H6-type transformerless single-phase inverter for grid-tied photovoltaic system

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Abstract: There has been an increasing interest in transformerless inverter for grid-tied photovoltaic (PV) system because of the benefits of lower cost, smaller volume as well as higher efficiency compared with the ones with transformer. However, one of the technical challenges of the transformerless inverter is the safety issue of leakage current which needs to be addressed carefully. In addition, according to the international regulations, transformerless inverter should be capable of handling a certain amount of reactive power. In this study, a new H6-type transformerless inverter for grid-tied PV system is proposed that can eliminate the threat of leakage current. The proposed topology has also the capability to inject reactive power into the utility grid. Three-level output voltage employing unipolar sinusoidal pulse-width modulation can be achieved with the proposed topology. The proposed topology structure and detail operation principle with reactive power control are investigated. The relationship among the existing topologies and their reactive power control capability are also discussed. The proposed topology is simulated in MATLAB/Simulink software to initially verify the accuracy of theoretical explanations. Finally, a universal prototype rated 1 kW has been built and tested. The experimental results validate the theoretical analysis and simulation results.

1 Introduction

Renewable energy technologies are becoming less expensive and more efficient, which have made it an attractive solution of recent energy crises [1, 2]. Furthermore, renewable energy sources have the advantage that the power is produced in close proximity to where it is consumed. This way the losses because of transmission lines are not present. Among a variety of renewable energy sources, photovoltaic (PV) is predicted to have biggest generation, up to 60% of the total energy by the end of this century [3, 4], because the energy which converted into electrical energy, is the light from the sun is free, available almost everywhere and will still be present for millions of years long after all non-renewable energy sources have been depleted [3, 5]. The PV generates direct voltage; thus, it requires a converter to convert into a voltage of corresponding amplitude at main frequency for feeding it into utility grid. However, the problem can arises because of the hazardous voltage that can be avoided by providing galvanic isolation between the PV module and the grid through a transformer [6, 7]. Nevertheless, the use of a transformer leads to additional drawbacks such as less efficiency, bulky, more expensive and less durability. In order to overcome these drawbacks, transformerless inverter has been introduced which has the benefits such as lower cost, higher efficiency, smaller size and weight [6, 8]. Owing to the missing galvanic separation, large voltage fluctuation both at main frequency and high frequency that depends on the topology structure and control scheme, resulted in leakage current flow from the PV module to the system through the inevitable parasitic capacitance with respect to ground potential [9, 10]. This ground leakage current increases the grid current harmonics and system losses and also creates a strong conducted and radiated electromagnetic interference [11–13]. Accordingly, some standards have been established to fix a maximum allowable leakage current such as the German DIN VDE 0126-1-1 standard which states that the grid must be disconnected within 0.3 s if the root-mean-square (RMS) value of leakage current is more than 30 mA [14]. The RMS values of the fault or leakage current and their corresponding disconnection times are presented in Table 1.

The half-bridge inverter family can eliminate the difficulties of leakage current and injection of DC current into the utility grid having the necessity of high input voltage (700 V) corresponds to 230 V AC application. On the other hand, the problem of leakage current and high input voltage can be solved by using the bipolar sinusoidal pulse-width modulation (SPWM) full-bridge inverter. However, the conversion efficiency of bipolar SPWM inverter is lower because of the high switching losses and magnetic inductor losses. Therefore to solve the problem of leakage current and low efficiency, many DC–AC inverter topologies based on full-bridge inverter have been proposed [6, 8, 15–25]. Gonzalez et al. [8] proposed full-bridge with DC bypass topology, in which two switches and two diodes are added with a full-bridge inverter. It exhibits low leakage current and high efficiency compared with the full-bridge inverter with bipolar modulation. Another topology with DC bypass is proposed in [21], referred as H5 topology. This topology is patented by SMA Solar Technology AG. Schmidt et al. [26] proposed a highly efficient and reliable inverter concept (HERIC) topology by adding two extra switches in the AC side of a full-bridge inverter. Two extended HERIC topologies are proposed in [16, 27]. Although these topologies can achieve high efficiency and low leakage current, they have not yet been analysed from the point of view of reactive power handling capacity.

In this study, a new transformerless grid-tied PV inverter topology is proposed based on the conventional full-bridge inverter with two additional power switches, which ensures the DC decoupling at the freewheeling mode. As a result, leakage current is minimised to safe level. The proposed topology is also capable to inject reactive power into utility grid; therefore, it can satisfy the requirement of the standard VDE-AR-N 4105. Finally, to verify the accuracy of theoretical analysis, a prototype inverter rated at 1 kW has been built and tested. This study is prepared as follows: topology relationship among existing topologies and their reactive power control capability are analysed in Section 2. The proposed circuit structure, detail operation principle with reactive power flow and differential mode (DM) characteristics of the proposed inverter are investigated in Section 3. Simulation and experimental results are depicted in Sections 4 and 5, respectively, and Section 6 concludes the study.
2 Analysis on existing transformerless topologies

2.1 Existing topology relationship analysis

As discussed in the literature, excellent common mode (CM) characteristics can be achieved with the full-bridge topology by employing bipolar SPWM, but the DM characteristic is poor. In contrast, unipolar SPWM improves the DM characteristics, but the CM characteristic is decreased [25]. Therefore, a lot of researches have been conducted on the transformerless PV inverter to achieve an excellent CM and DM characteristics. In Fig. 1, the existing H6-type transformerless topologies (named H6-I and H6-II) which are derived from the conventional H4 topology with almost identical freewheeling path inserted at different position are shown. These topologies are constituted of six metal–oxide–semiconductor field-effect transistor (MOSFET) switches (S1–S6) and two diodes (D1–D2). The operation principle of these topologies is depicted in Figs. 2 and 3. Four operation modes were proposed in each period of the utility grid to generate three-level output voltage state as $+V_{PV}$, 0 and $-V_{PV}$. It can be seen that the grid current is flowing through three switches which is very similar for both H6-I and H6-II topologies. However, these topologies were proposed to operate with unity power factor (PF) [19, 25]. The CM and DM characteristics of these topologies are presented in Table 2.

According to the above analysis, it can be observed that the CM and DM characteristics and the operation principle of these topologies are almost identical. The only difference among them is the freewheeling branch which is inserted at different position.

2.2 Reactive power control capability analysis

Recently, almost every international regulation imposes that a definite amount of reactive power should be handled by the grid-tied PV inverter. This is because of the problem of grid voltage stability. According to the standard VDE-AR-N 4105, grid-tied PV inverter of power rating below 3.68 kVA, should attain PF from 0.95 leading to 0.95 lagging [28]. When the inverter injects or absorbs reactive power, a phase shift is occurred between the voltage and current as shown in Fig. 4. The shifted degree can be calculated as follows

$$\theta = \cos^{-1} PF$$

where $\theta$ is the shifted phase and PF is the commanded power factor.

As shown in Fig. 4, the grid voltage and current have opposite polarity in the negative power region. Consequently, the PWM strategy should be changed to draw power in this region. In the

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**Table 1** Leakage current value and their corresponding disconnection time described in VDE 0126-1-1 standard [14]

<table>
<thead>
<tr>
<th>Leakage current value, mA</th>
<th>Disconnection time, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.3</td>
</tr>
<tr>
<td>60</td>
<td>0.15</td>
</tr>
<tr>
<td>100</td>
<td>0.04</td>
</tr>
</tbody>
</table>

**Fig. 1** Existing H6-type transformerless topologies with almost identical freewheeling path inserted in different position

- a H6-I [25]
- b H6-II [19]

**Fig. 2** Operational modes of H6-I topology [25]

- a Active
- b Freewheeling mode in the positive half-cycle of grid current
- c Active
- d Freewheeling mode in the negative half-cycle of grid current
case of topologies presented in Fig. 1, the anti-parallel diodes of MOSFETs will be activated if a phase shift is occurred between the voltage and current. Accordingly, the dependability of the system will be reduced because of the MOSFETs anti-parallel diode reverse recovery issues. Therefore the lack of reactive power handling capability constitutes a huge drawback of these topologies.

3 Proposed topology and operation principle

3.1 Proposed topology and operation principle

According to the analysis made in Section 2.1, we can derive a new H6-type topology that can overcome the drawback regarding reactive power controlling capability. Fig. 5a shows the circuit structure of the proposed H6-type PV inverter topology, where the two diodes are removed and MOSFETs are replaced with insulated-gate bipolar transistors (IGBTs), if compared with the topologies presented in Fig. 1. As a result, some differences are automatically created in the freewheeling path and control signals. An excellent DM and CM characteristics would be possible with the proposed topology by employing unipolar SPWM.

Fig. 5b shows the gate drive signal for the proposed circuit structure. It can be seen that when a phase shift is occurred

![Fig. 3 Operational modes of H6-II topology](image)

a Active
b Freewheeling mode in the positive half-cycle of grid current
c Active
d Freewheeling mode in the negative half-cycle of grid current

Table 2 Comparison of CM and DM characteristics among the topologies shown in Fig. 1

<table>
<thead>
<tr>
<th>Hybrid topology</th>
<th>$V_{cm} = \frac{(V_{AN} + V_{BN})}{2}$</th>
<th>$V_{dm} = (V_{AN} - V_{BN})$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Level</td>
<td>Frequency</td>
</tr>
<tr>
<td>H6-I</td>
<td>$V_{PV}/2$</td>
<td>0</td>
</tr>
<tr>
<td>H6-II</td>
<td>$V_{PV}/2$</td>
<td>0</td>
</tr>
</tbody>
</table>

![Fig. 4 Relationship between grid voltage $V_g$ and current $i_g$ with leading and lagging PF](image)

![Fig. 5 Proposed new transformerless grid-tied PV inverter topology](image)

a Circuit structure
b Control signal
between the voltage and current, the grid current \( i_g \) remains negative, in the short beginning of positive half period and positive, in the short beginning of negative half period. Therefore the proposed inverter is forced to operate at mode 3 and mode 6 as shown in Fig. 6. However, the proposed inverter operates in four stages within a grid period.

**Stage 1 (\( t_1 \):\( t_2 \)):** This is the positive power region in the positive half-cycle of grid current. In this stage, \( S_6 \) is always on, whereas \( S_1 \) and \( S_4 \) synchronously and \( S_5 \) complementary commutate with switching frequency. Two modes are proposed to generate the output voltage state of \( +V_{PV} \) and 0.

**Mode 1:** This is the active mode in stage 1. This mode starts by turning-on the switches \( S_1 \) and \( S_4 \), and the inductor current increases through grid as shown in Fig. 6a. The CM and DM voltages can be defined as follows

\[
V_{CM} = \frac{1}{2}(V_{AN} + V_{BN}) = \frac{1}{2}(V_{PV} + 0) = \frac{V_{PV}}{2} \tag{2}
\]

\[
V_{DM} = (V_{AN} - V_{BN}) = (V_{PV} - 0) = V_{PV} \tag{3}
\]

**Mode 2:** This is the freewheeling mode in stage 1. Fig. 6b shows the freewheeling path when \( S_1 \) and \( S_4 \) are turned-off. In this mode, \( V_{AN} \) falls and \( V_{BN} \) rises until their values are equal. The inductor current decreases through \( S_6 \) and the body diode of \( S_5 \). Therefore \( V_{AN} = V_{PV}/2 \) and \( V_{BN} = V_{PV}/2 \). The CM and DM voltages could be calculated in (4) and (5), respectively

\[
V_{CM} = \frac{1}{2}(V_{AN} + V_{BN}) = \frac{1}{2} \left( \frac{V_{PV}}{2} + \frac{V_{PV}}{2} \right) = \frac{V_{PV}}{2} \tag{4}
\]

\[
V_{DM} = (V_{AN} - V_{BN}) = \left( \frac{V_{PV}}{2} - \frac{V_{PV}}{2} \right) = 0 \tag{5}
\]

**Stage 2 (\( t_2 \):\( t_3 \)):** This is the negative power region in the positive half-cycle of grid current. In this stage, the inverter output voltage is negative but the current remains positive. In order to generate the output voltage state of \( -V_{PV} \) and 0, the proposed inverter continuously rotates between mode 2 and mode 3, which are shown in Figs. 6b and c. Mode 3 can be explained as follows:

**Mode 3:** In this mode, the switches \( S_2, S_3 \) and \( S_5 \) are turned-on and the filter inductors are demagnetised. Since the inverter output voltage is negative and the current remains positive, inductor

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**Fig. 6** Operating principle of the proposed topology with reactive power flow

- a Mode 1
- b Mode 2
- c Mode 3
- d Mode 4
- e Mode 5
- f Mode 6
current is forced to freewheel through the body diode of the switches S2, S5 and S3 and decreases rapidly for enduring the reverse voltage. The CM and DM voltages are calculated in (6) and (7), respectively

\[
V_{CM} = \frac{1}{2} (V_{AN} + V_{BN}) = \frac{1}{2} (0 + V_{PV}) = \frac{V_{PV}}{2}
\]

(6)

\[
V_{DM} = (V_{AN} - V_{BN}) = (0 - V_{PV}) = -V_{PV}
\]

(7)

Stage 3 (t3:t4): This is the positive power region in the negative half-cycle of grid current. In this stage, S5 is always on, while S2 and S3 synchronously and S6 complementary commutate with half-cycle of grid current. In this stage, S5 is always on, while S2

This is the positive power region in the negative half-cycle of grid current. In this stage, S5 is always on, while S2

Stage 4 (t4:t5): This is the freewheeling mode in stage 3 which is depicted shown in Fig. 6e. When the switches S2 and S3 are turned-off, the mid-point voltage \( V_{AN} \) falls and \( V_{AN} \) rises until their values are equal. The inductor current freewheels through the switch S5 and the body diode of S6. In this mode, \( V_{AN} = 1/2 V_{PV} \) and \( V_{BN} = 1/2 V_{PV} \). The CM and DM voltages can be calculated in the following equation

\[
V_{CM} = \frac{1}{2} (V_{AN} + V_{BN}) = \frac{1}{2} (\frac{V_{PV}}{2} + \frac{V_{PV}}{2}) = \frac{V_{PV}}{2}
\]

(8)

\[
V_{DM} = (V_{AN} - V_{BN}) = (\frac{V_{PV}}{2} - \frac{V_{PV}}{2}) = 0
\]

(9)

Stage 4 (t4:t5): This is the negative power region in the negative half-cycle of grid current. In this stage, the inverter output voltage is positive but the current remains negative. In order to generate the output voltage state of \(+V_{PV}\) and 0, the proposed inverter continuously rotates between mode 5 and mode 6, which are shown in Figs. 6e and f.

Mode 5: When the switches S2 and S3 are turned-on, the inductor current increases reversely through grid as shown in Fig. 6d. In this mode, \( V_{AN} = 0 \) and \( V_{BN} = V_{PV} \). Therefore the CM and DM voltages become

\[
V_{CM} = \frac{1}{2} (V_{AN} + V_{BN}) = \frac{1}{2} (0 + V_{PV}) = \frac{V_{PV}}{2}
\]

(10)

\[
V_{DM} = (V_{AN} - V_{BN}) = (0 - V_{PV}) = -V_{PV}
\]

(11)

Mode 6: In this mode, the switches S1 and S4 are turned-on and the filter inductors are demagnetised such as mode 4. Since the inverter output voltage is positive and the current remains negative, the inductor current is forced to freewheel through the body diode of the switches S1, S4 and S6 and decreases rapidly for enduring the reverse voltage. The CM and DM voltages become

\[
V_{CM} = \frac{1}{2} (V_{AN} + V_{BN}) = \frac{1}{2} (V_{PV} + 0) = \frac{V_{PV}}{2}
\]

(12)

\[
V_{DM} = (V_{AN} - V_{BN}) = (V_{PV} - 0) = V_{PV}
\]

(13)

It is clear that during the aforementioned four stages, \( V_{CM} \) remains constant at \( 1/2 V_{PV} \) and \( V_{DM} \) varies among \(+V_{PV}\), 0 and \(-V_{PV}\) from (2) to (13). Therefore the proposed inverter can keep the CM voltage constant during the whole grid period and achieve three-level output voltage with unipolar SPWM even though when inject reactive power into the utility grid.

3.2 DM characteristics of the proposed inverter

As analysis in the previous section, the DM voltage of the proposed inverter varies among \(+V_{PV}\), 0 and \(-V_{PV}\). Thus, a low-pass output filter would be optimised. In order to reduce the high-frequency voltage fluctuation between the PV module and the ground, two split inductors with identical values are used in the proposed inverter. The entire solution can be considered equivalent to the LC-type filter. The value of the filter inductor is calculated by considering the instant when the output current ripples reach maximum values. The factor representing such instant can be computed by the maximum value of (14) [20]

\[
\Delta I_{filter} = M \sin(\omega t) - M^2 \sin^2(\omega t)
\]

where \( M \) is the modulation index and \( \omega \) is the angular frequency. Fig. 7 shows the waveform of \( \Delta I_{filter} \) for different modulation indices. It can be seen that the maximum value of \( \Delta I_{filter} \) is 0.25. The value of the output filter inductor is calculated as follows

\[
L = \frac{V_{PV} \Delta I_{filter}}{f_s \Delta I_L}
\]

(15)

where \( V_{PV} \) is the input voltage, \( f_s \) is the switching frequency and \( \Delta I_L \) is the maximum ripple on the output current. A higher ripple value causes higher conduction losses. Therefore considering the above two factors, a value not higher than 20% is suggested. The output filter capacitor is calculated using (16) by selecting the cutoff frequency [25]

\[
C_o = \frac{1}{4 \pi f_c^2 L}
\]

(16)
4 Simulation results

The simulations are carried out to analyse and compare the operation and overall performance of the H6-I [25], H6-II [19] and the proposed topologies using MATLAB/Simulink software. The parameters used in simulation are same for all the topologies. Although, the H6-I and H6-II topologies had been considered for MOSFET switches, here it is verified using IGBT switches to compare their performances in the same environment. The PV module and the stray capacitance between the PV module and the

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**Fig. 9** Waveform of grid current (upper), DM voltage (middle) and leakage current (lower)

- a H6-I topology
- b H-II topology
- c Proposed topology

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**Fig. 10** Waveform of $V_{AN}$, $V_{CM}$ and $V_{BN}$

- a H6-I topology
- b H-II topology
- c Proposed topology
Table 3 Specification of the prototype

<table>
<thead>
<tr>
<th>Inverter parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>input voltage</td>
<td>400 VDC</td>
</tr>
<tr>
<td>grid voltage/frequency</td>
<td>230 V/50 Hz</td>
</tr>
<tr>
<td>AC output current</td>
<td>4.2 A</td>
</tr>
<tr>
<td>switching frequency</td>
<td>20 kHz</td>
</tr>
<tr>
<td>DC bus capacitor</td>
<td>470 µF</td>
</tr>
<tr>
<td>filter capacitor</td>
<td>2.2 µF</td>
</tr>
<tr>
<td>filter inductor I6</td>
<td>3 mH</td>
</tr>
<tr>
<td>PV parasitic capacitor Cpv1, Cpv2</td>
<td>75 nF</td>
</tr>
<tr>
<td>IGBT switches (S1-S6)</td>
<td>STG020NC60VD</td>
</tr>
<tr>
<td>diode</td>
<td>IDH08SG60C</td>
</tr>
<tr>
<td>PF controller</td>
<td>0.95 lag</td>
</tr>
<tr>
<td>controller</td>
<td>dSPACE 1104</td>
</tr>
</tbody>
</table>

The grid current has been replaced with a 400 V DC source and two capacitors of 75 nF each, respectively. The grid line-neutral voltage is 230 V with frequency of 50 Hz. The PF and the switching frequency are 0.95 lagging and 20 kHz, respectively.

The control block of the proposed inverter is shown in Fig. 8, where a maximum power point algorithm is not included. The grid voltage is sensed and fed to a phase-locked loop to generate a unity sinusoidal signal which is in-phase with the grid voltage. A proportional integral (PI) current controller is used to control the output current which ensures that the inductor current tracks the given reference value $i_{ref}$. The output of the PI controller is multiplied with the unity sinusoidal signal and sent to a comparator to generate the switching signals.

The grid current $i_g$, DM voltage $V_{DM}$ and leakage current $i_{leakage}$ of the H6-I, H6-II and proposed topologies are shown in Fig. 9. It can be seen that all the topologies have three-level output voltage with good DM characteristics which reduces the grid current ripple compared with the bipolar modulation. As a result, the size of the output filter is reduced. As shown in Figs. 9a and b, the grid current of both H6-I and H6-II topologies is sinusoidal but has a distortion during the time of negative power region because the zero voltage vectors are not achieved properly during this time. On the other hand, the proposed topology has improved the current distortion by achieving the zero voltage vectors during the period of negative power region as shown in Fig. 9c.

The waveform of $V_{AN}$, $V_{BN}$ and $V_{CM}$ of the H6-I, H6-II and proposed topologies are presented in Fig. 10. It is clear that large oscillation with the magnitude up to 100 V is present in the waveform of CM voltage for both H6-I and H6-II topologies during the time of negative power region which is depicted in Figs. 10a and b. As a result, the ground leakage current will be increased with H6-I and H6-II topologies when injecting reactive power into the utility grid. As shown in Fig. 10c, the voltage $V_{AN}$ and $V_{BN}$ are absolutely complementary to each other and the CM voltage is kept constant at 200 V, even during the period of negative power region. As a result, zero leakage current is observed with the proposed topology which is shown in Fig. 9c. Therefore it can be concluded from simulation results that the proposed topology with new modulation scheme could overcome the drawback regarding reactive power controlling capability.

5 Experimental results

In order to experimentally verify the operation principle and performance comparison, a 1 kW universal prototype has been built and tested using the same components. The specifications of the prototype are listed in Table 3. The implemented control circuit is shown in Fig. 8 and described in the simulation results section. Resistor and inductor loads are used in replacement of grid. It does not affect the validation of the topologies because the same resistor and inductor loads are used for all the topologies [27, 29]. The capacitance between the PV module and the ground is emulated with a thin film capacitor of 75 nF.

The experimental investigation on the three topologies for CM and DM characteristics are given in Figs. 11–13. The grid current $i_g$, DM voltage $V_{AB}$ and the enlarge view of $V_{AB}$ for the three topologies are shown in subfigure (a). Subfigure (b) indicates the waveform of the voltages $V_{AN}$, $2V_{cm}$ ($=V_{AN}+V_{BN}$) which is calculated in the oscilloscope using math function), $V_{BN}$ and leakage current. As shown in Figs. 11a and 12a, the DM voltage is not completely unipolar for both H6-I and H6-II topologies because the zero

Fig. 11 DM and CM characteristics of the H6-I topology
- $i_g$ (C2), $V_{AN}$ (C3) and enlarge view of $V_{AB}$ (Z1)
- $V_{BN}$ (C3), 2 $V_{cm}$ (P1), $V_{AN}$ (C4) and $i_{leakage}$ (C3)

Fig. 12 DM and CM characteristics of the H6-II topology
- $i_g$ (C2), $V_{AN}$ (C3) and enlarge view of $V_{AB}$ (Z1)
- $V_{BN}$ (C3), 2 $V_{cm}$ (P1), $V_{AN}$ (C4) and $i_{leakage}$ (C3)
voltage is not achieved at the negative power region, which can be more cleared from the magnified view of $V_{AB}$. As a result, the grid current of H6-I and H6-II topologies become distorted during the period of negative power region which is marked in the waveform of $i_g$. On the other hand, it is clear from Fig. 13a that the DM voltage of the proposed topology is fully unipolar and has three levels as $+V_{PV}$, 0 and $-V_{PV}$. Therefore it is experimentally verified that the proposed topology is modulated with unipolar modulation scheme and the DM characteristics are excellent. As shown Fig. 13a, the grid current is pure sinusoidal which lags the grid voltage. The total harmonic distortion (THD) for grid current is measured 1.7% which is shown in Fig. 14. Therefore the proposed topology can fulfil the requirement of IEEE standard 1547.1™-2005 [30]. It can be seen from Figs. 11b, 12b and 13b that a small spike is present in the waveform of CM voltage for all the three topologies. This problem arises because of the junction capacitance of the switches and turn-on delay time of the freewheeling diode. This CM voltage fluctuation can be minimised using different power switches. In addition, it is clear that an additional fluctuation is present in the CM voltage of H6-I and H6-II topologies during the negative power region as shown in Figs. 11b and 12b, which increases the ground leakage current. However, the RMS values of leakage current are measured 24.5, 26.2 and 19.6 mA with the H6-I, H6-II and proposed topologies, respectively. According to the requirements listed in the German standard VDE0126-1-1 [31], these RMS values of high-frequency leakage current is still minor and acceptable for grid-tied PV system. It is obvious that the proposed topology has the lowest leakage current compare with the other two topologies.

The experimental waveform of collector–emitter voltage and current across the switches S1, S4 and S6 are illustrated in Fig. 15. It is clear that no extra voltage and current stress are present. It can be seen from Fig. 15b, the current is forced to freewheel through the anti-parallel diode when the voltage is positive but the current remains negative, which validate the theoretical analysis made in Section 3.1. In addition, the blocking voltage of the added switches is half of the DC input voltage. As a result, the switching losses for the added switches are reduced considerably.
The efficiency comparison curve among the proposed, H6-I and H-II topologies with unity PF is presented in Fig. 16. The YOKOGAWA WT1800 precision power analyser has been used to measure the efficiency. It may be noted that the presented efficiency diagram covers the total power device losses and the filter inductor losses but it does not contain the losses for the control circuit. It is clear that the efficiency of the three topologies is almost same because of the equal switching and conduction losses. The maximum efficiency of the proposed inverter is measured 97.6%. The European efficiency can be calculated by combining several weighted factors at various output power, as expressed in (17) [8]

\[
\eta_{EU} = 0.03\eta_{95\%} + 0.06\eta_{90\%} + 0.13\eta_{80\%} + 0.10\eta_{70\%} + 0.48\eta_{60\%} + 0.20\eta_{50\%}
\]

(17)

The calculated European efficiency for the H6-I, H6-II and proposed topologies are 97.31, 97.39 and 97.22%, respectively. As expected, all the topologies have almost same European efficiency with a slight variation because of high performance freewheeling diode of the H6-I and H6-II topologies. The experimental performance comparisons for these three topologies are summarised in Table 4. It can be seen that the proposed topology can combine the superior performance of DM and CM characteristics.

6 Conclusions

This study proposes a new transformerless topology for single-phase grid-tied PV system. The proposed topology can overcome the drawbacks of H6-I and H6-II topologies regarding reactive power capability. Furthermore, the proposed topology has the following advantages:

1. The CM mode voltage is kept constant during the whole grid period even when inject reactive power into utility grid; thus, the leakage current is well suppressed.
2. As the isolated full-bridge inverter, the excellent DM characteristics are achieved in the proposed topology with unipolar modulation.
3. The blocking voltages of the added switches are half of the DC input voltage and the inductor current flows through three switches during the whole grid period. As a result, the switching losses and conduction losses are reduced considerably.
4. The proposed topology has the ability to inject reactive power into utility grid with low harmonic distortion.

The proposed topology is verified with a prototype rated at 1 kW, 240 V/50 Hz. The maximum efficiency of the proposed inverter is measured 97.6%. Therefore it can be concluded that the proposed inverter is an attractive solution for the new generation of grid-tied PV system.

7 Acknowledgments

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Table 4 Performance comparison among H6-I, H6-II and proposed topologies

<table>
<thead>
<tr>
<th>Parameters</th>
<th>H6-I</th>
<th>H6-II</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWM pattern</td>
<td>semi-unipolar</td>
<td>semi-unipolar</td>
<td>fully-unipolar</td>
</tr>
<tr>
<td>leakage current, m\text{A}_{\text{rms}}</td>
<td>24.5</td>
<td>26.2</td>
<td>19.6</td>
</tr>
<tr>
<td>THDI, %</td>
<td>4.6</td>
<td>4.3</td>
<td>1.7</td>
</tr>
<tr>
<td>European efficiency, %</td>
<td>97.31</td>
<td>97.39</td>
<td>97.22</td>
</tr>
</tbody>
</table>

8 References

3 Zhao, Z.: ‘High efficiency single-stage grid-tied PV inverter for renewable energy system’ (Virginia Polytechnic Institute and State University, 2012)
30 ‘Automatic Disconnection Device Between a Generator and the Public Low-Voltage Grid’, Germany Standard DIN VDE 0126, 2010

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