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Digital control strategy for a buck converter operating as a battery charger for stand-alone photovoltaic systems ☆

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ABSTRACT

This paper presents the design of a digital control strategy for a dc-dc type Buck converter used as an efficient lead acid battery charger in isolated electric photovoltaic systems. The strategy is designed to be implemented in a digital signal processor (DSP). The control acts depending on the state of charge of the batteries by regulating the drive duty cycle with the proper combination of incremental conductance MPPT technique and precise control of the battery current according to three charging stages, providing a joint solution which on one hand maximizes the production of solar energy available in the PV array, and on the other ensures a long battery lifetime, both aspects, which are generally investigated independently in technical literature, are treated simultaneously in our approach. The work explains in detail the converter modeling, the project of the compensator, as well as the development of MPPT used. Validation simulations are done via Matlab and experimental results from a prototype low power TMS320F2812 using a DSP from Texas Instruments, are provided and discussed, which show satisfactory performance of the proposed control system.

1. Introduction

The stand-alone PV system is characterized by having as a primary source the energy generated only by the PV panels. Therefore, a battery bank to store the captured energy to ensure power supply during the night or in periods with low solar radiation is necessary. Maintenance free lead-acid batteries are the main choice for stand-alone photovoltaic systems, due to their excellent cost-efficiency (Eftichios and Kostas, 2011; Hirech et al., 2013; Salas et al., 2006) and its availability in the market for a wide power band.

With regards to the high investment cost of a photovoltaic installation, these systems require maximizing the use of solar energy and reserve energy storage, to achieve the technical and economic sustainability (Desconzi et al., 2010).

The maximum use of electricity from a solar panel is obtained when it operates at maximum power point (MPP). This point varies depending on atmospheric conditions to which the panel is exposed. One must track the MPP at any weather condition. Approaches and techniques based on this principle are referred as MPPT (maximum power point tracking) and can increase the energy produced between 30 and 40% (Taghvaee et al., 2013).

An MPPT approach requires a dc-dc converter as an interface between the PV array and battery bank. The task of the MPPT is to control the duty cycle of the converter to regulate its voltage or current input and match the voltage and current of maximum power of the PV array under such atmospheric conditions.

Over the past few years, various types of control for dc-dc converters used as battery chargers in photovoltaic systems have been proposed. A widespread philosophy is to directly control the drive duty cycle thorough some MPPT algorithm to extract the maximum instantaneous power in PV panels, as shown in Eftichios et al. (2001), Anastasios et al. (2015), Cougo et al. (2007), Shaowu et al. (2013). This approach has an inconvenient: it adds stress to the switches and increases switching losses (Kislovski, 1990). Some authors propose incorporating PI control loops of current and/or voltage to interfere on the duty cycle of the converter as a compensating presence that reduces converter set-up time and avoids overshoot and oscillation, thus improving the dynamic response of MPPT, as is shown in Villalva et al. (2009, 2010), Enslin and Snyman (1992). In Eftichios and Kostas (2011), Chihchiang and Pi-Kuang (2005) the authors propose settings where the MPPT operates in combination with a load control algorithm of on-off

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type, where the concept and strategy of load regulation depends on the battery voltage and state of charge (SOC).

Clearly, the information referred to the control of dc-dc converters for photovoltaic applications is wide, although most of the work deepens the analysis of the MPPT algorithm and how it impacts on the PV panel efficiency. By 2005 at least nineteen different MPPT techniques were introduced in literature (Esram and Chapman, 2007). On the other hand, usually, little attention is given to the control of the converter as a battery charger, but the lead acid batteries require precise control of their loading and unloading processes to avoid shorten battery lifetime. This is of vital importance in isolated photovoltaic systems, where the battery bank is surely one of the most expensive components of the system, reaching 30% of total investment (Enslin et al., 1997) or even up to 46% when considered the maintenance costs (Desconzi et al., 2010). This increase in cost is mainly due to inefficient management of the battery charging and discharging processes which can lead to replacements of the batteries prematurely (Samuel et al., 2006).

Various techniques and algorithms for charging batteries have been used as reported in the literature: constant current, constant voltage, on-off, among others; these techniques often present the problem of not fully charging the battery, and also not protecting from premature aging (Hirech et al., 2013). On the other hand, three stages charging is the method most lead acid battery manufacturers recommend as the best and most efficient way to return full capacity to the battery and extend its useful life (Chargetek Inc., 2015).

This work presents in this context, a digital control strategy for a Buck power converter used as an efficient lead-acid battery charger on stand-alone photovoltaic system. The control strategy proposed here operates on battery SOC function, regulating the converter duty cycle aiming at two main purposes: on one hand, ensure maximum utilization of solar energy available in the PV array by using the MPPT incremental conductance algorithm, and otherwise extend the life of the battery bank through precise control for the battery load in three stages. The controller developed is based on a typical structure of two PI loops in cascade.

The Buck is modeled through the technique of moving averages in state space (Erickson and Maksimovic, 2001). The MPPT algorithm is described in detail and the design of analog compensators uses the technique known as factor k (Venable, 1983). Finally, the achievement of the digital compensators is done through classical discretization techniques using the indirect method.

Matlab/Simulink simulations and experimental results from a low-power prototype using a DSP TMS320F2812 from Texas Instruments are provided to prove the reliability and validity of the proposed control strategy.

2. Modeling

This section presents the PV model and the Buck converter small signal model.

2.1. Photovoltaic panel model

The simplest equivalent circuit of an ideal cell is that of a current source in parallel with a diode, having a series resistance, R_S that describes the voltage drop, the losses of the semiconductor material, the metallic contacts and their junctions. Another resistance in parallel R_P describes the losses of the electrical perturbations and perturbations in the PN transition zones. Fig. 1 shows the photovoltaic model where I_{PH} represents the generated current for a given radiation, the diode D represents the PN junction, I is the current produced by the cell to the external circuit, V is the voltage at the output terminals.

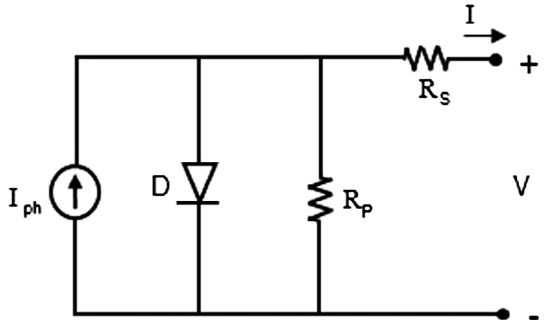

Fig. 1. PV cell model.

Eqs. (1)–(3) describing the PV cell model (Yu et al., 2004):

$$I = I_{ph} - I_r \cdot \left[e^{\frac{q\cdot(V+I\cdot R_S)}{n\cdot k\cdot T}} - 1 \right] - \frac{V + I \cdot R_S}{R_P} \tag{1}$$

$$I_r = I_{rr} \cdot \left(\frac{T}{T_r} \right)^3 \cdot e^{\left[\frac{q\cdot E_G}{n\cdot k} \cdot \left(\frac{1}{T_r} + \frac{-1}{T} \right) \right]} \tag{2}$$

$$I_{ph} = [I_{SC} + \alpha \cdot (T - T_r)] \cdot \frac{P_{sun}}{1000} \tag{3}$$

where I_r is the reverse saturation current, n the ideality factor of the junction, T the environment temperature, q the electron charge, k the Boltzmann constant, I_{SC} the short circuit current, α the short circuit temperature coefficient of the cell, T_r the reference temperature, P_{sun} the incident radiation, I_{rr} the reverse saturation current at T_r and E_G the silicon band-gap energy.

2.2. Model of the Buck converter

For linearization of the Buck converter the moving average in state space model is used (Erickson and Maksimovic, 2001). The method is widely used for modeling of switched power converters operating with PWM control. It consists of obtaining the weighted average state of circuit with respect to the operating duty cycle over a switching period.

2.2.1. State equations

The effects of resistive losses R_L in the inductor, and resistance equivalent of the series capacitor R_{SE} were included to obtain a more accurate model for Buck. The switch and the diode were considered ideal, the voltage supplied by the PV array was represented by a voltage source V_{PV} and the load current disturbance, by I_P. For the purpose of simplifying the analysis and since the model was control design oriented, the battery bank was simulated as a simple resistive load R. Fig. 2 shows the Buck circuit used in modeling.

In a buck converter, the control system regulates the switching of the electronic switch according to a duty cycle d, which corresponds to the amount of time of the switching period T, wherein the switch is conducting. The equivalent Buck circuit, during the time interval dT the switch is on, is given in Fig. 3(a). When the switch is off, during the time $(1-d)T$, the equivalent circuit is that of Fig. 3(b). Each circuit can be described using a state model. The state and inputs variables can be defined as:

$$x_1 = i_L(t),\ x_2 = v_C(t):\ \text{state}$$
$$V_{PV}(t),\ i_P(t):\ \text{Input}$$

The circuit for the buck converter when the switch is conducting can be represented by the differential Eqs. (4) and (5) and the one for when the switch is open is given by (6) and (7):