HF Transformer Based Grid-Connected Inverter Topology for Photovoltaic Systems

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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 modulation of this inverter with a lossless snubber circuit is proposed. Proposed modulation eliminates the over voltage spikes due to transformer leakage inductance. Commutation of the leakage inductance energy with this modulation is also discussed. The performance of the inverter with the proposed modulation is validated using simulation and experimental 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 achieve a standard single-phase ac voltage of 230Vrms and 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. Note that the output of the transformer can be connected to loads instead of grid in stand-alone applications.

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]–[7]. 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. The hardware for the inverter is built in the laboratory. The operation of the inverter with the proposed modulation has been validated experimentally.

II. OPERATION OF THE HF TRANSFORMER BASED 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. It can also be a stand-alone inverter feeding local loads. 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. $S_5$, $S_6$ 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 \( V_{\text{link}} \) will be a pure dc equalling \( nV_{\text{in}} \).

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 \( i_{\text{link}} \) 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:

\[
i_{\text{link}} = (\tilde{S}_9 - \tilde{S}_{11})i_L
\]

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 \( \pm i_L \). In sine-triangle PWM, with unity power factor (upf) operation, it can be verified that \( i_{\text{link}} \) is either zero or the absolute value of \( i_L \). Thus there are two transitions: one with very high and positive \( \text{di}_{\text{link}}/\text{dt} \) and other is very high and negative \( \text{di}_{\text{link}}/\text{dt} \).

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

\[
L_{\text{leakage}} = n^2L_{\text{lp}} + L_{\text{ls}}
\]

In (2), \( L_{\text{lp}} \) and \( L_{\text{ls}} \) 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 \( L_{\text{leakage}}\text{di}_{\text{link}}/\text{dt} \). 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. Current is normally controlled at unity power factor. However, when the energy from the panels is not available, the inverter can be operated in STATCOM mode [8].

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
A. 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 to be switched using a pulse width modulation (PWM) technique to control the output current in grid connected operation or output voltage in stand-alone operation. The PWM method can be conventional sine-triangle PWM, space vector PWM or some advanced PWMs [10], [11]. In this paper, sine-triangle PWM is used. The voltage reference for this PWM is generated by the closed-loop controller.

The modulation for the snubber switch $S$ is proposed as follows. 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 $S_9$ and $S_{11}$ are the switching states of the switches $S_9$ and $S_{11}$ respectively, then the switching state for the snubber switch $\tilde{S}$ is given by

$$\tilde{S} = S_9 \oplus S_{11} \quad (4)$$

One important point related to the modulation method proposed in this paper is the synchronization 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 output 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 large $di/dt$. This means no 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 $S_9$, 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 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

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

The value of the snubber capacitance has a direct effect on the transformer rms and peak currents. The variation of secondary peak and rms currents versus snubber capacitance value are shown in Fig. 5. It can be observed that beyond 10$\mu$F, the rms current variation is very small. However, the peak current variation becomes small only for a value of beyond 1000$\mu$F. If there is a strict requirement on peak current reduction, then higher capacitance has to be selected. However, higher capacitance would mean the choice of the capacitor will be electrolytic. For the smaller capacitance designs, polypropylene capacitors can be used which have higher lifetime and increase the system reliability.
VI. SIMULATION AND EXPERIMENTAL RESULTS

In this Section, the performance of the inverter is verified in time-domain simulations and experiments. The system ratings are specified in Table I. The experiments are performed at a power level of 800W.

TABLE I
SYSTEM PARAMETERS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV panel input voltage ($V_{pv}$)</td>
<td>35 – 40 V</td>
</tr>
<tr>
<td>Transformer turns ratio ($1 : n$)</td>
<td>1:10</td>
</tr>
<tr>
<td>Maximum power rating</td>
<td>3kW</td>
</tr>
<tr>
<td>Nominal grid voltage ($V_g$)</td>
<td>230 Vrms</td>
</tr>
<tr>
<td>Filter inductance ($L_f$)</td>
<td>8.8 mH</td>
</tr>
<tr>
<td>Switching frequency ($f_{sw}$)</td>
<td>20 kHz</td>
</tr>
<tr>
<td>Net leakage inductance w.r.t secondary ($L_{leakage}$)</td>
<td>34 µH</td>
</tr>
</tbody>
</table>

Fig. 6(a) shows the simulated link voltage of the topology without any snubber. It can be seen that the voltage has large spikes of upto 2.5kV. This is highly undesirable. The link voltage with the lossless snubber circuit is shown in Fig. 6(b). It can be observed that the voltage does not have 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 results are validated experimentally as shown in Fig. 7. The input voltage used for this experiment is only 10V. This is because, the peak voltage that can be seen in the link voltage without any snubber, in Fig. 7(a), is 170V. A rated input voltage of about 40V would result in a repetitive peak of 680V which can damage the 600V IGBTs used in the inverter. The result with lossless snubber with proposed modulation is shown in Fig. 7(b). It can be clearly observed that the overvoltage spikes are completely eliminated with the proposed modulation.

The snubber capacitor voltage for the circuit is shown in Fig. 8. The simulation result is shown in Fig. 8(a) and the experimental result is shown in Fig. 8(b). It can be seen that the capacitor voltage has a 100Hz ripple due to the single phase operation. The average capacitor voltage in simulation is 376V and in experiments it is observed to be 364V. The small deviation is mainly due to the circuit non-idealities such as device voltage drops, winding and track resistances.

The simulation and experimental results for the output current are shown in Fig. 9(a) and Fig. 9(b) respectively.

The secondary voltage and the primary currents are shown...
in the simulation and experimental results respectively in Fig. 10(a) and Fig. 10(b). The results are in agreement. The system efficiency is observed to be around 87%. It can be improved further by designing the HF transformer with interleaved windings which reduces the copper losses.

The picture of the hardware prototype built in the laboratory is shown in Fig. 11. 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. 11. The core volume of the HF transformer is 147.97 cm$^3$. However, the core volume is 4222.8 cm$^3$ 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 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 effectiveness of the proposed modulation scheme is verified using simulations and experimental results.

**REFERENCES**


