Modeling and Simulation of Closed Loop Controlled Buck Converter for Solar Installation

A.Kalirasu and S.S.Dash

Abstract—The stand-alone photo-voltaic energy system requires storage to meet the energy demand during period of low solar irradiation and night time. Storage batteries account for the most PV system failures and contribute significantly to both initial and the eventual replacement cost. Switch mode DC to DC converters are used to match the output of a PV generator to a variable load. This paper deals the design of DC to DC converter which makes voltage is maintained at a specified value. Digital simulation of open loop and closed loop controlled buck converter for solar installation is discussed. The simulation results are compared with the theoretical results. This converter has advantages like improved power factor, fast response and reduced hardware.

Index Terms—Buck converter, Solar cells, PV cells.

I. INTRODUCTION

Recently, the more and more growing interest in applications of Renewable Energy Sources (RES), with all the related problems of their optimal exploitation, has increased the need of experimental equipment to carry out measurements and tests, without the direct use of the renewable source. As a matter of fact, to investigate the behavior of a photovoltaic generator (PV), a wide outer surface is needed, since the produced energy depends on solar irradiance and temperature; moreover the weather conditions are not always reproducible. In this case the necessary investment to set up an experimental plant can be made severe by the continuous evolution of the involved technologies. A possible way to reproduce the behavior of a renewable source, whose electrical characteristic lies on a I-V plane (as in the case of a PV generator), is to use the I-V curve as a signal reference to suitably control a switching DC/DC converter. All these considerations suggest that any renewable source should be replaced by a hardware system capable of copying its behavior accurately. As for PVs, methodologies to obtain the I-V curves by using different DC/DC converter topologies are presented in [1]-[5]. In [4] a bi-directional DC/DC electronic converter is set up to measure and emulate the I-V behavior of a photovoltaic array. The control of such converters is based on the acquisition of all I-V data of a real PV array, without considering any mathematical relation between I and V, so its operation is

possible only in certain precise working conditions and if a highly performing and expensive DSP board, for data storage and processing, is used. Finally in [5] a real time circuit simulator of photovoltaic modules is presented, but no detailed study on the converter control design with regard to stability and dynamics is reported. A new approach to obtain I-V and P-V curves of photovoltaic modules by using DC/DC converters is given by [10]. A DC/DC converter based circuit model for a solar photovoltaic array is given by [11]- [13]. A new approach to mobile photo-voltaic systems is proposed; the system described in this paper is of very low power (5 W) and is intended mainly for recharging or powering small portable electronics devices [14]. Analysis of the buck converter for scaling the supply voltage of digital circuits is presented [15]. DC-DC of the buck type, MPPT command and circuit command buck (CCB) have analysed in Pspice and in experiments the operation of a PV system [16]. An integrated circuit approach, lowest voltage switching (LVS), for boundary mode buck converters are presented [17].

So far most Power Conversion Systems (PCSs) are mainly tested with a constant DC source. The above literature does not deal with a closed loop controlled buck converter system for solar installation. This work makes an attempt to simulate closed loop controlled buck converter. The paper is organized as follows: The second section of this paper deals with PV cell system. The third section of this paper deals with operational principle of buck converter. Simulation results are shown in section IV. The conclusion is given in section V.

II. PV CELL SYSTEM

The density of power radiated from the sun (referred to as the “solar energy constant”) at the outer atmosphere is 1.373kw/m². The final incident sun light on the earth surface has the peak density of 1kw/m² at noon in the tropics. The technology of photovoltaic (PV) is essentially concerned with the conversion of this energy in to usable electric form. The basic element of the PV system is the solar cell. Solar cell can convert the energy of sunlight directly into electricity. A simplified equivalent circuit of a solar cell consists of a current source in parallel with a diode variable resistor is connected to the solar cell generator as a load. The well-known general mathematical model for a PV cell is obtained by describing the relation between its terminal current and voltage through the single-diode equivalent circuit of the cell, reported in Fig. 1 [6][8]and [9]. It is described as a current source in parallel with the junction as shown in equation (1):

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$$I = I_{LG} - I_{OS} \{ \exp [q(V + I_n R_s) / AkT] - 1 \} - (V + I_n R_s) / R_{sh} \quad (1)$$

$$I_{LG} = [I_{SCR} + K_1(T - T_r)] \lambda / 1000 \quad (2)$$

$$I_{OS} = I_{OR} [T/T_r]^3 \exp [qE_{GO}(1/T_r - 1/T)/BK] \quad (3)$$

Where I and V are cell output current and voltage. I_{OS} is cell reverse saturation current, T is cell temperature in $^{\circ}C$, k is Boltzmann's constant, q is electronic charge, $K_1 (=0.0017)$ short-circuit current temperature coefficient at I_{SCR} , A is solar irradiation in W/m^2 , I_{SCR} is short-circuit current at $25^{\circ}C$ and $1000W/m^2$, I_{LG} is light-generated current, E_{GO} is band gap for silicon. $B=A (=19.2)$ are the ideality factors, $T_r (=301.180 K)$ is reference temperature, I_{OR} is cell saturation current at T , R_{sh} is shunt resistance and R_s is series resistance.

There are two possibilities to define the PV cell model parameters. Two diode model is based on the knowledge of the theoretical characteristics, usually provided by manufacturers [7] and one diode model is based on the model parameters identification, from experimental data and interpolation.

Fig1. Model of PV cell.

The stand-alone photo-voltaic energy system requires storage to meet the energy demand during period of low solar irradiation and night time. The battery storage in a solar system should be properly controlled to avoid catastrophic operating condition like overcharging or frequent deep discharging. Storage batteries account for the most PV system failures and contribute significantly to both initial and the eventual replacement cost. Charge controllers regulate the charge transfer and prevent the battery from being excessively charged and discharged. Switch mode DC to DC converters are used to match the output of a PV generator to a variable load. The DC to DC converters allow the charge current to be reduced continuously in such a way that the resulting battery voltage is maintained at a specified value. A practical photovoltaic energy conversion system block diagram is shown in Fig.2.

Fig2. Block Diagram of PV Installation system

III. OPERATIONAL PRINCIPLE

In the Figure3 can be seen a principle scheme for a buck converter. For buck converter presented below is presumed

that is working in continuous-conduction mode.

Fig3. Buck (DC-DC) converter

A Buck converter operates in continuous mode if the current through the inductor (I_o) never falls to zero during the commutation cycle. In this mode, the operating principle is described by the waveform in Figure 4.

Fig4. An ideal Buck converter operating in continuous mode

By varying the duty-cycle T_{on} / T of the switch, V_o the output voltage can be controlled. The voltage on the diode is fluctuating between 0 and V_{in} , but this is not acceptable in most of the applications. For this reason an inductor is necessary. In continuous-conduction mode, since in steady state the time integral of the inductor voltage over one time period must be zero. Consequently, in average value over the switching period (T) given by the following equation

$$(V_{in} - V_o) T_{on} = V_o(T - T_{on}) \quad (4)$$

$$\text{where } V_o / V_{in} = T_{on} / T = D \quad (5)$$

This means that the output voltage varies linearly with the duty-cycle. Assuming a lossless circuit, the input power P_{in} must be equal to the output power P_o . It yields,

$$V_{in} I_{in} = V_o I_o \quad (6)$$

And

$$I_o / I_{in} = V_{in} / V_o = 1/D \quad (7)$$

The equations of buck converter are as follows:

The average output voltage is given as,

$$V_o(\text{avg}) = D V_{in} \quad (8)$$

The ripple in output voltage is given as,

$$V_o(\text{ripple}) = V_{in}(1 - D)D / 8LCf^2 \quad (9)$$

And the ripple in output current is given as,

$$I_o(\text{ripple}) = V_{in}(1 - D)D / fL \quad (10)$$

where V_{in} is the input voltage, D is the duty cycle ratio, L is the inductance and f is the frequency of the buck converter.

Therefore, in the continuous-conduction mode, the Buck converter is equivalent to a DC transformer whose the turn ratio can be continuously controlled in a range from 0 to 1.

The Buck converter model presented as a modulated transformer is an ideal element that does not refract actually the energy conversion. For this, we have investigated to the refinement of the buck model by predicting and integrating the device conduction and switching losses in the Buck model.

The conduction losses are due to the device conduction characteristics. The conduction losses are function currents and depend on device characteristics. To find out the device conduction losses, we need to model the device static I-V characteristics. Their information is usually available from manufacturer's data sheets. Conduction losses in the semiconductor devices are then approximated using a piece-wise linear approximation of the device's on-voltage characteristics. The switching losses are a function of the switching frequency, the current in each device, and the device's dynamic characteristics. Switching losses include devices turn-on loss, turn-off loss and reverse recovery loss. The turn-on loss is calculated according to the voltage and current waveform during the turn-on / turn-off transition.

IV. SIMULATION RESULTS

Simulation is done using Matlab and the results are presented. The simulation model of Buck converter for solar installation system is shown in Fig 5a. The DC input voltage is shown in Fig 5b. The driving pulses of the MOSFET are shown in Fig 5c. The DC output voltage is shown in Fig 5d. The output voltage reaches 5V. Output voltage is free from ripple. The DC output current is shown in Fig 5e, it is 4.171A.

The open loop system with disturbance at the input is shown in Fig 6a. An external disturbance of step rise in input voltage of 5V is applied at $t = 7\text{sec}$ as shown in Fig 6b. At 7 sec, the output voltage increases from 5 to 6.7V as shown in the Fig 6c.

The closed loop system with disturbance is shown in Fig 7a. The input and output voltages with disturbance of the closed loop DC to DC buck converter are shown in Figs 7b&7c respectively. Output voltage is sensed and it is compared with a reference voltage. At 7sec, the output voltage is increased to 6.7V. Then the error is processed by a PI controller. The output of PI controller adjusts the pulse width to maintain the output voltage constant. The output voltage reduces and reaches the set value. PI controller uses the following equation.

$$V_0 = k_p e + k_i \int e dt \quad (11)$$

The proportional and integral gain values are 0.1 and 10 respectively.

The data used for simulation studies is as follows:

Parameter	Value		
	Open loop system without disturbance	Open loop system with disturbance	Closed loop system with disturbance
Input voltage	15V	20V	20V
Output voltage	5V	6.7V	5V
Duty cycle ratio	30%	30%	30%
Series Resistance(R_s)	1 Ω	1 Ω	1 Ω
Parallel Resistance(R_p)	100 K Ω	100 K Ω	100 K Ω
Inductance (L_1 & L_2)	3mH	3mH	3mH
Capacitance (C_1 & C_2)	1000 μ F	1000 μ F	1000 μ F
Load Resistance(R_l)	1.2 Ω	1.2 Ω	1.2 Ω

Fig5a. Simulink circuit of solar installation system

Fig5b. Input voltage

Fig5c. Driving pulses

Fig5d. DC Output voltage

Fig6c. Output voltage with disturbance of open loop system

Fig5e. DC Output current

Fig7a. Simulink model of Closed loop system with external disturbance at the input

Fig6a. Open loop system with external disturbance at the input

Fig7b. Input voltage with disturbance

Fig6b. Input voltage with disturbance

Fig7c. Output voltage with disturbance of closed loop system

V. CONCLUSION

This paper presents simulation of open loop and closed loop controlled buck converter system for solar installation system. Matlab models for open loop and closed loop systems are developed using the blocks of simulink and the

same are used for simulation studies. The closed loop system is able to maintain constant voltage. This converter has advantages like reduced hardware and good output voltage regulation. The simulation results are in line with the theoretical predictions.

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