

## **Grid Connected Photovoltaic System with Single stage Buck-Boost Inverter**

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**Abstract:** For very high voltage gain of a Photo-Voltaic system, this paper proposed a buck-boost inverter of single stage. DCM (Discontinuous conduction mode) and MPPT (maximum power point tracking) is employed to get one power factor. Minimization of switching losses is employed with only two switches and operated at very high frequency. Easy control capability, optimum size, affordable cost with high voltage gain made the system employable. AC voltage conversion is achieved along with boosting of DC voltage of Photo-Voltaic system of inverter. Obstacle shadow variations also reduced by means of having the possibility of reduced series connected modules; this ability is due to the high voltage gain. Since the proposed design has the two buck boost converter each one operates for only one half cycle and the Discontinuous conduction mode operates at unit power factor. Simulation results assure the proposed idea of the single stage interleaved inverter for high voltage gain applications.

**Index Terms:** Single Stage, Buck-Boost Inverter, Low-Cost, Grid-Connected, PV system, Simple-Control, DCM, MPPT.

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### **I. INTRODUCTION**

This Reference [1] gives clear idea about the difference between single stage and two stage inverters and the advantages of single stage inverter over two stage inverter. This paper also put forward different single stage inverter topologies and detailed comparison with this topology is presented. A complete steady-state analysis, including the design procedure and expressions for peak device stresses, is included. Necessary condition on the modulation index “M” for sinusoidal pulse width modulated control of this inverter topology has also been derived for discontinuous conduction mode operation. All the analytical, simulation and experimental results are presented.

Reference [2] gives idea about switching structures. These structures when used with buck, boost or buck –boost systems the gain of the systems is increased/ decreased. The main advantage of the switched structure converters is their lower energy in the magnetic elements, what leads to weight, size and cost saving for the inductors, and thus for the power supply, and less conduction losses, what leads to a better efficiency.

New single-stage grid-connected inverter, suitable for distributed generation applications, is proposed. The inverter is universal in the sense that it can be switched between buck, boost, and buck–boost configurations by appropriately altering the pulse width modular (PWM) control. Discontinuous current mode (DCM) operation is implemented to facilitate shuffling between configurations during the converter operation. Such flexibility ensures maximum benefit of the buck, boost, and the buck–boost operations (e.g., low device stresses, higher efficiency, higher boosting capability, etc.).

### **II. SWITCHED INDUCTOR BUCK-BOOST CONVERTER**

A true inverter takes power from a fixed dc source and applies it to an ac load such as a utility grid, an ac motor, a loudspeaker or a conventional product normally powered from an ac line. It is useful to distinguish two types of ac loads, active and passive. The utility grid is the most familiar active ac load. The utility waveform is controlled very precisely at a central location.

A converter connected to the grid cannot alter the timing of the sinusoid. Hence, phase delay control is used as the adjustment tool. Real ac loads often include magnetic transformers, which only function with ac signals. If dc voltage is imposed on a transformer, it can cause the flux to increase until the device no longer functions. This is the key consideration in inverters: Any dc component is unwanted and in fact can cause considerable trouble. A practical inverter circuits should not produce any dc output component.

Inverter applications usually use some type of transistor with reverse-parallel diode to give it bi-

directional current capability. Today, the power MOSFET is used up to 1-10kW, while IGBTs are used at power levels up to 100kW. For even higher levels, GTOs with reverse-parallel diodes can be substituted. Therefore, MOSFET is used to design 2kW DC to AC inverter.

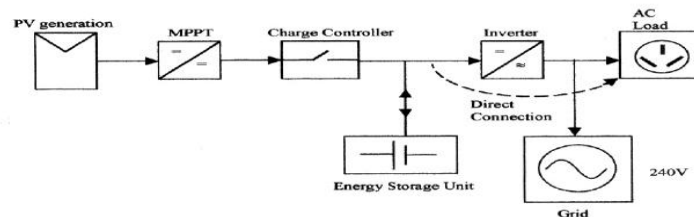


Fig 1: Grid-connected photovoltaic circuit diagram.

Traditional boost converter could operate according to the adjusted duty cycle. To increase the gain of the converter, its inductor has replaced by the switched inductor with this replacement the gain of the converter is improved.

The basic building blocks of a boost converter circuit are shown below

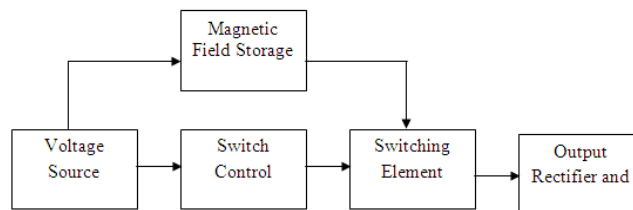


Figure 2: Basic building blocks of a boost converter

### III. PROPOSED SINGLE STAGE DC-AC INVERTER

The single stage boost inverter system consists of two buck boost converters. Each of these converters operates in DCM for one half cycle of the fundamental grid voltage. The resulting circuit acts as a current source inverter which feeds sinusoidal current into a low value capacitor across the grid. DCM operation helps in feeding sinusoidal current with near unity power factor (UPF) into the grid because the energy can be drawn in the form of “energy packets,” whose magnitudes vary in a sinusoidal manner.

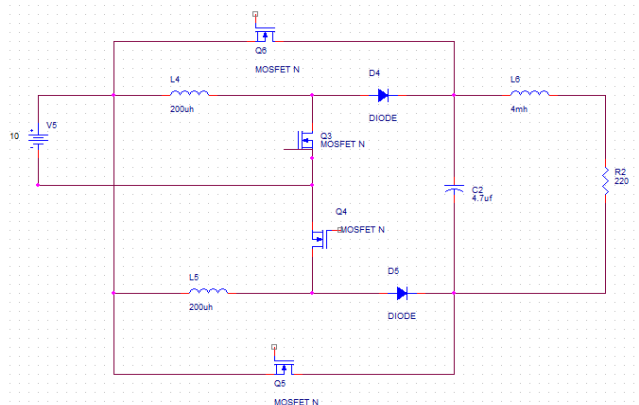


Figure 3: single stage boost inverter circuit.

Operation of the inverter is as follow, Switches SW1 and SW4 operate at switching frequency equal to grid fundamental frequency, each one operate for one half cycle. SW4 operates in the positive half cycle while SW1 operates in the negative half cycle. Switches SW2 and SW3 operate at high switching frequency.

To provide a high quality sine wave current and reduce the size of output filter each converter operates for only one half cycle. SW2 operates in the positive half cycle while SW3 operates in the negative half cycle.

During the positive half cycle the inverter has three modes of operation: Mode1: when switch SW3 is ON

Mode2: when diode D4 is ON Mode3: when both SW3 and D4 are OFF

The operation of converter must be in DCM mode to produce high quality sine wave. The single stage boost inverter has only four switches so that it has lower cost and lower switching losses as compared to two stage inverter.

Working of the single stage boost inverter:

The resulting circuit acts as a current source inverter which feeds sinusoidal current into a low value capacitor across the load. The power device SW2 and SW3 are switched at high frequency while SW1 and SW2 are kept continuously ON during the positive half cycle (or negative half cycle). SW2 and SW3 are switched as per sine triangle pulse width modulation (SPWM) method. When SW2 is ON, energy is stored in the boost inductor L<sub>1</sub> by the DC source. When SW2 is OFF, D1 gets forward biased, discharging the stored inductor energy into capacitor C<sub>f</sub> which feeds sinusoidal current into the load.

Condition for DCM operation:

The single stage boost inverter topology operates in DCM throughout the grid cycle if it sustains DCM operation during the peak interval. Applying the condition for Critical Conduction Mode or DCM during peak interval yields the critical value of the modulation index as below.

$$M = 1 / (1 + V_{in}/V_p) \text{ ----- (1)}$$

Where M: Modulation index. V<sub>in</sub>: Input voltage.

V<sub>p</sub>: Peak value of output sine voltage

Design of inductor L and capacitor C:

The buck-boost inductor, 'L' acts as an energy storage element, which stores energy from the PV source and transfers it to the load through capacitor. The maximum energy is transferred during the peak interval when PV is delivering rated power "P" W. If "Critical Conduction Mode" or DCM operation is ensured during this interval, DCM operation is guaranteed throughout the full sine wave cycle and for all environmental conditions. Thus, design of L is critical for proper operation of the converter. If the system can deliver a maximum dc power of "P" W, inductor should have a power handling capacity of "2P" W. This will ensure transfer of average power "P" W, into the load.

As the single stage boost inverter configuration operates in DCM, it transfers energy in the form of packets during each switching interval to feed high quality sinusoidal power into the load. Also, during each switching interval, the energy stored in the inductor is completely transferred to capacitor 'C' connected across the load. The design equation for inductor is as given below

$$L \leq \frac{V_{in}^2 * M^2 * T_s}{4 * P}$$

P: power that can be delivered by source.

T<sub>s</sub>: Switching period.

The design value is chosen in such a way that the maximum value of 'M' satisfies the above two conditions when the source is delivering rated power. This condition helps in ensuring DCM operation of the inverter configuration at any operating point under all environmental conditions. The design value of capacitor is as given below.

$$C = \frac{L * I_{pk-L}^2}{4 * V_{in} * \Delta V}$$

Where V: Ripple in voltage

I<sub>pk-L</sub>: Peak value of inductor current

Design of L<sub>f</sub>:

L<sub>f</sub> is the filter inductor which filters the high switching frequency component present in the current waveform fed into the load. For design, it requires the cut off frequency f<sub>c</sub> to be lesser than the switching frequency f<sub>s</sub>. Thus, the design value of L<sub>f</sub> is given by

$$L_f = \frac{1}{(2\pi f_c)^2 * C}$$

Where  $f_c$ : Cutoff frequency less than switching frequency.

#### IV. COMPONENT CALCULATIONS

In order for the circuit to function properly, the external components need to be calculated carefully. When the switch is on, the voltage across the inductor and the current is given by

$$V_L = L \frac{di}{dt} = L \frac{I_{Lpk}}{t_{on}} \quad I_{Lon} = \left[ \frac{V_{in} - V_{sat}}{L} \right] t_{on}$$

When the switch is off, the voltage across the inductor and the current is given by

$$V_L = L \frac{di}{dt} = L \left[ \frac{I_{Lmin} - I_{Lpk}}{t_{off}} \right] I_{Loff} = I_{Lpk} - \left[ \frac{V_{out} + V_F - V_{in}}{L} \right] t_{off}$$

$V_F$  is the forward voltage drop of the output rectifier and  $V_{sat}$  is the saturation voltage of the output switch. Since  $I_{Lon} = I_{Loff}$ , can be set equal to each other.

This operation gives a ratio for the on time over the off time. This ratio is given by

$$\frac{t_{on}}{t_{off}} = \frac{V_{out} + V_F - V_{in(min)}}{V_{in(min)} - V_{sat}}$$

The values of  $V_{in(min)}$ ,  $V_F$ ,  $V_{out}$ , and  $V_{sat}$  are 4.5 V, 0.8 V, 12V, and 0.3 V respectively.

The inverse of the frequency of operation yields the on time plus the off time.

The frequency of operation for this boost converter was chosen to be 62.5 kHz. Therefore,

$$t_{on} + t_{off} = \frac{1}{f} = 16 \mu s$$

$t_{on}$  and  $t_{off}$  Equations yield an on time of 9.834 $\mu$ s and an off time of 6.166 $\mu$ s. The duty cycle is given by

$$D = \frac{t_{on}}{t_{on} + t_{off}}$$

The calculated duty cycle of this circuit is 61.5%. The value of the external timing capacitor is calculated using

$$C_T = [4.0 * 10^{(-5)}] * t_{on}$$

The value of the timing capacitor is 390 pF. The peak current through the switch is given and the minimum required inductance is given by

$$I_{pkswitch} = 2 * I_{out} \left[ \frac{t_{on}}{t_{off}} + 1 \right] L_{min} = \left[ \frac{V_{in(min)} - V_{sat}}{I_{pkswitch}} \right]$$

The calculated value of the minimum inductance is 80  $\mu$ H. The resistance required for the current sense resistor is given by and the calculated value for the current sense resistor is 0.5  $\Omega$ . The value of the output capacitor is given by

$$R_{sc} = \frac{0.3}{I_{pkswitch}} \quad C_{out} = \frac{I_{out}}{V_{ripple}} t_{on}$$

Using a 0.6 V for  $V_{ripple}$ ,  $C_{out}$  is equal to 1.68  $\mu$ F. The values of the resistors used to control the duty cycle are given by

$$V_{out} = (1.25) \left[ 1 + \frac{R_2}{R_1} \right]$$

$R_1$  and  $R_2$  were chosen to be 2.4 k $\Omega$  and 20.64 k $\Omega$ , respectively.

## V. SIMULATION RESULT

Normal Basic boost converter:

The below diagram shows the Simulink model of the basic boost converter. The simulation parameters are as below.

$$V_i=100V,$$

$$L=40mH,$$

$$C=50\mu F \text{ Duty}=50\%$$

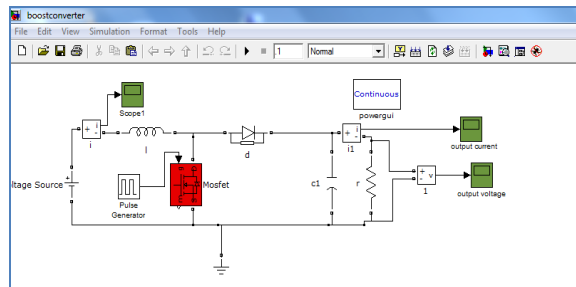


Figure 4: Normal boost converter simulink model

The output of this boost converter for the input voltage of 100V is as shown below. Some transient state is there in the output but after some time the output is stabilized to 200V that is the converter boosted the input 100V to 200V.

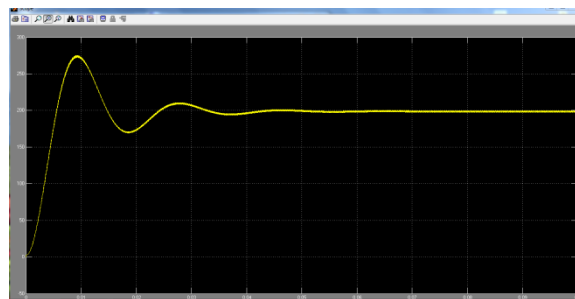


Figure 5: Basic boost converter output

Basic Switched inductor boost converter:

The below diagram shows the switched inductor boost converter Simulink diagram. In this converter the single inductor is divided into two parts and connected as shown in diagram. The same Simulink parameters are used for this converter also.

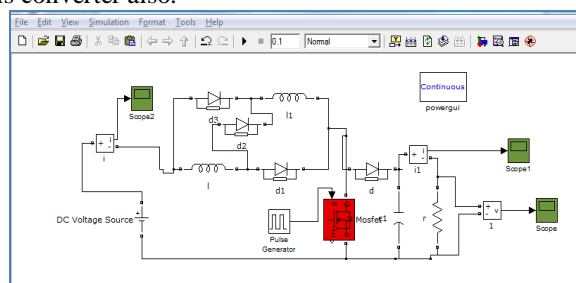


Figure 6: Switched inductor boost converter simulink model

The output of this switched inductor boost converter for the input voltage of 100V is as shown below.

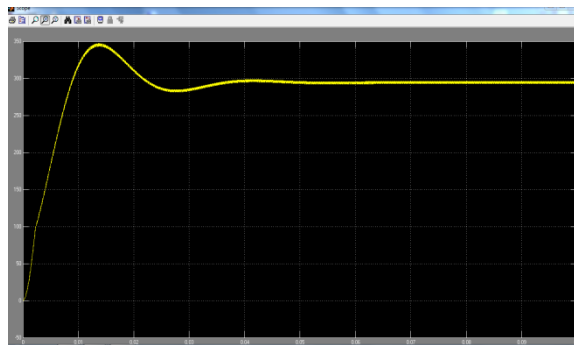


Figure 7: Switched inductor boost converter output

The above results show that the addition of switched inductor structures will increase the output voltage comparatively.

Comparison between Normal and switched boost inverter: Some transient state is there in the output but after some time the output is stabilized to 282V that is the converter boosted the input 100V to 282V. That means the output of this converter gains 82V i.e. the output is increased by 2 times

## VI. EXPERIMENTAL RESULT

The simulink diagram of single stage boost inverter is as shown below:

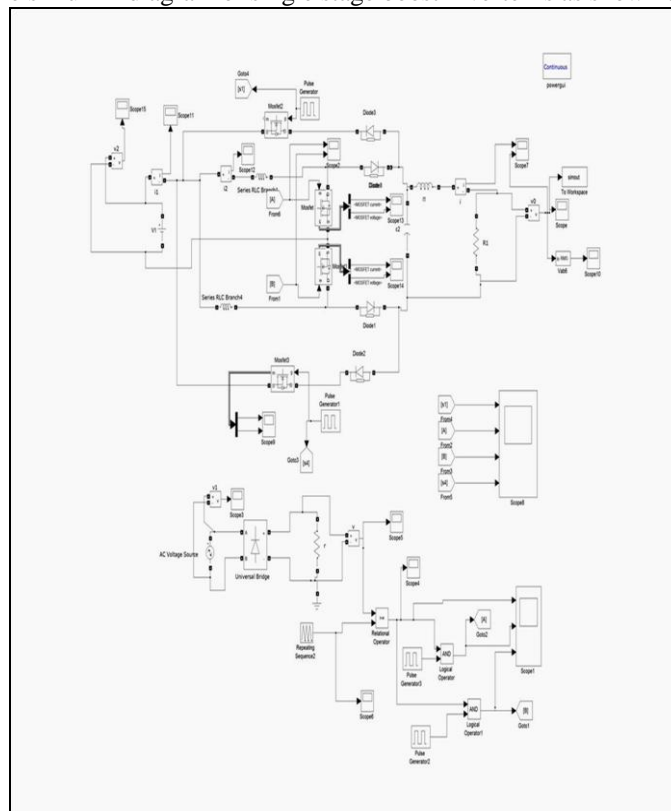


Figure 8: Simulink model of the single stage boost inverter circuit

Gate pulses:

The below figure shows the pulses produced for the four power MOSFETs. Out of these four pulses two pulses are of 50Hz signals and so the switching losses of the corresponding switches are very less can be neglected.

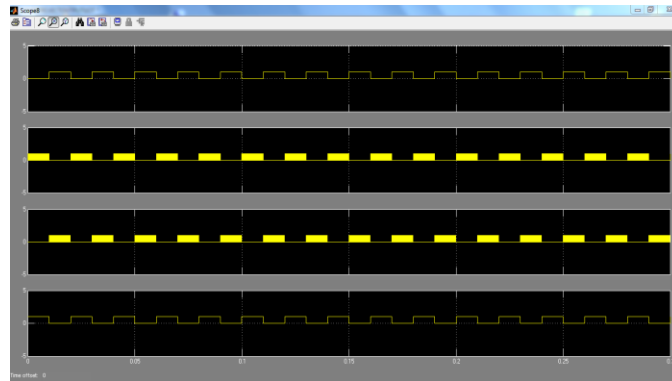


Figure 9: Gate pulses for POWER MOSFETs

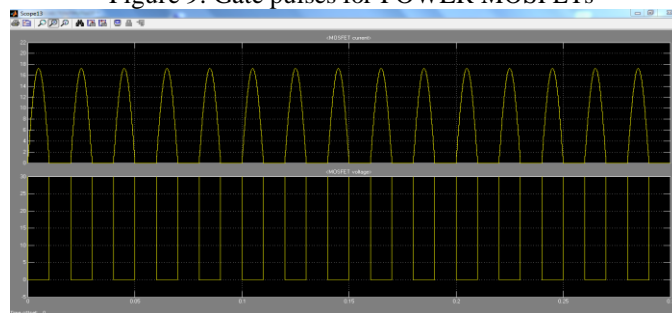


Figure 10: MOSFET's current and voltage:

Output waveform of single stage boost inverter with normal inductor:  
Output waveform of single stage boost inverter with normal inductor is as shown below. For an input voltage of 90V the output RMS sine wave voltage is 230V.

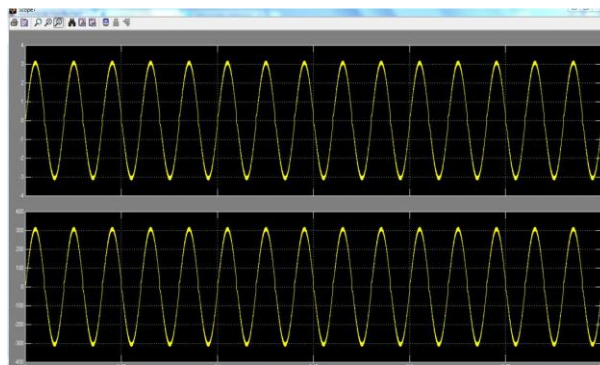


Figure 11: Output voltage waveform of single stage boost inverter with normal inductor for 90V input. The harmonic analysis of the sinusoidal waveform generated from the single stage inverter is as shown below.

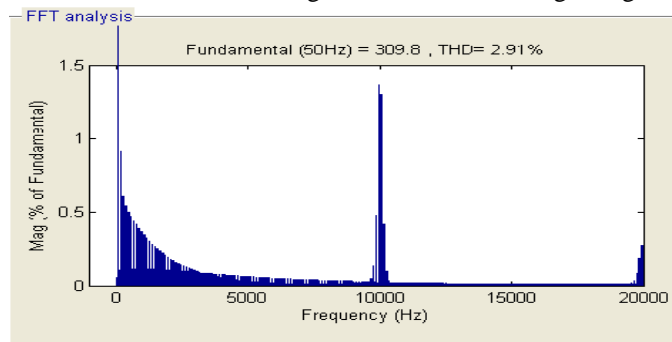


Figure 12: FFT of output sinusoidal waveform.

It clearly shows that the THD of the generated voltage is 2.91% that is less than 5%.  
 The simulink diagram of single stage boost inverter with switches inductor is as shown below:

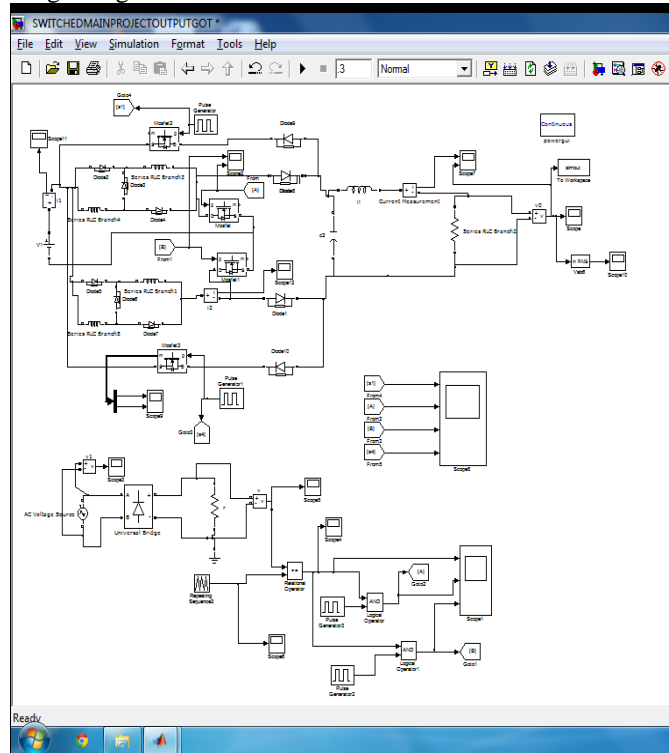


Figure 13 single stage boost inverter with switches inductor

Output waveform of single stage boost inverter with switched inductor structure:

The Output waveform of single stage boost inverter with switched inductor structure is as shown below. For an input voltage of 45V the output RMS sine wave voltage is 230V.

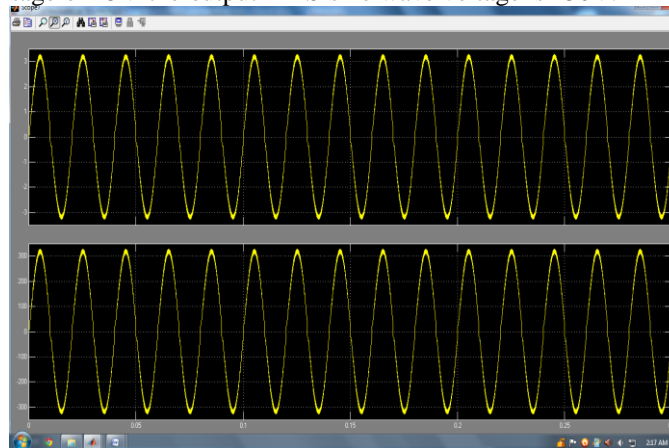


Figure 14: Output voltage waveform of single stage boost inverter with switched inductor for 45V input.

The harmonic analysis of the sinusoidal waveform generated from the single stage inverter with switched inductor structure is as shown below.



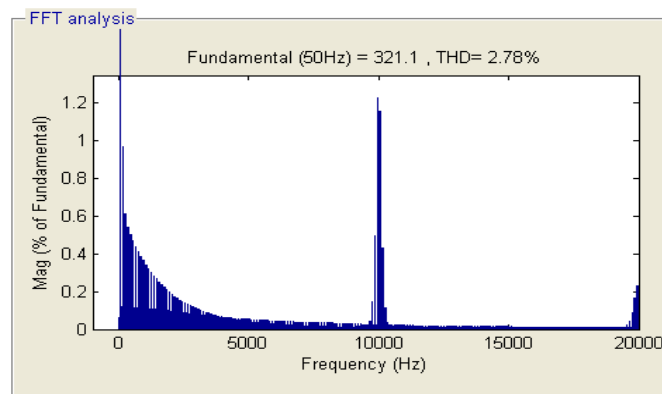


Figure 15: FFT of output sinusoidal waveform.

It clearly shows that the THD of the generated voltage is 2.78% that is less than 5%.

From both the outputs it is clear that the single stage boost inverter not only boosts the output but inverts the DC input to AC in a single stage with less number of switches and low losses. Also the addition of the switched inductor structure decreases the need of less input voltage for the production of same inverted output AC voltage.

## VII. CONCLUSION

The single stage boost inverter has been studied, designed and implemented in MATLAB/SIMULINK. The topology is simple, symmetrical and easy to control. The other desirable features include good efficiency due to optimal number of device switching's and reduced switching losses. The functionality and switching operation of single stage boost inverter in open loop have been depicted with simulation and experimental results for resistive load. These results assure the idea of the single stage interleaved inverter for high voltage gain applications.

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