A Novel LC Resonant Based Partial Booster Scheme for Improved Efficiency and Reduced Cost of Transformerless Photovoltaic Inverters

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Abstract

Traditionally, efficiency has been a top priority for photovoltaic inverters. However, another driving factor in photovoltaic inverter research has been cost reduction. Non isolated three phase inverters have come into the competition mainly to address this issue of cost reduction. This paper presents a new resonant based DC/DC converter control strategy for three phase PV inverter systems, in the sub 25 kW range. The proposed scheme has advantages of easy control and high efficiency. Further, cost reduction can also achieved, as the proposed topology can be efficient even at switching frequencies near to 50 kHz.

1. Introduction

Currently, the maximum open circuit voltage allowed on a photovoltaic (PV) panel string is technically limited to 1000V DC. This in turn limits the maximum power point (MPP) voltage to around 850 V. A ratio of 0.6 exists between minimum MPP voltage and maximum MPP voltage. This ratio results mainly from the variation in operating temperature of the solar panels. Thus the MPP voltage range is approximately 510 – 850V [3].
With this MPP voltage range of 510–850 V, the inverter cannot be directly connected to the 400V AC grid. This is because, the minimum DC link voltage required by an PV inverter to support 400V three phase AC grid is 650V (as zero sequence injection cannot be used in non isolated PV inverters). Hence, a two stage converter (DC/DC booster + inverter) is required, as shown in Fig.1a. The boost converter shown in Fig.1a is rated for full power and its role is to maintain the DC link voltage of the inverter at 650 V, when the PV panel voltage goes below 650 V.
Further increase in efficiency and decrease the cost of the DC/DC boost converter can be achieved by using a configuration shown in Fig. 1b. The configuration uses an isolated DC-DC converter (partial booster) which is only rated for partial power [1]. Where, the inverter DC link voltage generated is the sum of PV panel voltage and the output voltage of the partial booster.
If P_{DClink} is the power supplied by the DC link to the inverter, $P_{DC/DC}$ is the power supplied by the partial booster to the DC link, $V_{DC/DC}$ is the output voltage of the partial booster and if V_{PV} is the PV panel voltage. Then, the ratio of power supplied by the partial booster to the power demanded by the inverter from the DC link, can be given as

$$\frac{P_{DC/DC}}{P_{DClink}} = \frac{V_{DC/DC}}{V_{PV} + V_{DC/DC}} \quad (1)$$

Since the partial booster (in Fig. 1b) needs to be rated for only a fractional part of the total power, the losses and cost are simultaneously reduced. Such a topology has been proposed earlier [1]. But the efficiency of greater than 97 percent for the isolated DC/DC converter has not yet been achieved for a wide operating range with small size. This paper presents a

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novel scheme for this partial booster. The scheme is based on using a LC series resonant converter at constant switching frequency, which can give size reduction and at the same time high efficiency.

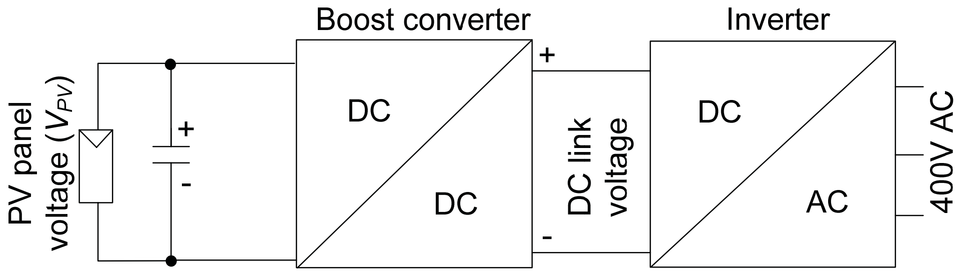

Fig. 1a. Connection to 400V grid using a fully rated boost converter and inverter.

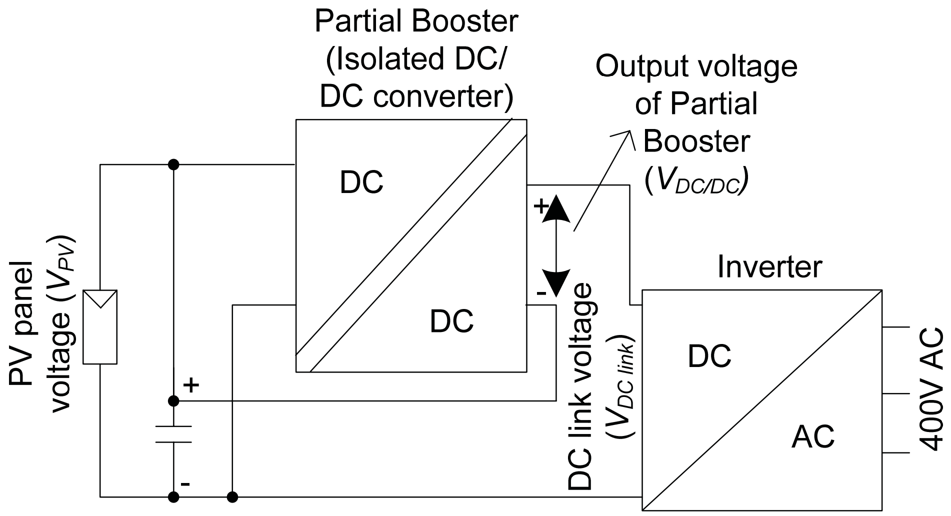

Fig. 1b. Topology using partially rated, isolated DC-DC converter.

2. Proposed idea

2.1. Conventional method

The conventional method of operation of the partial booster (shown in Fig. 1b) is to maintain the DC link at 650 V, in case the PV panel voltage goes below 650 V. This means that the range of DC link voltage is 850-650V while the PV panel MPP voltage varies between 850-510V. The equation which describes such a conventional method of operation of the partial booster is stated below.

$$\begin{aligned} V_{DClink} &= V_{PV} \text{ ; for } V_{PV} \geq 650\text{V} \\ &= 650\text{V; for } V_{PV} < 650\text{V} \end{aligned} \tag{2}$$

Where, V_{DClink} denotes the inverter DC link voltage and V_{PV} denotes the photovoltaic panel voltage.

When the system has to be operated according to equation (2), then the partial booster (in Fig.1b) has to have an “input versus output voltage characteristic” as described in Fig. 2.

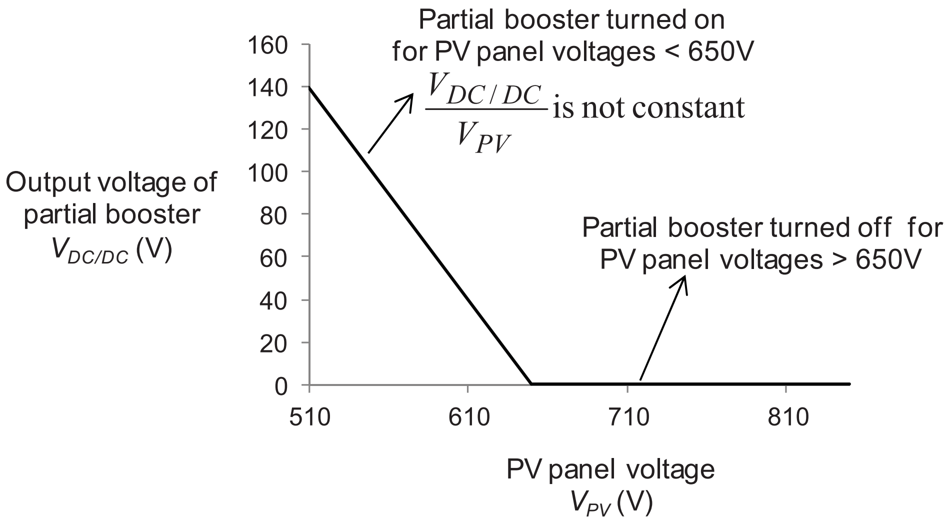

Fig. 2. Input vs output voltage characteristic of partial booster converter if operated according to a conventional method (as per equation 2). This operational mode is not suitable for resonant converters.

While the operation mode for the partial booster shown in Fig. 2 is ideally suited for pulse width modulated (PWM) converters, it is not ideally suited, for resonant converters. For a resonant converter, the operational frequency needs to be widely varied, in order to obtain such an input to output voltage characteristic [5]. This makes it difficult to optimize the size and efficiency of the resonant converter.

2.2. Proposed solution

Resonant converters are compact and known to give high efficiencies even at high switching frequencies (>50 kHz). But, a resonant converter can be best optimised for high efficiency and small size, only if operated at a fixed voltage gain (V_{out}/V_{in}). The optimization problem becomes complex, when the voltage gain demand becomes wider. Thus, the conventional idea of controlling the inverter DC link voltage according to equation (2) is not a good choice, when using resonant converters.

As discussed earlier, the inverter (in Fig. 1b) is operational for a wide range of DC link voltages from 850V to 650V. If the inverter is based on a three level concept, then its efficiency is almost constant throughout the given range of the DC link voltage [3, 4]. One can make use of this degree of freedom available on the inverter DC link voltage and operate the partial booster in the following pattern.

$$\begin{aligned} V_{DClink} &= V_{PV} \text{ ; for } V_{PV} \geq 650\text{V} \\ &= V_{PV} + KV_{PV} \text{ ; for } V_{PV} < 650\text{V} \end{aligned} \tag{3}$$

where, $K = \left(\frac{650\text{V} - 510\text{V}}{510\text{V}}\right)$ = 0.295, if the minimum value of the MPP voltage is 510 V.

When the system is operated according to equation (3), then the partial booster (in Fig.1b) needs to have an “input versus output voltage characteristic” as described in Fig. 3.

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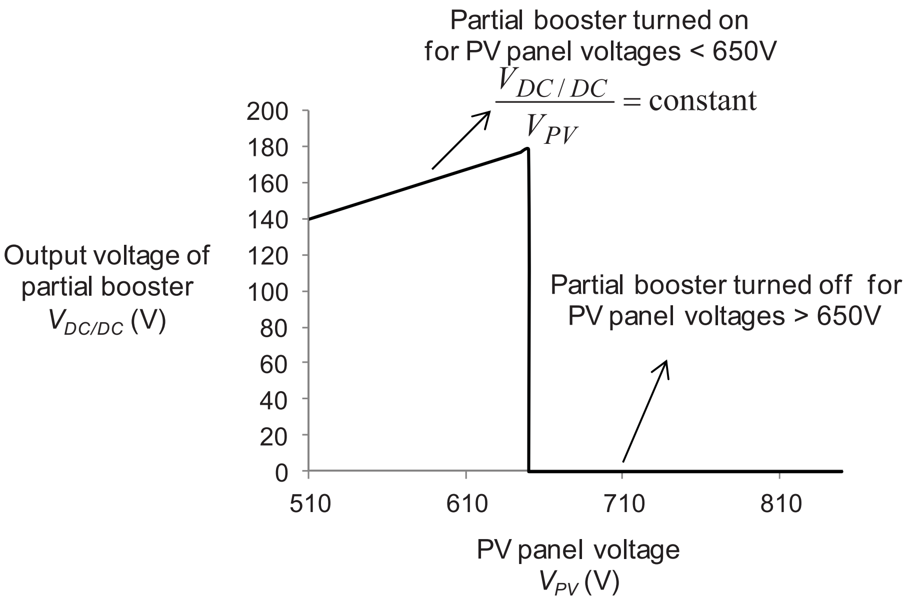

Fig. 3. Input vs output voltage characteristic of partial booster converter if operated according to the proposed method (as per equation 3). This operational mode is suitable for resonant converters

Operating a LC series resonant converter, close to its resonant frequency, results in a constant voltage gain characteristic [5], which matches exactly with the need as described in Fig. 3. Also, it is well known that operation of a resonant converter close to its resonant frequency, results in maximum efficiency. Further, since the operation frequency remains fixed, it is possible to optimize the size of the magnetic components to a higher degree.

Fig. 4a and 4b show the circuit representation of a transformerless photovoltaic inverter system, based on such a principle. Fig. 4a shows the conduction path of the current (in red) when the LC series resonant converter is not operational (for PV panel voltage>650V) while, Fig. 4b shows the current path (in red) when the LC series resonant converter is operational (PV panel voltage≤650V). Here, solid red line and dashed red line represent alternating current paths during switching.

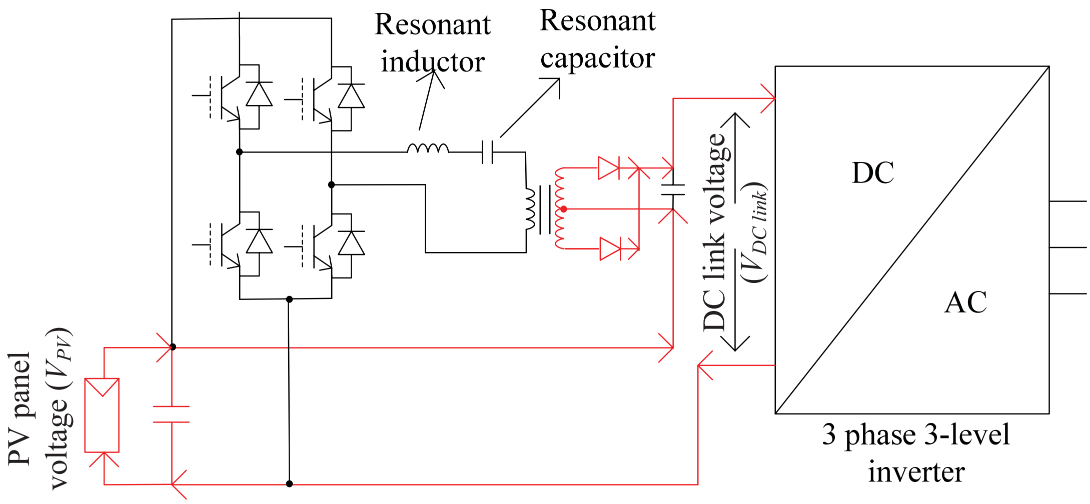

Fig. 4a. Conduction path when the booster is not operational (when PV panel voltage > 650V). Conduction path is shown in red.

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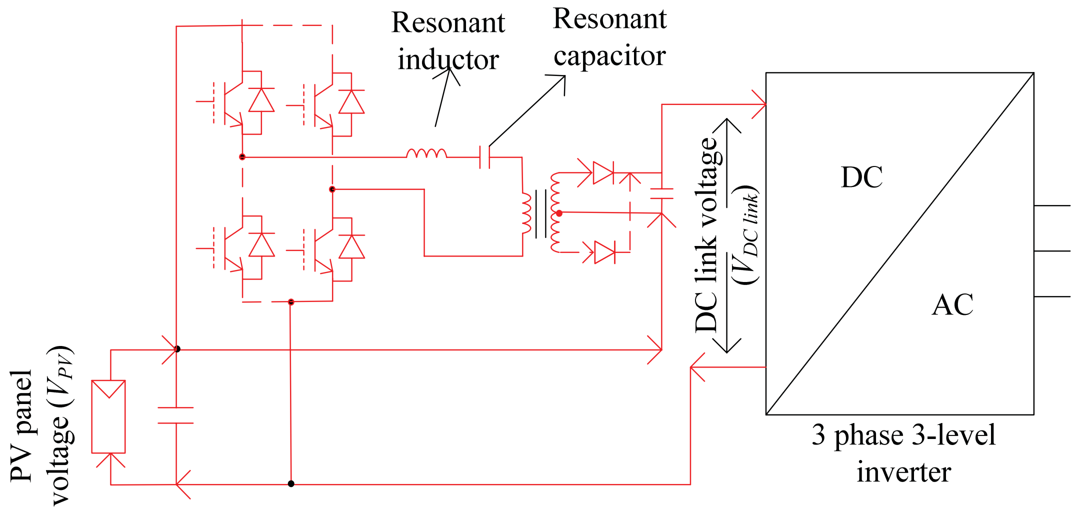

Fig. 4b. Conduction path when the booster is operational (when PV panel voltage ≤ 650V). Solid red line and dashed red line indicate alternating conduction paths.

3. Efficiency estimation

In order to estimate the efficiency of the proposed system, a 22 kW PV inverter system was analysed. Efficiency estimation was made only for the proposed resonant converter. For the inverter stage, practical efficiency results of a 22 kW 3-level inverter, as presented in [2] were used. Such a method was chosen in order to increase the accuracy of the predicted system efficiency.
The design values used for the efficiency estimation are summarised in Table I.

Table I: Design values used for efficiency calculations

System power rating	22 kW
Resonant converter power rating	5.75 kW
Input voltage / output voltage of LC series resonant converter (according to Fig.3.)	510-650 V/*K*(Input voltage), *K*=0.295
Resonant inductor	Inductance: 10 μH, core part number:T250-14 from Micro metals, copper losses at full load: 4.68 W, core losses at full load: 1.8 W, peak current: 20 A
Resonant converter switches	IGBTs, part number: IXA20IF1200HB-IXYS
Transformer secondary side diodes	Part number: DSEI 2x 61-IXYS
Transformer	Core losses at 650V input: 14.5 W, copper losses at full load: 43 W, power rating: 5.75 kW, frequency: 38 kHz
Switching frequency of resonant converter	38 kHz
Resonant frequency	36 kHz
Inverter	3 level inverter as described in [2]

3.1. Loss calculations

Semiconductor conduction losses: Conduction losses of the IGBTs were calculated using the classical method [5,6], which is described by

$$P_{cIGBT} = V_T I_{avg} + R I_{rms}^2 \tag{4}$$

where, P_{cIGBT} represents the IGBT conduction loss, V_T represents the current independent voltage drop component across the IGBT , I_{avg} is the average current through the IGBT, R is the differential on state resistance of the IGBT, I_{rms} is the root mean square value of the current through the IGBT.

The diode conduction losses on the secondary side of the transformer (Fig.4a.and 4b.) are calculated in a similar manner. All calculations were performed for a junction temperature of 125 ^{0} C.

Transformer losses: Transformer was assumed to have an efficiency of 99% at full load and at maximum input voltage of 650 V. The loss distribution at full load was assumed to be 75% copper losses and 25% core losses. The values of the assumed full load losses are shown in Table I. As the operating point varies, core losses were varied proportional to the input voltage. The copper losses were varied, proportional to the square of the root mean square of the winding currents.

Resonant inductor losses: A resonant inductor with inductance of 10 µH was selected for the analysis, which was designed using the software provided by Micrometals Corporation. The software calculated values of core and copper losses at full load current are shown in Table. I. At other operating points, inductor core losses were varied, proportional to the square of the peak current. The copper losses were varied, proportional to the square of the root mean square of the corresponding current.

Because of its operation close to resonant frequency, the switching losses in the resonant converter were assumed to be negligible.

4. Results

Fig. 5.a shows the variation of DC/DC stage efficiency ($\eta_{DC/DC}$) with load for the proposed resonant converter, with respect to overall system power.

$$\eta_{DC/DC} = \frac{P_{DClink}}{P_{DClink} + \text{losses in partial booster}} \tag{5}$$

where, P_{DClink} is the power demanded by the inverter from the DC link.

It can be noted that the curve for PV panel voltage of 800 V is much higher as compared to that for PV panel voltage of 600 V. This is because, the resonant converter is not operational at PV panel voltage of 800 V and hence, only the diode and transformer conduction losses exist, as shown by the red line in Fig. 4a.

Fig. 5b shows the variation of overall system efficiency with load. These curves are obtained, using the data presented in Fig. 5a and practical 3-level inverter efficiency results presented in [2]. It can be seen that, with the proposed topology, fairly high efficiencies can be achieved over a wide load range.

5. Conclusion

The proposed novel scheme of operating a partially rated LC series resonant converter at constant frequency, gives high system efficiencies. As resonant conversion is used, cost reduction can be achieved with minimum affect on efficiency, by going for higher switching frequencies. With the proposed scheme, better optimization of the magnetic components is possible, as a result of constant frequency operation and close to sinusoidal current shapes. Also, the proposed scheme is simple and easy to implement.

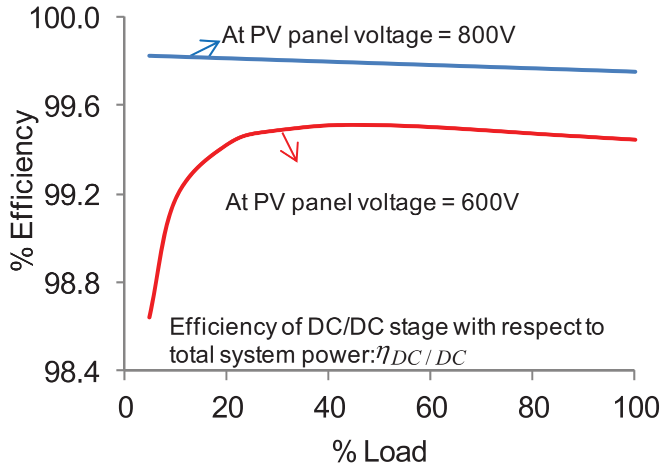

Fig. 5a. Efficiency of the proposed partial booster configuration stage with respect to the overall system power.

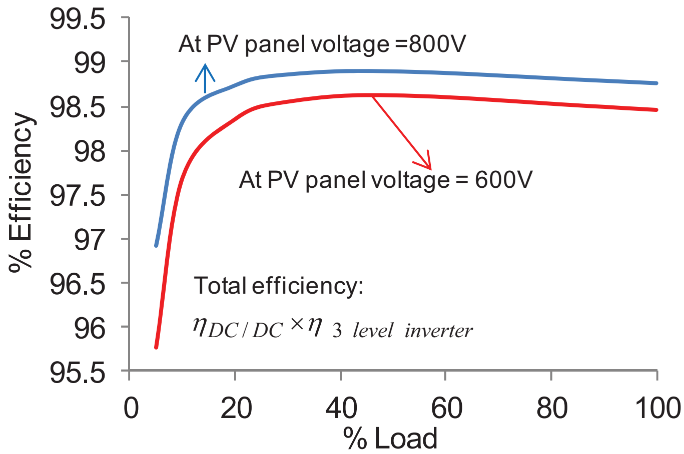

Fig. 5b. Total system efficiency including partial booster and 3-level inverter efficiency, with the proposed operation mode.

6. Literature

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