PV System with Z.V.T.Interleaved Boost Converter

Mr. M. Samuel Babu, Dr. V. Nagabhaskar Reddy and Dr. Ch. Sai Babu

Abstract: A photovoltaic power system with Zero Voltage Transition (ZVT) interleaved boost converter and full bridge converter with bi-directional power flow control strategy is proposed in this paper and verified with simulation results. ZVT interleaved boost converter is a combination of winding coupled inductors and active-clamp circuits which will step-up the very low voltage of Photo Voltaic (PV) Cell voltage into very high dc-bus voltage and steady-state model also explained. A bi-directional control strategy, which makes the full bridge converter as an inverter to transfer the power from PV Cell to utility grid and as well as rectifier to stabilize the high voltage dc-bus by drawing power from the grid.

Keywords: Bidirectional power flow control, Direct current control, Maximum power point tracking (MPPT) method, Photovoltaic (PV) system, steady-state model of ZVT-Boost converter.

I. INTRODUCTION

The photovoltaic (PV) Technology is a technology which directly converts the sunlight energy into the electricity using semiconductors. Energy reaching the earth is incredible. By one calculation, 30 days of sunshine striking the earth have the energy equivalent of the total of all the planet’s fossil fuels, both used and unused. Because of these so many advantages and increase in the energy demand makes today photovoltaic (PV) power systems more and more popular. There are several ways to deploy Photo Voltaic Distributed Generation (PVDG) systems. Among them four different system configurations are widely developed in grid connected PV power applications. They are centralized inverter system, string inverter system, multi-string inverter system and the module-integrated inverter system [1]–[4]. Centralized inverter system was used in the middle of 1980’s and

Noticed some disadvantages like miss matching losses, Rise of electric arc in dc wiring and no design flexibility. Module-Integrated inverter system was introduced in starting of 1990’s to overcome the disadvantages of centralized system but reduces the efficiency. String inverter system was used in the middle of 1990’s with the combined features of the centralized and the module integrated inverter system. Multi-string inverter system introduced in 2000’s and developed to combine the advantages of higher energy yield of string inverter with the low cost. A PV inverter has to fulfill three main functions in order to feed energy from a PV array into the utility grid. The first one is that the PV array voltage has to be boost and second one is to invert the DC current into AC current and finally shape the current into sinusoidal wave form. Two different methods of inverter topologies are there for grid-connected PV power systems as with the frequency transformers and without frequency transformers. Maximum efficiency is achieved with the line-commutated and self-commutated transformer less inverters. In every PVDG System the most important design constraint is to obtain a very high voltage gain, why because an open circuit voltage is about 21V for a typical PV module and the maximum power point is about 16V, but the utility grid nominal voltage is much more than this PV module voltage. So, the high voltage amplification is necessary to realize the grid connected function. The conventional system requires large numbers of PV modules connected in series and parallel which may had a problem of large power losses. There is another way to achieve this high voltage amplification by using line frequency transformers but line frequency step-up transformer has the disadvantages of larger size and weight. In transformer less photovoltaic power systems the power electronic converters plays very important role in the power conversion. Generally grid connected pulse width modulation (PWM) voltage source inverter are widely applied in PV System.

Fig.1 Block diagram of Proposed PV Power System.

In this paper a photovoltaic power system with ZVT Interleaved boost converter and full bridge converter with bi-directional power flow control strategy is proposed and
verified with the simulation results. ZVT Interleaved boost converter is a combination of winding coupled inductors and active-clamp circuits which will step-up the

![Fig. 2 proposed grid-connected PV Power System](image)

Very low voltage of PV Cell into very high dc-bus voltage and steady-state model also explained. A bi-directional power flow control strategy which makes the full bridge converter as an inverter to transfer the power from PV Cell to utility grid and as well as rectifier to stabilize the high voltage dc-bus by drawing the power from the grid. Fig 2 Represents the block diagram of this two stage grid connected PV power system. And Fig 2 represents the proposed circuit.

II. MODELING OF A P.V.CELL

![Fig.3 Equalent Circuit of a PV cell](image)

The use of equivalent electric circuits makes it possible to model characteristics of a PV cell. The method used here is implemented in MATLAB programs for simulations. The same modeling technique is also applicable for modeling a PV module. There are two key parameters frequently used to characterize a PV cell. Shorting together the terminals of the cell, the photon generated current will flow through the cell is defined as short circuit current \( I_{sc} \). Thus, \( I_{ph} = I_{sc} \) when there is no connection to the PV cell (open-circuit), the photon generated current is shunted internally by the intrinsic p-n junction diode. This gives the open circuit voltage \( V_{oc} \). The PV module or cell manufacturers usually provide the values of these parameters in their datasheets.

The simplest model of a PV cell equivalent circuit consists of an ideal current source in parallel with an ideal diode as shown in the fig 3. The current source represents the current generated by photons \( I_{ph} \) and its output is constant under constant temperature and constant incident radiation of light.

The PV panel is usually represented by the single exponential model or the double exponential model. The single exponential model is shown in fig. 3. The current is expressed in terms of voltage, current and temperature as shown in equation 1.

\[
I = I_{ph} - I_{sat} \left[e^{\frac{qV}{nkT}} - 1\right]
\]

Equation (1) Shows that the output characteristics of solar cell is non linear and vitally effected by radiation, temperature and load conditions.

Photon generated current is which is equal to Short circuit current \( I_{sc} \) directly proportional to the radiation.

\[
I_{ph}(G_a) = I_{sc} \frac{G_a}{G_{as}}
\]

Where ‘\( G_{as} \)’ is irradiance at standard test conditions and ‘\( G_a \)’ is the absolute irradiance. Short circuit current of a solar cell directly depends on the temperature \( T \) and standard test conditions temperature \( T_s \).

\[
I_{sc}(T) = I_{sc}(T_s)[1 + \Delta I_{sc}(T - T_s)]
\]

Where \( I_{sc} \) is the short circuit current at the standard test conditions. Then photon current will be

\[
I_{ph}(G_a, T) = I_{sc}(T_s) \left[1 + \Delta I_{sc}(T - T_s)\right].
\]

The saturation current also depends on irradiance and cell temperature

\[
I_{sat}(G_a, T) = I_{ph}(G_a, T) e^{\frac{qV_{oc}(T)}{nkT}}
\]

III. STEADY-STATE MODEL OF HIGH STEP-UP ZVT INTERLEAVED BOOST CONVERTER

![Fig. 4 ZVT-interleaved boost converter Equivalent circuit](image)

Here each winding-coupled inductor are modeled as the combination of a magnetizing inductor, an ideal transformer with corresponding turn’s ratio and a leakage inductor in series with the magnetizing inductor. The open circles and asterisks are indicated the coupling method of the each coupled inductor. Where \( L_m \) 1 and \( L_m \) 2 are the magnetizing inductors, \( L_{lk1} \) and \( L_{lk2} \) are the leakage inductors including the reflected leakage inductors of the second and third windings of the coupled inductors respectively. \( C_{S1} \) and \( C_{S2} \) are the parallel capacitors, including the parasitic capacitors of the switches. \( C_{C1} \) and
$C_{c2}$ are the clamp capacitors. $N$ is the turns ratio $n_2 / n_1$.

In paper [5] the operating principle and the steady-state wave-forms of the high step-up ZVT Interleaved boost converter was discussed. A full bridge DC-DC converter also can be replaced this ZVT Interleaved boost converter but for high step-up gain applications the conduction losses will be increase and converter efficiency will be decreases. And other than this DC-DC converter a resonant converters like LLC, LCC are attractive but most of these resonant converters are induces some inherent problems like electromagnetic interference (EMI). Comparing with all these power electronic converters proposed ZVT Interleaved boost converter has the following advantages.

1. As the turn’s ratio increases, the voltage gain increases without extreme duty ratio, so that the current ripples will reduces.

$$M = \frac{V_{out}}{V_{in}} = \frac{N+1}{1-D}. \quad (6)$$

2. As increasing the turn’s ratio voltage stress up on the main switches is reduced. The normalized voltage stress of the main switches is given by

$$V_{ds} = \frac{V_{out}}{N+1} \quad (7)$$

3. For both main switches and auxiliary switches ZVT soft switching is achieved during the whole switching transition.

To simplify the calculation, the following conditions are assumed.

1) The capacitance of the active-clamp circuits should be large enough so that the voltage Ripple on the main switches can be ignored and voltage across each switch is considered as constant when they turn off.

2) The magnetizing inductance is much larger than the leakage inductance, so the magnetizing current $i_{Lm}$ is taken as a constant in one switching period.

3) The dead times of the main switches and the corresponding auxiliary switches are ignored.

Based on the previous assumptions, the partial key waveforms of this converter are shown in Fig. 5, which have reached a steady State.

Applying KVL for the ZVT Interleaved boost converter Equantl circuit, the output voltage will be given by

$$V_{out} = V_{ds1} + V_{i2} + V_{i2}^* \quad (8)$$

Where $V_{i2}$ and $V_{i2}^*$ respectively represent the voltage of the second winding $L_{2b}$ and the voltage of the third winding $L_{2c}$.

![Fig. 5 Partial key waveforms of the converter](image)

A. Stage A (Main Switches $S_1$ OFF and $S_2$ ON).

Based on the voltage-second balance to the magnetizing inductor, the switching voltage of $S_1$ is given by

$$V_{ds1} = \frac{V_{in}}{1-D} \quad (9)$$

From the waveform of $i_{L1}$ shown in Fig. 5, it can be found that

$$V_{Lk} = V_{Lk1} = L_{k1} \times \frac{\Delta i}{\Delta t} = \frac{\Delta t}{(1-D) f_s} \quad (10)$$

As shown in Fig. 5, the voltages on the winding coupled inductors are decided by

$$V_{o1} = V_{o2a} = V_{ds1} - V_{Lk} \quad (11)$$

$$V_{o2} = N \times V_{o1} \quad (12)$$

$$V_{o2}^* = N \times (V_{in} - V_{Lk2}) \quad (13)$$

Therefore, substituting (9), (12), and (13) into (8), the equation of the output voltage in Stage a is obtained

$$V_{out} = (N+1) \times V_{ds1} - 2 \times N \times V_{Lk} \quad \frac{N+1}{1-D} \times V_{in} - 2 \times N \times L_{k1} \times \frac{\Delta i}{(1-D) f_s} \quad (14)$$

B. Stage b (Both Main Switches $S_1$ and $S_2$ are ON)

Likewise, from the wave forms shown in Fig. 5, it can be Found that

$$V_{ds1} = 0 \quad (15)$$
Considering the polarity of the voltages on the winding coupled inductors in stage b, the voltage expressions for the winding-coupled inductors are also obtained by

\[ V_{21}^0 = V_{Tm1} = V_{k1} - V_{in} \]  
\[ V_{22}^0 = N \times V_{n1}^0 \]  
\[ V_{s2}^0 = N \times (L_{k2} + V_{in}). \]

Therefore, substituting (15), (16), and (18) into (8), the equation of the output voltage in Mode 2 is obtained

\[ V_{out} = 2 \times N \times V_{Lk} = 2 \times N \times L_{k1} \frac{\Delta l}{N} \]  

In addition, from the waveform of \( \delta \) shown in Fig. 5, the charge through the output nodes during one switching period is decided by

\[ Q_1 = 2Q_{DC1} = (\Delta t_1 + \Delta t_2) \times \frac{\Delta l}{N} \]

The charge through the load in one switching period is

\[ Q_2 = \frac{V_{out}}{R} \times \frac{\Delta l}{N} \]

Therefore, the charge-conservation equation can be found that

\[ (\Delta t_1 + \Delta t_2) \times \frac{\Delta l}{N} = \frac{V_{out}}{R} \times \frac{1}{I_L} \]

Therefore, the equations (11), (17), and (20) can be solved to obtain the expression for the steady-state model of the converter.

\[ M = \frac{V_{out}}{V_{in}} \]

\[ = (N + 1) \frac{\sqrt{(1-\delta)^2 + 4N^2 \delta^2 L_{k1} R - (1-\delta)M}}{4N^2 \delta L_{k1}} \]

Where \( L_{nk} \) is the equivalent leakage inductance of the winding coupled inductors, and \( L_{k} = L_{k1} = L_{k2}, \) and \( R \) is the equivalent load of the converter.

Table 1 presents the values calculated by the two steady state models based on equation (8) and based on the equation (24) are compared with the simulation results to verify the proposed model. It is clear that the proposed steady-state model approaches the simulation results closely.

IV. CONTROL STRATEGY OF FULL-BRIDGE CONVERTER WITH BIDIRECTIONAL POWER FLOW

Fig. 1 represents the block diagram of the two-stage grid-connected PV system. Here bi-directional power flow concept is implemented by the full-bridge converter by using a direct-current-control strategy. The full bridge converter is a voltage source pulse width modulating converter (VS-PWM). The instantaneous load current is forcefully made to accurately follow the sinusoidal reference current by this VS-PWM converter, which synchronizes with the utility grid voltage. Furthermore, the bidirectional flow of power facilitates to compensate the dc-bus for the ac-side voltage variations, which helps to stabilize the dc-bus voltage in startup and cloudy situations and improves the stability of overall system.

A. Control of the Bidirectional Power Flow

Fig.6 represents control block simulation diagram. The error signal \( U_e \) will go on increasing if \( U_{dc} > U_{ref} \) and the VS-PWM converter works as a PWM rectifier, which draws the energy from the utility grid to the capacitor of dc bus, to stabilize the dc voltage. Furthermore, the bidirectional control strategy guarantees that the dc-bus voltage is stabilized to a required value by the back-end VS-PWM converter, whether the front-end dc–dc converter works or not. Therefore, it is avoided that the ZVT Interleaved Boost converter to works in an open-circuit state.

B. Direct Current Control with Compensation Units

From the Fig. 6, it is clear that the detected load currents \( I_{out} \) and reference current \( i_{ref} \) are compared and generates an error signal which is processed by a PI regulator in the current feedback control loop. In direct current control strategy will have very low harmonics in steady state compared with the other control methods. Generally the grid voltage is not an ideal sinusoidal waveform in practice. Therefore, it is hard to achieve low total harmonic distortion (THD) of the output current by using the simple direct current control strategy in the real grid condition so here two compensation units are added to the current control loop as the control units. Where the first one is with Compensation coefficient \( K_d \) which is directly processes the magnitude of reference.
currents $i_{ref}$ and inversely proportional dc-bus voltage. And $K_d$ is defined as

$$K_d = \frac{U_{ref}}{U_{dc}} \quad (25)$$

The PI regulator in the grid-voltage-feed forward control multiplies the real, defective grid voltage with a proportion gain $K_f$ as a second compensation unit. Its output $\omega$ and the output $\omega$ of PI regulator in current feedback loop are together fed to the PWM modulator to produce the drive signals for the inverter switches. Therefore, the modulation wave $\omega_{mod}$ includes the defective component of grid voltage to compensate grid voltage fluctuation and obtain highly sinusoidal current waveforms. The feed forward effect depends on the value of $K_f$.

In addition, the frequency $\omega$ and phase $\phi$ of reference current $i_{ref}$ are calculated to synchronize with utility grid voltage $U_{grid}$ by a phase-locked-loop (PLL) system.

V. UTILITY GRID

Generally utility grid is defined as summing point of all the generating stations near by the load and the distribution system. In this paper grid act as A.C. load with required nominal voltage of 480V and 60 Hz when the full bridge converter works in a inverting mode and considered as a voltage source with a 480V, 60 Hz when full bridge converter works in rectifying mode.

VI. SIMPLE MPPT SOLUTION BASED ON POWER BALANCE

Maximum Power Point tracking, frequently referred to as MPPT, is an electronic system that operates the Photovoltaic (PV) modules in a manner that allows the modules to produce all the power. MPPT is an electronic system that varies the electrical operating point of the modules so that the modules are able to deliver maximum available power. Many MPPT solutions are developed to ensure the optimal utilization of PV modules [11], [12].some of the popular MPPT techniques are available like

1. Fractional Open-Circuit Voltage
2. B Fractional Short-Circuit Current
3. Perturb and Observe
4. Incremental Conductance

The implementations generally involve sensing the output current and voltage of PV modules, and the MPPT algorithms use the information to maximize power drawn from the PV modules. Unfortunately, such realizations are costly and complex [11], [12].In this paper a simple perturb and observe MPPT solution is adopted in view of the power balance. Table 1 describes the algorithm for employing $U_e$

<table>
<thead>
<tr>
<th>Perturbation in D</th>
<th>Change in $U_e$</th>
<th>Next perturbation in D</th>
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Table 1

P&O ALGORITHM EMPLOYING $U_e$

Fig.7 flow chart of P & o MPPT Method

Fig.7 represents the flow chart for the perturbs and observe MPPT technique. And perturbing the duty ratio $D$ of the ZVT Interleaved boost converter perturbs the PV array current and voltage, and consequently, perturbs the PV array power. The operating point is then adjusted to maximize PV array power. The other advantage is the simple MPPT solution ensures the maximization of the power transferred to the utility grid, but not the output power from PV array. If we ignore the whole system losses, the power that transmitted from PV array is equal to the utility grid. And as discussed earlier, the magnitude of the load current $i_{ref}$ directly depends on the output $U_e$ of the negative PI controller in the voltage loop. Therefore, the majority of MPPT algorithms can be implemented by controlling the value $U_e$ rather than the calculated power value by multiplying the inputs from voltage and current sensors, which holds universality.

VII. SIMULATION RESULTS AND DISCUSSION

The fig.8 represents the input and out voltage wave form of Z.V.T. Interleaved boost converter. A P.V.cell voltage of 50v is boosted up to around 366 which is 7 times to the input voltage.

Fig.9 represents the voltage wave form of grid connected P.V.System when full bridge inverter is operated in rectification mode , here the Z.V.T.Interleaved boost converter is failed to boost up the P.V.Cell voltage to bus voltage .then the inverter is act as rectifier and power draws from the grid and stabilize the grid connected P.V.System.

Fig.10 represents voltage wave forms of grid connected P.V.System when the full bridge inverter is operated in inverting mode, here boosted D.C.voltage is converted into A.C. and power is fed to the grid.
Table 2 presents that the values calculated by the two steady state models are compared with simulation results to verify the proposed model. It is clear that the proposed steady-state model approaches the simulation results closely.

**Fig. 8** Z.V.T. Interleaved Boost Converter voltages

**Fig. 9** When Circuit Operated In Rectification Mode

**Fig. 10** When Circuit Operated In Inverting Mode

**TABLE II**
STEADY-STATE MODEL VERIFICATION
VIII. CONCLUSION

The proposed PV system employs a ZVT-interleaved boost converter which can boost the low voltage of the PV array up to a high dc-bus voltage. Accordingly an accurate steady-state model is obtained and verified by the simulation results and a full bridge inverter with bi-directional power flow is used which can inverting the dc current into a sinusoidal waveform synchronized with the utility grid and stabilize dc bus voltage.

REFERENCES


