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A maximum power point tracker for PV systems using a high performance boost converter

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Abstract

This work deals with the design and experimental implementation of a MPP-tracker for photovoltaic systems, which is a high efficiency dc/dc boost converter operating in continuous conduction mode (CCM). The converter is able to draw maximum power from the PV panel for a given solar radiation level and environment temperature by adjusting the duty cycle of the converter. Additionally, a passive nondissipative turn-on turn-off snubber is used, so that high efficiency and reduced electromagnetic interference (EMI) levels due to the soft switching operation can be obtained. The snubber improves the converter efficiency since the energy that would be dissipated during turning on and turning off is transferred to the load. The control technique, implemented with a single-chip microcontroller 80C51, is based on the perturbation and observation method, where the maximum power point is tracked with periodical calculation of the panel output power. Simulation and experimental results describe the performance of the proposed MPP-tracker.

Keywords: Photovoltaic systems; Maximum power point tracker; Boost converter; Microcontroller

1. Introduction

During the Kyoto conference on climate change (COP3) held in December 1997, it was agreed that by the year 2012 the developed countries would reduce at least 5% of the greenhouse gas emissions compared with the year 1990 (Muhida et al., 2003). Moreover, energy shortages, such as the Brazilian and Californian energy crisis in 2001, and also the need for sustainable energy systems, have enforced the search for energy supplies based mainly on renewable energy resources. Many renewable energy technologies today are well developed, reliable and cost competitive compared with conventional fuel supplied generators.

Photovoltaic (PV) generation assumes increased importance as a renewable source due to advantages such as the absence of fuel cost, little maintenance and no noise and wear due to absence of moving parts. However, two important factors limit the implementation of

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Nomenclature

PV	photovoltaic
MPP	maximum power point
CCM	continuous conduction mode
EMI	electromagnetic interference
PWM	pulse width modulation
I	current
V	voltage
V_{oc}	open circuit voltage
I_{sc}	short circuit current
P_{MPP}	maximum power point
S_b	boost converter switch
A/D	analog-to-digital
P&O	perturbation and observation
V_P	photovoltaic panel voltage
I_P	photovoltaic panel current
P_A	actual output power
P_P	previously measured output power
L_s	commutation cell inductor
C_s	commutation cell capacitor
C_a	commutation cell storage capacitor
D_{s1}, D_{s2} and D_{s3}	commutation cell diodes
ZCS	zero current switching
ZVS	zero voltage switching
D	duty cycle

photovoltaic systems i.e. high cost and low efficiency in energy conversion. In photovoltaic systems, the PV panel represents 57% of the total cost of the system, and the battery storage system corresponds to 30% of the cost. Other system components such as inverters and MPP-tracker contribute only with 7% (Hua and Lin, 2003). Due to the high cost of solar cells, it is necessary to operate the PV panel at maximum power point (MPP). The maximum power produced by a solar cell changes with solar radiation and temperature. A PV panel is a nonlinear power source, because the output power depends on the load voltage, and weather conditions, which are unpredictable. In order to optimize the ratio between output power and cost of installation, photovoltaic systems are supposed to draw maximum power from the modules continuously, regardless of weather conditions or load voltage. Maximum power point trackers, commonly known as MPP-trackers, are systems that operate PV modules so that maximum power can be achieved. A MPP-tracker is not a mechanical tracking system that "physically moves" the modules to make them point more directly at the sun, but an electronic system that varies the electrical operating point of the modules so that they are able to deliver maximum power. It can be used with a mechanical tracking system, but the systems are completely different.

MPP-trackers have been widely implemented with several techniques and power conditioners. In the work developed by Maheshappa et al., the PV array voltage (or current) is compared with a constant reference voltage (or current), which corresponds to the PV voltage (or current) at the maximum power point, under specific atmospheric conditions, as MPP will depend on the chosen reference. In the work proposed by Medeiros and Antunes, the neural network requires a new training at each change of the system size. The incremental conductance method (Solodovnik et al., 2004) leads to good accuracy in tracking the MPP even under rapidly changing weather, but a digital signal processor (DSP) is necessary in the implementation.

Within this context, this work presents the design and experimental implementation of a real time maximum power point tracker for photovoltaic systems. The MPP-tracker proposed in the paper is a high efficiency dc/dc boost converter operating in continuous conduction mode (CCM). The converter draws maximum power from the PV panel for a given solar radiation level and the environment temperature, by adjusting the duty cycle of the converter. A passive nondissipative turn-on turn-off snubber is also introduced in order to achieve high efficiency and to reduce EMI levels due to soft switching operation. The converter efficiency is consequently improved since the energy that would be dissipated during turning on and turning off is transferred to the load. The perturbation and observation algorithm searches the maximum power point according to actual insolation and temperature. The algorithm is implemented using microcontroller 80C51, whose output signal sets the duty cycle of a pulse width modulation (PWM) boost converter. Experimental results demonstrate the performance of the proposed MPP-tracker.

2. Solar cell characteristics

A solar cell consists of semiconductor material which converts solar radiation into dc current using the photovoltaic effect. The most important qualities of a solar cell are described by the *I–V* characteristic. Typical current versus voltage and power versus voltage characteristic curves of a solar cell at different levels of solar irradiation are illustrated in Figs. 1 and 2, respectively. Fig. 3 shows that the operating point at which the solar generator can deliver maximum power for a given radiation intensity is

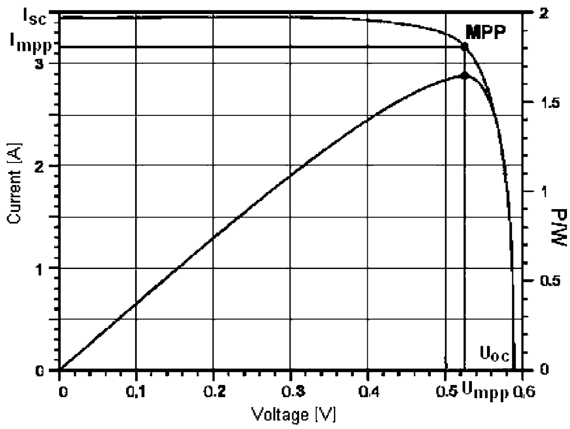

Fig. 1. Typical characteristic curve of a solar cell.

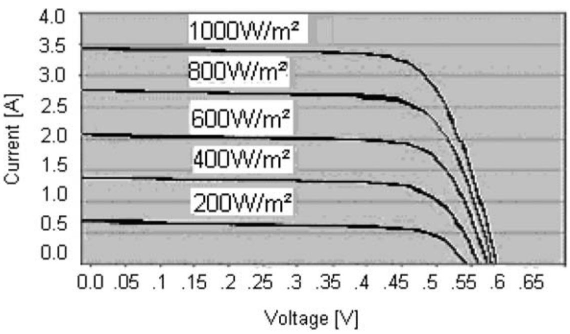

Fig. 2. Typical current versus voltage characteristic curves of a photovoltaic cell.

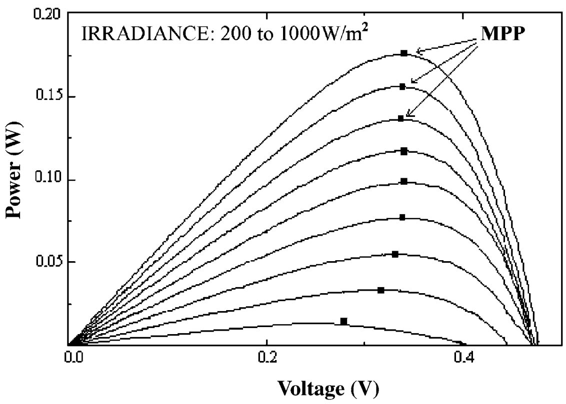

Fig. 3. Typical power versus voltage characteristic curves of a solar cell for different irradiance levels.

placed near the bend of characteristic curve. Three points of the curve are of particular interest: open circuit voltage V_{oc}, short circuit current I_{sc} and maximum power point P_{MPP}. It is possible to notice that the solar cell behaves as a current source left at P_{MPP}, and it assumes voltage source behavior right at P_{MPP}. From Fig. 2, it is observed that for each curve of solar irradiation, there is a specific voltage for which the cell operates at proper maximum power point. This is the optimum voltage for the operation of the solar cell. Considering that most of the loads supplied by PV systems operate with constant voltage, it is necessary to track the maximum power point of the solar cell regardless the load voltage.

3. MPP-tracker

Maximum power point tracking means that the photovoltaic generator is always supposed to operate at maximum output voltage/current rating. In principle, a MPP-tracker is a dc/dc converter that sets the solar generator to operate at MPP independently of the load. Hence the main function of a MPP-tracker is to adjust the panel output voltage to a value in which the panel transfers maximum energy to the load (Torres, 1998).

The block diagram of the MPP-tracker proposed in this work is shown in Fig. 4, and the schematic is depicted in Fig. 5. Switch S_b is PWM controlled, operating

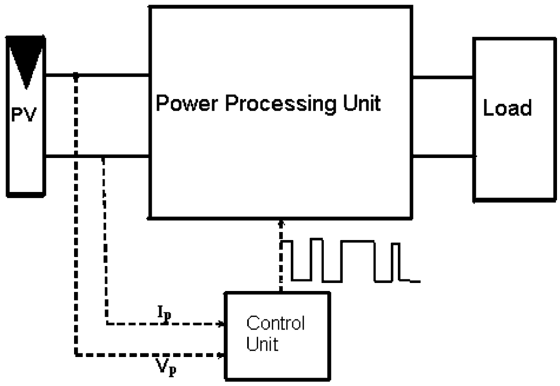

Fig. 4. Block diagram corresponding to the boost converter.

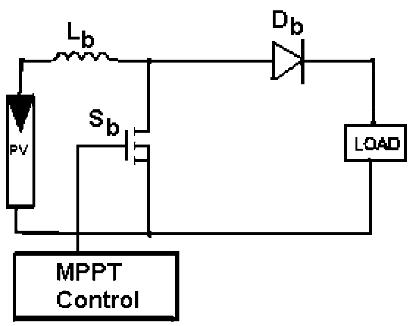

Fig. 5. Schematic of the boost converter.

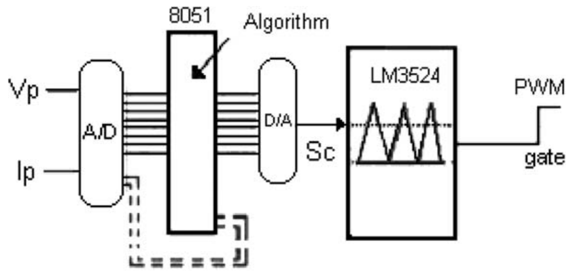

Fig. 6. Control circuit.

with switching frequency equal to 33 kHz. By adjusting the duty cycle of S_b, the converter can draw maximum power from the PV panel.

The MPP-tracker control circuit is implemented with microcontroller 80C51, which presents an 8-bit analog-to-digital (A/D) converter and an 8-bit digital-to-analog (D/A) converter, according to Fig. 6.

4. Control algorithm

The control algorithm searches the MPP comparing the output power of the PV module before and after the duty cycle of the converter is changed. A simple algorithm based on perturbation and observation (P&O) method has been developed for real time tracking. Perturbation and observation (P&O) method periodically increases/decreases the panel voltage and compares the PV output power with that of the previous cycle. If the perturbation leads to an increase/decrease in module power, the subsequent perturbation occurs in the same/opposite direction. Therefore the MPP-tracker continuously seeks the peak power condition. The P&O method has been widely used due to the simple feedback structure and reduced number of parameters (Hua and Shen, 1998a,b).

Fig. 7 shows the flowchart that corresponds to the implemented algorithm. By measuring photovoltaic panel voltage (V_P) and current (I_P), the output power of the PV panel is calculated and compared with that obtained previously. At start-up, duty cycle is set to 0.1, and if the actual output power (P_A) is equal or greater than the output power measured previously (P_P), duty cycle is increased, otherwise it is decreased. In fact, the P&O method allows the PV panel to operate around the maximum power point.

5. The snubber circuit

In order to improve the efficiency of the boost converter, a snubber circuit is introduced. The snubber circuit transfers to the load the energy that would be dissipated during turning on and turning off. The proposed snubber circuit is shown in Fig. 8.

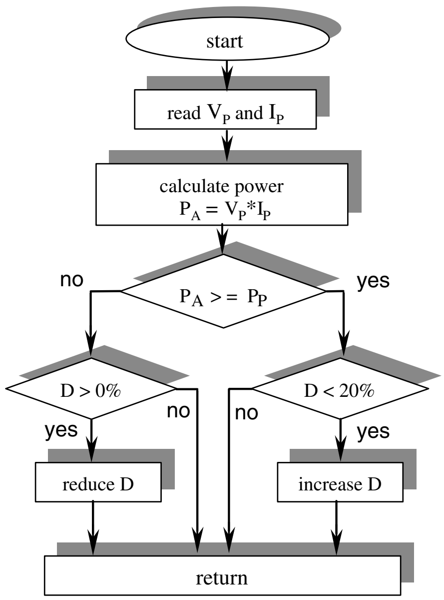

Fig. 7. Algorithm flowchart.

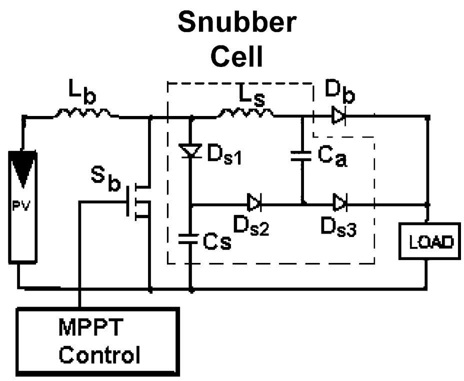

Fig. 8. Boost converter associated with the proposed snubber circuit.

Inductor L_s reduces the reverse recovery peak current through diode D_b and consequently maximum di/dt. Capacitor C_s limits the voltage increasing ratio (dv/dt) during turning off. The energy stored in the remaining component is transferred to capacitor C_a, which delivers it to the load through diodes D_{s1}, D_{s2} and D_{s3} (Chehab and Barbi, 2001).

From simulation results shown in Figs. 9–12, one can see that switching losses during turning on and turning off are drastically reduced when the snubber cell is used.

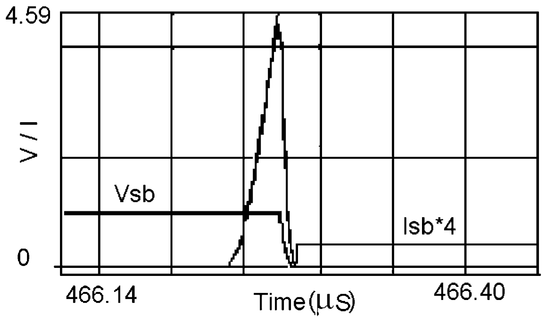

Fig. 9. Switch S_b turning on without the snubber circuit.

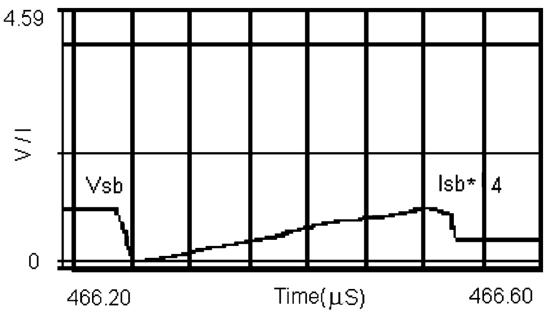

Fig. 10. Switch S_b turning on with the snubber circuit.

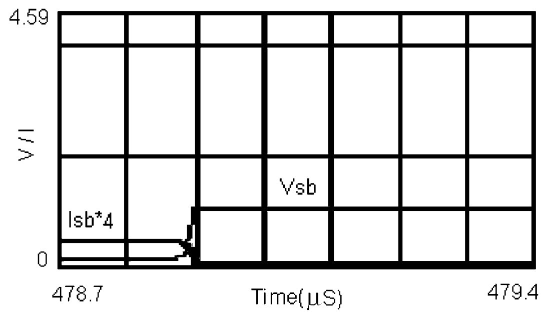

Fig. 11. Switch S_b turning off without the snubber circuit.

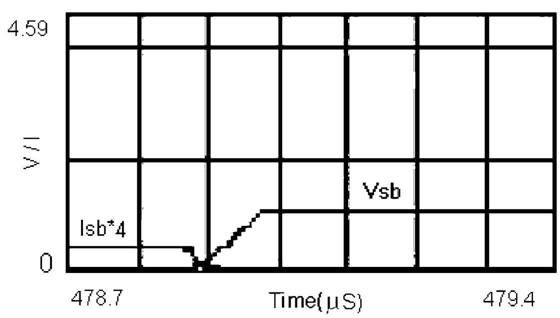

Fig. 12. Switch S_b turning off with the snubber circuit.

Switch S_b is turned on in *pseudo* zero current switching (ZCS) mode and turned off in *pseudo* zero voltage switching (ZVS) mode. The reverse recovery peak current and di/dt during turning on are reduced, as well as the increasing rate of the voltage across the switch (dv/dt) during turning off. The nearly lossless switching of S_b minimizes EMI levels and increases the converter efficiency.

6. Experimental results

A laboratory arrangement has been implemented in order to verify the performance of the maximum power point tracker proposed in this work, and also the performance of the snubber circuit. Two sets of panels have been adjusted, each one of them composed by seven series connected PV modules. One set is connected directly to a resistive load, and the other one connected to a similar resistive load, but the MPP-tracker is placed between the modules and the load, as shown in Fig. 13. In a sunshine day at latitude of 4° below the equator, in a city called Fortaleza, state of Ceará, located in northeastern Brazil, where the average solar irradiation is 1000 W/m^2, 14 measurement sessions were carried out. Fig. 14 shows results representing collected data. The panel connected to the load through the MPP-tracker provides 45% more energy to the load than the other one.

In Fig. 15, one can see that the converter efficiency when the snubber circuit is used increases about 4% due to the additional energy that is transferred to the load.

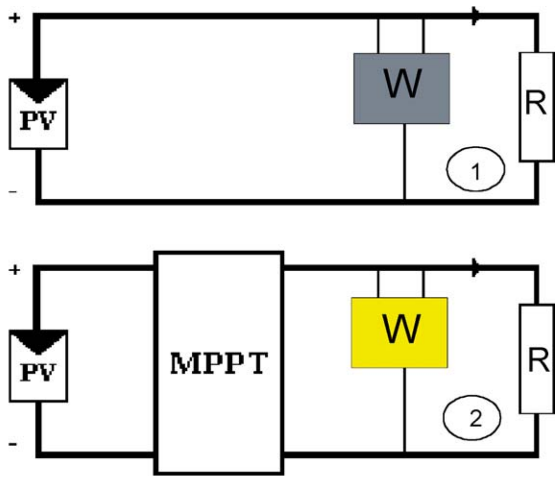

Fig. 13. Experimental arrangement, where W is a wattmeter.

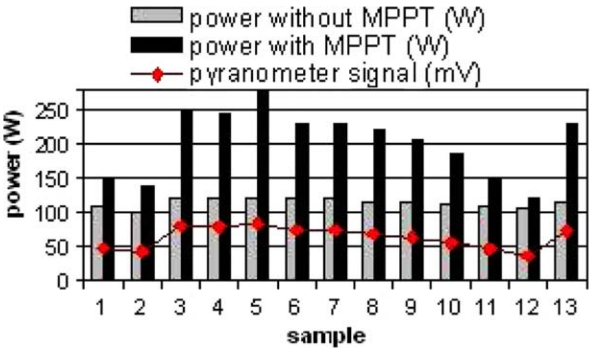

Fig. 14. Experimental data.

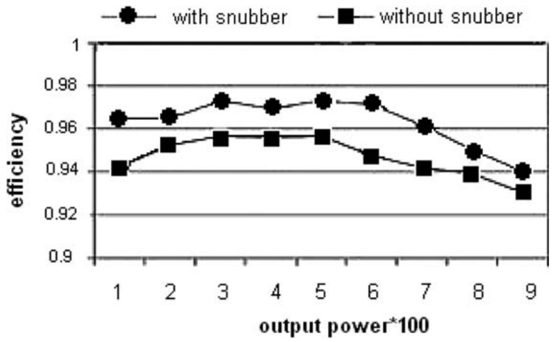

Fig. 15. Efficiency of the MPP-tracker with and without the snubber circuit as a function of the output power.

7. Conclusion

This work has presented the design and laboratory implementation of a microcontrolled maximum power point tracker. The MPP-tracker is a dc/dc boost converter with a passive nondissipative turn-on turn-off snubber, controlled by a single chip microcontroller that employs the perturbation and observation algorithm. The use of a microcontroller allows simple modification of the system, if additional renewable energy sources are required e.g. more PV modules. The proposed snubber further improves the converter efficiency and reduces EMI generation. Simulation and experimental results describe the performance of the designed MPP-tracker. The MPP-tracker increased about 45% the energy transfer from the PV panel to the load. The efficiency of the power converter using the snubber circuit increased 4%, because the amount of energy that is transferred to the load increases, since switching losses are minimized.

Acknowledgments

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Appendix. Dc/dc boost converter design

The dc/dc boost converter has been designed according to the following specifications:

- array A: 7 photovoltaic modules connected in series,
- array B: 7 photovoltaic modules connected in series,
- mounted panel: array A connected in parallel with array B,
- dc/dc converter input voltage (V_i): 91–105 V,
- dc/dc converter output voltage (V_o): 106 V,
- switching frequency (f_s): 33 kHz,
- panel peak power: 742 W_P (1000 W/m^2; 25 °C; AM 1.5),
- maximum output voltage ripple (ΔV_C): 5%,
- maximum input current ripple (ΔI): 20%,
- continuous conduction mode.

The basic equations necessary to the boost converter design are presented below. Eq. (A.1) is the transfer function between the output voltage (V_o) and the input voltage (V_i) of the boost converter, and D is the duty cycle (Barbi and Martins, 2000). Eqs. (A.2) and (A.3) are used to determine the boost inductance L_b and the output capacitance C_o.

$$\frac{V_o}{V_i} = \frac{1}{(1-D)} \tag{A.1}$$

$$\Delta I = \frac{V_i \cdot D}{f_s \cdot L_b} \tag{A.2}$$

$$\Delta V_C = \frac{I_o \cdot D}{f_s \cdot C_o}. \tag{A.3}$$

From the aforementioned specifications, Eq. (A.1) gives

$0 \leqslant D \leqslant 0.41.$

Using Eq. (A.2), the boost inductance can be determined.

$L_b = 238\ \mu H.$

With Eq. (A.3), output capacitance C_o is calculated.

$C_o = 5.64\ \mu F$.

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