A New High Efficient Transformerless Inverter for Single Phase Grid-tied Photovoltaic System with Reactive Power Control

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Abstract—There has been an increasing interest in transformerless inverter for grid-tied photovoltaic (PV) system due to low cost, high efficiency, less weight, etc. Therefore, many transformerless topologies have been proposed and verified with real power injection only. Recently, almost every international regulation has imposed that a definite amount of reactive power should be handled by the grid-tied PV inverter. According to the standard VDE-AR-N 4105, grid-tied PV inverter of power rating below 3.68kVA, should attain power factor (PF) from 0.95 leading to 0.95 lagging. In this paper, a new high efficient transformerless topology is proposed for grid-tied PV system. The new topology structure and detailed operation principle with reactive power flow is described. The proposed circuit structure does not lead itself to the reverse recovery issues which allow utilizing MOSFET switches to increase the overall efficiency. Finally, to validate the proposed topology, a 1kW laboratory prototype is built and tested. The experimental results show that the proposed topology can inject reactive power into utility grid without any additional current distortion and leakage current. The maximum efficiency and European efficiency of the proposed topology is measured and found to be 98.54% and 98.27%, respectively.

Keywords—common mode, converter, high efficient, leakage current, reactive power, transformerless.

I. INTRODUCTION

Recently, the photovoltaic power generation system has been focused as one of the most significant energy sources due to the rising concern about global warming, and the increase of electrical power consumption [1]. The milestone of 100GW installed PV power all over the world was achieved at the end of 2012 and increased to 140GW at the end of 2013, and the majority are grid connected as shown in Fig. 1 [2]. Therefore, it has been predicted that the future grid-tied PV system will play an important role in the regulation of the conventional power system [3].

In general, PV power generation system includes solar arrays and power conversion unit [4-6]. In most countries and areas, a line-frequency transformer or a high-frequency transformer has been utilized in the grid-tied PV system to create a galvanic isolation between the PV module and the grid. However, the use of line-frequency or high-frequency transformer makes the entire system bulky, costly, and less efficient. In contrast, transformerless PV inverter system has been drawing attention more and more for its low cost, high efficiency, small size and weight [7, 8]. The exclusion of transformer, and hence its isolation capability, has to be considered carefully. Because of the parasitic capacitance between the PV module and the ground, the fluctuating common mode (CM) voltage that depends on the topology structure and switching scheme can inject a capacitive leakage current [9]. The existence of leakage current increases grid current harmonics and system losses, deteriorates the electromagnetic compatibility and, more significantly, lead to a safety threat [5, 10, 11].

In order to solve the problem of leakage current, many dc-ac inverter topologies have been proposed [7, 8, 10, 12-16]. Most of the inverter topologies described in literature and commercially available show the European efficiency in the range of 96%-98% [17]. Therefore, to boost the efficiency, some transformerless topologies use MOSFET switches because of its low switching and conduction losses [7, 12, 18-21].
The most attractive transformerless topology is the Highly Efficient and Reliable Concept (HERIC) topology which is shown in Fig. 1(a). Two switches and two diodes are added in the ac side of full-bridge topology to decouple the PV module from the grid during the freewheeling period [20]. As shown in Fig. 1(b), the topology which has been proposed in [7] replaces the two switches freewheeling branch with one bi-directional switch and four diodes. Yu et al. proposed a H6-type topology as shown in Fig. 1(c), in which two switches and two diodes are added in the dc side to decouple the PV module from the grid [12]. An extension of this topology has been presented in [21]. All the topologies can achieve high efficiency and low leakage current. However, recently almost every international regulation has imposed that a definite amount of reactive power should be handled by the grid-tied PV inverter. This is due to the problems of grid voltage stability. According to the standard VDE-AR-N 4105 which is updated in 2011, grid-tied PV inverter of power rating below 3.68kVA, should attain PF from 0.95 leading to 0.95 lagging [22]. The topologies shown in Fig. 1 have been verified with real power injection only. The dependability of these topologies will be reduced if a phase shift between the voltage and current is occurred due to the low reverse recovery issues of the MOSFETs anti-parallel diode.

In this paper, a new transformerless inverter for single phase grid-tied PV system is proposed. The proposed topology can utilize MOSFET switches to boost the efficiency because the inherent circuit structure does not lead itself to the reverse recovery issues even when inject reactive power. The proposed circuit structure and detail operation principle with reactive power flow are investigated in section II. The control system for the proposed topology is also presented in section III. It has shown that the proposed inverter can handle a certain amount of reactive power if necessary. Finally, the proposed topology is verified with a prototype of rated 1kW/50Hz for unity power factor and other than unity power factor which is shown in section IV and section V concludes the paper.

II. PROPOSED TOPOLOGY AND MODULATION SCHEME

A. Structure of the proposed topology

Fig.1 shows the proposed transformerless inverter topologies consisting of six MOSFET switches (S1-S6) and six diodes (D1-D6). The proposed topology is derived from [12] by splitting the MOSFET phase-legs. The inherent structure of the proposed topology can overcome the low reverse-recovery issues of MOSFETs body-diode even when inject reactive power into the utility grid which allows utilizing MOSFET switches without any reliability or efficiency penalty. The proposed topology can also employ unipolar-SPWM with three-level output voltage.

B. Operation principle analysis with reactive power flow

The switching pattern of the proposed topology is shown in Fig. 4, where S1, S2, S3, S4, S5, and S6 represent the gate drive signals of the switches S1, S2, S3, S4, S5, and S6, respectively. The operation principle of the proposed topology within a grid period which is shown in Fig. 5 is divided into four regions that can be explained as follows:

Region 1: In this region, both the grid current and voltage are positive. During the period within this region, S2 is always on, while S1 & S3 synchronously and S5 complementary commutate with switching frequency. There are always two states that generate the output voltage state of +Vpv and 0.

State 1(t0:t1): In this state, the switches S1 & S3 are turned-on and the inductor current increases through grid as shown in Fig. 5(a). The inverter output voltage VAB, and the CM voltage can be defined as: VAB=+Vpv and VCM=1/2(VIN+VOUT)=1/2(Vpv +0)=1/2Vpv.

State 2(t1:t2): When the switches S2 and S3 are turned-off, the inductor current freewheels through S2 and D5. In
this state, the inverter output voltage and the CM voltage could be as follows: \( V_{AB} = 0 \) and \( V_{CM} = 1/2(V_{IN}+V_{2N}) = 1/2(1/2V_{PV} + 1/2V_{PV}) = 1/2V_{PV} \).

**Region II:** In this region, the inverter output voltage is negative, but the current remains positive. During the duration of this region, S5 is always on, while S4 & S6 are turned-on and S2 complementary commutate with switching frequency. There are also two states which generate the output voltage state of \(-V_{PV}\) and 0.

**State 3(3:4):** In this state, the switches S4 and S6 are turned-on and the filter inductors are demagnetized. Since the inverter output voltage is negative and current remains positive, the inductor current flows through the diode D1 and D2, and decreases rapidly for enduring the reverse voltage. The output voltage and the CM voltage become: \( V_{AB} = -V_{PV} \) and \( V_{CM} = 1/2(V_{IN} + V_{2N}) = 1/2V_{PV} \), respectively.

**State 4(4:5):** At \( t=t4 \), the switches S4 and S6 are turned-off and S2 is turned-on. Therefore, the inductor current flows through S2 and D5 like as state 2 (Fig. 5(b) can be referred as equivalent circuit). This state is called as energy storage mode. The output voltage and the CM voltage become: \( V_{AB} = 0 \) and \( V_{CM} = 1/2V_{PV} \), respectively.

**Region III:** In this region, both the grid current and voltage are negative. During the period of this region, S5 is always on, while S4 & S6 are turned-off and S2 complementary commutate at the switching frequency. There are always two states that can be explained as follows:

**State 5(5:6):** When the switches S4 & S6 are turned-on, the output voltage become, \( V_{AB} = -V_{PV} \) and the inductor current increases through the utility grid. In this mode, \( V_{IN} = V_{PV} \) and \( V_{IN} = 0 \). Therefore, the CM voltage is \( V_{CM} = 1/2(V_{IN} + V_{2N}) = 1/2(V_{PV} + 0) = 1/2V_{PV} \).

**State 6(6:7):** At \( t=t7 \), the switches S4 and S6 are turned-off and S2 is turned-on. Therefore, the inductor current flows through the switch S5 and D6. In this state, \( V_{IN} = 1/2V_{PV} \) and \( V_{IN} = 1/2V_{PV} \). Therefore, the CM voltage can be computed as: \( V_{CM} = 1/2(V_{IN} + V_{2N}) = 1/2V_{PV} \).

**Region IV:** In this region, the inverter output voltage is positive, but the current remains negative. There are also two states.

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**III. CONTROLLING OF THE PROPOSED TOPOLOGY**

The control system for the proposed topology is depicted in Fig. 6, which contains an orthogonal signal generator (OSG) unit to calculate active and reactive power, two proportional integral (PI) controllers for active and reactive power control, a grid current controller and a SPWM generation block [3]. Based on the OSG system, the active power \( P \) and reactive power \( Q \) for the proposed topology can be calculated by using the following equations which is shown in Fig. 7 [3, 23, 24]:

\[
P_{cal} = 1/2\left(v_{gsa}i_{gsa} + v_{gsb}i_{gsb}\right)
\]

\[
Q_{cal} = 1/2\left(v_{gsb}i_{gsa} - v_{gsa}i_{gsb}\right)
\]

where \( v_{gsa}, v_{gsb}, i_{gsa}, \) and \( i_{gsb} \) represents the \( \alpha \) and \( \beta \) components of grid voltage and current. Based on equation (1) and (2), the current in \( \alpha\beta \)-reference frame can be derived as follows:

\[
i_{gsa} = 2\left(P_{cal} * v_{gsa} + Q_{cal} * v_{gsb}\right) / \left(v_{gsa}^2 + v_{gsb}^2\right)
\]

\[
i_{gsb} = 2\left(P_{cal} * v_{gsb} + Q_{cal} * v_{gsa}\right) / \left(v_{gsa}^2 + v_{gsb}^2\right)
\]
According to the single phase P-Q theory, the grid-in current reference can be generated by regulating the averaged active and reactive power [23, 25, 26]. Since the active and reactive power are constant in steady state, so to control them two PI controllers has been used as shown in Fig. 6. The grid reference current can be derived with the help of OSG system in the following equation [23, 25]:

\[
\begin{align*}
\mathbf{i}_{g}^{*} &= \left[(P_{\text{ref}} - P_{\text{cal}})G_{p}(s) + (Q_{\text{ref}} - Q_{\text{cal}})G_{q}(s)\right] \sqrt{\frac{v_{g}^{2} + v_{g}^{2}}{2}} \\
&= \left[(P_{\text{ref}} - P_{\text{cal}})G_{p}(s) + (Q_{\text{ref}} - Q_{\text{cal}})G_{q}(s)\right] \sqrt{\frac{v_{g}^{2} + v_{g}^{2}}{2}}
\end{align*}
\]

(5)

where \(P_{\text{ref}}\) and \(Q_{\text{ref}}\) are the power references, \(G_{p}(s)\) and \(G_{q}(s)\) are the transfer function of PI based controller that can be defined as follows:

\[
\begin{align*}
G_{p}(s) &= K_{p} + \frac{K_{i}}{}s \\
G_{q}(s) &= K_{q} + \frac{K_{i}}{}s
\end{align*}
\]

(6)

(7)

where \(K_{p}p_{p}, K_{ip}, K_{qp},\) and \(K_{iq}\) are the proportional and integral gain for the active and reactive power.

In order to control the grid current, several existing control methods such as conventional PI, repetitive controller (RC), proportional resonant (PR) controller, and deadbeat (DB) controller can be adopted due to the capability of tracking reference signal without steady state error [27-29]. Since the PR controller has better performance of tracking the reference signal if compared to the normal PI and RC controller, it is selected to control the grid current for the proposed topology. The block diagram of the PR controller with harmonic compensator is shown in Fig 8, where \(G_{c}(s), G_{h}(s), G_{d}(s),\) and \(G_{f}(s)\) are the transfer function of fundamental current controller, harmonic compensator, inverter and LC filter, respectively. The transfer functions are given below [27, 30]:

\[
G_{c}(s) = \frac{K_{p} + K_{i}\frac{s}{s^2 + \omega f^2}}{s^2 + \omega f^2}
\]

(8)

\[
G_{h}(s) = \sum_{k=5,7,...}\frac{K_{h}r}{s^2 + (k\omega f)^2}
\]

(9)

\[
G_{d}(s) = \frac{1}{1 + 1.5T_{s}}
\]

(10)

where \(K_{p}, K_{i}\) are the proportional and resonant gain, \(\omega f\) is the fundamental frequency, \(K_{h}\) is the resonant gain at the \(n\)th-order harmonic, \(h\) is the harmonic order, and \(T_{s}\) is the sampling period.

### TABLE I. SPECIFICATION OF THE PROTOTYPE

<table>
<thead>
<tr>
<th>Inverter Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage</td>
<td>400V DC</td>
</tr>
<tr>
<td>Grid Voltage / Frequency</td>
<td>230V / 50Hz</td>
</tr>
<tr>
<td>Rated Power</td>
<td>1000 W</td>
</tr>
<tr>
<td>AC output current</td>
<td>4.2A</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>20kHz</td>
</tr>
<tr>
<td>Filter capacitor</td>
<td>2.2 µF</td>
</tr>
<tr>
<td>Filter Inductor</td>
<td>1mH</td>
</tr>
<tr>
<td>PV Parasitic Capacitor</td>
<td>Cpv1, Cpv2</td>
</tr>
</tbody>
</table>

### IV. EXPERIMENTAL RESULTS

In order to experimentally verify the performance of the proposed topology, a 1 kW prototype is built and tested. The specifications of the prototype are listed in table I. The PV module is replaced with a 400VDC voltage source and the parasitic capacitance between the PV module and the ground is emulated using a thin film capacitor of 75nF.

#### A. Differential-mode and Common-mode Characteristics Verification with Unity Power Factor

The experimental waveforms of the DM characteristics are shown in Fig 9 for unity power factor. It can be seen that the grid voltage and the grid current are pure sinusoidal and achieved unity power factor. The total harmonic distortion is measured and found to be 2.5% that can meet the requirement of IEEE Std. 1547.1™-2005 [31]. Furthermore, in Fig 9, the inverter output voltage (DM voltage) has three levels as \(+V_{P}, 0,\) and \(-V_{P}\), which proves that the proposed topology is modulated using unipolar-SPWM.
Fig. 9. Experimental waveforms of $V_g$, $i_g$ and $V_{AB}$ for unity power factor

Fig. 10. Experimental waveforms of $V_{AN}$, $V_{BN}$ and $V_{CM}$ for unity power factor

Fig. 11. Experimental waveforms of $V_g$, $i_g$ and $V_{AB}$ with other than unity power factor

Fig. 12. Experimental waveforms of $V_{AN}$, $V_{BN}$ and $V_{CM}$ under unity power factor

Fig. 13. Measured efficiency of the proposed topology

The measured efficiency of the proposed topology for unity power factor is depicted in Fig. 13. The YOKOGAWA WT1800 precision power analyzer has been used to measure the efficiency. It can be noted that during the efficiency measurement only the losses for power switches and filter circuit are taken into consideration. The maximum efficiency of the proposed inverter is measured 98.54%. The European efficiency is calculated using equation (11) and found to be 98.27%.

$$
\eta_E = 0.03\eta_{sw} + 0.06\eta_{sw} + 0.13\eta_{sw} + 0.10\eta_{sw} + 0.48\eta_{sw} + 0.2\eta_{sw}.
$$

V. CONCLUSION

This paper has presented a new high efficient transformerless topology for grid-tied PV system. The
inherent circuit configuration of the proposed topology does not lead itself to the reverse recovery issues which allow utilizing MOSFET switches even though when inject reactive power, thereby increasing the overall efficiency. The CM voltage kept constant at the mid-point of DC bus voltage, as a result, the ground leakage current is reduced considerably. The proposed inverter can inject reactive power into the utility grid with low leakage current and low harmonic distortion. Finally, to demonstrate the feasibility and effectiveness of the proposed topology, a 1 kW prototype was built and tested. The experimental results verified the theoretical analysis. Therefore, it can be concluded that the proposed inverter is an attractive solution for grid-tied PV system.

REFERENCES


