Photovoltaic with Battery Energy Storage System Using Buck Converter

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Abstract

In this paper different DC/DC converter topologies used in photovoltaic with battery energy storage systems (PV-BESS) are evaluated in terms of performance and component ratings. DC/DC converter moves operational point toward solar array's maximum power point (MPP). A maximum power point tracking (MPPT) method based on incremental conductance (IC) scheme with variable step size is presented. Finally simulation results are presented and buck topology is pointed out as the best candidate for PV-BESS.

Key words: Photovoltaic (PV) Systems; Battery Energy Storage System (BESS); Maximum Power Point Tracking (MPPT).

1. Introduction

The excessive problem of greenhouse emissions worldwide and global energy crises, has prompted interest in the issue of renewable energy sources. Among all renewable energy sources photovoltaic is more attractive due to its great abundance and falling trend in cost of PV-cells.

PV systems can be divided into two categories: stand-alone PV systems and grid-connected PV systems. In grid connected PV systems electrical power is generated and injected into AC system. Stand alone PV systems are usually used to feed remote AC or DC loads. It is usually desired to make use of the maximum energy can be drawn from PV-array. As AC system can absorb any amount of power generated by the PV-array, grid-connected PV systems can fulfill this function. But in the case of stand-alone loads, as the load may not be able to absorb all the generated power unless a provision for energy storage (e.g. BESS). So BESS is sometimes used as energy backup and/or in order to balance energy flow during high irradiation periods and peak load periods.

In order to design and simulate a PV system, it's necessary to adopt a PV array model that exhibits its accurate behavior under all environmental conditions. An equivalent circuit based on PV array's simple model is used in this paper. There are numerous method to extract model parameters [1-4].

In PV systems with BESS, DC/DC converters are employed to impose PV array operate in MPP. In literature many MPPT methods have been developed and implemented to improve the energy conversion efficiency in PV-BESS [5]. Among all MPPT techniques the incremental conductance (IC) is more popular due to its high accuracy and good adaptability to the rapidly changing atmospheric conditions. Variable step size in IC technique improves tracking accuracy as well as tracking dynamics [6].
Finally an evaluation is carried out over candidate topologies for DC/DC converter of PV-BESS via simulation and the buck topology is shown to have some advantages over buck-boost and SEPIC in terms of performance and component ratings.

2. PV Array Model

Simple equivalent circuit of PV-cell is illustrated in Fig. 1.

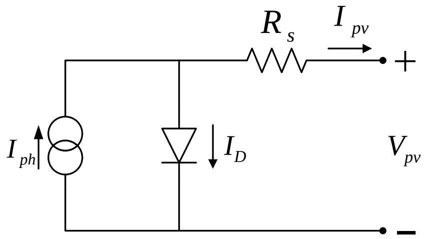


Fig. 1 simple equivalent circuit of PV-cell.

Characteristic equations are :

$$I_{pv} = I_{ph} - I_0\left(\exp\left(\frac{V_{pv} - I_{pv}R_s}{V_T}\right) - 1\right) \tag{1}$$

$$V_{pv} = V_T \ln\left(\frac{I_{ph} - I_{pv} + I_0}{I_0}\right) - I_{pv}R_s \tag{2}$$

In the above equation, V_T is junction thermal voltage:

$$V_T = AkT/q \tag{3}$$

Where :

- I_{ph} - photo-generated current in standard test condition (STC).
- I_0 - dark saturation current in STC.
- A - diode quality (ideality) factor.
- R_s - cell series resistance.

are the five parameters of the equivalent circuit, while k is Boltzmann’s constant, q is the charge of the electron and T is the ambient temperature.
In order to include irradiance and temperature dependence of the equivalent circuit parameters , I_0 and I_{ph} can be expressed as [7]:

$$I_{ph}(T) = I_{ph}(T_1)(1 + k_i(T - T_1)) \tag{4}$$

$$I_{ph}(G) = I_{ph}(G_1) \times G/G_1 \tag{5}$$

$$I_0(T) = I_0(T_1)(T/T_1)^{3/A} \times \exp\left(\frac{-qV_g}{Ak} \times \left(1/T - 1/T_1\right)\right) \tag{6}$$

$$I_0(T_1) = I_{sc}(T_1)(\exp(qV_{oc}(T_1)/AkT_1) - 1) \tag{7}$$

In above equations V_g is band gap voltage that is 1.12eV for crystalline Silicon and 1.75 for amorphous Silicon. G, V_{oc}, I_{sc} and k_i are solar irradiance in W/m^2, open circuit voltage, short circuit current and thermal coefficient of short circuit current of PV-cell, respectively. Specifications given in product datasheet can be used to determine all parameters in above equations. If diode current is neglected in short circuit condition, I_{sc} can be used as I_{ph}.

Diode quality factor (A) is considered as a constant value and 1.3 can be a good value for it as suggested in [7].

R_s isn't included in product datasheets and must be determined according to slope of the I-V curve at $V=V_{oc}$:

$$R_s = -dV/dI\big|_{V=V_{oc}} - 1/X_V \tag{8}$$

$$X_V = I_0(T_1)(q/AkT_1)\cdot e^{(qV_{oc}(T_1)/AkT_1)} \tag{9}$$

I-V curves is usually given in product datasheet, otherwise it must be measured in STC.

Therefore by updating I_{ph}, I_0 and V_T values in every environmental condition in (1) or (2), an accurate PV-cell electrical model will be achieved. Specifications and V-I curves provided in 36-cell 60W OFFC PV-array datasheet are used for implementation and simulation a PV-array model based on (2). Typical electrical specifications of 36-cell 60W OFFC PV-array are presented in Table 1. Simulation results of PV-array model are shown in Fig. 2.

3. Survey of DC/DC Topologies Suitable For PV-BESS

In a PV system, operating point is desired to be at MPP or at it's right side in order to absorb power less than MPP. Hence according to **Error! Reference source not found.**, PV-array's operating voltage tends to vary between 16V and 25V. If a 12V Lead-Acid BESS is used, its voltage varies between 8V in fully discharged to 14V in fully charged condition. Some of more common buck and buck-boost topologies and their equivalent circuits during switch on and switch off period are shown in Appendix-A. Those topologies can be categorized into two groups:

- Fundamental topologies, including buck and buck-boost topology.
- Developed topologies, including SEPIC (Single Ended Primary Inductor Converter), Cuk, Positive output (PO) Luo converter and Negative output (NO) Luo converter topology.

A comparison must be made between these topologies in order to choose more suitable one for PV-BESS. Reference [8] provides a thorough analysis of operational principle for all mentioned converters with constant DC source at input and resistive load at output. But in this case output is BESS with quite constant voltage so that operational principles might be a bit different .

Maximum Power (Pmax)	60W
Voltage @ Pmax (Vmp)	17.1V
Current @ Pmax (Imp)	3.5A
Guaranteed minimum Pmax	58W
Short-circuit current (Isc)	3.8A
Open-circuit voltage (Voc)	21.1V
Temperature coefficient of Voc	–(80±10)mV/°C
Temperature coefficient of Isc	(0.065±0.015)%/°C
Temperature coefficient of power	–(0.5±0.05)%/°C

Table 1 Typical electrical specification of 36-cell 60W OFFC PV-array.

In view of input current pulsation, converters show different behavior. As they have switch in series with PV-array, all converters except Cuk and SEPIC draw pulsating current. Therefore maximum available PV power can't be utilized. Using a parallel capacitor in PV-array terminal as a low pass filter can solve this problem. The capacitor rating determined by :

$$C = (\Delta T \times I_{in}) / \Delta V \tag{10}$$

$$\Delta T = (1 - D) / f_s \tag{11}$$

Where ΔV, D and f_s are acceptable voltage fluctuation around PV-array operating point, converter duty cycle and switching frequency, respectively.

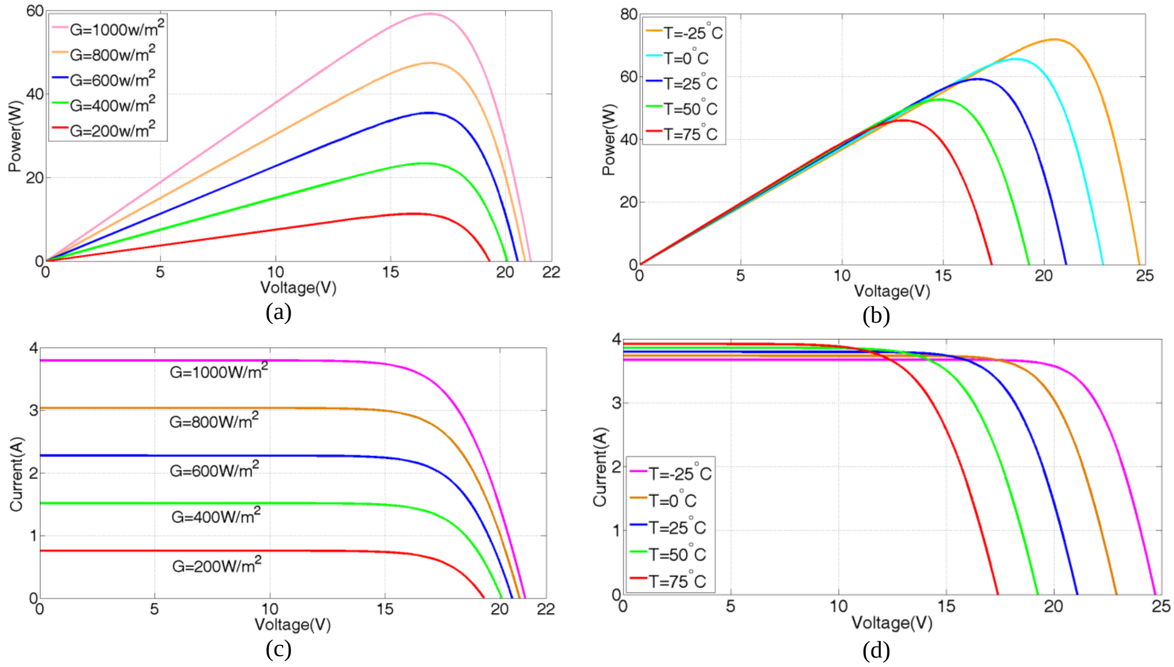


Fig. 2 Simulation results for different temperature and irradiance

Output current pulsation can be of great importance due to BESS degradation. In view of output current all converters give nonpulsating charge current, except SEPIC and Buck-boost. Therefore these two topologies will not be mentioned in following. In view of switch drive system, except SEPIC and Cuk other topologies need floating gate drive that impose some complexity and extra cost. But duo to inverting output, Cuk needs isolated power supply for gate drive system.

under the assumption that input and output parameters for converter be as below:

$$V_i = V_{MPP} = 17.1V, I_i = I_{MPP} = 3.5A, \Delta I_i / I_i < 0.05 \quad , \quad V_o = 12V, I_o = 4.8A, \Delta I_i / I_i < 0.1$$

Component ratings for a Buck Converter with shunt capacitor at input in switching frequency of 5kHz are [8]:

$$D = 12/17.1 = 0.7 \quad , \quad L_{\min} = 2.96mH \quad , \quad I_{sw} = 3.5A \quad , \quad I_D = 1.04A \quad , \quad C_{in} = 197\mu F$$

PO Luo Converter with shunt capacitor at input:

$$D = 12/(12+17.1) = 0.412 \ , C = 166\mu F \ , C_{in} = 390\mu F \ , L_{1_{\min}} = 4.16mH \ , L_{2_{\min}} = 1.46mH$$

$$I_{sw} = 3.4A \ , I_D = 2.83A$$

Cuk Converter:

$$D = 12/(12+17.1) = 0.412 \ , C = 68.5\mu F \ , I_{sw} = 3.5A \ , L_{1_{\min}} = 4.16mH \ , \ L_{2_{\min}} = 1.46mH \ , I_D = 2.83A$$

NO Luo Converter with shunt capacitor at input:

$D = 12/(12+21.1) = 0.412$, $C_{in} = 390\mu F$, $C = 166\mu F$, $L_{1_{min}} = 1.71mH$, $L_{2_{min}} = 62\mu H$

$I_{sw} = 3.5A$, $I_D = 4.83A$

According to these calculations, components of buck topology have lower ratings rather than others. In addition it has simpler structure. Hence it is more suitable for PV-BESS.

4. MPPT Algorithm

As shown in **Error! Reference source not found.** MPP changes in different environmental conditions. The higher the irradiation or the lower the temperature, the higher the MPP will be. Correspondingly, the power electronics converter has to assure that PV-array operates always at the MPP. Until now numerous methods have been proposed in literature [9]. Perturb and observe (P&O) method are mostly applied in MPPT controller due to its simplicity and ease of implementation. In P&O perturbation is made in operating voltage of PV-array, while Hill Climbing perturbation is made in duty cycle of power electronics converter and is easier to be implemented. However, due to perturbation oscillation around MPP always appear in both methods that cause some power loss. So Incremental Conductance (IC) has been proposed, that works based on this fact that slope of PV-array power versus voltage is zero at MPP. IC shows better performance under fast variation in environmental conditions. Moreover oscillations around MPP would be eliminated in theory since the derivative of the power with respect to the voltage is zero at MPP. Basis of IC method is shown in Table 2.

at MPP	$dP/dV = 0$	$\Delta V/\Delta I = -V/I$
left of MPP	$dP/dV < 0$	$\Delta V/\Delta I < -V/I$
right of MPP	$dP/dV > 0$	$\Delta V/\Delta I > -V/I$

Table 2. Basis of IC method.

Therefore MPP can be tracked by comparing instantaneous conductance (V/I) and incremental conductance (ΔV/ΔI).

IC method is generally used with fixed step size. Large step size contributes to fast dynamics but large oscillation around MPP which results in a relatively low efficiency. Small step size reverses this situation . So using IC method with variable step size proportional to $|\Delta P/\Delta V|$ is employed herein to solve this issue [10]. Update rule for Buck converter duty cycle can be obtained as follows:

$$D(k) = D(k-1) \pm \Delta D = D(k-1) \pm C \times |\Delta P/\Delta V| \quad (12)$$

Where coefficient C is the scaling factor which is manually tuned at the design time to adjust the step size. Flow chart for IC MPPT with variable step size algorithm is shown in **Error! Reference source not found.**.

Simulation is carried out to evaluate performance of Buck topology under variable step size INC MPPT algorithm. Generic battery model [11] that is available as a block in MATLAB/SIMULINK® and PV-array model that was developed in section II are used to develop a simple PV-BESS shown in **Fig. 4**. A buck converter is used as the power interface between the PV-array and draws maximum power from PV-array.

Simulations has been performed on the Buck converter and MPPT algorithm under environmental conditions (temperature and irradiance) with parameters listed in Table 3.

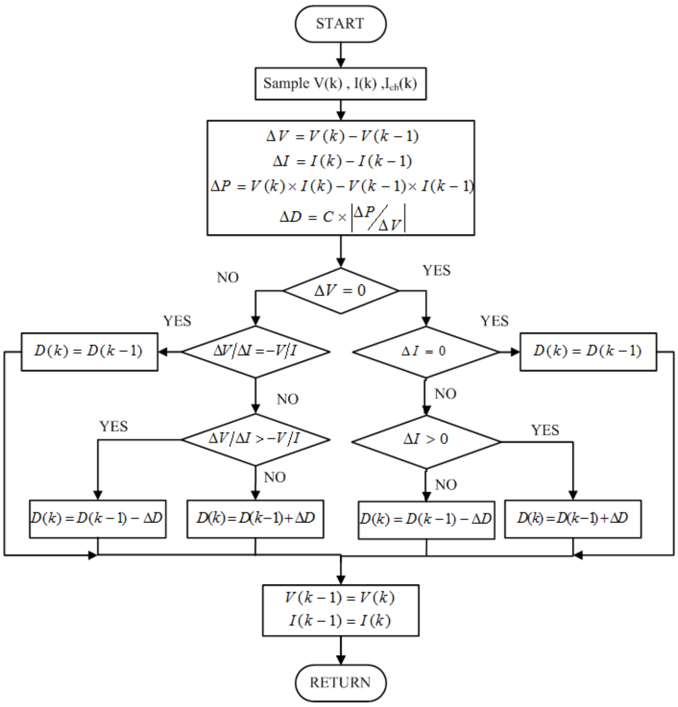


Fig. 3 Flowchart of modified IC MPPT algorithm.

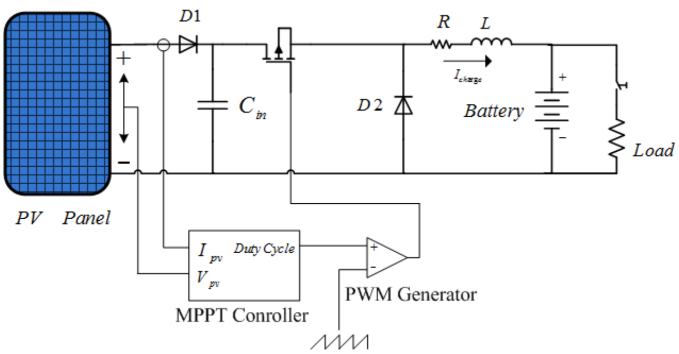


Fig. 4 PV-BESS schematic.

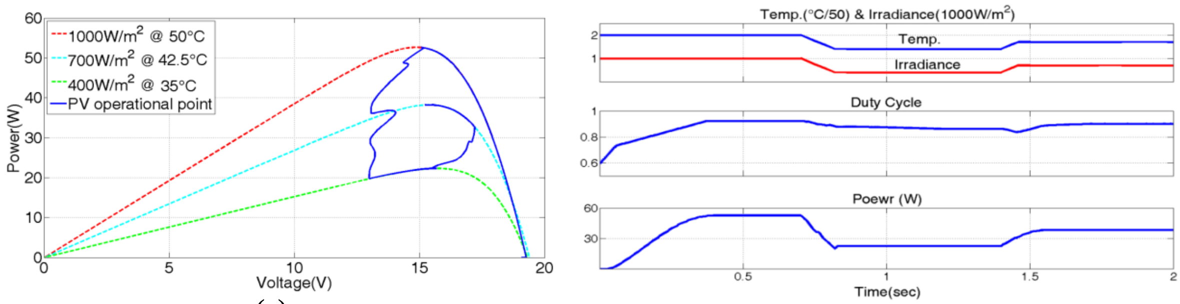
Parameters name	Symbol	value
Input capacitor	C_{in}	200µF
Output inductor inductance	L	10mH
Output inductor Resistance	R	0.01Ω
Battery Rated Capacity	-	6.5Ah , 12V
scaling factor of MPPT	C	0.002

Table 3. Parameters used in simulation

According to simulation results that are presented in Fig. 5(a) and (b) , buck converter shows good performance under variable step size IC MPPT method. PV-BESS and MPPT efficiency are as follow [12]:

$$\eta_{MPPT} = \frac{Drawn\ \ PV\ \ Power}{Max.\ \ Available\ \ PV\ \ Power} = \frac{52.46}{52.69} = 99.5\% \tag{13}$$

$$\eta_{PV-BESS} = \frac{Power\ \ injected\ \ to\ \ BESS}{Max.\ \ Available\ \ PV\ \ Power} = \frac{48.27}{52.69} = 91.97\% \tag{14}$$



(a) (b)

Fig. 5 (a) Operational point of PV-array and , (b) PV output power and DC/DC duty-cycle variation through MPPT.

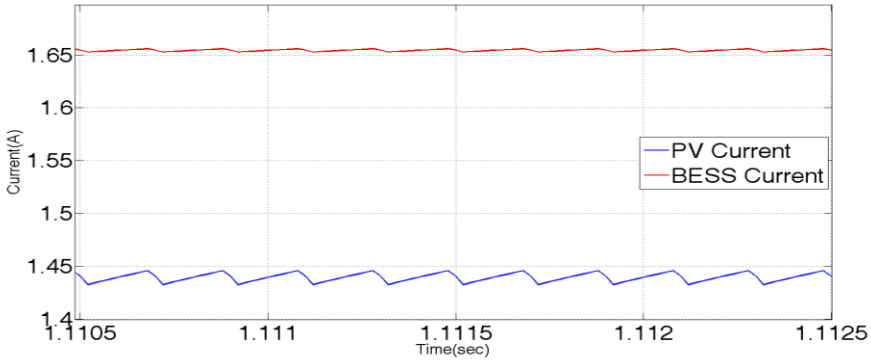


Fig. 6 PV-array and BESS current.

Zoomed view of PV-array and BESS current are shown in Fig. 6, both of them are continuous and have low ripple. Specially, despite Inherent discontinuous current at buck converter input, using shunt capacitor at its input cause converter to draw low ripple continuous current from PV-array.

5. conclusion

A simple PV-array model has been presented that exhibits its accurate behavior under all environmental conditions and can be easily implemented in MATLAB/Simulink®. For interfacing PV-array and BESS some suitable DC/DC converters has been evaluated against performance and component ratings afterwards it was shown that lower component ratings are needed for buck topology, moreover, it has simpler structure and using shunt capacitor at its input *causes converter to draw low ripple continuous current from PV-array. It results in full utilization of PV-array generated electric power*. Therefore it is more suitable for PV-BESS. Incremental Conductance (IC) method with variable step size is used to adjust converter's duty-cycle so that PV-array works at MPP. Finally simulation results of PV-BESS has been presented and it is indicated that both PV-BESS and MPPT system have acceptable efficiency.

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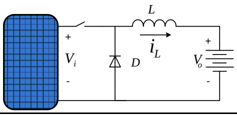
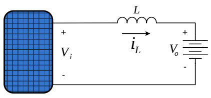
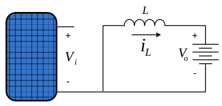
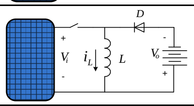
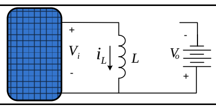
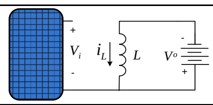
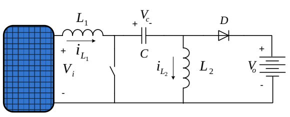
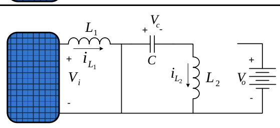
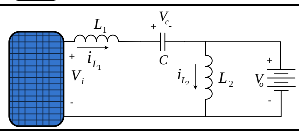
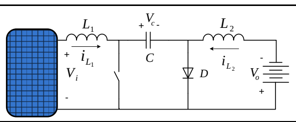
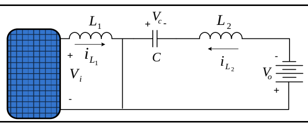
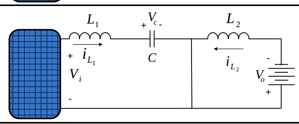
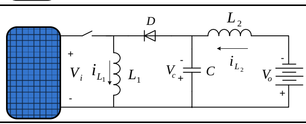
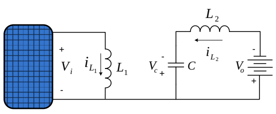
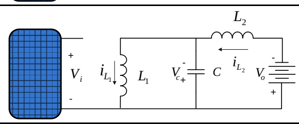
Appendix -A

	Converter schematic	Equivalent circuit (SW is on)	Equivalent circuit (SW is off)
buck			
Buck-boost			
sepic			
cuk			
Negative output Luo converter			
Positive output Luo converter