ANALYSIS AND DESIGN OF AN HIGH VOLTAGE GAIN INTERLEAVED DC-DC BOOST CONVERTER FOR SOLAR PV APPLICATIONS

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ABSTRACT

A converter with MPPT controller for PV systems is developed for extracting maximum power from the PV array. The proposed converter is designed from the existing two phase interleaved boost converter. Current from the PV array should also be drawn with minimal ripple. The high output DC voltage can then be used for high power applications or integrated to the utility grid. The main contribution of this research work is the output voltage of a solar array is low and it needs to be boosted to feed high power applications or integration to the grid. However, this must be done with high efficiency, while ensuring that maximum power is drawn from the PV array. Many techniques have been identified that attempt to increase the output voltage of a photovoltaic source, but these have limitations due to low efficiency, complexity and cost. Using the proposed DC-DC converter, it is possible to obtain high boost ratios with high efficiency and low cost of the entire photovoltaic system. The proposed converter is also suitable for high and variable power applications.

Keywords- PV System, DC-DC converter, high gain, soft switching, interleaved boost converter

I. INTRODUCTION

The photovoltaic system is considered the specific solution for the recent energy crises. Since this system is recyclable and has a long service life, it is distributed throughout the earth and is mainly pollution-free. To transmit PV energy to the load, the high efficiency interface is essential. In this article, we have proposed a high boost interleaved boost converter with a two-stage switched capacitor and coupled inductor. The MPPT controller is also used to increase the efficiency of the photovoltaic power generation system. This method produces a high voltage gain with a low duty ratio, compared to other techniques, the voltage voltage across the switch is greatly reduced, which also reduces ripple and conduction loss. Two-stage switched capacitors not only extend the voltage gain, but also effectively use the coupled inductor. The passive clamp circuit causes the main switches to be switched off with zero voltage switching and the zero current switching is activated due to the inherent loss of the inductor. Since the current drop rate is controlled by the leakage inductance, the problem of the reverse recovery of the diode is alleviated and the efficiency is improved.

Nowadays, with global energy shortage, renewable energy resources have turned the attention of many researchers. Among renewable energy technologies Photo-Voltaic (PV) system is one of the most widely used technique. Generally in PV power generation system two main problems occur, that is power generation varies with weather condition and its low conversion efficiency. A DC to DC high step up converter is very essential to overcome the inherent low voltage characteristic. These converters were widely used in many applications such as automobile head lamps as a high-intensity discharge lamp, Uninterruptible Power System (UPS) and also for the communication power system. Conventional converter has been used to provide high step up gain, but it has a drawback of high voltage stress on the switches, which makes high performance low voltage devices unsuitable. If the duty ratio approaches unity, the overall efficiency gets degraded, so the conventional converters like boost and buck-boost converters can’t satisfy the application needs [1-3], [17].

To produce high step up voltage gain many topologies have been presented with a minimum duty ratio [4]. With simple structure DC-DC fly back converter generates a high voltage gain. Due to leakage inductance of
transformer there is a high voltage stress on the active switches, and the voltage stress on the active switches can be clamped using few Energy-Regeneration techniques [5],[6] & [17].

By increasing the turns of the transformer, the existing isolated voltage-type converter like phase-shifted full-bridge converter, able to produce high step-up gain, but more electrolytic capacitors are essential to reduce the input current ripples. Other isolated converters like active-clamp dual boost and active-clamp full bridge boost converter can achieve high efficiency and high step up conversion [7],[8].

To improve conversion efficiency switched capacitor based converter was proposed to achieve a large voltage conversion ratio [9], [10]. But this technique produces high transient current and large conduction loss in the switch, and also to obtain extremely high step up conversion more switched capacitor cells are needed, which makes the circuit complex [11], [18].

Based on switched-capacitor cell concepts many topologies were presented to reduce the electromagnetic interference and switching loss by using soft-switching schemes [12], [19]. The coupled-inductor technique is another solution to achieve high step-up gain by adjusting the turn ratio [13]. The parasitic capacitor and the leakage inductance of the coupled-inductor will resonate together, and to absorb voltage ringing on the output diode, proper snub circuit is used. Both cost and complexity of the circuit gets increased by using two active switches with additional protection circuit.

For universal power factor correction interleaved voltage doubler circuit was proposed with automatic current sharing capability and to increase low-line efficiency lower active switch stress is used. However the diode stress remains very high and the voltage gain is not high enough. High step up ratio converter and ultra-step-up converter has proposed to provide large step-up voltage ratios, but the diode voltage stress remains high [14].

Low conversion efficiency and its dynamic weather condition are the major problem in the PV power generation system. To increase the efficiency of PV system, it should be operated at maximum power point at any time. To overcome this many MPPT algorithms was proposed [15], [16] & [20]. In this paper, modified two-phase interleaved boost converter is cascaded together, which has an advantage of the automatic current sharing capability simultaneously. This proposed technique greatly reduces the voltage stress of switches and diodes which greatly enhance the overall efficiency.

II. PROPOSED TOPOLOGY

The proposed converter is integrated with MPPT controller for high step-up conversion as shown in 1.

L1, L2  - Magnetizing Inductances

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D₁, D₂, D₃, D₄ - Clamp diodes
C₁, C₂ - Clamp capacitors
C₃, C₄ - Output capacitors
S₁, S₂ - Main Switches

The interleaved boost converter is added with two capacitors and two diodes. During the period of energy transfer
the stored energy in partial inductor is stored in one of the capacitors together with the stored energy of other
 capacitor is moved to the output to gain higher voltage. When compared with interleaved two phase boost converter,
the proposed converter will achieve twice the voltage gain, and both active switches and diodes produce only less voltage stress. Since this proposed converter is integrated with MPPT controller, it automatically tracks for the maximum MPP and produce higher conversion ratios. Our main objective of this converter is to achieve high voltage gain and steady state analysis is made for duty cycle more than 0.5 and when it operates in continuous conduction mode. In discontinuous conduction mode and when the duty ratio less than 0.5, there is no sufficient energy transfer between the inductor, blocking capacitor, capacitor at the output side and load side, hence in this mode achieving high voltage gain is not possible. In addition, automatic current sharing characteristic is featured when there is a duty ratio greater than 0.5 and due to the blocking capacitor charge balance. The automatic current sharing capability is not possible under the condition when the duty ratio is less than 0.5.

(i) Mode 1:
In this mode when \( t_0 \leq t < t_1 \), S₁ and S₂ switches are turned ON, where D₁, D₂, D₃, D₄ are turned OFF. The current flow path is shown in Fig 2. To store energy in L₁ and L₂, both \( i_{L1} \) and \( i_{L2} \) gets increased. Diodes D₁ and D₃ voltages are clamped to \( V_{C1} \) and \( V_{C2} \) of capacitor voltage respectively, and diodes D₄ and D₂ voltages are clamped to \( (V_{C4} - V_{C2}) \) and \( (V_{C3} - V_{C1}) \).

From capacitors C₃ and C₄ load power is supplied and its corresponding equation is shown below.

\[
V_{in} = L_1 \frac{di_{L1}}{dt} = L_2 \frac{di_{L2}}{dt}
\]  

(1)
\[
C_1 \frac{dV_{c1}}{dt} = C_2 \frac{dV_{c1}}{dt} = 0
\]  
(2)

\[
C_3 \frac{dV_{c1}}{dt} = C_4 \frac{dV_{c4}}{dt} = -\left(\frac{V_{c3}+V_{c4}}{R}\right)
\]  
(3)

(ii) Mode 2:

In this mode when \(t_1 \leq t < t_2\), switch S2 is turned OFF, while switch S1, diodes D2 and D3 remains conducting. The current flow of this stage is shown in Fig 3 And the C1 stored energy and inductor L2 stored energy is released to load and to the C3 of the output capacitor, while the part of inductor L2 stored energy is stored in C2. The Capacitor voltage of this mode \(V_{C3}=V_{C2}+V_{C1}\), this makes \(i_L2\) to decrease linearly and \(i_L1\) to increase continuously.

The equation corresponding to this is shown below.

\[
V_{in} = L_1 \frac{di_{L1}}{dt}
\]  
(4)

\[
V_{in} - V_{c2} = L_2 \frac{di_{L2}}{dt}
\]  
(5)

\[
C_1 \frac{dV_{c1}}{dt} = I_{c2} - I_{L2}
\]  
(6)

\[
C_2 \frac{dV_{c2}}{dt} = I_{c1} + I_{L2}
\]  
(7)

\[
C_3 \frac{dV_{c1}}{dt} = -I_{c1} - \left(\frac{V_{c3}+V_{c4}}{R}\right)
\]  
(8)
(iii) Mode 3:
In this mode when \( t_2 \leq t < t_3 \), both S1 and S2 are turned ON, other operations are same as that of mode 1.

(iii) Mode 4:
When \( t_4 \leq t < t_5 \), Switch S2 remains conducting in this mode of operation and switch S1 is turned OFF.

Diode D_1 and D_4 also conducting. Then the energy stored in inductor L_1 and the energy stored in C_2 is released to load and to the C_4 of the output capacitor, while the output capacitor \( V_{C4} = V_{C2} + V_{C1} \). This makes \( i_{L1} \) to decrease linearly and \( i_{L2} \) remains increasing continuously.

\[
L_1 \frac{di_{L1}}{dt} = V_{in} - V_{C4} + V_{C2} = V_{in} - V_{C1} \quad (10)
\]

\[
V_{in} = L_2 \frac{di_{L2}}{dt} \quad (11)
\]

\[
C_1 \frac{dV_{C1}}{dt} = i_{C2} + i_{L1} \quad (12)
\]

\[
C_2 \frac{dV_{C2}}{dt} = i_{C1} - i_{L1} \quad (13)
\]

\[
C_3 \frac{dV_{C3}}{dt} = -\left( \frac{V_{C3} + V_{C4}}{R} \right) \quad (14)
\]

\[
C_4 \frac{dV_{C4}}{dt} = -i_{C2} - \left( \frac{V_{C3} + V_{C4}}{R} \right) \quad (15)
\]
The operations of the proposed converter are symmetric and easy to implement. From the key operating waveforms as shown in Figure 4, it is clear that four diodes and two active switches attain low voltage stress with uniform current sharing.

1. Voltage Stress Analysis

Assume that, the capacitor voltage ripple can be ignored to simplify the voltage stress analyses of the converter components. The voltage stresses on the solid state power switches S1 and S2 can be obtained directly from the modes of operation. The volt second relationship of inductors L1 and L2 is getting from the following conditions

\[ DV_{in} + (1 - D)(V_{in} - V_{C1}) = 0 \]

and

\[ DV_{in} + (1 - D)(V_{in} - V_{C2}) = 0 \]  \hspace{1cm} (16)

The capacitor \(V_{C3}\) and \(V_{C4}\) can be obtained by using the following relationship

\[ V_{C3} = V_{C1} + V_{C2} = \frac{2}{1 - D} V_{in} \]
and

\[ V_{C4} = V_{C1} + V_{C2} = \frac{2}{1-D} V_{in} \]  (17)

Therefore the output voltage of the converter is

\[ V_0 = V_{C3} + V_{C4} = \frac{4}{1-D} V_{in} \]  (18)

Hence, the voltage conversion ratio of the interleaved boost dc-dc converter is

\[ M = \frac{V_0}{V_{in}} = \frac{4}{1-D} \]  (19)

Hence, the voltage stresses on the solid state power switches S1 and S2 are from the modes of operation is

\[ V_{S1} = V_{S2} = \frac{1}{1-D} V_{in} \]  (20)

By substituting the output voltage equation to the above condition, voltage stresses on the active solid state power switches is arrived. Therefore the voltage stress on power switches is

\[ V_{S1} = V_{S2} = \frac{V_0}{4} \]  (21)

from the above relationship, it can be stated that the voltage stress of power switches of the proposed converter is equal to one fourth of the output voltage. Hence, the proposed converter enables one to adopt lower voltage rating devices to further reduce both switching and conduction losses.

### III. SIMULATION RESULTS

The performances of the proposed converter with MPPT controller for PV system are discussed in this section.

The input 25V and output 400V with 400W rating is constructed using the proposed converter. Both switch S1 and S2 has the equal duty ratio of 0.75 with switching frequency 40Hz. The interleaved construction can reduce the input ripples, output ripples and the size of inductors by increasing the switching frequency.
Figure 5 Input and output Voltage
Figure 6 Results obtained for blocking capacitor & Output capacitor
Figure 5 shows the input voltage and the corresponding output voltage of our proposed method. And in Figure 6 the blocking capacitor waveform and output capacitor waveform are shown. The active switch voltage stress is 1/4th of the voltage output as shown in Figure 7. Power loss distribution is analyzed and came to the conclusion that from the switches, diodes and from the inductors major losses are occurring. In this paper, we proposed a converter to reduce the voltage stress on switches and diodes, which effectively reduces the major losses.

IV. PERFORMANCE ANALYSIS

For evaluating the proposed converter performance, it is compared with the other existing high step up converters reported in literature. Comparison is presented in table 1 in terms of voltage gain and active switches normalized voltage stress.

<table>
<thead>
<tr>
<th>Duty Ratio</th>
<th>Voltage Gain</th>
<th>Voltage Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Doubler</td>
<td>0.5 0.6 0.7</td>
<td>0.5 0.6 0.7</td>
</tr>
<tr>
<td>High Step Up Ratio Converter</td>
<td>4 5 6</td>
<td>0.5 0.5 0.5</td>
</tr>
<tr>
<td>Proposed Converter</td>
<td>5 6.1 7</td>
<td>0.4 0.43 0.45</td>
</tr>
<tr>
<td></td>
<td>8 10 14</td>
<td>0.25 0.25 0.25</td>
</tr>
</tbody>
</table>

The proposed converter characteristic curve and the comparison of the voltage gains normalized voltage stress, of the conventional existing converters also shown in Figure 8 and Figure 9.
When compared with the other existing boost converters, the Converter proposed can attain higher voltage gain as shown in Figure 8, lower voltage stress for active switches as shown in Figure 9. For the application required more voltage gain, this proposed converter is more suitable and can attain higher efficiency by adopting lower voltage rating on the switching components.
This proposed converter along with the MPPT controller can achieve maximum efficiency of 96% as shown in Figure 10. From the PV array we can obtain maximum power using MPPT controller. This MPPT controller can effectively track the maximum power point from the PV array. Our proposed converter with an MPPT controller can generate 2.4 times of more PV power when compared with the converter without using MPPT algorithm. The result shows that our proposed converter with MPPT controller is proven to be effective and can generate maximum power from the PV system.

V. CONCLUSIONS

This paper analyzed a converter with MPPT controller for PV systems. The MPPT algorithm is developed for extracting maximum power from the PV array. The proposed converter is designed from the existing two phase interleaved boost converter. It not only achieves high voltage gain, it achieves it with the reduced duty cycle. This leads the way to reduce both conduction and switching loss by choosing MOSFETs and diodes of lower voltage rating. The converter also features the uniform automatic current sharing capabilities without adding any additional circuit. While comparing with other conventional converter, the proposed converter along with MPPT controller provides better conversion efficiency and further the proposed converter is validated by using the rating 25V input and 400V output. The result shows that for high step up voltage gain applications; this proposed method has proven very effective.

REFERENCES