JPE 9-2-18

ICPE'07 Selected Paper

Design and Control of Novel Topology for Photovoltaic DC/DC Converter with High Efficiency under Wide Load Ranges

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ABSTRACT

In this paper, design and control is proposed for a four input-series-output-series-connected ZVS full bridge converter for the photovoltaic power conditioning system (PCS). The novel topology for a photovoltaic (PV) DC/DC converter that can dramatically reduce the power rating and increase the efficiency of a PV system by analyzing PV module characteristics is proposed. The control scheme, including an input voltage controller is proposed to achieve equal sharing of the input voltage as well output voltages by a four series connected module. Design methods for ZVS power stage are also introduced. The total PV system is implemented for a 250-kW PV power conditioning system (PCS). This system has only three DC/DC converters with a 25-kW power rating and uses only one-third of the total PV PCS power. The 25-kW prototype PV DC/DC converter is introduced to verify experimentally the proposed topology. In addition, an experimental result shows that the proposed topology exhibits good performance.

Keywords: PV PCS, ISOS(input-series-output-series-connected), ZVS(Zero Voltage Switching), DC/DC Converter

1. Introduction

Since the start of the Industrial Age more than 150 years ago, the world economy has been running on fossil fuels, which were cheap as there was no cost associated with their production but only with their extraction and transportation. The negative effects on the environment became visible only in the last 30 years or so. Renewable energy resources will be an increasingly important part of power generation in the new millennium. Besides assisting in the reduction of the emission of greenhouse gases, they add much needed flexibility to the energy resource mix by decreasing the dependence on fossil fuels. Due to their modular characteristics, ease of installation and because they can be located closer to the user, Photovoltaic (PV) Systems have great potential as distributed power sources to the utilities. PV systems are installed on the roof of residential buildings and connected directly to the grid [1]-[2](called Grid-Tie or Grid Connected). In these PV systems, a power conditioning system (PCS) should have high efficiency and low cost. In general, the standard

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configurations that are used to implement PV PCS are of two types: 1) isolated and 2) nonisolated. In particular, the nonisolated PCS type has a higher efficiency than the isolated PCS type because it does not need a galvanic transformer.

This paper proposes a novel topology for a nonisolated DC/DC converter with very high efficiency under a wide input PV module voltage range and presents an approach on how the proposed PV DC/DC converter can be designed. Furthermore, an experimental result shows that the proposed topology exhibits a good performance.

2. Novel Topology for Non-isolated PV DC/DC Converter

The proposed novel topology is shown in Fig. 1[11]. It consists of a four series module isolated full bridge DC/DC converter and an input photovoltaic cell voltage connected to the anode of DC/DC converter rectifier diode. Then the DC link (inverter input) voltage is expressed as follows:

$$V_{DC}=V_C+V_{PH} \tag{1}$$

Where V_{DC} is the DC link voltage, V_C is the output of DC/DC converter, and V_{PH} is photovoltaic cell voltage.

The small power rating isolated full bridge DC/DC converter generates only the difference voltage between the PV module voltage and the required DC link voltage of the inverter. Therefore, since the DC/DC converter must not generate the whole required voltage in the proposed topology, the required power capacity of DC/DC converter is reduced dramatically.

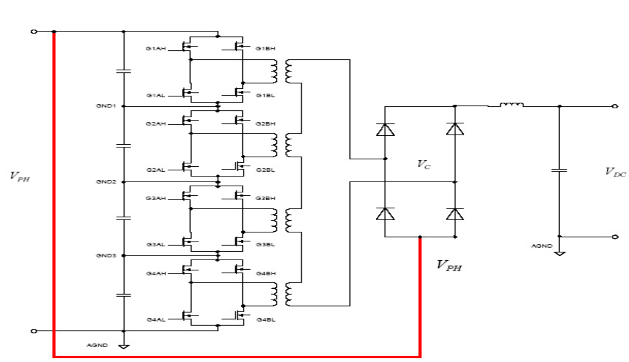


Fig. 1 The proposed four series module full bridge converter

The advantages of the proposed topology are as follows:

- High efficiency under wide load range.
- Low voltage rate power switch.
- Need only a one-third power level DC/DC converter of conventional DC/DC converter.

Fig. 2 shows the new proposed topology to get high DC link voltage from the inverter. The small isolated DC/DC converter generates only the difference voltage between the PV module output voltage and the required DC link voltage of the inverter.

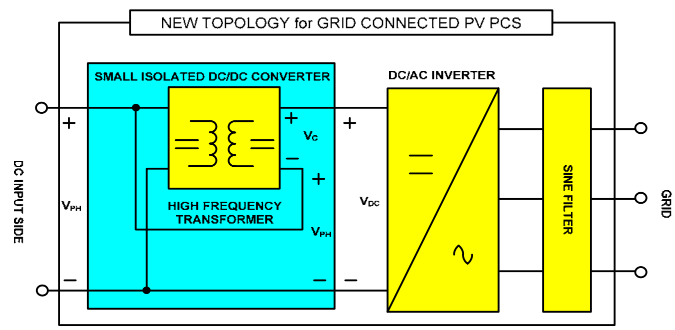


Fig. 2 The proposed PV PCS with the novel DC/DC converter

The efficiency flow diagram is shown in Fig. 3 The proposed converter efficiency is expressed as follows:

$$\eta_{new}=Q+(1-Q)\times\eta_c \tag{2}$$

$$Q=\frac{P_S-P_C}{P_S} \tag{3}$$

Where, η_{new} : The efficiency of proposed topology converter, P_S: The total system power, P_C: The DC/DC converter power, η_C : The efficiency of proposed topology converter, Q: The ratio of direct power over total power.

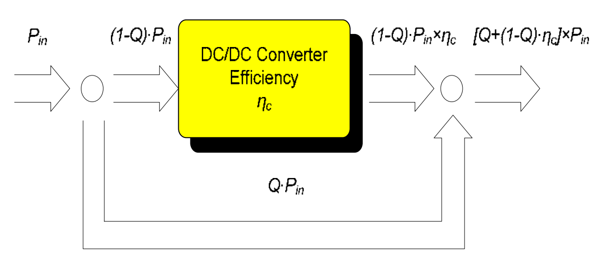


Fig. 3 The proposed converter efficiency flow diagram

Table 1 The calculation of proposed converter efficiency with respect to power sharing condition

PV cell Voltage	Power sharing of converter	Proposed converter Efficiency(η_{new})
600V	4.6%(30V/650V)	(0.954+0.046×0.7)=0.986
550V	15.4%(100V/650V)	(0.846+0.154×0.85)=0.977
500V	23%(150V/650V)	(0.77+0.23×0.92)=0.981
450V	30%(200V/650V)	(0.7+0.3×0.93)=0.98

Table 1 shows the proposed converter efficiency with respect to power sharing conditions. In general, the efficiency of the basic module full bridge ZVS DC/DC converter is not high, maximum efficiency is around 93% under rated power load conditions [3]-[5].

3. Design and Control of the Proposed Topology for PV DC/DC Converter

In this section, design of the controller and power stage for the proposed topology are presented.

3.1 Controller

The Fig. 4 shows the proposed DC/DC converter controller which consists of voltage, current loop, and power limit function with common duty ratio.

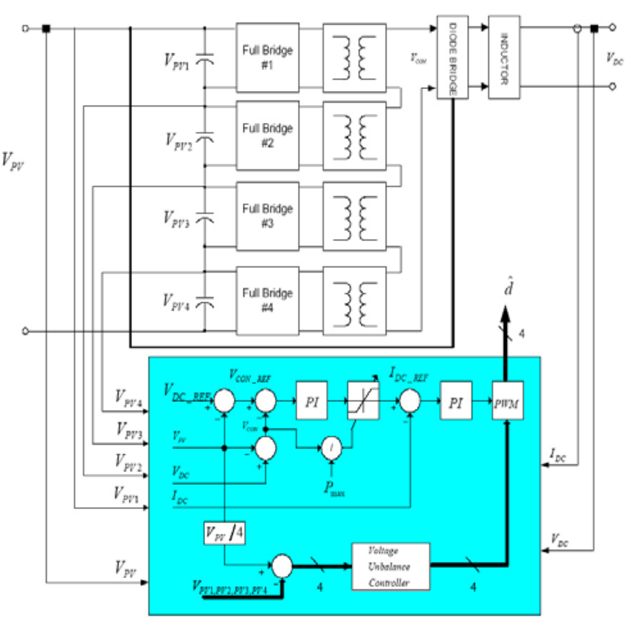


Fig. 4 Block diagram of the proposed DC/DC converter controller

where V_{PV1} is input voltage of full bridge #1, V_{PV2} is input voltage of full bridge #2, V_{PV3} is input voltage of full bridge #3, V_{PV4} is input voltage of full bridge #4, V_{PV} is PV module voltage, V_{DC} is DC link voltage (inverter input voltage), V_{CON} is converter output voltage ($V_{CON} = V_{DC} - V_{PV}$), V_{DC_REF} is reference voltage of DC link which is 650V, V_{CON_REF} is reference voltage of converter output ($V_{CON\_REF} = V_{DC\_REF} - V_{PV}$), I_{DC} is DC link current, and P_{MAX} is maximum power rating of the DC/DC converter which is 25kW.

We can find a saturation current level (V_{CON} / P_{MAX}), also we can get a reference current of DC link (I_{DC_REF}) through a current limit function. The developed 250kW PV PCS has MPPT [6]-[8] (Maximum Power Point Tracking) function in the inverter controller and not in the converter controller. The proposed DC/DC converter controller only keeps a DC link voltage (650V).

The proposed DC/DC converter's input voltage consists of four series. Therefore it should have an input voltage balancing controller for each DC/DC module. Each individual converter, in addition to the input voltage balancing controller, adjusts the PWM value, such that the converter input voltages are maintained equal[9]-[11].

3.2 Small-Signal Analysis of the Proposed Topology

The small-signal analysis presented in this paper uses the fact that the phase shift ZVS converter is a buck derived topology. The description of the circuit operation consists of the effective duty cycle d, output filter inductor i_L, the leakage inductance L_{lk}, the input voltage $V_{in}(=V_{in1}+V_{in2}+V_{in3}+V_{in4})$, and switching frequency f_s. The small signal transfer functions of this converter, therefore, will depend on L_{lk}, f_s, and the perturbations of the filter inductor current $\hat{i}_L$, input voltage $\hat{v}_{in}$, and duty cycle of the primary voltage $\hat{d}$.

Fig. 5 shows the small-signal equivalent circuit of a four module ISOS (Input Series Output Series) ZVS full-bridge converter system. In this figure, the overall small-signal model can add four input voltage feedback loops to the common voltage and current control loop. The small-signal circuit model of each module is the basic phase shift ZVS full bridge PWM converter. The contribution of $\hat{d}_i$ and $\hat{d}_v$ is represented by two controlled sources and the contribution of $\hat{d}$ by two independent sources.

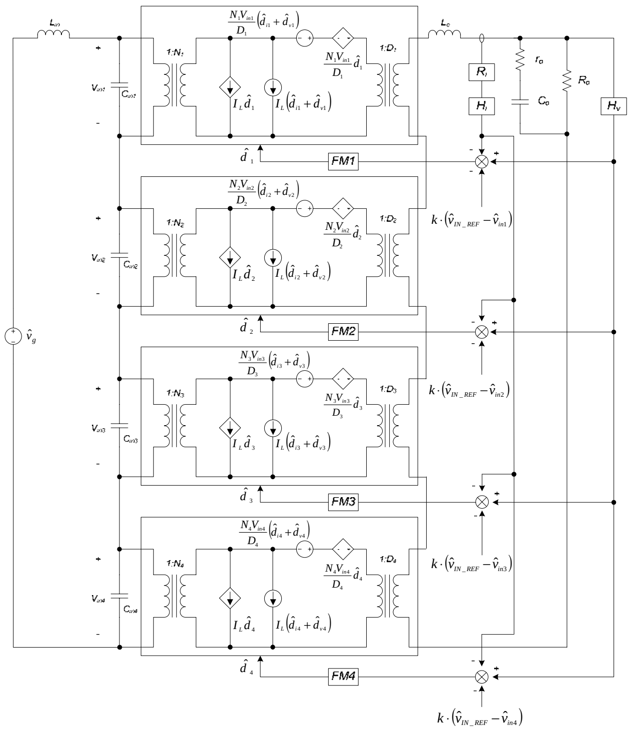


Fig. 5 The small-signal equivalent circuit of four ISOS ZVS full bridge converter

The duty cycle modulation due to the change of the filter inductor, denoted as $\hat{d}_i$

$$\hat{d}_i = -\frac{R_d}{nV_{in}}\hat{i}_L \tag{4}$$

The duty cycle modulation due to the change of the input voltage, denoted as $\hat{d}_v$,

$$\hat{d}_v = \frac{R_d I_L}{nV_{in}^2}\hat{v}_{in} \tag{5}$$

Where $R_d = 4n^2 L_{lk} f_s$

The transfer function of the output filter is

$$H_o \equiv \frac{1}{\Delta f} = \frac{1}{s^2 LC + s\frac{L}{R} + 1} \tag{6}$$

Input impedance of output filter is

$$Z_f \equiv \frac{R\Delta_f}{1 + sRC} \tag{7}$$

The control to output transfer functions of the proposed converter is

$$G_{dv} = \frac{nV_{in}\omega_o^2}{s^2 LC + s\left(\frac{1}{RC} + \frac{R_d}{L}\right) + \omega_o^2} = \frac{nV_{in}\omega_o^2}{s^2 + s2\omega_o\xi + \omega_o^2} \tag{8}$$

Where $\xi = \frac{1}{2R}\sqrt{\frac{L}{C}} + \frac{R_d}{2}\sqrt{\frac{C}{L}}$ is the damping of the second-order denominator.

The current loop gain Ti is determined by

$$T_i = FM \cdot R_i \cdot H_i(s) \cdot G_{di}(s) \tag{9}$$

Where *$G_{di}(s)$* is control-to-output current transfer function. *Ri* and *FM* are the equivalent current gain and modulator gain, respectively. *$H_i(s)$* represents the sampled-and-hold effect in the current loop

$$G_{di}(s) = \frac{1}{\Delta(s)}\frac{1}{LC}\frac{V_o}{DR}(1 + sCR) \tag{10}$$

$$\Delta(s) = s^2 + s\left(\frac{1}{CR} + \frac{rL + rC}{L}\right) + \frac{1}{LC}$$

Once the current loop is designed, the current loop closed power stage can be treated as a new power stage for the voltage loop designed. The system loop gain defined as follows:

$$T_v = H_v(s) \cdot \frac{FM \cdot G_{dv}(s)}{1 + FM \cdot R_i \cdot H_i(s) \cdot G_{di}(s)} \tag{11}$$

For Hv(s), an integrator plus one pole and one zero compensator defined as follows:

$$H_v(s) = \frac{K_v\left(1 + {s}/{\omega_{Zv}}\right)}{s\left(1 + {s}/{\omega_{Pv}}\right)} \tag{12}$$

Fig. 6 shows the designed overall loop gain T_v which has a wide control bandwidth with suitable phase margin(45°).

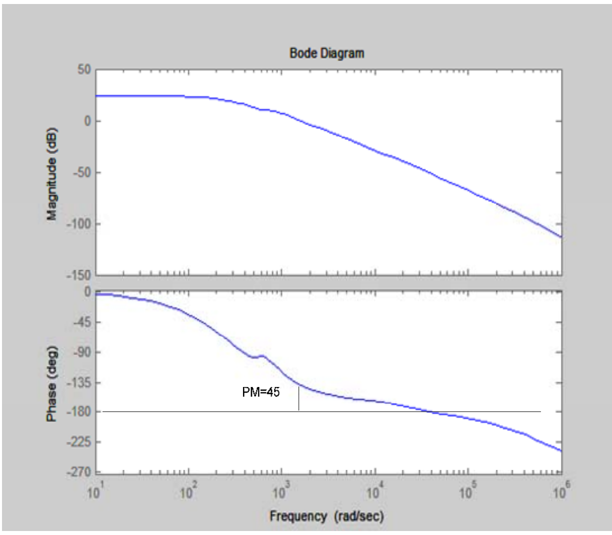


Fig. 6 The overall loop gain of proposed four ISOS converter

3.3 Main Transformer

To reduce the leakage inductance, this experiment uses a sectional edge winding technique.

Fig. 7 Main transformer with edge winding technique

This reduces the leakage inductance and increases PWM control range. Applying a Sectional Edge Winding technique to this transformer we can reduce the temperature of the transformer copper under rated power conditions.

The transformer coil used a flat copper wire at right angles with transformer bobbin. The advantages of the edge winding technique are as follows:

- Reduce skin effect at transformer coil.
- Reduce capacitance between primary and secondary coil.
- Reduce leakage inductance of primary transformer.
- Easy assembly of the transformer.

It was found that selected ferrite material is not fully utilized in the present design where the optimum operating point is given by f_s = 33 kHz, B_{ac} = 0.2T.

3.4 ZVS Condition

The features of full bridge topology are minimum current and voltage stress on the devices. It can also be operated in zero voltage switching (ZVS) leading to reduced electromagnetic emissions (EMI) and lower size and cost EMI filters.

Elements of the resonant tank are the resonant inductor (L_r) and capacitor (C_r). To satisfy ZVS conditions, the energy stored in the resonant inductance must be greater than the energy required to charge and discharge the FET output and transformer capacitances of the leg in transition within the maximum transition time.

$$\frac{1}{2} \times L_r \times I_{pri}^2 > \frac{1}{2} \times C_r \times V_{in}^2 \tag{13}$$

Where V_{in} is input voltage and I_{pri} is primary input current of the transformer.

Since resonant capacitance and input voltage are known, this term becomes a constant and leakage inductance has been quantified. Considering resonant capacitance, input voltage and primary current, the reasonable value of the transformer leakage inductance in this case is 3.5*u*H.

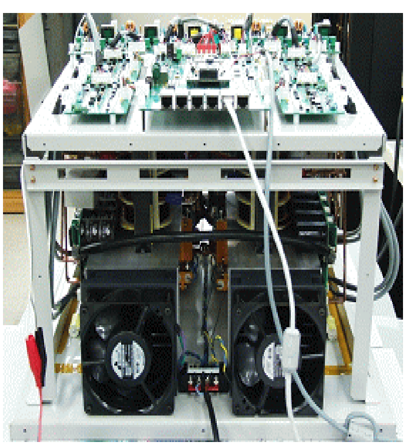
4. Experimental Results

Table 2 shows the specification of the proposed DC/DC converter. The basic topology is the Zero Voltage Switching (ZVS) method. The switching device is CoolMOS MOSFET. Input voltage is PV cell voltage. Output voltage means output voltage of the isolated DC/DC converter. And DC link voltage means summation of the PV cell voltage and converter output voltage.

Table 2 The specification of the proposed converter

Classification	Descriptions
Input PV Cell voltage	450~650V
Converter output voltage	0~200V
DC link voltage	650V
Switching frequency	33.333kHz
Rated power	(6.25kW×4) = 25kW
Transformer turn ratio	N_p:N_s=6T:3T (Magnetics: 0_49928 E100 R)
Leakage inductance	3.5uH

(a)



(b)

Fig. 8 Implemented proposed system
(a) 250kW PCS (b) 25kW DC/DC converter

Fig. 8 shows the proposed 250kW PV PCS and four series connected 25kW DC/DC converter. The photovoltaic cell voltage range is 400~850V. DC link voltage is 650V and DC/DC output power is 25kW. Fig. 9 shows the ZVS waveform of lagging leg MOSFET with 100% load condition.

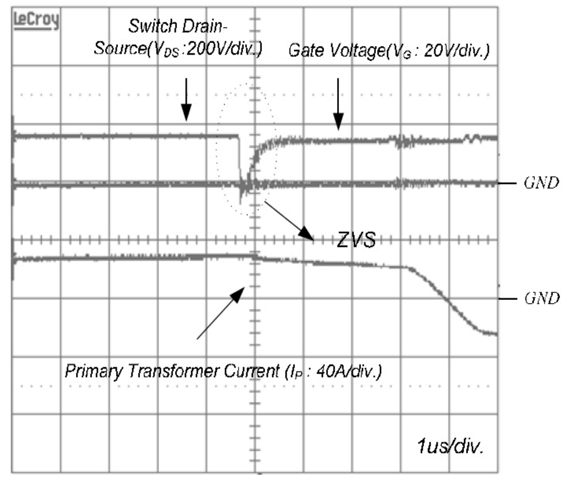


Fig. 9 ZVS waveform at 100% load condition, Primary transformer current (I_P:40A/div.), Switch drain source voltage (V_{DS}:200V/div.), Gate voltage (V_G:20V/div.)

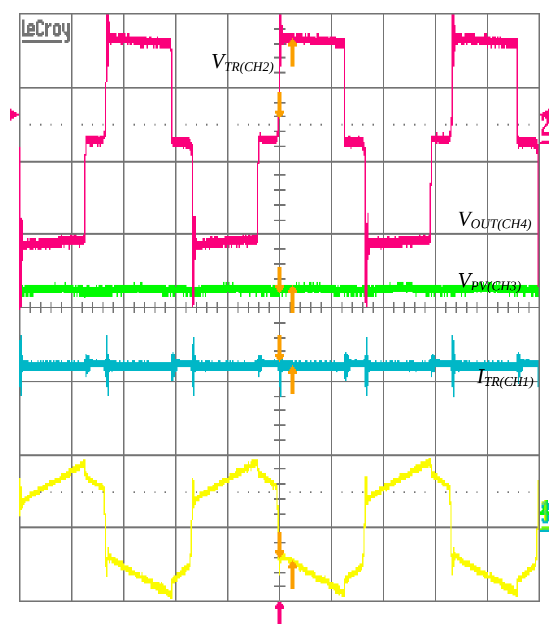


Fig. 10 Primary transformer current (I_{TR}:20A/div.), DC Link voltage ($V_{DC\ link}$:200V/div.), Input PV Cell voltage (V_{PV}:200V/div.), Primary transformer voltage (V_{TR}:100V/div.)

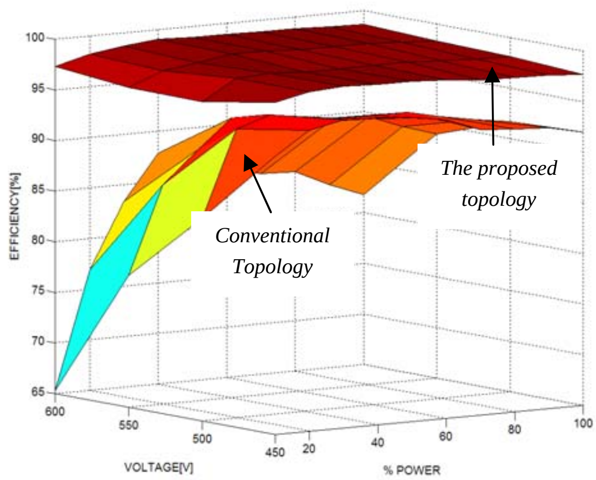


Fig. 11 The 3D curve of efficiency between conventional converter and the proposed converter

Fig. 10 shows the waveforms of the Primary transformer current, voltage, Photovoltaic module voltage and DC link voltage. When PV cell voltage is 450V then DC link voltage is 650V. Fig. 11 shows the 3D curve of efficiency between conventional converter and the proposed converter with respect to load condition and cell voltage.

5. Conclusions

In this paper, the novel topology is proposed for the photovoltaic DC/DC converter with very high efficiency. The advantages of the proposed topology are as follows:

- High efficiency (Flat efficiency curve) under wide PV cell voltage and load range.
- Low voltage rate power switch.(series-connected)
- A need for only 30.7% power level from the DC/DC conventional converter.

The simple proportional controller with the input voltage feedback has been proposed for the 4 ISOS-connected converters for the photovoltaic power conversion system. The input series connection has significant advantages such as the possibility of using MOSFETs efficiently for high input voltage applications.

The small-signal analysis shows that an equivalent phase shift ZVS full bridge converter module can be used in the control loop design process in spite of input voltage feedback loop. Also suitable 25kW DC/DC converter design is presented based on the full bridge ZVS converter. The performance of the proposed scheme has been verified by experimental results.

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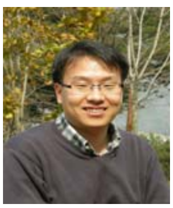

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