Interleaved Boost Converter with MPPT Controller for Photovoltaic System

M. Marimuthu
Assistant Professor
Department of EEE,
Saranathan College of Engg.,
Trichy, Tamilnadu, INDIA.
Email: marimuthuoffice@gmail.com

A. Kamalakkannan
Assistant Professor
Department of EEE,
Saranathan College of Engg.,
Trichy, Tamilnadu, INDIA.

M. Karthick
Assistant Professor
Department of ICE,
Saranathan College of Engg.,
Trichy, Tamilnadu, INDIA.

ABSTRACT

This paper presents the modelling of Photovoltaic topology with MPPT technique for interleaved boost converter feeding a R Load using MATLAB/Simulink. In high power application interleaved operation of two or more boost converter has been proposed to increase the output power. A detailed mode analysis of interleaved topology is presented. The interleaved topology used decreases current rating of switching device since current in each phase is distributed.

Keywords: Boost converter, maximum Power Point Tracking (MPPT), photovoltaic (PV) power generation, Interleaved Soft Switching Boost Converter (ISSBC).

I. INTRODUCTION

As photovoltaic (PV) solar cells become more important in energy generation, much research and development is focused on extracting the maximum amount of power. The electrical power generated by PVs is not uniform over the full operating range. There is an optimum operation point called the Maximum Power Point (MPP) that yields maximum power generation [1]. PV electrical characteristics vary with temperature and light intensity, which changes the MPP. There are a number of Maximum Power Point Tracking (MPPT) techniques available in which perturb and observe method has been proposed.

The output power of the solar cell is easily changed by the surrounding conditions such as irradiation and temperature and also its efficiency is low. Thus high efficiency is required for the power conditioning system, which transmits power from the PV array to the load. In general, a single-phase PV PCS consists of two conversion stages. The dc/dc converter is the first stage and it performs maximum power point tracking and guarantees the dc-link voltage under low irradiance conditions.

PV module represents the fundamental power conversion unit of a PV generator system. The output characteristics of PV module depends on the solar insulation, the cell temperature and output voltage of PV module. Since PV module has nonlinear characteristics, it is necessary to model it for the design and simulation of maximum power point tracking (MPPT) for PV system applications. The mathematical PV models used in computer simulation have been built for over the past four decades [2]-[4]. Almost all well-developed PV models describe the output characteristics mainly affected by the solar insulation, cell temperature, and load voltage. However, the equivalent circuit electronics, such as SPICE. Recently, a number of powerful component-based electronics simulation software package have become popular in design and development of power electronics applications. However, the Sim Power System tool in MATLAB/Simulink package offers wind turbine models but no PV model to integrate with current electronics simulation technology. This motivates me to model photovoltaic with MPPT technique.

In high power application boost converters are often paralleled in an interleaved manner to increase the output current and reduce the output current ripple. However, the drawback of this converter is that the voltage across the switch is very high during the resonance mode. The voltage across the switch depends on the parameters of the resonant components (i.e., resonant inductance and resonant capacitance) and the resonant inductor current. In this paper, the optimal design of the resonant components and the interleaved method is applied for resonant current reduction. Since the interleaved method distributes the input current according to each phase, it can decrease the current rating of the switching device. Also it can reduce the input current ripple, output voltage ripple, and size of the passive components [5]-[7]. Therefore, the output power of the PV array can be boosted with high efficiency.

II. THEORETICAL BACKGROUND

A. Photovoltaic Array

Photovoltaic systems convert into electricity. Figure 1 shows the equivalent circuit of the ideal photovoltaic cell.
The basic equation from the theory of semiconductors[8] that mathematically describes the I-V characteristic of the ideal photovoltaic cell is

\[
I = I_{PV,Cell} - I_0,Cell \left[ \exp \left( \frac{qV}{\alpha kT} \right) - 1 \right]
\]

(1)

Where \(I_{PV,cell}\) is the current generated by the incident light, it is directly proportional to the sun irradiation and \(I\) is the Shockley diode equation, \(I_0\) is the reverse saturation current of the diode, \(q\) is the electron charge \([1.602\times10^{-19}c]\), \(k\) is Boltzmann constant \([1.380\times10^{-23}J/K]\), \(T\) is the temperature of the p-n junction, and \(a\) is the diode ideality constant.

The basic equation (1) of the elementary photovoltaic cell does not represent the I-V characteristic of a practical photovoltaic array. Practical arrays are composed of several connected photovoltaic cells and the observation of the characteristics at the terminal parameters to the basic equation (1).

\[
I = I_{PV,\text{array}} - I_0 \left[ \exp \left( \frac{V + R_s I}{V_a} \right) - 1 \right] - \frac{V + R_s I}{R_p}
\]

(2)

Where \(I_{PV,\text{array}}\) and \(10\) are the photovoltaic and saturation currents of the array and \(V_t = NSKT/q\) is the thermal voltage of the array with \(N\) cell connected in series. Cells connected in parallel increase the current and cells connected in series provide greater output voltages. If the array is composed of \(N_p\) parallel connections of cells the photovoltaic and saturation currents may be expressed as: \(IPV = IPV, cellNP\), \(10 = I0,cellNp\). In (2) \(R_s\) is the equivalent series resistance of the array and \(R_p\) is the equivalent parallel resistance. This equation originates the I-V curve seen in Figure, where three remarkable points: short circuit (0,ISC), maximum power point (Vmp, Imp) and open circuit (VOC,0).

Figure 1: Single-diode model of the theoretical photovoltaic cell and equivalent circuit of a practical photovoltaic device including series and parallel resistances

Figure 2: Characteristic I-V curve of the photovoltaic cell. The net cell current \(I\) is composed of the light-generated current \(I_{PV}\) and the diode current \(I_d\)

Eq. (2) describes the single – diode model presented in Figure 1. Some authors have proposed more sophisticated models that present better accuracy and serve for different purposes. For example, in [9]-[13] an extra diode is used to represent the effect of the recombination of carriers. In [14] a three – diode model is proposed to include the influence of effects which are not considered by the previous models. For simplicity the single diode model of Figure 1 is studied in this paper.

The light generated current of the photovoltaic cell depends linearly on the solar irradiation and is also influenced by the temperature according to the following equation

\[
I_{PV} = (I_{PV,n} + K_1 \Delta T) \frac{G}{G_n}
\]

(3)

Where \(IPV\), \(n\) is the light-generated current at the nominal condition (usually 250C and 1000W/m²), \(\Delta T = T-T_n\) (being \(T\) and \(T_n\) the actual and nominal temperature[k]), \(G\) [W/m²] is the irradiation on the device surface, and \(G_n\) is the nominal irradiation.

The diode saturation current \(I_0\) and its dependence on the temperature may be expressed by (4)

\[
I_0 = I_{0,cell} \left( \frac{T_n}{T} \right) \exp \left( \frac{qE_g}{ak} \left( \frac{1}{T_n} - \frac{1}{T} \right) \right)
\]

(4)

Where \(E_g\) is the band gap energy of the semiconductor (Eg. 1.12eV for the polycrystalline Si at 250C, and 10, \(n\) is the nominal saturation current

\[
I_{0,n} = \frac{I_{0,cell}}{\exp \left( \frac{qE_g}{ak} \left( \frac{1}{T_n} - \frac{1}{T} \right) \right) - 1}
\]

(5)

With \(V_t\), \(n\) being the thermal voltage of \(N\) series-connected cell at the nominal temperature \(T_n\).

The saturation current \(I_0\) of the photovoltaic cells that compose the device depend on the saturation current density of the semiconductor (\(J_0\), generally given in [A/cm²]) and on the effective area of the cells. The current density \(J_0\) depends on the intrinsic characteristics of the photovoltaic cell, which depend on several physical parameters such as the coefficient of diffusion of electrons in the semiconductor, the lifetime of minority carriers, the intrinsic carrier density.

The value of the diode constant \(a\) may be arbitrarily chosen. Many authors discuss ways to estimate the correct value of this constant [8], [11]. Usually \(1 \leq a \leq 1.5\) and the choice depends on other parameters of the I-V model. Some values says, there are different opinions about the best way to choose \(a\). Because expresses the degree of ideality of the diode and it is totally empirical, any initial value of a can be chosen in order to adjust the model. The value of a can be latter modified in order to improve the model fitting if necessary. This constant affects the curvature of the I-V characteristic and varying a can slightly improves the mode accuracy.

The photovoltaic model described in the previous section can be improve if equation (4) is replaced by
The dc output of the solar cell array is transmitted directly to the load through L and Dout. In this mode, the main inductor current

\[ I_o = \frac{I_{sc,n} + k_2 \Delta T}{\exp\left(\frac{V_{oc,n} + k_3 \Delta T}{aV_r}\right) - 1} \]

(6)

This modification aims to match the open-circuit voltages of the model with the experimental data for a very large range of the temperature. Eq. (6) is obtained from (5) by including in the equation the current and voltage coefficients \(K_v\) and \(K_I\). The saturation current \(I_0\) is strongly dependent on the temperature and (6) proposes a different approach to express the dependence of \(I_0\) on the temperature so that the net effect of the temperature is the linear variation of the open–circuit voltage according the practical voltage/temperature coefficient. This equation simplifies the model and cancels the model error at other regions of the I-V curve.

### B. Interleaved Boost Converter

The interleaved boost converter consists of two single-phase boost converters connected in parallel. The two PWM signal difference is 1800 when each switch is controlled with the interleaving method.

Because each inductor current magnitude is decreased according to one per phase, we can reduce the inductor size and inductance when the input current flows through two boost inductors. The input current ripple is decreased because the input current is the sum of each current of inductor \(L_1\) and \(L_2\).

Figure 3 shows the proposed single-switch type soft switching boost converter [15]. One resonant inductor, two capacitors, and two diodes are added to a conventional boost converter for soft switching using resonance. Figure 4 shows the interleaved soft-switching boost converter (ISSBC) proposed in this paper. Two single-phase soft-switching boost converters are connected in parallel and then to a single output capacitor.

Each mode is presented during one switching cycle of steady-state operation of the proposed converter.

For illustrating the soft-switching operation using resonance, we describe the operation modes of a single-phase soft-switching boost converter, which consists of the proposed ISSBC.

The key waveforms associated with the operation stages are shown 5. There are operation modes shown in Figure 6, and the duty ratio is assumed to be 0.5 in order to simplify the analysis. The operation can be analysed in terms of eight modes according to the operations in following:

All switching devices and passive elements are ideal.

The parasitic components of all switching devices and elements are ignored.

It is assumed that the initial value of each operation mode is equal to zero.

**Mode 1 (t0 ≤ t < t1):** The switch is in the off state and the dc output of the solar cell array is transmitted directly to the load through L and Dout. In this mode, the main inductor

\[ i_{L_1}(t) = I_1 = \frac{V_0 - V_{in}}{L} \]

(7)

\[ i_{L_2}(t) = 0, \quad v_{cr}(t) = V_0, \quad \dot{v}_{cr}(t) = 0 \]

(8)

\[ i_L(t_1) = I_1 \]

(9)

**Mode 2 (t1 ≤ t < t2):** in mode 2, the switch is turned on under zero-current switching (ZCS) because of the resonant inductor \(L_r\). In this case, as the output voltage is supplied to the resonant inductor \(L_r\) and the resonant voltage \(V_{cr}\) becomes zero, the two auxiliary diodes \(D_1\) and \(D_2\) are turned on and the mode starts. In this mode, the resonant inductor current \(i_{L_1}\) becomes equal to the main inductor current \(i_{L_2}\), the current of the output side diode \(D_{out}\) becomes zero

\[ i_{L_2}(t_2) = I_{min}, \quad t_{L_2}(t_2) = t_{min} \]

(10)

\[ i_{L_1}(t) = I_{min} + \frac{V_0}{Z_r} \sin \omega_r t \]

(11)

\[ v_{cr}(t) = V_0, \quad \dot{v}_{cr}(t) = 0 \]

(12)

\[ t_{L_2}(t_1) = I_2 = \frac{V_0}{Z_r} \cos \omega_r t \]

\[ \omega_r = \frac{1}{\sqrt{L_r C_r}}, \quad Z_r = \sqrt{\frac{L_r}{C_r}} \]

(13)

(14)

(15)

(16)

**Mode 3 (t2 ≤ t < t3):** when the output current \(i_{D_{out}}\) becomes zero, the mode starts. In this mode, the resonant inductor \(L_r\) and the resonant capacitor \(C_{r}\) resonate and voltage of \(C_{r}\) decrease from the output voltage \(V_0\) to zero. In this case, the main inductor current \(i_{L_1}\) flow through \(L_r\) and switch

\[ i_{L_1}(t_2) = I_{min}, \quad v_{cr}(t_2) = 0 \]

(17)

\[ i_{L_2}(t) = \frac{V_0}{Z_r} \sin \omega_r t \]

(18)

\[ t_{L_2}(t) = I_2 = \frac{V_0}{Z_r} \cos \omega_r t \]

(19)

\[ v_{cr}(t) = 0, \quad \dot{v}_{cr}(t) = 0 \]

(20)

\[ t_{L_2}(t) = I_{min}, \quad t_{L_2}(t) = I_2 \]

(21)

**Mode 4 (t3 ≤ t < t4):** when the resonant capacitor voltage \(V_{cr}\) becomes zero, the two auxiliary diodes \(D_1\) and \(D_2\) are turned on and the mode starts. In this mode, the resonant inductor current is separated in two parts. One is the main inductor current \(i_{L_1}\) and the other is the current turning though the two auxiliary diodes. The main inductor current \(i_{L_1}\) increases linearly

\[ i_{L_1}(t) = I_{min} + \frac{V_{in}}{L} t \]

(22)

(23)

(24)

(25)

(26)

**Mode 5 (t4 ≤ t < t5):** In mode 5, the switch turns off under the zero-voltage condition because of the auxiliary resonant capacitor \(C_a\). There are two current loops. One is the \(L_r-C_a\) loop for which the voltage of the resonant capacitor \(C_a\) increases linearly from zero to the output voltage \(V_0\). The other is the \(L_r-C_{r}-D_1\) loop for which the second resonance occurs. The energy stored in \(L_r\) is transferred to \(Ca\). The
resonant current $i_{Lr}$ decreases linearly and the voltage across $C_a$ becomes maximal

$$t_L(t) = I_2 = I_{\text{max}}$$  \hspace{1cm} (22)

$$t_L(t) = I_2 \cos \omega_a t$$  \hspace{1cm} (23)

$$v_c(t) = Z_r I_2 \sin \omega_a t, \quad v_c(t) = V_o$$  \hspace{1cm} (24)

$$\omega_a = 1/\sqrt{L_r C_a}$$  \hspace{1cm} (25)

$$Z_a = \sqrt{L_r / C_a}$$  \hspace{1cm} (26)

**Mode 6 ($t_5 \leq t < t_6$):** When the resonant capacitor voltage $v_{Cr}$ is equal to the output voltage $V_o$, the mode starts. In this mode, the energy flow from $L_r$ to $C_a$ is completed and the resonant current $i_{Lr}$ becomes zero

$$t_L(t) = I_2 - \frac{V_o - V_{\text{in}}}{L} t$$  \hspace{1cm} (27)

$$t_{Lr}(t) = I_2 \cos \omega_a t$$  \hspace{1cm} (28)

$$v_c(t) = Z_r I_2 \sin \omega_a t, \quad v_c(t) = V_o$$  \hspace{1cm} (29)

$$v_c(t) = Z_a I_2$$  \hspace{1cm} (30)

**Mode 7 ($t_6 \leq t < t_7$):** In mode 7, the voltage of $C_a$ decreases, continuously resonates on the $D_2$–$C_a$–$L_r$–$D_{out}$–$C_o$ loop and the energy is transferred from $C_a$ to $L_r$. When the $C_a$ voltage becomes zero, the resonant current $i_{Lr}$ is the reverse of the current direction of mode 6. When the voltage of $C_a$ becomes zero, the anti-parallel diode of the switch turns on and it transitions to the next mode

$$t_L(t) = I_2 - \frac{V_o - V_{\text{in}}}{L} t, \quad i_{Lr}(t_6) = I_4$$  \hspace{1cm} (31)

$$t_{Lr}(t) = \left(\frac{V_o}{Z_a} - I_2\right) \sin \omega_a t, \quad t_{Lr}(t) = I_5$$  \hspace{1cm} (32)

$$v_c(t) = V_o$$  \hspace{1cm} (33)

$$v_c(t) = V_o - (V_o - Z_a I_2) \cos \omega_a t = V_2$$  \hspace{1cm} (34)

**Mode 8 ($t_7 \leq t < t_8$):** There are two current loops. The main inductor current $i_L$ transmits energy to the output through $D_{out}$ and decreases linearly. The resonant inductor current $i_{Lr}$ also transmits energy to the load through $D_{out}$ and flows through the anti-parallel diode of the switch. When the resonant inductor current $i_{Lr}$ becomes zero, mode 8 ends

$$V_L(t) = I_4 \frac{V_o - V_{\text{in}}}{L} t, \quad t_{Lr}(t_8) = I_6$$  \hspace{1cm} (35)

$$t_{Lr}(t) = I_5 - \frac{V_o}{L_r} t, \quad t_{Lr}(t_5) = 0$$  \hspace{1cm} (36)

$$v_c(t) = V_o$$  \hspace{1cm} (37)

$$v_c(t) = 0$$  \hspace{1cm} (38)

Figure 3: Proposed single switch soft switching boost converter

Figure 4: Interleaved soft switching boost converter

Figure 5: Operation modes of proposed converter
Experimental Parameters

PV Module:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>IM</td>
<td>$I_{mp}$</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>MP</td>
<td>$V_{mp}$</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Pmax,m</td>
<td>$P_{max,m}$</td>
<td>1.2kW</td>
<td></td>
</tr>
<tr>
<td>SC</td>
<td>$I_{sc}$</td>
<td>5.8</td>
<td></td>
</tr>
<tr>
<td>OC</td>
<td>$V_{oc}$</td>
<td>235</td>
<td></td>
</tr>
<tr>
<td>PV</td>
<td>$I_{pv}$</td>
<td>5.814</td>
<td></td>
</tr>
<tr>
<td>Rs</td>
<td>$R_s$</td>
<td>0.221</td>
<td></td>
</tr>
<tr>
<td>Rp</td>
<td>$R_p$</td>
<td>405.415</td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>a</td>
<td>1.3</td>
<td></td>
</tr>
</tbody>
</table>

Interleaved boost converter:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
<td>$V_{in}$</td>
<td>200-350</td>
<td>V</td>
</tr>
<tr>
<td>Output voltage</td>
<td>$V_0$</td>
<td>400</td>
<td>V</td>
</tr>
<tr>
<td>Rated power</td>
<td>$P_0$</td>
<td>1.2</td>
<td>kW</td>
</tr>
<tr>
<td>Main inductor</td>
<td>$L_{1}, L_{2}$</td>
<td>1</td>
<td>mH</td>
</tr>
<tr>
<td>Resonant inductor</td>
<td>$L_{1,1}, L_{2,2}$</td>
<td>50.6</td>
<td>£H</td>
</tr>
<tr>
<td>Resonant capacitor</td>
<td>$C_{r1}, C_{r2}$</td>
<td>10</td>
<td>nF</td>
</tr>
<tr>
<td>Auxiliary capacitor</td>
<td>$C_{a1}, C_{a2}$</td>
<td>10</td>
<td>nF</td>
</tr>
<tr>
<td>Output capacitor</td>
<td>$C_{out}$</td>
<td>10</td>
<td>µF</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>$f_{sw}$</td>
<td>30</td>
<td>KHz</td>
</tr>
</tbody>
</table>

D. MPPT Controller: P&O MPPT Algorithm

The MPPT algorithm used in the simulations is a hill climbing P&O technique. The boost converter duty ratio is changed and the resulting change in power is observed. The duty ratio is then changed again based on the previous sample such that the new duty ratio is closer to the MPP. In this simulation, the boost converter duty ratio and the average power generated by the PV are measured and compared to the value during the previous sample. The sample rate is 100Hz. The change in duty ratio and change in average power are multiplied together and then compared to zero. If the product is positive, the duty ratio is incremented by 1%. If the product is negative, the duty ratio is decremented by 1%. If the product is zero, the control toggles between incrementing and decremented the duty ratio by 1%. This prevents the simulation from getting stuck at one duty ratio, and does not appear to add additional oscillation around the equilibrium point. The duty ratio is limited between 0 and 90% to keep the boost converter in a suitable operating range.

III. SIMULATION MODEL

The Simulink model of the P&O MPPT algorithm is shown in Figure 7. The algorithm takes PV cell power as an input, adjusts the duty ratio accordingly, and outputs a PWM signal that drives the boost converter. The PV module is modeled in Simulink as shown in Figure 8. The generated current $I_m$ is obtained by the simulation subsystem model of PV array as shown in Figure 9.
The overall closed loop simulation of photovoltaic array with MPPT is shown in Figure 10.

### IV. SIMULATION RESULTS

**Figure 10:** Overall closed loop simulation model with MPPT controller

**Figure 11:** I-V of PV module

**Figure 12:** P-V curve of PV module

**Figure 13:** MPPT pulse with 180° phase shift

**Figure 14:** Output voltage of interleaved boost converter with MPPT

**Figure 15:** Output current of interleaved boost converter with MPPT

**Figure 16:** Output of photovoltaic model

### IV. CONCLUSION

In this paper, we proposed a soft switching interleaved boost converter with MPPT controller. The computer simulation of the converter has been carried out using MATLAB. From the results, it was confirmed that the resonant components are well designed. The output voltage and current waveforms of the proposed ISSBC were shown. From the simulation results, it can be observed that, the proposed model of photovoltaic system is working well with interleaved boost converter.

### REFERENCES


