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One Cycle Controlled Single–Stage Transformerless Buck-Boost Inverter

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***Abstract:** The rate of utilization of renewable energy sources is increasing nowadays. Since renewable energy source depends on environmental conditions, its output will vary according to the variations of weather condition. In order to get a steady output at the load side, an inverter is required that shows the property of bucking and boosting the input voltage by eliminating the input disturbances. This paper proposes one cycle controlled buck-boost inverter. It has the ability to buck and boost the input voltage by rejecting its disturbances. The detailed Matlab/Simulink model has been used to verify the performance of the system. Three test conditions are used to substantiate the performance of the proposed inverter such as the ability to buck and boost the input voltage, rejects the disturbances in the input side. Test results validate that the proposed inverter used for the applications where input varies.*

***Keywords:** Buck-Boost Inverter, One cycle control, Single Stage, Steady output.*

I. INTRODUCTION

The most commonly used power converter topology for converting DC to AC is conventional Voltage Source Inverter (VSI) [1]. In VSI the instantaneous average output voltage is always less than the input DC voltage [2]. In order to solve the above-mentioned demerit, there are two solutions used. One is the use of line frequency step-up transformer, but this solution will increase the size, weight, and losses. Another solution is to use the boost converter before VSI. Since both converter and inverter operate at high-frequency, the switching losses will be high and hence the efficiency of the system will be less. Additionally, a capacitor used as the dc link in VSI has less lifetime. Consequently, it diminishes the system acceptability [3], [4]. An alternative to the VSI is Current Source Inverter (CSI). It shows boosting characteristics that is, the instantaneous output voltage will be always greater than the input DC voltage [5]. The main demerit of CSI is the use of dc-link high-value inductor to receive the constant current from the input supply [6]. In the case of high input voltage, the CSI uses the buck converter before it. This causes similar disadvantages to VSI. Furthermore, the advantages of both VSI and CSI can be obtained by using the Z-source inverter (ZSI). The ZSI has only one conversion stage because it shows buck-boost property.

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When the input voltage is less than the required output voltage it will adjust the duty ratio and operates in buck mode and vice versa [7]. But it requires two inductors in its power loop that will increase the complexity of the controller by increasing the order of the system [8], [9]. So, in order to overcome these weaknesses, the differentially connected buck-boost inverter was proposed in [10]. The two converters are connected differently, both will operate at 180^0 apart, so this constraint makes the design of the controller complex. Another two-leg buck-boost inverter in [11] overcomes the control complexity but the switching losses are high because the number of high-frequency switches is more. The buck-boost inverter proposed in [12] provides less switching losses but two inductors were used in each half-cycle to increase the gain. But, this shows high control complexity. In [2] author presented a novel buck-boost inverter with four switches and two diodes among them only two switches operate in high switching frequency and the power loop consists of only one inductor. But one of the drawbacks of that inverter is that the diode becomes forward bias at an undesirable time, so inverter fails to give the expected result.

In order to overcome the above-mentioned drawbacks, we proposed a modified buck-boost inverter that gives high gain. In addition to that only one switch is switched at a high frequency so that the efficiency of the system can be improved. Moreover, only one inductor is participating in the power loop so that it is a second-order system, so the control of the inverter will be comparatively easier. The proposed inverter is shown in Fig. 1. The principle of operation of the inverter is discussed in section II. Section III discusses one cycle control technique of the proposed inverter. The results are discussed in detail in section IV. The final conclusion is provided in section V.

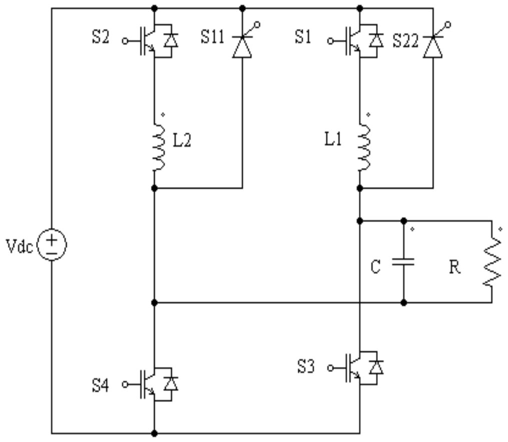

Fig. 1 The proposed buck-boost inverter

II. PRINCIPLE OF OPERATION

The proposed inverter consists of four active switches, among them, two switches operate at high frequency and the other two in line frequency. The switching at each half cycle of the inverter consists of three modes of operation. These modes depend on the charging, discharging and null stages of the inductor and are explained as follows.

A. Mode 1 (tn0 ≤ t ≤ tn1)

In mode1 switches, S1 and S3 will be ON as shown in Fig.2. This is the energy storage mode from tn0 to tn1. The inductor L1 is directly connected to the input voltage source for charging. At the same time, the charge stored in the capacitor will be discharged to the load. So, the current through the inductor will increase and the voltage across the capacitor will decreases as shown in fig.5. From Fig. 2 the change in current through the inductor and voltage across the capacitor can be written as follows:

$$i_{L1}(tn1) - i_{L1}(tn0) = \frac{V_{dc}}{L_1}(tn1 - tn0)$$

(1)

$$V_c(tn1) - V_c(tn0) = \frac{i_o}{C}(tn1 - tn0)$$

(2)

Here $i_{L1}(tn1)$ is the current through inductor at the end of mode 1, $i_{L1}(tn0)$ is the current through inductor at the initial stage of the mode1, V_{dc} is the dc input voltage, $V_c(tn0)$ is the voltage across the capacitor at the starting of the mode 1, $V_c(tn0)$ is the voltage across the capacitor at the final stage of mode 1 and i_o is the output current.

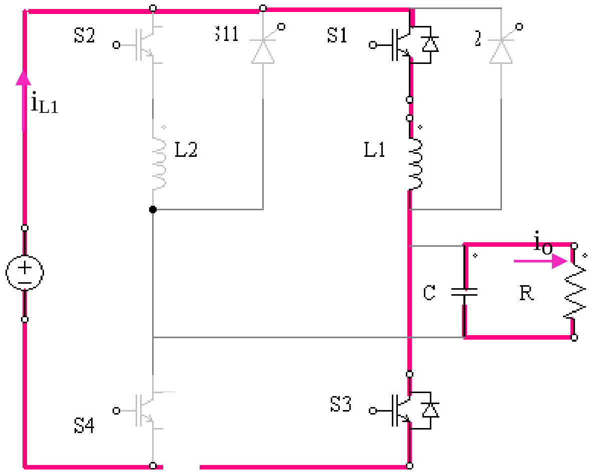

Fig. 2 Mode 1 operation.

B. Mode 2 (tn1 ≤ t ≤ tn2)

Mode 2 starts when the switch S3 is switched off as shown in Fig. 3. At that point in time inductor voltage reverses and thyristor becomes forward bias. So, the switch S11 is switched on and the energy stored in the inductor is discharged to the load side during tn1 to tn2. Thus, the inductor current will reduce and the capacitor voltage will increase as shown in Fig.5. From Fig. 3 the change in current through the inductor and voltage across the capacitor can be written as follows.

$$i_{L1}(tn2) - i_{L1}(tn1) = \frac{V_o}{L_1}(tn2 - tn1)$$

(3)

$$V_c(tn2) - V_c(tn1) = \frac{i_{L1} - i_o}{C}(tn2 - tn1)$$

(4)

Here $i_{L1}(tn2)$ is the current through the inductor L1 at the end of mode 2, $V_c(tn2)$ is the voltage across capacitor C at the time tn2 and V_o is the output voltage.

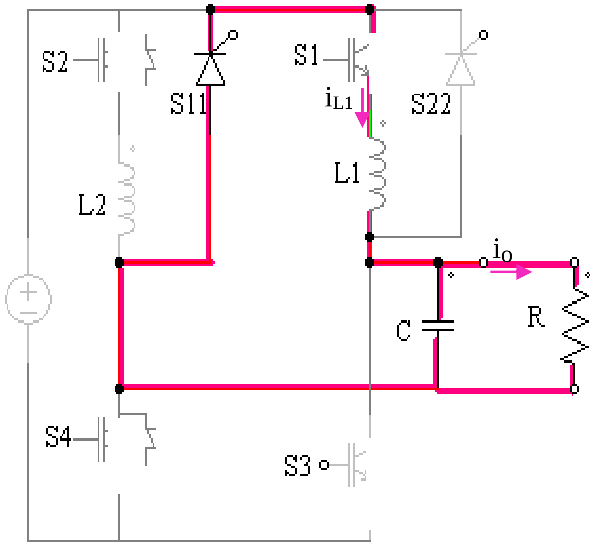

Fig. 3 Mode 2 operation.

C. Mode 3 (tn2 ≤ t ≤ tn3)

Since this inverter operates in the discontinuous mode the energy stored in the inductor will become null at tn2 and thyristor S11 will become OFF as shown in Fig.4. So, from tn2 to tn3 energy stored in the capacitor is discharged through the load resistor as shown in Fig.5. From Fig. 4 the change in current through the inductor and voltage across the capacitor can be written as (5) and (6) respectively. Since charge stored in an inductor (L1) is a null change in current in the inductor is zero.

$$i_{L1}(tn3) - i_{L1}(tn2) = 0$$

(5)

$$V_c(tn3) - V_c(tn2) = \frac{i_o}{C}(tn3 - tn2)$$

(6)

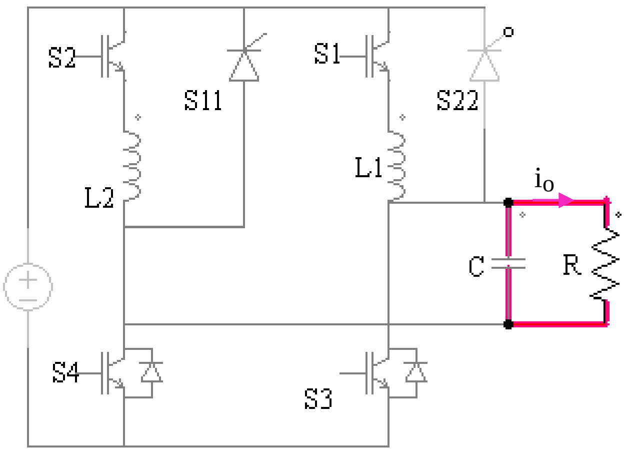

Fig. 4 Mode 3 operation.

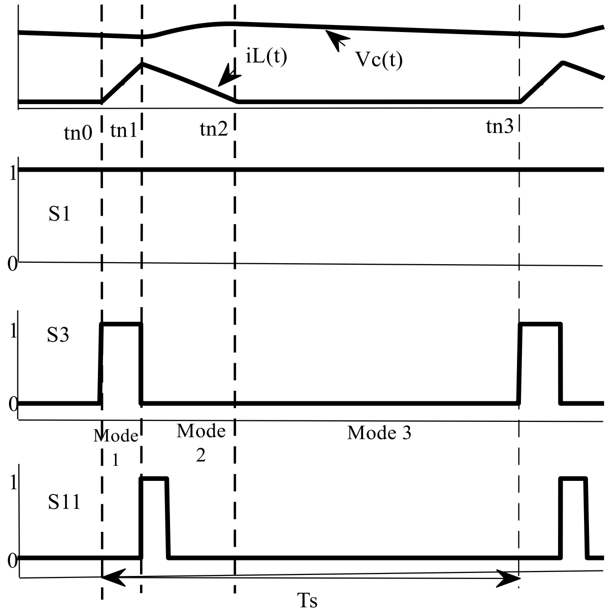

Fig. 5 The formation of pulses, inductor current, and capacitor voltage during tn0 to tn3.

III. ONE CYCLE CONTROL TECHNIQUE

The proposed inverter is pulsed and nonlinear. Traditionally, the linearizing technique is used to linearize the state variable equations and apply linear feedback [13], [14]. But this technique reduces the ability of the inverter for fast response at varying input and load conditions. Accordingly, the output of the inverter requires a high settling time, once the input or load has been varied. This defect limits the use of single-stage inverters in different applications particularly in grid-connected solar PV [15]. Owing to that, this paper, used nonlinear control technique called One Cycle Control (OCC). The main attraction of this control is that the nonlinear system is controlled by nonlinear control technique [16], [17]. So, this system will show fast response and eliminate the input disturbances. Meanwhile, the switching frequency of the buck-boost inverter is high thus, while considering the switching time period input and output are constant.

The one-cycle control is a simple controller consist of a RS flip-flop, integrator, comparator as shown in Fig.6. The operation of the OCC is such that, the constant frequency clock pulses set the RS flip-flop at every switching period. The integrator circuit integrates the input voltage that generates linearly rising waveform as shown in Fig.7. The integrator output is compared with the rectified reference signal. Once the integrated input voltage touches the reference voltage instantly the flip-flop is reset and it will reset the integrator to zero, thus a sawtooth waveform is generated from integrator as shown in Fig. 7 [18], [19].

The duty ratio of the switches depends on the reference voltage and input voltage. Since the input voltage is integrated, the slope of the integrator is directly depending on the input voltage. If the input voltage is higher, the rate of change of integrator output will be high so that, the slope of the integrator will be steeper, and at the same time it reaches the reference voltage quickly. Because of that, the duty ratio will be less. Similarly, for low input voltage duty ratio will be high [14]. The duty ratio varies depending on the input voltage and the reference voltage. The condition of one cycle controller is that the average input voltage should be the same as the reference voltage as given in (7) [20].

$$\frac{1}{T_s}\int_0^{dT_s} V_{dc}\, dt = V_{ref}$$
(7)

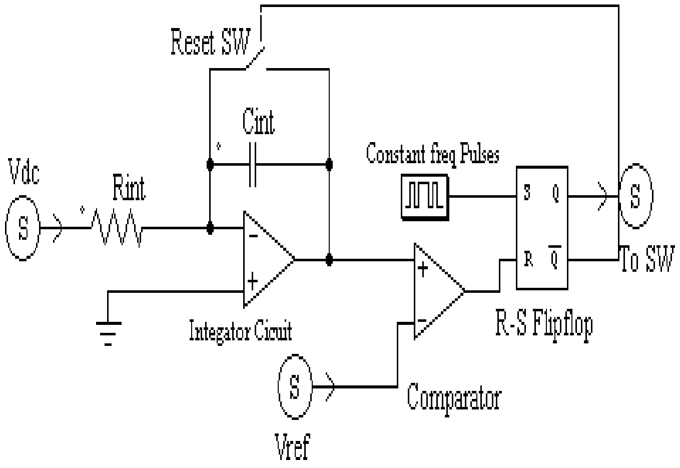

Fig. 6 One cycle control Circuit

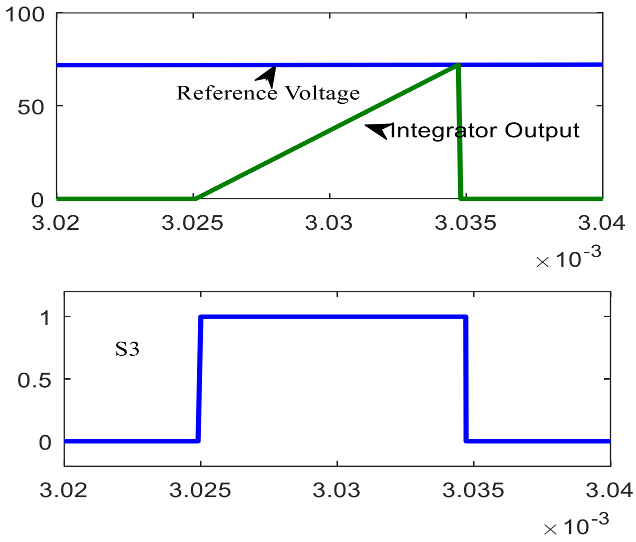

Fig. 7 operation of One cycle control technique

IV. SIMULATION RESULTS AND DISCUSSION

In order to authenticate the performance of the inverter topology and control technique, the system is implemented in Matlab/Simulink. The Simulink diagram is shown in Fig.8. The one-cycle control generates switching pulses according to the input and the reference voltage for the switches. The other elements that were designed for the simulation are given in Table 1. Further, to validate the performance of the inverter and control technique it is verified at three different test conditions. The first test is steady-state operation at a particular dc input voltage and constant load. In second test input voltage is varied by steps. In the third test, the load is varied.

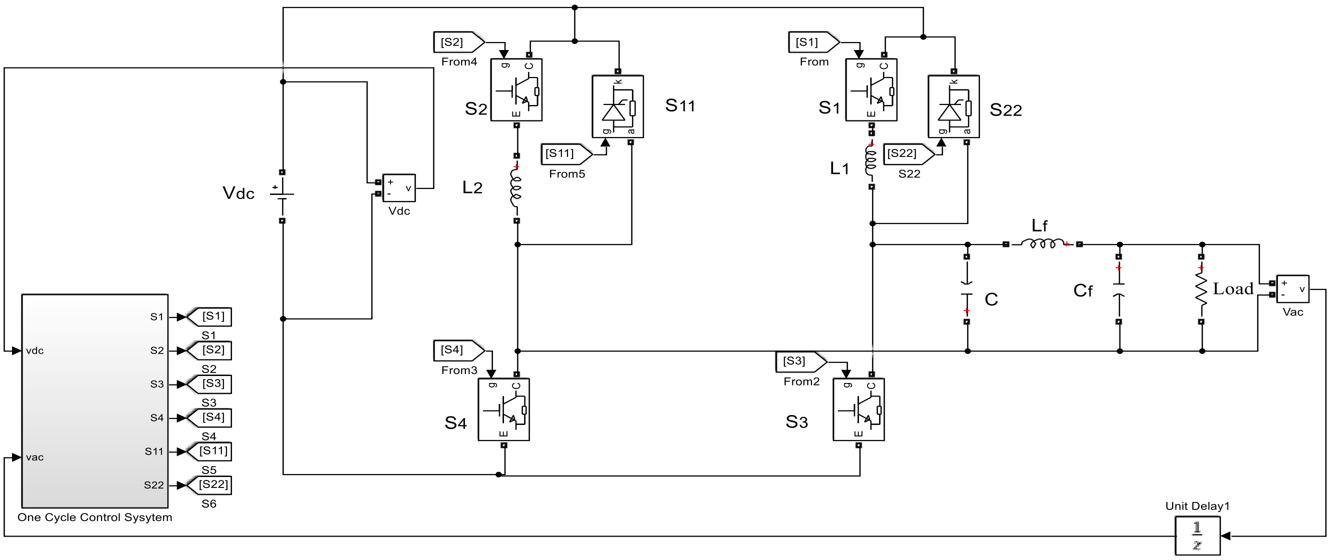

Fig. 8 Simulink diagram of one cycle controlled buck-boost inverter

TABLE I ELEMENT VALUES AND DESIGN EQUATIONS

Elements	Design Equation	Value
V_{dc}		75V
V_o		110 V_{RMS}
Line frequency (F_o)		50 Hz
P_{out}		500 W
Switching Frequency (F_{sw})		40 kHz
Filter inductor (L_f)		1mH
Load Resistance (R_L)	$R_L = \frac{V_{opeak}^2}{2\ P_{out}}$	24.025 Ω
Maximum Duty ratio (D_{max})	$D_{max} = \frac{V_{dc}}{V_{opeak}}$	0.48
$D^/$ (inductor discharging period)	$D^/ = \frac{V_{dc}}{V_{opeak}} D$	0.232
Inductor ($L = L_1 = L_2$)	$L = \frac{V_{dc}\,.D\,.D^/\,.T_{SW}\,.(D\ +\ D^/)}{2\,.\ I_o}$	11.52 µH
Capacitor (C)	$C = \frac{1}{L_1\,.\omega_{SW}{}^2}$	5.512 µF
Filter Capacitor (C_f)	$C_f = \frac{1}{(2.\pi.F_c)^2\,.L_f}$	4.793 µF

T_{SW} = Switching time period ($1/F_{SW}$), I_o = Output current,

D. Test 1: Steady-state operation

In the steady-state, the input voltage is set at 75V and the resistive load is 24.05Ω. The one-cycle control technique outputs are shown in Fig.9. It clearly demonstrates that the control techniques provide proper gate signals by integrating the input signal and it is compared with the reference signal. The steady-state output current and voltage are shown in Fig.10. Fast Fourier Transform (FFT) analysis of the output current is shown in Fig.11. It clearly reveals that the high harmonics are in the vicinity of switching frequency. In order to eliminate such harmonics, the LC filter is designed with a cutoff frequency (F_c) 2.3 kHz. The output voltage and current with output filter are shown in Fig.12 and the FFT analysis of the output current is shown in Fig. 13 and it is evident that by the introduction of filter the THD changed from 4.63% to 0.59%.

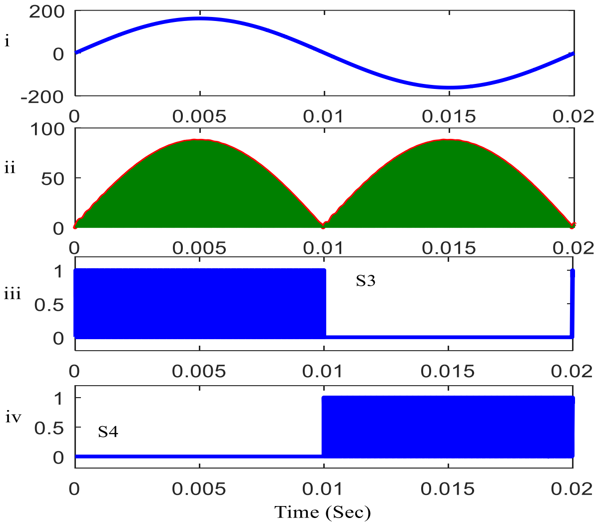

Fig. 9 One cycle control signal output waveforms (i) Reference signal, (ii) Comparator inputs, (iii) Switching pulses to switch S3, (iv) Switching pulses to switch S4

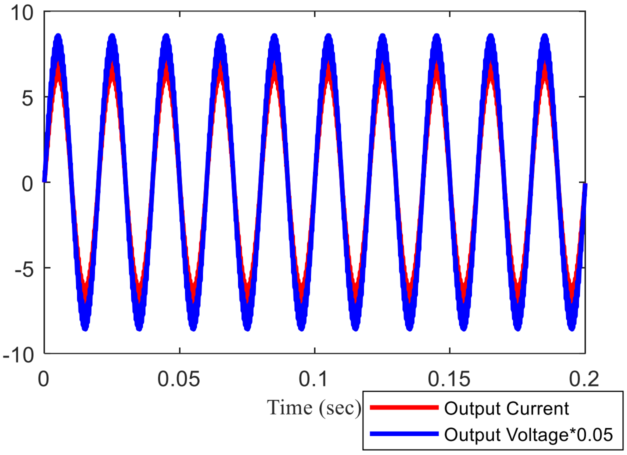

Fig. 10 Output current and voltage during steady operation without filter

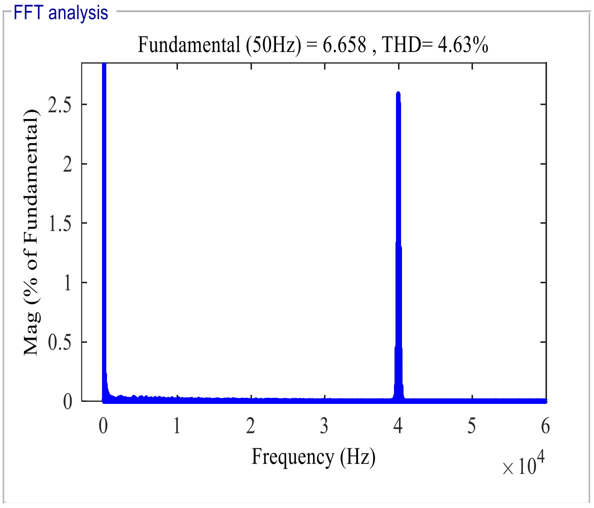

Fig. 11 FFT analysis result of output current without filter

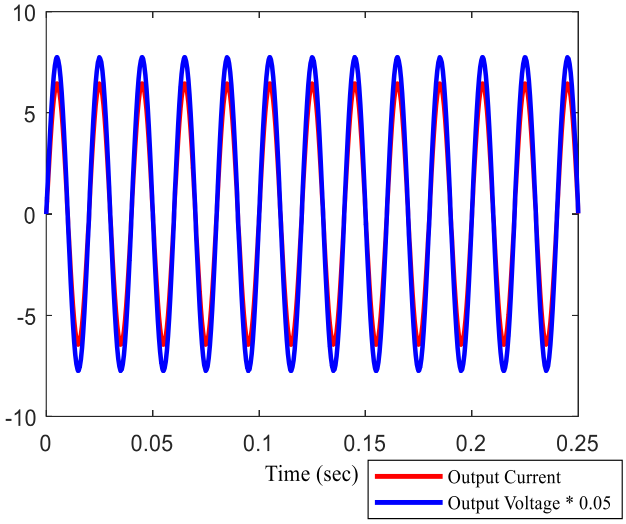

Fig. 12 Output current and voltage waveforms during steady operation with filter

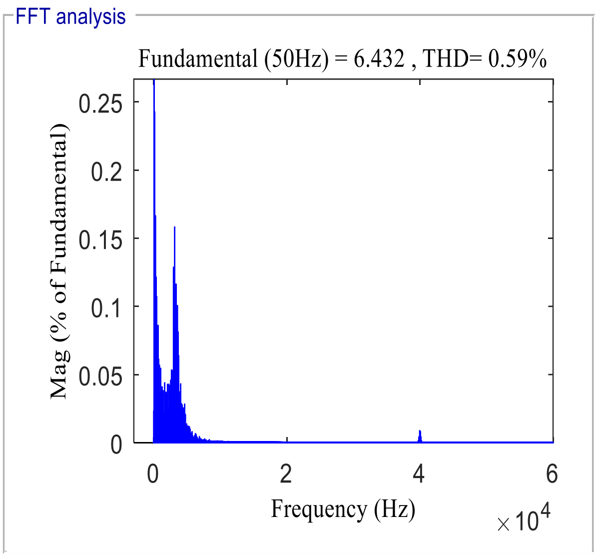

Fig. 13 FFT analysis of output current with filter

E. Test 2: Input voltage disturbances

Test 2 is done to verify the ability of the system to eliminate the input voltage disturbances. This is done by varying the input voltage from 75V to 250 V by steps. Fig.14 shows the input and output voltage of the inverter. The output waveforms validate that system shows no variations in the output voltage even though input voltage varies. This is because, as the input voltage varies the rate of change of integrator output varies. To be more precise, if the input voltage increases integrator output reaches the reference signals at a faster rate. So, that duty ratio of switch S3 will be reduced. Physically it can be interpreted as inductor charging time will be modified in such a way that, energy stored in the inductor will be sufficient to produce the required output voltage as shown in Fig. 15. So, the output voltage will not be affected by the increase in input voltage. Similarly, in the case of a decrease in the input voltage integrator takes more time to reach the reference signal. So, that duty ratio will increase as a result inductor charging time increases. Since energy stored in the inductor is more, output voltage shows no variations as input voltage decrease.

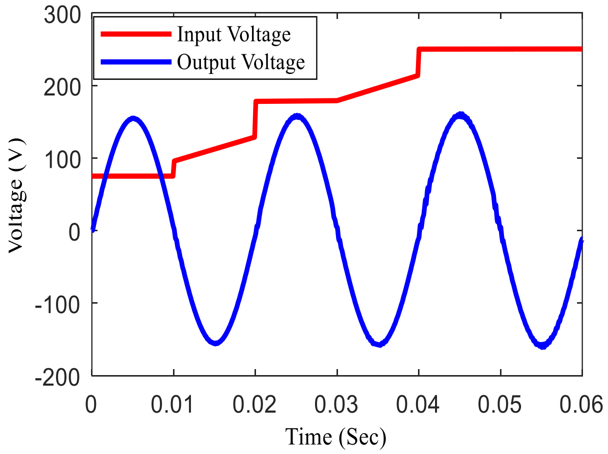

Fig. 14 Input voltage and output voltage at test 2

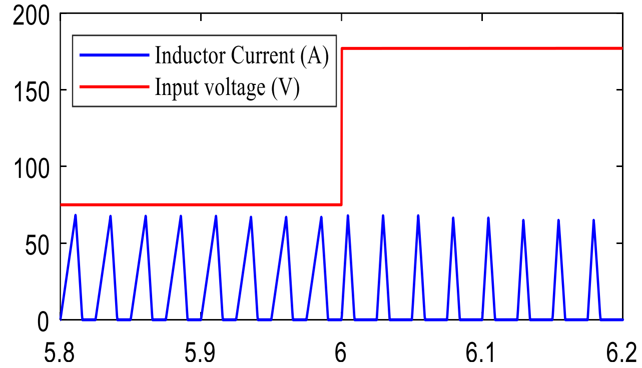

Fig. 15 Input voltage and inductor current waveforms

V. CONCLUSIONS

This paper proposed one cycle controlled buck-boost inverter. The detailed Matlab/Simulink model was used to test the performance of the proposed buck-boost inverter. The results reveal that the proposed inverter can operate at both buck and boost mode without any delay. Moreover, three test conditions are carried out to verify the performance of the one cycle controlled buck-boost inverters such as the ability to reject the disturbances in input voltage and load. Test results specifically show that the proposed inverter is suitable for applications with varying input voltage and load. Hence, it is recommended as the inverter for applications such as UPS design, conversion of renewable energy.

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