1. Introduction

The photovoltaic is the most promising renewable energy source due to its merits such as infinite power, pollution free and available in abundance. However, the output of photovoltaic is low and has to be boosted. High step up DC-DC converter plays a major role in renewable energy applications that includes photovoltaic system, fuel cell, grid system, electric vehicle applications, etc. Due to build in low voltage characteristics of photovoltaic, high step up DC-DC converter is used. The conventional boost converter with high duty ratio causes switching and conduction losses. Hence the conventional boost converter is not preferred. By using transformer with large turns ratio, high step up conversion can be achieved by isolated converters. But due to large turn's ratio, the leakage inductance is high, voltage and current spikes increases. An isolated converter requires large filter as the input current is pulsed\textsuperscript{2-5}. Coupled inductor can achieve high step up conversion ratio, but has high voltage stress, reverse-recovery problem and decreases the conversion efficiency\textsuperscript{6,7}. To solve the problems of coupled inductor various methods are used.

High voltage conversion ratio is achieved using switched capacitor\textsuperscript{8-11}. But needs large number of switches and leads to complex control strategies\textsuperscript{12}. The design rules are proposed for high efficient switched capacitor converters by C. Chun-Kit, T. Siew-Chong, et al.\textsuperscript{13} The switching losses and EMI are reduced by using soft switching technique for switched converter topologies\textsuperscript{14-16}. A family of interleaved DC-DC converter with winding cross coupled inductor and voltage multiplier cells is proposed in\textsuperscript{17-19}. Interleaved converter
with voltage doubler characteristics and converter with MPPT technique is proposed in\textsuperscript{20,21}. The transformer-less two phase interleaved DC-DC converter with high voltage gain without large duty cycle and reduced voltage stress is proposed by Ching-Tsai Pan, Chen-Feng, Chuang, Chia-Chi Chu\textsuperscript{1}. In this paper, input parallel output series configured interleaved DC-DC converter is proposed for photovoltaic system using MPPT algorithm. The output power of photovoltaic cell varies with respect to temperature and irradiation and reduces the conversion efficiency. Thus continuous tracking of maximum power point is necessary to maximize output power of photovoltaic. To make efficient, MPPT algorithm is used to extract maximum output power from photovoltaic panel. An overview of MPPT algorithm has been proposed by Mohamed A. Eltawil, Zhengming Zhao\textsuperscript{22}. The modified perturb and observe algorithm for photovoltaic system is proposed in\textsuperscript{23}. These methods are based on various factors such as complicacy, cost, hardware implementation and faster convergence. Though several MPPT methods are proposed, perturb and observe has more advantages due to its simplicity and operation under dynamic and static condition. Thus, in this paper transformer-less interleaved boost converter using Perturbs and Observes (P&O) to extract maximum output power with proper duty cycle is proposed. In this paper, Section II describes the operating principle of proposed input parallel output series configured interleaved DC-DC converter. In Section III, PV modeling and MPPT algorithm are discussed. The simulation of transformer-less interleaved converter with and without MPPT are discussed in Section IV. The conclusion is summarized in Section V.

2. Transformerless Interleaved Converter

The proposed interleaved converter consists of two inductors $L_1$ and $L_2$ with active switched $S_1$ and $S_2$ across the output of photovoltaic panel as shown in Figure 1. The diodes and blocking capacitors are used to store part of the energy of inductor and this stored energy is begin transferred to the output capacitors $C_1$ and $C_2$ to achieve high voltage gain. The proposed converter produces uniform current sharing through the inductor which eliminates the usage of additional circuitry and also complicated control methods.

In order to avoid the pulsating output period, the duty cycle of the proposed converter is made greater than 0.5 and also operated in continuous conduction mode. If the converter operates with duty cycle less than 0.5, then the voltage gain cannot be improved as it is not possible for the inductor ($L_1, L_2$) to transfer energy to blocking capacitors ($C_{b1}, C_{b2}$), output capacitors ($C_1, C_2$) and load. In addition, with duty cycle less than 0.5, the uniform current sharing cannot be achieved.

![Figure 1. Transformerless interleaved DC converter.](image)

The proposed model consists of PV panel, MPPT Perturb and Observe algorithm and transformer-less interleaved converter. The P&O algorithm used to extract maximum power from the PV panel and decides proper duty ratio for the converter. The converter has four modes of operation.

2.1 Mode 1

The switches $S_1$ and $S_2$ are turned ON and diodes $D_1$, $D_2$, $D_3$, $D_4$ are turned off. In this mode, energy is stored in inductor $L_1$ and $L_2$ due to increasing current $i_{L1}$ and $i_{L2}$. The diodes $D_1$ and $D_2$, voltages are clamped to blocking capacitor $C_{b1}$ and $C_{b2}$ voltages.

\[
V_{d1} = V_{c1} - V_{b1} \tag{1}
\]

\[
V_{d2} = V_{c2} - V_{b2} \tag{2}
\]

2.2 Mode 2

The active switches $S_1$ is turned ON and $S_2$ is turned off. Stored energy of blocking capacitor $C_{b1}$ and part of energy stored in inductor $L_2$ is delivered to output capacitor $C_2$ and load. At the same time, part of energy stored in inductor is delivered to $C_{b2}$. In this mode,

\[
V_{c3} = V_{b1} - V_{b2} \tag{3}
\]

Hence inductor current $i_{L1}$ increases and $i_{L2}$ decreases.
2.3 Mode 3
The mode 3 is similar to mode 1 operation.

2.4 Mode 4
The active switches S₂ is turned ON and S₁ is turned off. The stored energy of blocking capacitor C₂ and part of energy stored in inductor L₁ is delivered to output capacitor C₂ and load. At the same time, the part of energy stored in L₁ is delivered to C₁. Therefore

\[ V_{c2} = V_{b1} + V_{b2} \]  

In this mode, current i₁ decreases and i₂ increases.

2.4.1 Analysis of Parameters
The various parameters to analyze the proposed transformer-less interleaved converter are as follows.

2.4.1.1 Voltage Gain
Voltage gain of the interleaved boost converter is defined as the ratio of output voltage to input voltage. The voltage across output capacitor is given by

\[ V_{c1} = V_{b1} + V_{b2} = 2 \frac{V_i}{1 - D} \]  

\[ V_{c2} = V_{b1} + V_{b2} = 2 \frac{V_i}{1 - D} \]  

From (5) and (6), the output voltage is given by

\[ V_o = V_{c1} + V_{c2} = 4 \frac{V_i}{1 - D} \]  

Therefore, the voltage gain = \( \frac{V_o}{V_i} = \frac{4}{1 - D} \)  

2.4.1.2 Voltage Stresses on Active Switches
By neglecting the voltage ripples of capacitors, the voltage stress on active switches S₁ and S₂ are given by

\[ V_{s1} = V_{s2} = \frac{V_i}{1 - D} \]  

By substituting (7) in (9), the voltage stress on active switches is given by

\[ V_{s1} = V_{s2} = \frac{V_o}{4} = 0.25V_o \]  

From (10), the voltage stress of active switches is 0.25 times that of output voltage. Thus, one can choose low voltage rating power devices to reduce conduction and switching losses. The voltage stress diodes D₁, D₂, D₃ and D₄ are given by

\[ V_{D1} = V_{D2} = V_{D3} = \frac{V_o}{2} \]  

\[ V_{D4} = \frac{V_o}{4} \]  

2.4.1.3 Uniform Current Sharing
The current through the inductor are uniform and given by

\[ I_{L1} = I_{L2} = \left( \frac{2}{1 - D} + \frac{DC_{b1}}{(1 - D)C_1} \right) I_o \]  

Where C₁=C₂ and Cₙ₁=Cₙ₂.

3. PV Modeling and MPPT Algorithm

3.1 Modeling of PV
Figure 2 shows the mathematical model of photovoltaic cell. It is represented as current source Iₚᵥ connected parallel with the diode D and resistance Rᵥₚ. The diode D represents the PN junction of the solar photovoltaic cell, Iₚᵥ represents the generated current of photovoltaic, Rᵥₚ is the shunt resistance whose value is high to eliminate leakage current between ground and solar cell and Rᵥₚ is the series resistance which includes the resistance of the metal links.

\[ \text{Figure 2. Photovoltaic Model.} \]

The output current of the solar photovoltaic cell is given by

\[ I_{pv} = \frac{V_{oc}}{R_{p} + R_{sh}} \]
\[ I = I_{pv} - I_d - I_{sh} \tag{14} \]

where \( I_{pv} \) is the generated current of photovoltaic cell.
\( I_d \) is the diode current.
\( I_{sh} \) is the current through shunt resistance.

\[ I = I_{pv} - I_s \left( \frac{q(V + R_s I)}{NkT} - 1 \right) - \frac{(V + R_s I)}{R_{sh}} \tag{15} \]

where \( I_s \) is the reverse saturation current of diode.
\( q \) is electron charge, 1.6x10^{-9} C.
\( V \) is the voltage across diode.
\( T \) is the photovoltaic cell temperature, K.

3.2 MPPT Algorithm

Perturb and Observe (P&O) is the simplest algorithm out of all the other MPPT methods. The method of perturbation is used in the algorithm to find the maximum point and it’s an iterative method. By adjusting the operating voltage of photovoltaic, the output power is either increased or decreased.

![Flowchart of perturb and observe algorithm.](image)

Figure 3. Flowchart of perturb and observe algorithm.

Figure 3 shows the flowchart of perturb and observe algorithm. In this algorithm, the voltage and current of the PV panel are measured. The duty cycle of the converter is initialized. Let \( P(t) \) be the power of the instant and \( P(t-1) \) be the power of (t-1)th instant. The change in power \( \Delta P \) is calculated. If the change in power \( \Delta P \) is positive and the difference between voltages at \( t^{th} \) and \( (t-1)^{th} \) instant is positive, then the duty cycle is increased and if the output power comparison is negative then duty cycle is decreased. If the change in power \( \Delta P \) is negative and the voltage comparison is positive then the duty cycle is increased otherwise decreased. The duty cycle varies based on the output power of the PV panel.

4. Simulation Circuit and Results

The simulation results of transformer-less interleaved converter without and with MPPT are explained.

4.1 Simulation Results of Transformerless Interleaved converter without MPPT

Figure 4 shows the simulation diagram of the transformer-less interleaved converter without MPPT. The PV panel supplies voltage to the converter. The simulation diagram of PV panel consists of current source, diode and resistance. The output of PV panel is 27V and current varies with irradiance. Figure 5 shows the output voltage and current of PV panel without MPPT.

![Simulation circuit of transformerless interleaved converter without MPPT.](image)

Figure 4. Simulation circuit of transformerless interleaved converter without MPPT.

The output of PV panel is given to converter. The simulation circuit of converter consists of MOSFET switches \((S_1, S_2)\), diodes \((D_1, D_2, D_3, D_4)\), blocking capacitor \((C_{b1}, C_{b2})\) and output capacitors \((C_1, C_2)\). The duty ratio of both switches \( S_1 \) and \( S_2 \) are equal to 0.5 and the switching frequency is given as 40 kHz. Figure 6 shows the gate pulse of switches \( S_1 \) and \( S_2 \) and the waveform of the inductor current. The inductor current ripples \((\Delta I_{11} \text{ and } \Delta I_{12})\) are found to be 1.1A. Figure 7 shows the waveform of voltage stress of the active switches without MPPT. The voltage stress of switch is 55V and it is found to be one fourth of the output voltage.
Figure 5. Waveforms of PV panel output voltage and current without MPPT.

Figure 6. Gate pulse of switches and input current of inductor without.

Figure 7. Voltage stress waveform of switch without MPPT.

Figure 8. Diode voltage stress waveform without MPPT.

Figure 9. Blocking capacitor voltage stress waveform without MPPT.

Figure 10. Output capacitor voltage stress waveform without MPPT.

The input voltage 27V is step up to 213V using converter with the voltage gain of 8 and duty ratio 0.5. The output current and power of converter supplied to the load is 1.065A and 226.6W respectively. Figure 11 shows the waveform of output current, voltage and power of supplied to the load.
Performance Analysis of Transformer-Less Two Phase Interleaved High Gain DC Converter using MPPT Algorithm

4.2 Simulation Results of Transformer-Less Interleaved Converter with MPPT

The simulation circuit of transformer-less interleaved converter with MPPT is shown in Figure 12. The perturb and observe algorithm is coded in embedded MATLAB function. The input voltage and current of PV panel is given to MPPT algorithm. The range of duty cycle is assigned between 0.5 and 0.85. Based on the change in power and voltage, the duty cycle is varied and PWM signals are given to active switches $S_1$ and $S_2$ of the converter.

Figure 13 shows the output voltage and current of PV panel. The output voltage of PV panel is 28V. The gate pulse of switches and input current of inductor is shown in Figure 14. The input inductor current $I_{L1}$ varies between 4.25A and 4.75A and $I_{L2}$ between 4.25A and 3.75A. Therefore, input current ripples of inductor are 0.5A. The waveform of voltage stress of the active switches with MPPT is shown in Figure 15. The voltage stress of switch is 45V and it is found to be one fourth of the output voltage.
Figure 16 shows the diode $D_1$, $D_2$, $D_3$ and $D_4$ voltage stress waveform with MPPT. The voltage stress of diodes $D_1$, $D_2$ and $D_3$ is 100V and voltage stress of diode $D_4$ is 40V. Figure 17 shows the waveform of blocking capacitor voltage stress. The voltage stress of blocking capacitor is 43V. Figure 18 shows the waveform of output capacitor voltage stress with MPPT. The voltage stress of the output capacitor is 111.52V and found to be half of the output voltage of the converter.

![Figure 16. Diode voltage stress waveform with MPPT.](image)

![Figure 17. Blocking capacitor voltage stress waveform with MPPT.](image)

![Figure 18. Output capacitor voltage stress waveform with MPPT.](image)

Figure 19 shows the waveform of output current, voltage and power of transformer-less interleaved converter with MPPT. The input voltage 28V is step up to a voltage of 223V using converter with MPPT. The output current and power of converter to the load is 1.11A and 248.2W respectively. The comparison of transformer-less interleaved converter with and without MPPT is tabulated in Table 1. The parameters such as voltage stress of active switches, inductor current ripples, output power, output voltage and output current are compared. The transformer-less interleaved converter with MPPT extracts maximum power of 248.2W. Thus, the output power of converter is 21.6W greater than that of converter without MPPT.

![Figure 19. Waveform of output current, voltage and power of transformerless interleaved converter with MPPT.](image)

| Parameters                        | With MPPT | Without MPPT |
|-----------------------------------|-----------|--------------|
| Input current ripples of inductor (Amp) | 0.5       | 1.1          |
| Voltage stress of active switches (Volt) | 45        | 55           |
| Output voltage of converter(Volt)  | 223       | 213          |
| Output current of converter(Amp)   | 1.11      | 1.065        |
| Output power of converter(Watt)    | 248.2     | 226.6        |

5. Conclusion

In this paper, the input parallel output series configured transformer-less interleaved converter with and without MPPT algorithm are compared. The various parameter such as input current ripples of inductor, voltage stress...
of active switches, converter output current, voltage and power are analyzed. The blocking capacitor voltage and output capacitor voltage of interleaved converter with and without MPPT is found to be one fourth and one half of output voltage respectively. However, perturb and observe MPPT algorithm provides proper duty ratio to the active switches of converter to achieve a power output of 248.2W which is 1.1 times that of converter output power without MPPT. Thus, comparing the simulation results of converter with and without MPPT, we conclude that with MPPT the converter inductor input current ripples is reduced to 0.6A, the voltage stress of active switches is reduced to 10V. The converter with MPPT also increases the output current to 0.045A, the output voltage to 10V and output power to 21.6W. Thus, the proposed converter with MPPT shows better performance.

6. References

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