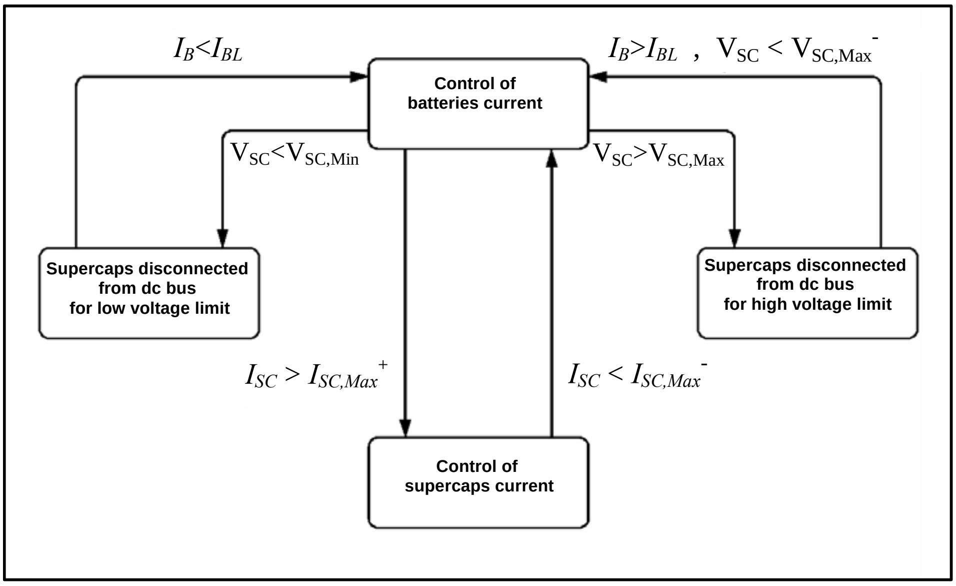

Fig.3 - Block diagram of the states and the transitions of the supercapacitors control algorithm

B. Control algorithm of the fuel cell output power

The fuel cell is an auxiliary energy source for the power generation system with renewable sources. According to the energy management defined before, the fuel cell has to work with constant output power, i.e.:

$$P_{FC} = P_{FCM}$$

If the load power is lower than the reference power P_{FCM}, the fuel cells recharge the battery. However, the charge process has to be made with reduced current when the battery voltage reaches its maximum allowable value $V_{B,Max}$, corresponding to the maximum state of charge of the battery.

The control has to be submitted to the condition:

$$V_B<V_{B,Max} \tag{6}$$

which have a priority higher than that of constant fuel cell power. The control algorithm provides to switch from a constant power control to a constant battery voltage control. The fuel cell works therefore with reduced power with the aim of keeping the battery voltage equal to the limit voltage. The battery voltage has to be lower than the limit voltage (typically 2.4 V per cell) because otherwise dissociation process, involving release of hydrogen, may arise inside the cells and lead to an irreversible deterioration of the whole battery. The control algorithm of fuel cells can be realised again with a discrete state machine; this control has to satisfy only one condition on the system and then its structure is easier than the supercapacitor algorithm. The fuel cell control algorithm is realised in particular with two different states corresponding to the constant fuel cell power control and to the battery voltage control (fig.4). Both the controls regulate respectively their outputs with PI blocks.

The transition from the power control to the voltage control takes place when the dc bus V_B becomes greater than the maximum allowable voltage $V_{B,Max}$. The back transition occurs instead load requires a power greater than the maximum fuel cell power and the batteries have to discharge. Specifically, the transition happens when it is satisfied the condition:

$$P_{FC} > P_{FCM}$$

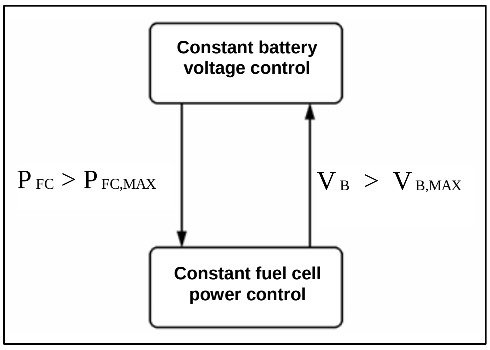

Fig.4 –Block diagram of the states and the transitions of the fuel cell control algorithm

3. Experimental results

The suggested control algorithm has been verified by experimental tests carried out on a sample drive supplied by fuel cells, electrochemical batteries and supercapacitors. The block diagram of the used sample drive is reported in fig.5.

The battery pack is the series of 20 elements of 12 V for stationary applications, each one with a capacity of 4.5 Ah (C10). The supercapacitor bank is the parallel of two modules of 75 V, each one with a capacity of 3.3 F. The fuel cells have a rated power of 1 kW with a dc output of 48 V. The hydrogen needed for supplying the fuel cells (about 1 Nm^3/h) is provided by an alkaline-based electrolyser. The load is an induction motor of 4.5 kW driven by a VSI inverter and mechanically connected to a synchronous generator supplying a passive electrical load.

The experimental tests on the drive have been made with the aim of verifying the capability of both algorithms of realising duty-cycles programmed by the user. In the first test the load is increased until the current supplied is 10 A, then is hold constant to this value for 1 minute and finally is decreased to zero. During the cycle, the fuel cell voltage and current (fig. 6a and 6b) are constant according to the control strategy which implies constant power operation of fuel cells. The battery current (fig. 6e) is constant and equal to the reference value only until the supercapacitors have not discharged themselves up to their minimum allowed voltage. When the lower limit voltage is reached (40 V), the supercapacitors are disconnected from the dc bus and the battery current presents a step increase. The battery current peaks and the gradual battery discharge yield a decrease of the dc bus voltage, as fig. 6f shoes. At the end of the cycle, the required load power decreases and the supercapacitors can be recharged.

Another test has been made for verifying the effectiveness of the fuel cell control algorithm, in particular the reduction of the fuel cell power when the battery is charged up to its limit voltage. Figs. 7 highlight that the fuel cell output power is lower than the rated (corresponding to 14 A) at the beginning of the test, because the battery voltage is equal to the selected limit voltage (275 V). After 25 s, the dc bus voltage decreases, because the load is suddenly connected, and the fuel cells immediately increase their power up to the reference power. When the load current decreases, the fuel cells recharge again the battery with reduced power.

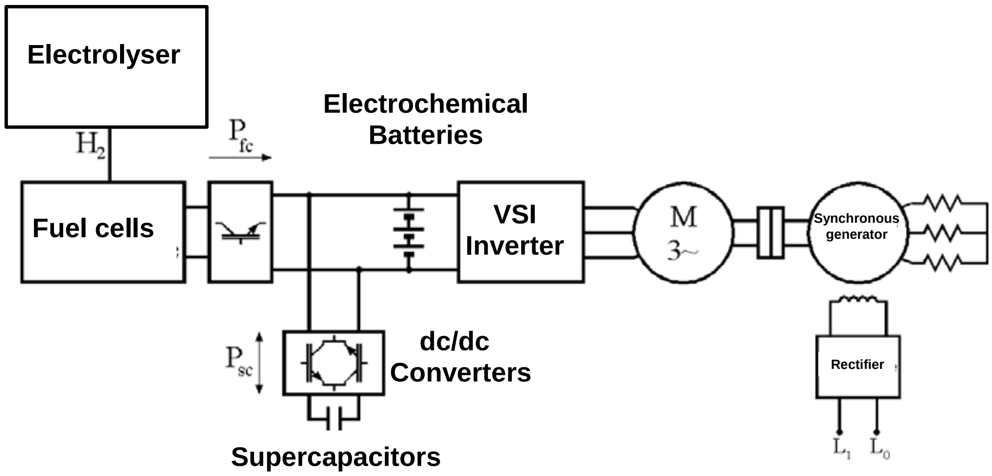

Fig.5 – Block diagram of the drive used for experimental tests

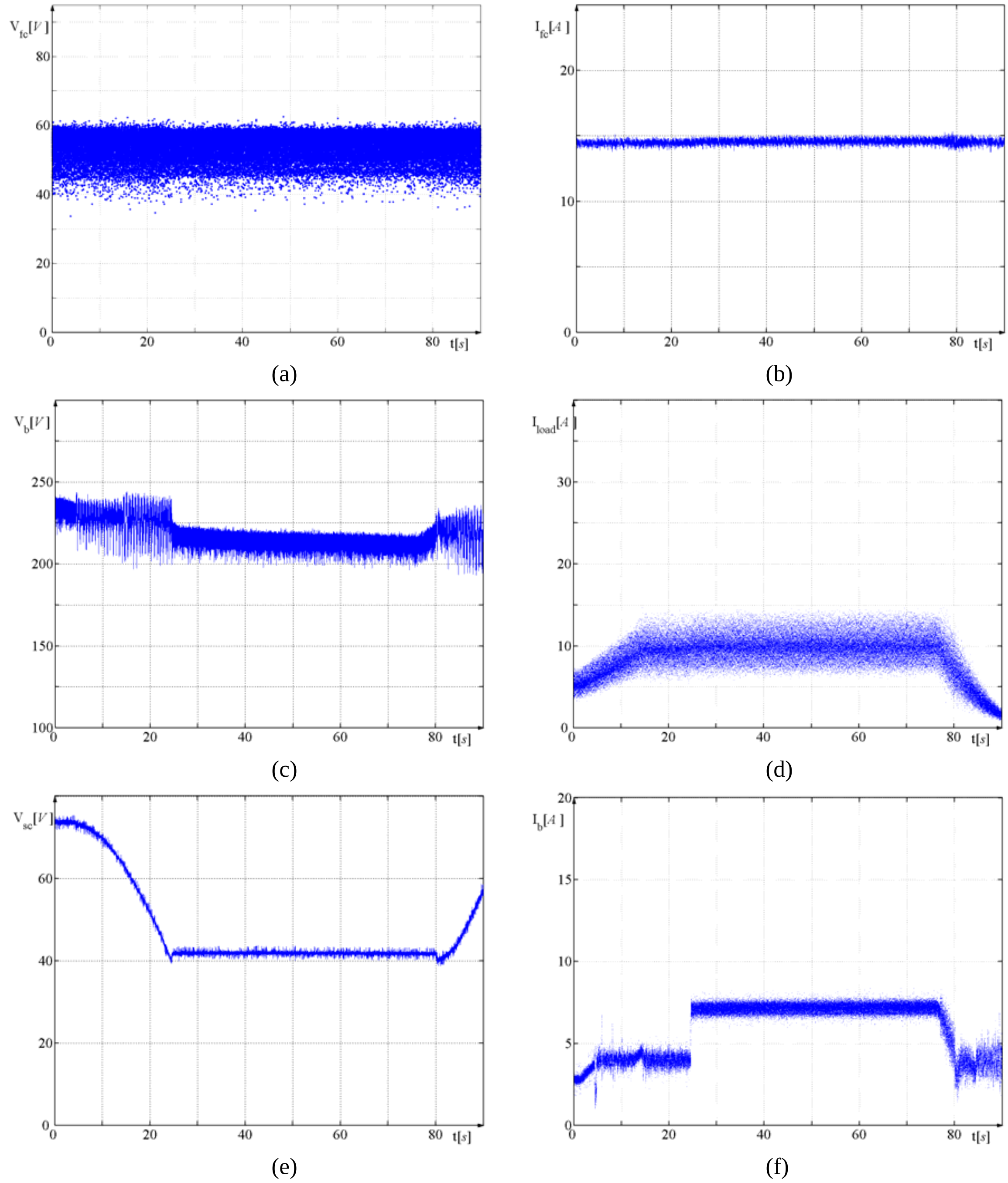

Fig.6- Experimental results of the first duty-cycle considered: fuel cell voltage (a), fuel cell current (b), supercapacitor voltage (c), VSI dc current (d), battery current (e) and dc bus voltage (f)

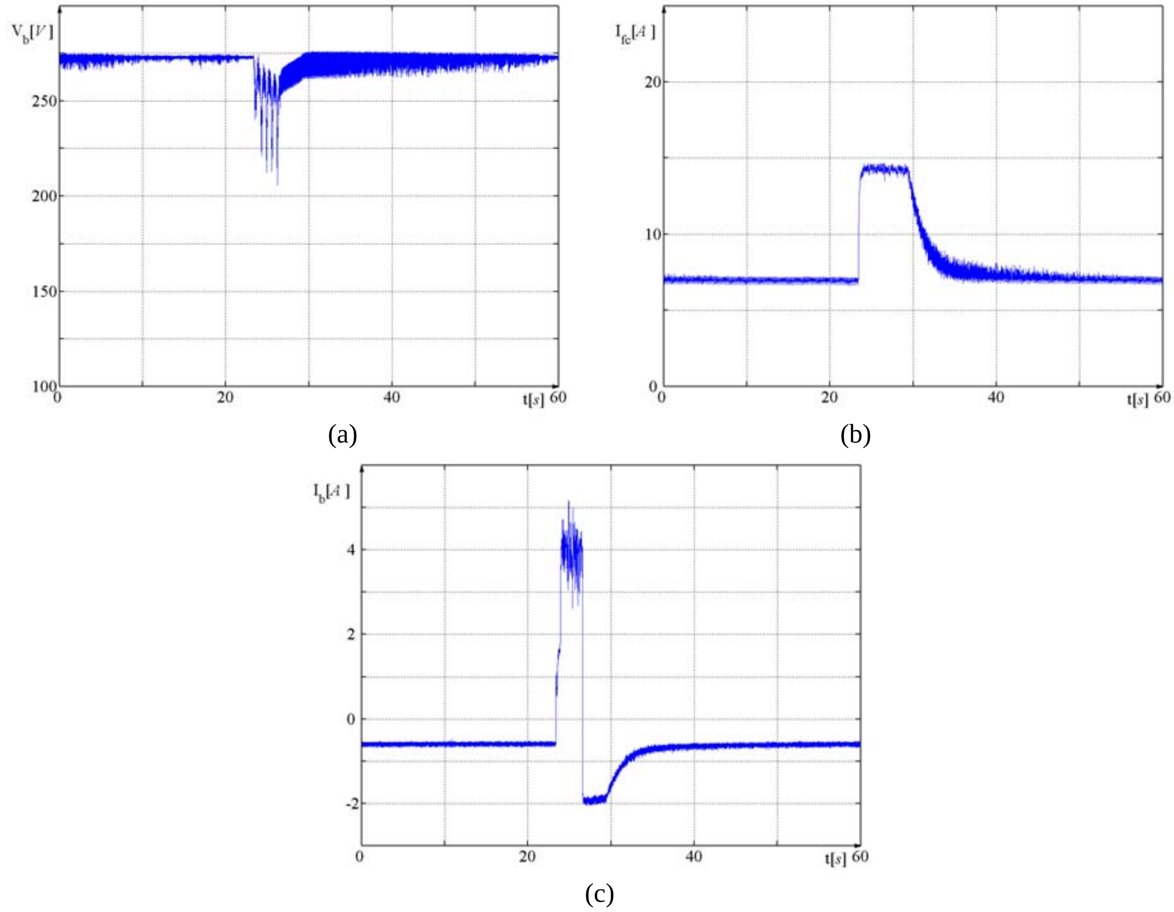

Fig.7- Experimental results of the second cycle test: dc bus voltage (a), fuel cell current (b), battery current (c)

4. Conclusions

Nowadays the compound storage and generation systems represent an extremely efficient solution for stand alone generation systems based on renewable sources. The integration of different technologies produces very good performances but in compound systems must be preliminarily defined a proper strategy to control the power flows. In the paper a simple control strategy has been proposed with reference to a system constituted by electrochemical batteries, supercapacitors and an auxiliary fuel cells generation source. In particular the control strategy aims to keep constant the fuel cell power and to limit the charge and discharge batteries current. The strategy control implementation is done by means of two hierarchical control algorithm set-up for the converters.

The validation of the proposed solutions has been done by means of experimental tests on electrical drives evidencing good performances.

References

[1] Yang, J.M.; Cheng, K.W.E.; Wu, J.; Dong, P.; Wang, B.: *"The study of the energy management system based-on fuzzy control for distributed hybrid wind-solar power system"*, Proc. of the 1st International Conference on Power Electronics Systems and Applications (2004), pp. 113 – 117

[2] Agbossou, K.; Kolhe, M.; Hamelin, J.; Bose, T.K.: *"Performance of a stand-alone renewable energy system based on energy storage as hydrogen"*, IEEE Trans. on Energy Conversion (2004), vol. 19, issue 3, pp. 633 – 640

[3] Duryea, S.; Islam, S.; Lawrance, W.: *"A battery management system for stand-alone photovoltaic energy systems"*, IEEE Industry Applications Magazine (2001), vol. 7, issue 3, pp. 67 – 72

[4] Muller, H.; Rudolf, A.; Aumayr, G.: *"Studies of distributed energy supply systems using an innovative energy management system"*, 22nd International Conference on Power Industry Computer Applications (2001), pp. 87 – 90