PV Charger System Using A Synchronous Buck Converter

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Abstract. The paper describes the design, simulation and practical implementation of a PV system specifically designed for battery charging applications. A DC-DC synchronous Buck converter is digitally controlled by a dsPIC33F to extract the maximum power from the PV panel and feed it to the battery, according to the data received through the sensors. The system proves to be stable to rapid weather changing conditions due to the MPPT algorithm together with the two PI controllers.

1 Introduction

The energy demand increase continuously during last years, consolidating the position of the renewable sources like the photovoltaic panels and wind generators. Although still expensive compared with the conventional sources, the renewable energy offers certain long term advantages like the “eco friendly” property. The renewable energy becomes now a competitive alternative to the conventional sources as his price continuous to drop over the years. The solar energy is probable the best known for his fast growth during last decades. Some studies (a projection by the International Energy Agency) states that within fifty years most of the energy will be produced by the solar generators. The solar energy can be directly converted into electricity by meaning of the photovoltaic cells (PV). However, some technical challenges are associated with the PV panels that must be overcome in order to get the full advantage of this kind of energy generators. This paper will present the implementation of a solar battery charger that can be used to provide electricity to a fully autonomous system.

2 The PV Cell

A PV cell is basically a large photodiodethat will convert the incident solar energy to electricity based on the well known photovoltaic effect. The electrical equivalent model of a PV cell is depicted in Figure 1.

![PV cell equivalent model](image)

Fig 1: PV cell equivalent model [1]

A PV panel is made from n cells connected in series like in Figure 2. The cell must be identical in terms of the electrical characteristics. The current source in Figure 1, \( i_{sun} \), is proportional to the amount of irradiation, and linear with respect to the PV cell temperature. The current is given by Equation 1:

\[
i_{cell} = \frac{i_{sun}}{n}
\]
where $i_{sun}$ and $i_{sun,STC}$ is the short circuit current at the given working point and STC (standard test conditions), respectively. The constant $k_{temp}$ is the temperature coefficient of $i_{sun}$. $T_{cell}$ and $T_{cell,STC}$ are the actual and STC cell temperatures, respectively. Finally $P_{sun}$ and $P_{sun,STC}$ are the irradiances at the present operating point and at STC, respectively [1]. The current through the diode is expressed by Equation 2,

$$i_d = i_S \left( e^{\frac{q u_d}{k A T_{cell}}} - 1 \right)$$

where $i_S$ is the reverse saturation current, $A$ is the diode idealization factor (usually defined between 1 and 5), and $u_d$ is the voltage across the diode.

The PV cell equivalent model contains some additional elements $R_p$ and $R_s$. These circuit elements are associated with parasitic like the connection wires between cells. A more detailed description of these parasitic elements is found in [4]. The $C_{cell}$ is the capacity associated with the PN junction of the diode. Finally, the current, voltage and power generated by a single PV cell are expressed by the Equations (3), (4) and (5).

$$i_{cell} = i_{sun} - i_d$$

$$u_d = u_{cell} + R_s \times i_{cell}$$

$$P_{cell} = u_{cell} \times i_{cell}$$

A family of curves that plot the $i_{cell}$ and $u_{cell}$ versus the irradiation is depicted in Figure 3 [1].

The power delivered by the PV cell under different irradiation conditions is depicted in Figure 4 [1].

The power delivered by the PV cell has a maximum at certain voltage and this maximum depends on the irradiation. In order to extract the maximum available power delivered by the PV panel in certain illumination conditions, a certain techniques must be implemented in the system that process the photovoltaic energy (ex. a battery charger or a grid connected inverter).
3 The Maximum Power Point Tracking (MPPT) algorithms

The main problem solved by the MPPT algorithms is to automatically find the panel operating voltage that allows maximum power output. In a larger system, connecting a single MPPT controller to multiple panels will yield good results but in the case of partial shading the combined power output graph will have multiple peaks and valleys (local maxima). This will confuse most MPPT algorithms and make them track incorrectly. Some techniques to solve problems related to partial shading have been proposed but they either need to use additional equipment (like extra monitoring cells, extra switches and current sensors for sweeping panel current) or complicated models based on the panel characteristics (panel array dependent). These techniques only make sense in large solar panel installations and are not the scope of this paper.

Ideally, each panel or small cluster of panels should have their own MPPT controller. This way the risk of partial shading is minimized, each panel is allowed to function at peak efficiency and the design problems related to converters handling more than 20-30 Amperes are eliminated. A typical solar panel power graph in Figure 5 shows the open circuit voltage to the right of the maximum power point. The open circuit voltage (V\textsubscript{OC}) is obviously the maximum voltage that the panel outputs, but no power is drawn at this voltage. The short circuit current of the panel (ISC) is another important parameter because it is the absolute maximum current you can get from the panel.

![Solar Panel Power Graph](image)

The literature on this subject generally agrees that the maximum amount of power that can be extracted from a panel depends on three important factors: irradiance, temperature and load. Matching panel and load impedances with a DC-DC converter makes sense because for example if you have a 5V/2A load and a 20W panel that has the MPP at 17.5V/1.15A, connecting the load directly won’t even work. Considering a simple resistive load, and the short circuit current of 1.25A, the panel will only be able to provide about 3V/1.2A or less than 4W out of 20W.

Temperature mainly changes the panel voltage operating point while irradiance mainly changes the panel operating current. The available power at certain moment will depends on the atmospheric conditions, the sun irradiance and the temperature. The MPPT algorithm will ensure that the maximum available power is extracted from the PV regarding the atmospheric conditions.

There are a few MPPT algorithms that can be easily implemented using an 8/16-bit microcontrollers. Most notables are the “Fractional Open Circuit Voltage”, “Fractional Short Circuit Current”, “Perturb and Observe” and “Incremental Conductance”. The first algorithms have some drawbacks that make them “suboptimal” for the MPPT implementation. The “Perturb and Observe” algorithm will be described and implemented in this application.
4 Perturb and Observe (P&O) algorithm

This is one of the most discussed and used algorithms for MPPT. The algorithm involves introducing a perturbation in the panel operating voltage and observing the effects in the output power. The flow chart of this algorithm is depicted in Figure 6.

![Flowchart of Perturb and Observe Algorithm](image)

Looking at Figure 6 makes it easy to understand that decreasing voltage on the right side of the MPP increases power. Also increasing voltage on the left side of the MPP increases power. This is the main idea behind P&O algorithm. Modifying the panel voltage is done by modifying the converter duty cycle. The way this is done becomes important for some converter topologies.

Let’s say that after performing an increase in panel operating voltage, the algorithm compares the current power reading with the previous one. If the power has increased it keeps the same direction (increase voltage), otherwise changes direction (decrease voltage). This process is repeated at each MPP tracking step until the MPP is reached. After reaching the MPP, the algorithm naturally oscillates around the correct value. The basic algorithm uses a fixed step to increase or decrease voltage. The size of the step determines the size of the deviation while oscillating about the MPP. Having a smaller step will help reduce the oscillation but it will slow down tracking, while having a bigger step will help reach MPP faster but will increase power loss when it oscillates. To be able to implement P&O MPPT, the application needs to measure the panel voltage and current. While implementations that use only one sensor exist, they take advantage of certain hardware specifics, so a general purpose implementation will still need two sensors.

5 MPPT Hardware Platform

The implementation is usually a kind of DC-DC converter with current and voltage sensors on the input side (solar panel). If battery charging is implemented on the same platform, then another set of current and voltage sensors is required on the output side. For this application the synchronous Buck converter with digital control was chose. The block schematic is depicted in Figure 7. The entire MPPT and charging algorithm is fully digitally controlled by the microcontroller. Two PI controllers that run concurrently are used to regulate the output voltage and current in order to implement the charging sequence from Figure 8.
In order to implement the MPPT and charging algorithms, the input and output voltages and currents are monitored with sensors. The battery is a sealed acid, 12V nominal one. The typical charging algorithm for sealed acid batteries is presented in Figure 8. As we can see in this figure, the constant current charge period lasts somewhere between 4-6 hours depending on the battery and charges it roughly 70% of the nominal capacity. The remaining 30% of required energy is filled with the slower voltage constant charge that lasts another 6-9 hours. The last stage of the battery charging (float charge) is essential for the well-being of the battery as it compensates for self-discharge and keeps the battery at full charge. If this stage is not performed in time, the battery will lose the ability to receive full charge and due to sulfation, the performance will decrease.
A Simulink© model was developed in order to validate the proposed MPPT algorithm. The diagram is depicted in Figure 9. The hardware was constructed around the dsPIC33FJ16GS502 digital signal controller (DSC) from Microchip. Block schematic of the practical PV charger and the associated waveforms for the input and output voltages are depicted in Figure 11 and Figure 12. The practical results of the prototype (fig.13) are well correlated with the simulation. The main disadvantage of P&O MPPT algorithm is the relatively high ripple produced in the PV voltage. This ripple is associated with some power losses but even in these conditions the algorithm can extract more than 95% of the PV available power. Some tuning of the final application is necessary to achieve the maximum performance. The low computational power requested by this algorithm make possible implementation on a low cost, 8 bit microcontrollers. The overall performance is good and make this algorithm the most popular when for implantation of the MPPT controllers.

6 Conclusions

A PV charger that implements the Perturb & Observe algorithm was developed in order to maximize the power transfer from the PV panel to the battery. The Simulink© model match well the behaviour find in the practical implementation. The simplicity recommends this algorithm to be used by low cost microcontrollers. However, the drawbacks of this algorithm can be overcome by more advanced algorithms like the “Incremental Conduction” that will require more computational power. Further work will concentrate on the more advanced algorithms that will improve the performance of the MPPT controller.

References