

Short communication

# The use of battery–capacitor combinations in photovoltaic powered products

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Received 27 January 2005

Available online 11 August 2005

## Abstract

This paper analyzes smart combinations of rechargeable batteries and capacitors in energy storage media of photovoltaic (PV) powered products. Important in a mature design of such products is an efficient energy transfer from PV converter into the storage media and from storage towards the energy consuming application. In this paper, an introduction sets the stage for combining batteries and capacitors followed by a background section, a section on experiments and a synthesis section analyzing the test results and anticipation on future developments. The final section presents a summary of conclusions.

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*Keywords:* Mature design; Photovoltaic (PV); Battery–capacitor combinations; Energy conversion; Sustainable products; Synergy

## 1. Introduction

In photovoltaic powered products, the energy of the photovoltaic cells can either be used directly or can be used to recharge batteries, which in turn can power the application electronics [1]. Important in a mature design of such photovoltaic (PV) powered products is an efficient energy transfer; on one side from the PV cells as energy provider into the energy storage media and on the other from the energy storage media towards the energy consuming application. More specific in this paper, the storage media is not restricted to rechargeable batteries only but is extended to include capacitors–battery combinations.

In literature, battery–capacitor combinations are mainly used in high-current pulse applications [2,3]. In these combinations, the advantage of high power density or the ability to deliver large discharge rates by the capacitor is combined with the high energy density of the battery. The combination in this case yields more than the two components separately, so a good example of synergy. This capacitor in these examples is placed at the output side of the battery. In this paper,

however, the entire energy chain of PV powered products is analyzed. The features introduced by placing capacitors at the input circuitry of the battery between the PV cells and the battery will be highlighted. The central questions here are: can capacitors improve the matching between PV cells and the battery, and can the additional capacitors improve the energy transfer from PV cells into the battery?

## 2. Why battery–capacitor combinations?

### 2.1. General

Before analyzing battery–capacitor combinations, let us look at the particular features of batteries and capacitors, which could make this combination favourable.

In applications of Li-ion batteries, large discharge currents will generate heat, which could result in an efficiency reduction of the conversion of chemical to electrical energy. Moreover, this elevated temperature will cause an increase of the internal resistance and capacity fading [4–7]. Delivering large current surges is not quite the favourite use of Li-ion batteries. Capacitors on the other side can discharge in an exponential way and can, therefore, deliver large current

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pulses. This feature is in particular advantageous for product applications in which large currents need to be drawn, such as for example, at initialization stage of electro-motors to overcome stiction and products with large inrush currents. Also, they can be used to cope with the increasing demands for current peaks in digital circuitry. By placing the capacitor in the output circuitry of the battery, e.g. in parallel, the battery is prevented from unnecessary deep-discharge cycles, since the current can in this combination be drawn from the capacitor [8]. Such a battery–capacitor combinations results in a better reliability and longer battery life, or in a more sustainable product. This is a clear demonstration of synergy. Note, however, that this advantage is only possible at the expense of increased weight and volume of the storage system [9].

In this paper, the storage media are taken as the central part of the energy chain. So, the discussion on the means to improve energy transfer efficiency is divided along the two sides of the storage media namely: on one side to store as much as possible energy coming from the PV cells into the storage media and on the other to use the available stored energy as efficient as possible. The first mentioned means will be really PV powered product related; while those concerning storage and usage efficiency improvement can be more or less considered as applicable to any product which has an energy supply that uses rechargeable storage media. Both tracks of improvement are, however, treated in this paper to stress the integral approach of the whole energy chain. Combining PV with a suboptimal energy-consuming product would be a bad immature design.

## 2.2. Storing photovoltaic energy

### 2.2.1. Some benchmark experiments

The mechanisms for storing photovoltaic energy into Li-ion batteries were analyzed in some benchmarking experiments on solar-batteries. In these solar-batteries, which were designed to replace conventional batteries in cellular phones, the battery is directly coupled and recharged by photovoltaic cells. These benchmarking experiments show that:

- Direct recharging of Li-ion batteries by photovoltaic cells is possible. To obtain a fully charged battery, however, it usually took a longer time than grid recharging. Placing the PV-battery for instance in summer on the windowsill, a 12 h charge is needed instead of the 3 h by the mains grid.
- The battery capacity during lifetime decreases more rapidly in the solar-batteries than in the standard cellular batteries. After 1 year benchmarking, a fully charged solar-battery could power a cellular phone for 4 days, while the standard battery recharged on the grid could power the phone up to 6 days. This is a clear demonstration of capacity fading in the solar-battery.

Storing photovoltaic energy directly in batteries seems not be quite efficient. For a logical explanation for these discrepancies, we have to return to the basics of Li-ion cycling.

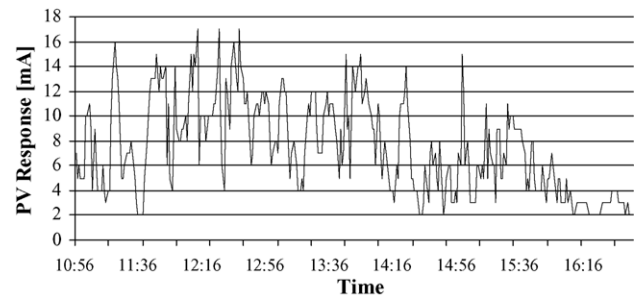


Fig. 1. Typical output of a photovoltaic cell during 1 day.

As a start, one could pay attention to the main requirements for proper recharging of these batteries. For instance, there is certain minimum requirement of constant current (CC) and voltage (CV) to be met. During recharging the current is kept constant till a voltage of 4.1 V is reached, then the voltage is kept constant at 4.1 V, and as a result of increasing internal resistance the current diminishes.

Measurements on the photovoltaic-batteries show that the PV recharge current delivered is smaller than the recommended  $C/2$  value; it, therefore, results in a longer recharging time. In addition, the current coming directly from a photovoltaic cell due to the weather conditions is not constant. Quite often as a result of cloud formations passing in front of the sun, the current will be fluctuating as can be seen in Fig. 1.

The result of this fluctuating input current is a recharging sequence that is quite often interrupted. The battery is charged for a while but before it is fully charged it is already partially used or discharged. Whether this is causing capacity fading is not clear, since each interruption will be counted as one new cycle. Note, however, that these cycles are shallow discharge cycles. For Li-ion batteries, it is claimed that the Department of discharge (DOD) would not determine the maximum number of charge–discharge cycles or lifetime [10,11]. On the other side, small discharges and pulsed charging are claimed to enhance battery lifetime [12]. So, the poor performance of this solar-battery cannot completely be explained.

### 2.2.2. Quick recharging of energy storage media

It would be preferable and really advantageous for mobile applications like cellular phone and digital cameras to have the ability of quick recharging its batteries. The drawback, however, of these quick recharge sequences is an elevated temperature, which results in the loss of battery capacity and in a reduced battery life [11].

A possible solution could be the use of capacitors [13]. Here, the exponential charge curve of capacitors is exploited for quick collection of the available current. After storing the current in the capacitor, the actual recharge of the battery then can take place in a much longer time scale. The capacitor buffer can be used for reducing the battery charge current and as a result, the temperature of the battery will not surpass the critical limit during recharging. This in turn will reduce the capacity fading due to cycling at elevated temperature [5,6].

So, the use of capacitors in combination with batteries could yield:

- Means for quick collection of the available energy, which then can be slowly transferred and stored into a battery. By slow charging, the battery temperature will not rise excessively, avoiding a decline in capacity and lifetime.
- Means for quick emergency charging.

### 3. Experiments

Since experiments on the use of capacitors to enhance the pulse output of batteries have been reported frequently in literature [2,3], we focussed in our experiments on the interface between PV cells and battery and the advantage of using capacitors at the input of Li-ion batteries.

#### 3.1. Capacity fading in imperfect re-charged Li-ion batteries

In the framework of research on PV powered medical products, the influence of charge characteristics during charge–discharge cycles on the energy density and capacity of Li-ion batteries was investigated by a group of students in a Project Advanced Products (PAP) task at our faculty [14].

They found that indeed the capacity of Li-ion batteries decreases each cycle. This decrease is even larger if the battery is not fully charged each cycle. They found a degradation of about 2% in 37 cycles.

#### 3.2. Efficiency of charging capacitors

Charging a capacitor by a photovoltaic cell means that the charging current will be fluctuating as can be seen in Fig. 1. Therefore, we investigate how the charging efficiency depends on the charging current. This charging was executed in two ways as can be seen in Fig. 2a and b:

- directly without any other interface component;
- with the aid of an inductance which acts as a charge buffer.

The results are presented in Fig. 3.

The direct method yields a large dependency of the efficiency on the level to what extent the capacitor has been charged. The inductance improved the efficiency significantly and made it less dependent on the state of charge.

#### 3.3. Efficiency of energy transfer from capacitors to Li-ion batteries

Having the energy of the photovoltaic cell stored in a capacitor as buffer, the next step would be to transfer this energy into a battery. To test transfer efficiency, we used a DC/DC converter that kept the input voltage of the battery constant at about 4.1 V. During recharging, however, the internal resistance of the battery increases, therefore, the

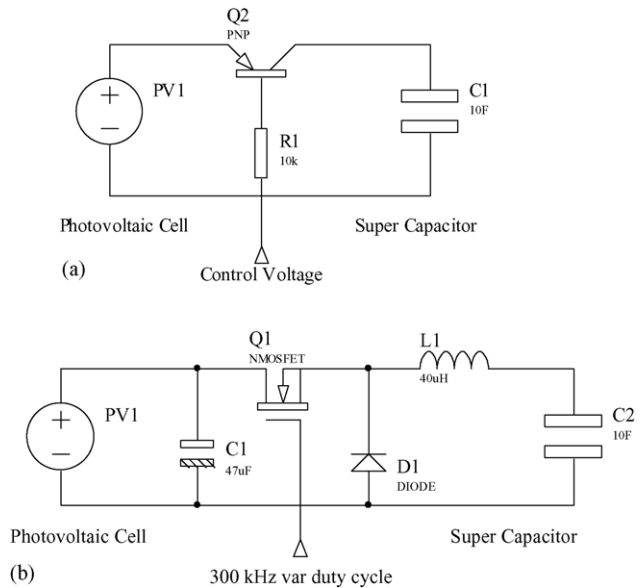


Fig. 2. (a) Direct charging of capacitor (linear) and (b) charging of capacitor via inductance (switching).

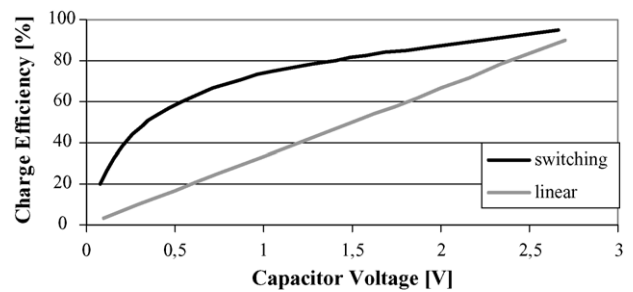


Fig. 3. Capacitor voltage vs. charge efficiency.

load varies resulting in an amount of power ranging from 802 down to 8 mW. The DC/DC converter has two modes: a buck-boost mode and a burst mode. Figs. 4 and 5 show that the efficiency depends on the load. Below the 34.5 mW, the DC/DC converter must switch from buck-boost mode to burst mode.

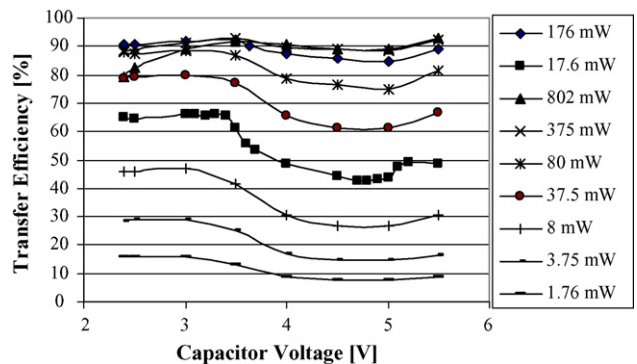


Fig. 4. The DC/DC switching regulator in buck-boost mode.

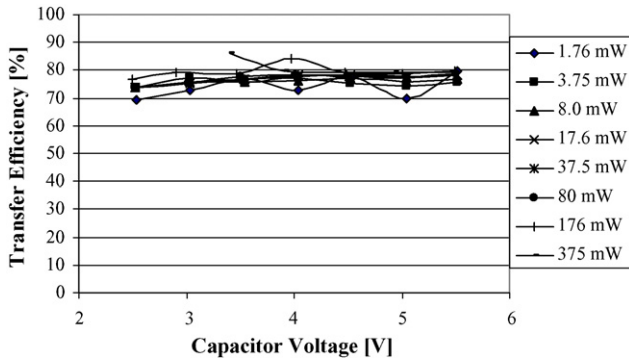


Fig. 5. The DC/DC switching regulator in burst mode.

## 4. Synthesis and design strategies

### 4.1. Lessons learned from the benchmark experiments on solar-batteries and other experiments

To circumvent the drawbacks encountered during the benchmark experiments of the solar-battery one could use capacitors in combination with PV rechargeable batteries for the following cases:

- to buffer the PV current, and therefore reduce the number of cycles induced by fluctuating solar irradiance;
- to buffer the PV current and to allow a well defined recharging of the battery from the capacitor.

The use of capacitors in a combined battery–capacitor system would, therefore, improve the battery performance by improving the recharging sequence and prolong battery life and yield synergy.

### 4.2. Synthesis

In PV powered products, capacitors are found to be useful both at the input and the output of the battery. The implementation is, however, defined by the actual function to be executed. As mentioned earlier, the addition of capacitors at the output to improve the surge capacity of the battery will be at the expense of larger weight and volume and should, therefore, be tuned to the application. The use of super-capacitors will reduce significantly the volume and weight. On the input side, the buffer function of the capacitor will be the main advantage.

### 4.3. Future developments

#### 4.3.1. Enhancing the power and energy density of energy storage media

To enhance the energy density of super-capacitors, new concepts have emerged in which one of the electrodes of the capacitor is transformed in a battery-type electrode. These combinations are usually referred to as an ‘asymmetrical’ device [15].

#### 4.3.2. Interfacing PV and energy storage media

Recent developments are the photocapacitor, which combines a dye sensitized PV cell (DSC) with a super-capacitor in one device [16]. The photogenerated charges are stored at the electric double layer of the capacitor. In view of the use of capacitors as buffer to improve the transfer efficiency from PV cells into batteries, this device could be a potential candidate.

## 5. Conclusions

- Definitely an added value is introduced by a combined battery–capacitor power supply in PV powered products both at the input and the output of the battery. A clear demonstration of synergy.
- In case a capacitor is used as a buffer between photovoltaic cell and battery the transfer efficiency depends on smart discrimination of the switch-point between buck-boost and burst mode.
- There will be a break-even-point reached in which it will be no more advantageous to have the complicated construction of combining batteries with capacitors simply because the technological performance improvement of the batteries have counterbalanced the additional complication of this combination.

## Acknowledgment

This research is funded by NWO, the Netherlands Organization for Scientific Research.

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