Simulation of Single Stage Inverter with High Voltage Gain for Distributed Energy Resources Using PSIM

Anu Joseph Padanilam, R. Meenal

Abstract—This paper presents the simulation of high voltage gain single stage inverter for distributed energy resources using PSIM software. In this, a Cuk derived circuit is integrated with Flyback auxiliary circuit to achieve high voltage gain. Here the capacitors of Flyback and Cuk circuits are paralleled for charging and connected in series for discharging. Due to capacitive voltage dividing, DC side switch voltage stress is reduced and losses are also reduced, hence gain can be increased. Simulation results are given to show the merits of the inverter.

Index Terms—Distributed energy resources (DER), Cuk derived voltage source inverter, Flyback auxiliary circuit, high voltage gain, PSIM

I. INTRODUCTION

In today’s world, distributed energy resources have come to light because of the increasing concern about energy demand and environmental aspects like global warming. Distributed energy resources (DER) generate electricity from small energy resources like solar and wind. Distributed generation (DG) allows collection of energy from many sources and may give lower environmental impacts and improved security of supply. DG systems are used to deliver electrical power to utility grid [5] or used as standalone power supplies in remote areas [7]. Solar cells, fuel cells, batteries and ultra capacitors are all low voltage DC source, hence a high voltage DC-AC conversion is essential and many DC/AC converters have been proposed. The resulting efficiency of a two stage or a multistage converter will be degraded because of its complexity and high cost [3]. We can also use a DG unit with shunt active power filter capabilities but the integration of power quality features increases the overall current and cost [2]. Photovoltaic modules are connected into single phase grid connected inverter. But the use of electrolytic capacitors increases reliability which further increases cost [4]. Sepic, cuk or zeta derived DC/AC converters are also proposed. Here the control of AC and DC parts of converter circuit is integrated to achieve ideal characteristic of single stage three phase Sepic AC/DC rectifier. Boost mode is used and maximum output power at reasonable cost is limited [6]. However only very few existing DC/AC converter can achieve high voltage while maintain rather good efficiency [1].

In this paper, a high voltage gain single stage inverter for distributed energy resources has been proposed. Here a cuk derived circuit is integrated with flyback auxiliary circuit to achieve high voltage gain. Capacitors of the flyback and cuk circuit are paralleled for charging and connected in series for discharging. The DC side switch voltage stress is reduced due to capacitive voltage dividing and low voltage rating devices can be used to further reduce both switching and conduction losses to increase conversion efficiency. This inverter achieves high voltage gain and suitable for DER applications.

II. SINGLE STAGE INVERTER

In this Inverter, Cuk derived voltage source inverter is integrated with Flyback auxiliary circuit [1] to achieve high voltage gain. The output capacitor of the flyback circuit is placed in series with the secondary side capacitor of Cuk converter. Also, through this capacitor voltage divider, the voltage stress of DC side switch will be reduced significantly. From fig.1 there is one DC side switch Q and four AC side switches QA, QB, QA and Qb. The capacitors of cuk and flyback circuits are paralleled for charging and connected in series for discharging [7]. Due to capacitor voltage dividing, DC side switch voltage stress is reduced. Vf denote the input voltage, \(L_b\) denote the input boost inductor. \(C_P\) and \(C_S\) represents the Primary and secondary capacitors. \(C_f\) is the energy storing capacitor. Two diodes \(D_s\) and \(D_p\). \(L_o\), \(C_o\) and \(R\) represent the output inductor, output capacitor and resistor respectively. \(L_e\) and \(L_m\) denote leakage inductance and magnetizing inductance respectively. The low influence of coupling coefficient \(\alpha\) of flyback circuit renders inverter design flexible and easy. The cuk converter can step up or step down the output voltage by controlling the duty cycle of the switch.

Manuscript received February 2014.
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Fig. 1 Circuit diagram of Single stage inverter
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\[ \alpha = \frac{L_m}{L_k + L_m} \]  

The inverter boosts its input voltage to DC link voltage by controlling the duty cycle of the DC side switch. The figure 2 below shows the modulation scheme of the inverter.

Fig. 2 Modulation Scheme of the Inverter

III. OPERATING PRINCIPLE OF SINGLE STAGE INVERTER

There are five modes of operation. The five modes are explained briefly.

**Mode I:** Switches QA and QB are turned ON. Q, Qa, Qb are turned OFF. Ds and Df are forward biased. Energy stored in boost inductor Lb and leakage inductance Lk is released to capacitors in primary and secondary sides of transformer Tc. Then input power is delivered to secondary side through Tj to charge Cf. Output power is supplied from output filter.

**Mode II:** Switches Q, QA and QB are turned ON. Switches Qa, and Qb are turned OFF. Ds are Df are reverse biased. Magnetizing inductor Lm and input boost inductor Lb are charge by Vs. At the same time, output power is still supplied from output filter.

**Mode III:** Switches Q, QA and QB are turned ON and Qa and QB are turned OFF. Diodes Ds and Df are reverse biased. Current through Lb and Lm increase to store energy in boost inductor Lb and magnetizing inductor Lm. Capacitors Cf and Cj are connected in series to give DC- link voltage \( V_{bus} = V_{Cf} + V_{Cj} + N_c V_{cp} \) to deliver energy through switches QA and QB to externally connected AC load.

**Mode IV:** Switches Q, QA and QB are turned ON and QA and QB are turned OFF. Ds and Df are reversed biased. Input boost inductor Lb and magnetizing inductor Lm are charged by Vs. Mean while AC side of the inverter enters into freewheeling operation mode and output power is supplied from output filter.

**Mode V:** Switches Qa and Qb are turned ON and Q, QA and QB are turned OFF. Ds and Df are forward biased. Energy stored in boost inductor Lb and leakage inductance Lk is released to capacitors Cf and Cj. At the same time, input power is delivered to secondary side through Tj to charge Cj and the AC side of the inverter remains in freewheeling mode and output power is still supplied from output filter.

The key waveforms of the single stage inverter are shown in Fig. 3.

IV. DESIGN EQUATIONS

\( T_s \) is the switching period of DC side switch Q, \( k \) is the duty ratio of Q and \( m(t) \) is the modulation index of the AC side inverter. The turn ON period of switch is \( kT_s \) and the corresponding turn OFF period of Q is \( (1-k)T_s \). Based on the previously mentioned operating modes, the voltage conversion ratio of the inverter can be calculated according to voltage second balance principle of inductors. The voltage second balance equation for inductor Lb becomes:

\[
(V_S - V_C) - V_C (k-M) + V_0M = 0
\]

From (3) and (4), voltage across capacitors \( C_f \) and \( C_j \) of the inverter can be obtained.

\[ V_C = V_S \]  
\[ V_{Cf} = \frac{k}{1-k} N_c V_S \]  
\[ V_{Cj} = \frac{\alpha k}{1-k} N_f V_S \]  

Voltage conversion ratio or Gain \( G_v \) of the inverter is

\[ G_v = \frac{V_o}{V_i} = \left( \frac{1}{1-k} N_c + \frac{\alpha k}{1-k} N_f \right) M \]
V. SIMULATION OF SINGLE STAGE INVERTER

The Single stage Inverter is simulated using PSIM software. We can use PSIM software version 9. Simulation results are shown to understand the merits of the inverter. Given below is the Table I of the circuit design parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Part No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage Vs</td>
<td>24V</td>
</tr>
<tr>
<td>Input Boost inductor Lb</td>
<td>300µH</td>
</tr>
</tbody>
</table>
| Transformer (Tc & Tf)       | 1. Transformer Tc
  Turns ratio= 1:Nc, where Nc = 1.23
  Leakage inductance Lk = 1.2Mh
  Magnetizing inductance, Lm = 800µH
  2. Transformer Tf
  Turns ratio= 1:Nf, where Nf = 1.72
  Leakage inductance Lk = 1.2µH
  Magnetizing inductance Lm = 500µH |
| Capacitors                  | C0 = 2.2µF     |
| Output inductor L0          | 1mH            |
| Diodes Ds and Df            | 15S2TH06FP     |
| DC side switch Q            | IXHQ30N60P     |
| AC side switches QA,QB,Qa & Qb | IXFH120N20P   |
| Switching frequency         | 20kHz          |
| Duty cycle, k               | 0.8            |
| Modulation index, M         | 0.75           |

We have to design a control circuit for DC side and AC side switches. The input to the DC switch Q is a triangular waveform which is shown in fig.2 as the modulation scheme of the inverter. Fig. 6 shows the simulated circuit using PSIM software.

![Fig. 6 Simulated diagram of single stage inverter PSIM](image)

It can be seen that for an input voltage $V_s = 24V$, the 230V peak AC output voltage can be achieved with a duty cycle of 0.8 of the DC side switch and modulation index of 0.75. The maximum value of line voltage $V_{AB}$ is about 314V. The DC side circuit can be seen as a boost function for boosting the low input voltage and the AC side circuit is used to invert a DC voltage to an AC output. We can control the voltage gain by changing the values of duty cycle $k$ of the DC side switch and modulation index $M$ of the AC side switches.

Simulation results

![Fig. 7 Waveforms of input voltage $V_s$ and modulation scheme](image)
By understanding the modes of operation of the inverter, we can analyze the same in fig.10 and fig.11 waveforms. Voltages across the capacitor $C_P$ are charged to 24V and voltages across the capacitor $C_S$ are charged to 119.1V and that of $C_f$ is charged to ~164.28V. Note that the voltage spikes in $V_{dsQ}$, $V_D S$ and $V_D f$ in fig.8, fig.10 and fig.11 is due to leakage inductance of the power transformer $T_f$. An output voltage of 230V is obtained with an output current of 1.92A and line voltage $V_{AB}$ about 314V. Both the capacitors $C_P$ and $C_S$ share most of the output voltage for reducing the voltage stress of the dc side active switches. Voltage stress by the bus voltage of the proposed inverter is given by

$$\frac{1}{N_c + \alpha k N_f} = 0.38V \quad (11)$$

The voltage stress by the bus voltage of conventional circuit is given by

$$\frac{1}{N_c} = 0.81V \quad (12)$$

From (11) and (12), we can see that the voltage stress is reduced in case of proposed inverter compared to that of conventional circuit. So when the voltage stress is reduced, losses are also reduced and hence efficiency of the inverter will be high and gain will be high. Increasing the values of $k$ and $M$, the output voltage will increase and we can get an ac output above 230V. The AC output that we obtain can be connected to a grid. Gain of the inverter is calculated to be 9.7, which is more compared to that of conventional circuit with a gain of 3.75. Table II shows the voltage gain for the single stage inverter and a conventional circuit.

<table>
<thead>
<tr>
<th>TABLE II. VOLTAGE GAIN OF DIFFERENT INVERTERS</th>
</tr>
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<tbody>
<tr>
<td><strong>Circuits</strong></td>
</tr>
<tr>
<td>High voltage gain single stage inverter</td>
</tr>
<tr>
<td>Voltage Gain</td>
</tr>
<tr>
<td>$\frac{1}{N_c + \alpha k N_f} M (1 - k)$</td>
</tr>
<tr>
<td>Conventional Cuk derived single phase inverter</td>
</tr>
<tr>
<td>$\frac{M}{1 - k}$</td>
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VI. CONCLUSIONS

A High voltage gain single stage inverter is designed for Distributed Energy Resources (DER) applications and simulated using PSIM software. Due to capacitive voltage dividing, DC side switch voltage is reduced. In other words efficiency will be high. For an input voltage of 24V, 230V output voltage is obtained and voltage stress is about 0.38V. Gain of the inverter is higher compared to the conventional circuit. Operating principle, design equations and simulation results are given to show the merits of the single stage inverter.

REFERENCES


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