High-Frequency Transformer Based Grid-Connected Inverter Topology for Photovoltaic Systems

Abhijit Kulkarni and Vinod John
Department of Electrical Engineering,
IISc Bangalore, India

Abstract—Inverters are required to convert the DC power from photovoltaic (PV) panels to AC. In grid connected inverters, the AC output is directly fed into the electric grid. In this paper, a high-frequency transformer based inverter topology is presented. This leads to a very compact inverter. The closed-loop control and modulation of this inverter with a lossless snubber circuit is proposed. The performance of the inverter is validated using simulation results.

Index Terms—Photovoltaic systems, inverters, transformers, snubbers

I. INTRODUCTION

Photovoltaic panels are used in many grid-connected inverters as the energy sources [1]. The PV panels generate DC power of hundreds of watts normally at a low voltage of less than 50V. In order to interface the PV inverters to the grid, a voltage stepping up operation is required which is normally achieved by transformers. The transformers also provide electrical isolation which is important from safety perspective.

There are different inverter topologies possible. A simple topology is shown in Fig. 1. This topology uses a line-frequency (50Hz) transformer to step up the inverter voltage and interface to the grid.

The boost-stage used in the circuit is optional. The inverter section can be directly fed in by the PV panels. Maximum power point tracking (MPPT) is required to obtain the maximum available power from the panels. If the boost converter is used, as in Fig. 1, then MPPT is performed on the boost converter switch. The inverter performs the dc bus voltage regulation and feeds current into the grid at unity power factor.

This topology is suitable for low power ratings of few hundreds of watts. As the power level increases, the size of the interface transformer increases. This results in bulky power circuit and losses in magnetics can also be significant. Another issue with this topology is the introduction of lower order harmonics in the grid current [2].

There are many inverter topologies that use a high-frequency (HF) link transformer [3]–[6]. This is because the size of the transformer core reduces with the increase in the operating frequency. The circuit topology discussed in this paper is shown in Fig. 2.

Ideally, this topology does not require any snubber. However, due to the transformer leakage inductance, a snubber circuit is required. Otherwise the semiconductor switches will be subjected to high voltage spikes. In this paper, a lossless snubber circuit is considered which is shown in Fig. 2.

A modulation method is proposed which ensures proper operation of the circuit topology. Closed loop control of the output inverter is also presented. The performance of the inverter circuit is verified in simulations which is discussed in this paper. The hardware for the inverter is built in the laboratory. The experimental investigations of the hardware are in progress.

II. OPERATION OF THE HF TRANSFORMER BASED GRID-CONNECTED INVERTER

A. Ideal Operation

As shown in Fig. 2, the HF inverter consists of the switches $S_1, S_2, S_3$ and $S_4$. The HF rectifier consists of switches $S_5$ through $S_8$. Output inverter is the conventional H-bridge with an inductive filter connected to grid. All the switches used are assumed to be ideal. The HF transformer is a step up transformer and it is assumed that the transformer does not have any leakage inductances and the magnetizing inductance is assumed infinite. The complete circuit is assumed to be lossless.

The HF inverter and rectifier are switched in square wave mode. That is, for the HF inverter, $S_1, S_4$ are switched together to apply positive voltage across the transformer primary. Similarly $S_2, S_3$ are switched on to apply negative voltage to the transformer. The switch pairs have a duty ratio of 0.5. The HF rectifier is also switched in square wave mode. $S_5, S_8$ are switched together with $S_1, S_4$. Similarly $S_6, S_7$ are switched together with $S_2, S_3$. This type of modulation ideally results in a dc voltage across the dc link. If input dc voltage is $V_{in}$ and the transformer turns ratio is $1:n$, the link voltage $V_{link}$ will be a pure dc equalling $nV_{in}$.

The various waveforms for the ideal operation are shown in Fig. 3. Note that the sawtooth carrier and triangle carrier
are used for the HF inverter-rectifier and output inverter respectively. These carriers must be synchronized.

**B. Operation of the Practical Circuit**

Due to the switching of the inverter devices, the dc link current $i_{link}$ shown in Fig. 3(h) is discontinuous. If $\tilde{S}_9$ and $\tilde{S}_{11}$ are the switching states of the switches $S_9$ and $S_{11}$ respectively, then the link current can be expressed as:

$$i_{link} = (\tilde{S}_9 - \tilde{S}_{11})i_L$$

(1)

Where $i_L$ is the output current which is sinusoidal and regulated. $\tilde{S}_9$ and $\tilde{S}_{11}$ take values of zero and one. Thus depending on the value of the switching states, the link current is either zero or $+i_L$ or $-i_L$. In sine-triangle PWM, with unity power factor (upf) operation, it can be verified that $i_{link}$ is either zero or the absolute value of $i_L$. Thus there are two transitions: one with very high and positive $di_{link}/dt$ and other is very high and negative $di_{link}/dt$.

Practically the transformer has a leakage inductance. The effective leakage inductance seen from the secondary side is given by

$$L_{leakage} = n^2 L_{lp} + L_{ls}$$

(2)

In (2), $L_{lp}$ and $L_{ls}$ are the transformer primary and secondary leakage inductances respectively and transformer has a turns ratio of 1 : n.

Due to the leakage inductance, the link voltage and the device voltages will see large overvoltages because of $L_{leakage}di_{link}/dt$. There will be a very large positive overvoltage during the positive transition and during the negative transition the voltage goes to zero as it cannot go negative due to the back diodes of the switches. Thus, the link voltage will have large spikes and the stress on the semiconductor devices will be very large which is highly undesirable.

**III. CLOSED-LOOP CONTROL AND MODULATION**

**A. Control of the Injected Grid Current**

The current injected into the grid depends on the available input power from the PV panels for a given grid voltage amplitude. The closed-loop control of the complete topology involves the control of the output inverter to inject a current with minimal harmonic distortion into the grid.

MPPT algorithm needs to be used to compute the maximum power available from the panels. From this, the required current reference is generated. The control block diagram is shown in Fig. 4. The current controller block shown in the

![Fig. 4. Closed-loop control block diagram.](image-url)
figure is a PR controller with the following transfer function. \( k_p \) and \( k_i \) are designed using the standard design procedure available [7]. The grid fundamental frequency is \( \omega_0 \) rad/s.

\[
G_{PR}(s) = k_p + \frac{k_i s}{s^2 + \omega_0^2}
\]  
(3)

The feed-forward term indicated in Fig. 4 can be any harmonic compensating signal due to dead-time effect etc.

B. Modulation of the Semiconductor Switches

The HF inverter and rectifier switches are modulated in square-wave mode as explained in Section II-A and indicated in Fig. 3. The output inverter switches are modulated using sine-triangle pulse width modulation (PWM). The voltage reference for the sine-triangle PWM is generated by the closed-loop control as shown in Fig. 4.

The modulation for the snubber switch \( S \) is proposed in this paper. This switch is turned on during every active state of the output inverter. That is, whenever the diagonal switches of output inverter are turned on, the snubber switch is also turned on. It is turned off when the zero state starts. If \( \bar{S}_9 \) and \( \bar{S}_{11} \) are the switching states of the switches \( S_9 \) and \( S_{11} \) respectively, then the switching state for the snubber switch \( \bar{S} \) is given by

\[
\bar{S} = \bar{S}_9 \oplus \bar{S}_{11}
\]  
(4)

One important point related to the modulation method proposed in this paper is the synchroniztion between the triangle and the sawtooth carriers. They must be synchronized in such a way that the polarity reversal of the primary/secondary voltage occurs during the zero state of the output inverter. This type of synchronization can be achieved by coinciding the zero of sawtooth waveform with the negative peak of the triangle shown in Fig. 3. If this is not followed then the snubber action will not be effective.

IV. COMMUTATION OF THE LEAKAGE INDUCTANCE ENERGY

In this section, the commutation of energy in leakage inductance is explained qualitatively in the following points.

1) Consider the instant when the output inverter is in zero state i.e., \( i_{\text{link}} = 0 \). The grid current is assumed to circulate between \( S_9 \) and the diode of \( S_{11} \). Snubber switch \( S \) is off as per (4). The transformer primary/secondary voltages are assumed to be positive and the snubber capacitor \( C_s \) is being charged via diode \( D_s \).

2) At the end of the zero state, the active state of the output inverter begins which means \( i_{\text{link}} = i_{\text{grid}} \). But now \( S \) is turned on and hence \( C_s \) discharges through \( S \) to supply the necessary \( i_{\text{link}} \) and hence the transformer current does not have any \( di/dt \). This means no over-voltage spike on the semiconductor devices.

3) At the end of the active state, another zero state begins and \( C_s \) will again start getting charged via diode \( D_s \).

4) During this zero state, the transformer applied voltage changes polarity (see Fig. 3(e) and Fig. 3(h) at \( t = T_s/2 \)). Then the secondary current will start flowing through \( S_6 \), stray capacitance \( C_{\text{stray}} \) and \( S_7 \). It discharges \( C_{\text{stray}} \) so that the link voltage goes to zero. Then it will decay to zero with a slope of \( nV_{\text{in}}/L_{\text{leakage}} \).

The same steps will repeat in the negative half cycle of the transformer applied voltage. Thus, it is concluded that there are no over-voltage spikes. However, the link voltage is discharged to zero whenever the polarity of the transformer applied voltage reverses.

V. SELECTION OF SNUBBER CAPACITOR

The snubber capacitance value must be such that the resonance frequency between \( C_s \) and \( L_{\text{leakage}} \) is much lower than the switching frequency of the inverter. Otherwise, it can be shown that the over-voltage spikes cannot be eliminated effectively. The resonance frequency is given by

\[
f_{\text{res}} = \frac{1}{2\pi\sqrt{L_{\text{leakage}}C_s}}
\]  
(5)

Fig. 5 shows the rms current of the capacitor for different values of \( C_s \) for different power factor operation of the inverter. Note that beyond a value of 1000\(\mu\)F, there will not be any significant improvement in the rms current rating of \( C_s \). As the system is normally operated under unity power factor, the rms current rating for \( C_s \) will be about 9A.

![Rms current carried by snubber capacitor \( C_s \) as a function of the operating power factor and capacitance value.](image)

VI. SIMULATION RESULTS

In this section, the performance of the inverter is verified in time-domain simulation. The simulation software used is PSIM. The system ratings are specified in Table I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV panel input voltage ( V_{\text{pv}} )</td>
<td>35–40V</td>
</tr>
<tr>
<td>Transformer turns ratio ( (1-n) )</td>
<td>1:10</td>
</tr>
<tr>
<td>Rated Power</td>
<td>3kW</td>
</tr>
<tr>
<td>Nominal grid voltage ( V_{\text{g}} )</td>
<td>230V rms</td>
</tr>
<tr>
<td>Filter inductance ( L_f )</td>
<td>8.8mH</td>
</tr>
<tr>
<td>Switching frequency ( f_{\text{sw}} )</td>
<td>20kHz</td>
</tr>
<tr>
<td>Net leakage inductance w.r.t secondary ( L_{\text{leakage}} )</td>
<td>34(\mu)H</td>
</tr>
</tbody>
</table>

![Link voltage with the lossless snubber circuit is shown in Fig. 6(b). It can be observed that the voltage does not have](image)
any overvoltage spikes. It is also not a pure dc quantity. This is because of the transformer current reset that happens during the transformer voltage polarity reversal.

The snubber capacitor voltage for the circuit is shown in Fig. 7. It can be seen that the capacitor voltage has a 100Hz ripple due to the single phase operation.

The grid current and grid voltage are shown in Fig. 8. It can be seen that the circuit is operating under unity power factor. All the waveforms are for the rated full load of 3kW.

Fig. 9. Picture of the inverter built in laboratory showing (1) HF Inverter, (2) HF Rectifier and output inverter, (3) Gate-drive circuit, (4) FPGA controller board and (5) HF transformer.

The inverter hardware has been built in the laboratory. The picture of the hardware is shown in Fig. 9. All the different circuit boards have been labelled in the figure.

If the topology shown in Fig. 1 were used, the size of the transformer would have been much larger than the one shown in Fig. 9. The core volume of the HF transformer is 147.97cm³. However, the core volume is 4222.8cm³ for an equally rated line frequency transformer which is about 28 times larger. Thus the HF transformer based inverter is considerably compact and hence light-weight compared to the line-frequency transformer in the topology shown in Fig. 1.

VII. CONCLUSION
In this paper, a high-frequency transformer based grid connected inverter is presented for photovoltaic energy conversion system. The requirement of such a topology in comparison to a line frequency interface transformer is explained and it is shown to be very compact. The operation of the circuit and practical difficulties are discussed. A lossless snubber is effective in reducing the peak voltage stress in the power semiconductor switches. The modulation and closed-loop control for the inverter topology is presented. The complete analysis is verified using simulations.

REFERENCES