Validation of an Inverter Topology for Transformerless Grid-Connected Photovoltaic System

Asim Datta, Rishiraj Sarker, Sanjay Debbarma and Amit Kumar

Abstract Solar photovoltaic (PV) systems are getting more and more widespread due to the recent price reduction in modules and technological developments of power electronics devices to be used in designing power conditioning unit. Generally, a strong affinity in grid-connected PV inverter topology is to use transformer in the grid interface. However, due to transformer, systems become bulky and involve additional losses. The elimination of the transformer abolishes galvanic isolation between the PV system and the utility grid, thus treating from the danger of direct current (dc) injection into the grid. Therefore, the choice of a proper topology for transformerless grid-connected application is crucial to avoid undesirable operational effects. This paper provides a detailed performance study of an IGBT-based modified full-bridge inverter topology from the aspect of single-phase transformerless grid-connected PV system application. Detailed simulation results under different environmental conditions are presented to validate suitability in the transformerless grid-connected application.

Keywords Photovoltaic · Grid-connected system · Transformerless
Ground leakage current

1 Introduction

Among the various renewable energy sources, solar energy has always been in the forefront to substitute major percentage of fossil fuel dominance in the energy sector. Especially in a country like India, where availability of solar is in abundance,

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government must give more traction towards improvement of technologies for photovoltaic (PV) power conditioning and integration with the electric grid [1].

Nowadays, the rising directions of PV technology comprise the increase in photovoltaic conversion efficiency and in power conditioning efficiency. The power processing deals fundamentally with power electronics interface optimization while in the photovoltaic conversion includes the PV current generation process and maximum power point tracking (MPPT) [2]. The power electronics interfacing is usually a two-stage process with conversion of dc–dc followed by dc–ac power or a single power electronic stage with dc–ac power conversion followed by a transformer [3]. This is done to achieve a regulated voltage and frequency which is good enough to be synchronized with the ac voltage grid. But the introduction of more power electronic switches introduces more losses in the overall system. The incorporation of a transformer makes the system more bulky if it is a line frequency transformer or introduces noise in the system if it is a high-frequency transformer [4]. Transformerless grid interface for PV system is, therefore, getting more and more attention by the research community to make the whole system, starting from PV panels to the synchronization process with the power grid, more efficient and feasible [5]. However, such a system can generate high leakage current in the absence of an isolation transformer between the dc PV generator and the ac grid [6]. This leakage current can produce electromagnetic interference in other nearby systems and can also cause dc offset in the inverter output current flowing into the load and the connected grid.

Technological advancement can make feasible the use of an inverter avoiding transformer and has no impact on the system characteristics relating to grid interfacing and personal safety. For transformerless application, it is essential to develop new inverter topology that avoids the ground leakage current by making constant common-mode voltage of the inverter.

Thus, the main challenge to make a transformerless grid-tied PV system realizable comes in the control strategy and the injection of leakage current in the system [7, 8]. Control strategy poses an issue in the fact that both the MPPT and the current control scheme need to be regulated by tuning the power electronic switches of the converter [9]. Thus, balancing the two controls may be somewhat difficult [10]. The issue of leakage current can be prominent if the inverter switches are modulated using unipolar pulse width modulation (PWM) scheme [5, 10]. The bipolar PWM scheme has an inherent capability to minimize the leakage current. Nonetheless, unipolar PWM is more suitable than bipolar PWM because the dominant high-frequency component in unipolar PWM is half the switching frequency of bipolar PWM [11]. This helps in lower filter requirements as compared to bipolar PWM.

The conventional H-bridge inverter, when modulated using a unipolar modulation scheme, generates excessive leakage current in the system in the absence of an isolation transformer between the PV system and the utility grid [6]. In this study, a modified H-bridge topology of ac/dc inverter is considered for transformerless grid-connected system applications. Thus, emphasis has been given to study the leakage current elimination performance of the topology, i.e. whether can reduce or completely eliminate the ground leakage current. A detailed simulation-based study validates performance of the inverter.

2 Inverter Topology for Grid-Connected Systems

A single-phase H-bridge inverter topology, which is applied quite often in grid-connected PV system, is a H-bridge inverter as shown in Fig. 1. Different modulation schemes could be adopted to this topology. Based on the output waveform shape, they are categorized into two classes, namely unipolar [6, 10, 12] and bipolar PWMs [10, 13]. During positive half cycle of the inverter output voltage, switches $S1$ and $S2$ are commutated at the modulation frequency, while switch $S4$ is on. For the negative half cycle, $S3$ and $S4$ commutate at the switching frequency and $S2$ is on. In the inverter topology, two switches are on simultaneously, and one diode and one switch only conduct at the modulating frequency under imposed rated input voltage. Generation of a pulsating common-mode voltage with magnitude $V_{PV}/2$ at the triggering frequency is the primary disadvantage of the scheme. Thus, when the full bridge is part of a conversion stage without a transformer, unipolar modulation techniques cannot be adopted.

With a bipolar PWM scheme, the crosswise pairs of switches $S1$–$S4$ and $S2$–$S3$ are triggered at the modulating frequency, therefore,

$$V_{cm} = V_{PV}/2 \tag{1}$$

The switching losses become twice with the scheme as two diodes and two switches are triggered at the modulating frequency with the imposed rated input voltage. Furthermore, current ripples become double compared to the unipolar modulation switching scheme as the output voltage varies between $+V_{PV}$ and $-V_{PV}$. Therefore, bipolar PWM technique is to be avoided.

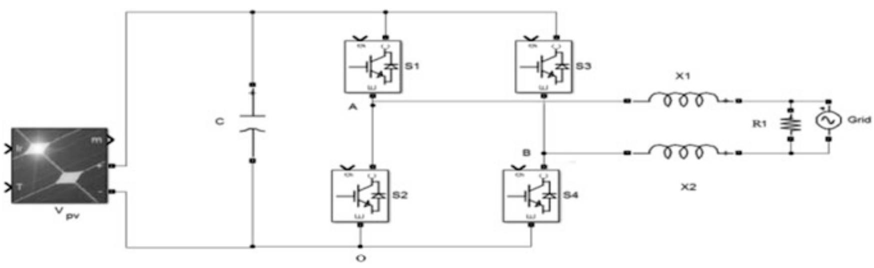

Fig. 1 Full-bridge inverter

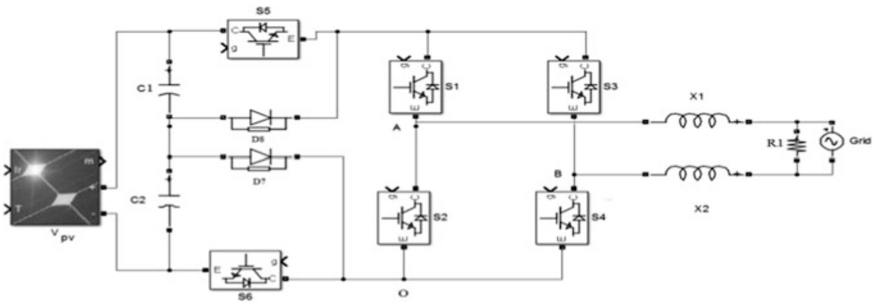

Fig. 2 H6 topology of inverter for grid-tied application without transformer

A modified topology (H6) for transformerless application is shown in Fig. 2 [10]. This topology comprises two diodes and six switches. There are two modes of operation for the H6 topology:

Mode 1: When *S*1 and *S*4 are ON: For modulating the input voltage, switches *S*5–*S*6 conduct at the modulating frequency. *S*2 and *S*3 also commutate at modulating frequency, but complimentarily with *S*5 and *S*6.
Case 1: When *S*5 and *S*6 ON: In this case the output current increases flowing through the path *S*5, *S*1, *S*4, and *S*6.

During the time, the value of common-mode voltage can be calculated as:

$$V_{CM} = (V_{AO} + V_{BO})/2 = \frac{V_{PV} + 0}{2} = V_{PV}/2 \tag{2}$$

Case 2: When S2 and S3 ON: The output current splits into two routes. One is through *S*1, the grid circuit and the freewheeling path of *S*3. Another part follows through *S*4, the grid circuit and the freewheeling path of *S*2.

Now voltage V_{AB} tends to zero and due to diodes *D*7 and *D*8, the voltages V_{AO} and V_{BO} are maintained at $V_{pv}/2$. Hence, common-mode voltage can be calculated as:

$$V_{CM} = (V_{AO} + V_{BO})/2 = (V_{PV}/2 + V_{PV}/2)/2 = V_{PV}/2 \tag{3}$$

Mode 2: When *S*2 and *S*3 ON: For modulating the input voltage, switches *S*5–*S*6 conduct at the modulating frequency. *S*1 and *S*4 also commutates at the modulating frequency, but complimentarily with *S*5 and *S*6.
Case 1: When *S*5 and *S*6 ON: In this case the output current decreases flowing through *S*5, *S*3, grid circuit, *S*2, and *S*6. The common-mode voltage value is:

$$V_{CM} = (V_{AO} + V_{BO})/2 = \frac{0 + V_{PV}}{2} = V_{PV}/2 \tag{4}$$

Case 2: When *S*1 and *S*4 ON: The output current follows two routes: the first one is through *S*3, grid circuit and the freewheeling diode of *S*1; the second one is through

$S2$, grid circuit and the freewheeling diode of $S4$. Now also voltage V_{AB} tends to zero and the voltages V_{AO} and V_{BO} are maintained at $V_{pv}/2$ through diodes $D7$ and $D8$. Hence, common-mode voltage can be calculated as:

$$V_{CM} = (V_{AO} + V_{BO})/2 = \left(\frac{V_{PV}}{2} + \frac{V_{PV}}{2}\right) = V_{PV}/2 \quad (5)$$

As the common-mode voltage of the inverter is invariable during all the switches states, leakage current could be limited to nearly zero.

3 Validation of Transformerless Inverter Topology

A MATLAB/SIMULINK model (shown in Fig. 2) is developed to simulate the topology, and the results are presented. Parameter values used in the MATLAB/SIMULINK model are presented in Table 1. $X1$ and $X2$ are reactances due to split filter inductances $L1$ and $L2$.

3.1 Simulation Results

In the case of uniploar sinusoidal PWM, for half cycle (positive or negative) of the inverter output voltage, the crosswise switches $S1$–$S4$ (or $S2$–$S3$) are triggered at modulating frequency (F_{sw}). Output voltage (V_{AB}) of the inverter and the common-mode voltage (V_{cm}) with unipolar PWM scheme are shown in Fig. 3a, b, respectively. During positive half cycle, $V_{AO} = V_{PV}$ (i.e. 400 V), and $V_{BO} = 0$. Whereas, in the negative half cycle, $V_{AO} = 0$, and $V_{BO} = V_{PV}$ (i.e. 400 V) (shown in Fig. 3a). Henceforth, it causes varying V_{CM} of amplitude $V_{PV}/2$ (i.e. 200 V) at the modulating frequency which is presented in Fig. 3b.

In the case of bipolar sinusoidal PWM, $S1$–$S4$ and $S2$–$S3$ are triggered alternatively at modulating frequency. Output voltage of the inverter, V_{AB}, and the common-mode voltage, V_{CM}, with bipolar PWM scheme are shown in Fig. 4a, b, respectively. At any instant of triggering either ($V_{AO} = 0$, $V_{BO} = V_{PV}$) or ($V_{AO} = 0$, $V_{BO} = V_{PV}$) (as presented in Fig. 4a). Hence, V_{CM} is constant at $V_{PV}/2$ (i.e. 200 V)

Table 1 Parameters used in simulation model

Parameter	Value
Switching frequency	$F_{sw} = 10$ kHz
PV voltage	$V_{PV} = 400$V
Filter capacitance	$C = 3$ μF
Filter inductance	$L1 = L2 = 30$ mH
Grid voltage	220 V
Grid frequency	50 Hz

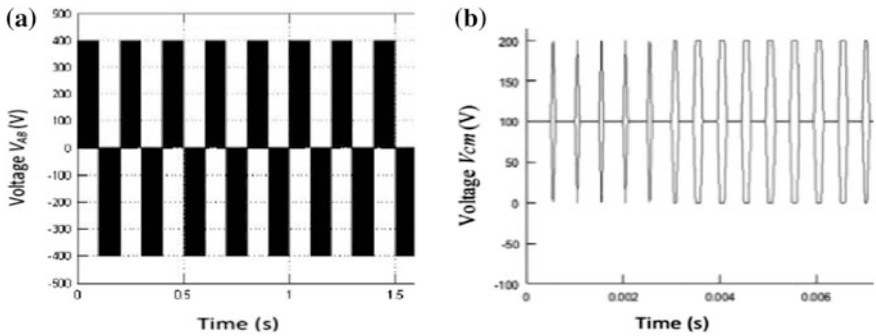

Fig. 3 **a** Output voltage (V_{AB}) of the inverter with unipolar scheme, **b** common-mode voltage (V_{CM}) of the inverter with unipolar scheme

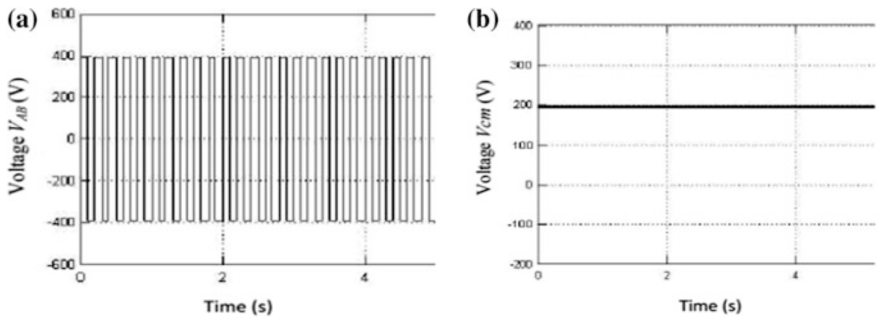

Fig. 4 **a** Output voltage (V_{AB}) of the inverter using bipolar scheme, **b** common-mode voltage (V_{CM}) for bipolar scheme

(as presented in Fig. 4b). The simulation shows that common-mode voltage is constant in bipolar mode, whereas in case of unipolar mode, it is fluctuating.

3.2 Performance Study Under Different Ambient Conditions

PV array always posses an intricate relationship among output voltage, current, and power producing a nonlinear output [8]. Frequent changes in environmental conditions (i.e. solar insolation and temperature) exhibit frequent shifts of the current–voltage (*I*–*V*) characteristic curve. As temperature raises output voltage of solar array increases and vice versa, but has smaller effect on the output current. Changes in solar insolation have proportional effect on output current of PV array. In order to achieve maximum power, MPPT is a regular adjustment of PV array output under variable ambient conditions.

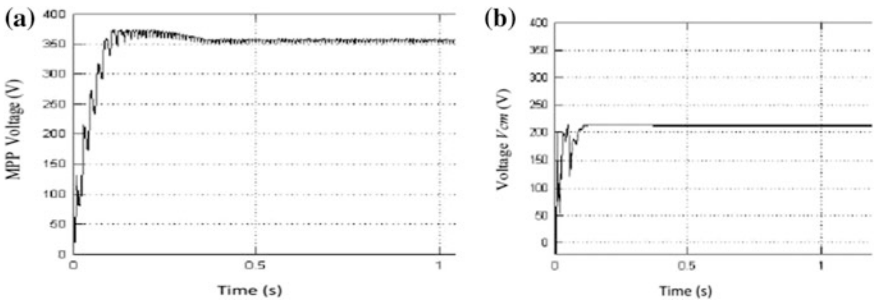

Fig. 5 **a** MPP voltage of the system, **b** common-mode voltage (V_{CM}) of the H6 topology

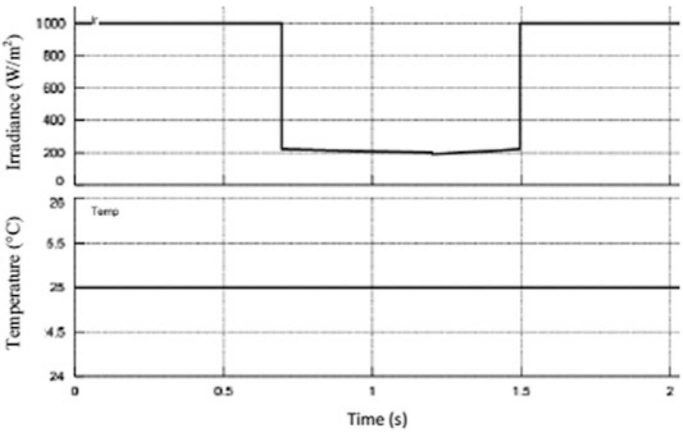

Fig. 6 Variation of irradiation (W/m^2) at constant temperature (25 °C)

Maximum power point (MPP) voltage and corresponding V_{CM} of the inverter under 1000 W/m^2 illumination and 25 °C ambient temperature are shown in Fig. 5a, b, respectively. The common-mode voltage, shown in Fig. 5b, obtained for the improved inverter topology is a constant one under steady condition.

A variation in irradiation (W/m^2) at constant temperature (25 °C), as shown in Fig. 6, is applied. It can be observed in Fig. 7 that during the period of 0.7–1.5 µs, the MPP voltage has reduced due to the decreased value in irradiance. Figure 8 shows the corresponding change in common-mode voltage V_{CM} of the inverter. In a particular ambient condition, V_{CM} remains constant.

3.3 Discussion

Using the circuit parameters given by the theoretically analysis and simulation adjustments, the system converges to MPPs stably with acceptable accuracy as

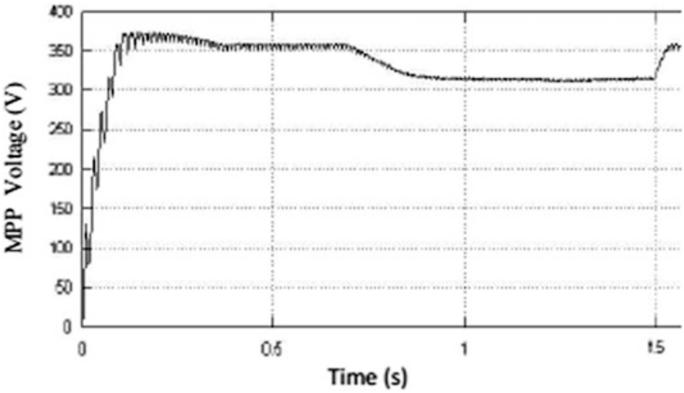

Fig. 7 Variation of MPP voltage

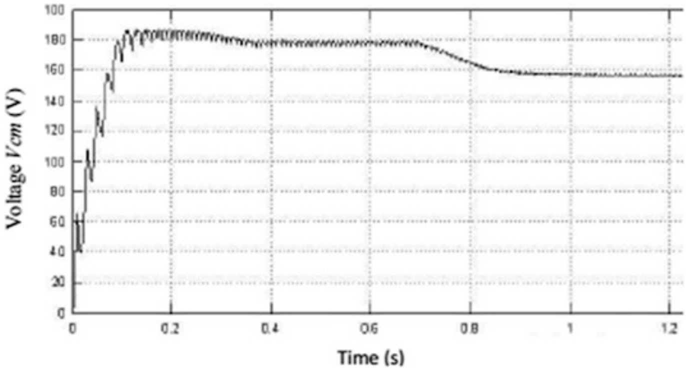

Fig. 8 Variation of common-mode voltage (V_{CM})

demonstrated by the simulation results. The modified topology under validation can be a reliable and efficient one for connecting photovoltaic system to the grid. The simulation result shows that the system inherently converges to the operating point around the MPP. As the common-mode voltage value is constant during all commutation states, ground leakage current can be limited to almost zero.

4 Conclusion

The work involves the validation of single-phase PV converter topology with six switches and two diodes for a transformerless grid-connected PV application. With the converter, PV system is also simulated to verify the ground leakage current issue of the transformerless system. The system produces no pulsating common-mode voltage, thus supporting the ground leakage current suppression ability. MPPT has been used for boosting the voltage of the PV array. The effect of changing irradiance is seen in the output power of the converter.

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