# Performance Analysis and Study of Buck-Boost Converter

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**Abstract:**

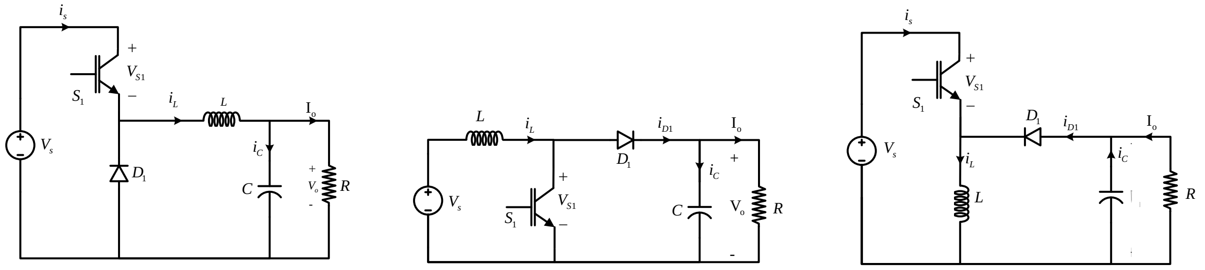
The renewable energy systems like solar, battery storage systems, electric vehicles and small-scale wind power plants requires with very fast and dynamic control converters to control transients occurring due to external and internal effects. The basic dc converters operate at very high switching speeds so that fast and effective control of power with less distortion in the load side voltage and current can be achieved. The buck-boost converters are preferably used to achieve less or more or equal to supply voltage. The size of the filter inductance decides mostly weight of the converter and reduced with increase of switching frequency. This paper shows the hardware and practical implementation of buck-boost regulator.

*Keywords:* buck-boost, electric vehicles, modern converters.

## 1. Introduction

In present modern world, in portal electronic devices are demanding high quality, reliable, more energy density, less weight and highly efficient dc-dc power converters with full scaled control mechanism which are from few milliwatt to kilowatt ranges[1]. Now the current technologies are trending towards too smart energy storage system with better control techniques. The electrical energy storage system is mainly designed with lead-acid, lithium ion and supercapacitor type of batteries [2]. The health and better performance characteristics battery storage system depends of charge or discharge rates of each battery of storage. The performance characteristics of each battery can effectively improve with controlling charge flow rate of battery. The battery requires very fast and dynamic controlled power converters i.e. non-isolated and isolated converters [3]. Majorly isolated converters are designed to range up too few watts but non-isolated converters are used to few kW[4].

In Fig.1, represents the basic dc-dc regulator circuits. The buck converter converts output voltage less than supply voltage, boost converter converts more than supply voltage and buck-boost converter convert both either more or less than supply voltage. The buck converter input current is discontinuous but output voltage and current is continuous. In case of boost converter both source and load currents are continuous with more ripple voltage on load [5]. Each converter can be selected as per application which meet desired parameters. In solar power applications, these three converters will play an important role for controlling charge flow rate and MPPT system [6-7]. In electric vehicles, the battery storage system with an integration of renewable energy is used. The charging of battery banks from utility supply with help of PFCs and high frequency isolated half or full bridge inverters[8]. The regenerative braking of electric vehicles requires fast and dynamic control of power flow, it can be easily implemented using dc-dc converter [9-10]. The mathematical modelling, analysis, simulation and hardware testing of buck-boost converter will be explained in later sections.



(a) (b) (c)

Fig. 1 (a) Buck, (b) Boost and (c) Buck-boost converters

## 2. Mathematical modelling

The mathematical modelling and analysis of buck-boost converter, Fig.1(c)is made with consideration of certain assumptions, as follows.

i. Internal impedance of the source is zero
ii. The peracetic elements of the power switch (IGBT) is zero
iii. The switching transients and snubber circuit effects are negligible.
iv. The ESR of filter inductor and capacitor are zero
v. The output ripple voltage is very small i.e. less than 1% of average load voltage and considered as negligible.

The converter analysis made into two modes:

**Mode1:**When the switch is 'on' for duration of $0 \le t \le kT_s$, the equivalent circuit model is shown in Fig.2(a).The voltage across the inductor $v_L$ is supply voltage $V_s$ and current $i_L$. The inductor current rises to maximum $I_2$.

**Mode2:**When the switch is 'off' for duration of $kT_s \le t \le T_s$. The stored energy in inductor $\frac{1}{2}LI_2^2$ is transferred to capacitor and the load. The equivalent circuit model for this mode is shown in Fig.2(b). The voltage across the inductor $v_L$ is load voltage $-V_o$ and inductor current reaches to $I_1$. The inductor value is sufficient so that current is continuous [9].In Fig.3(a), represents the inductor voltage and current for each switching frequency of the power switch. The stored energy during mode1 is transferred in mode2 so that average energy is zero over a time period. Applying the volt-sec balance equation [10].

$$\int_T v_L dt = 0 \qquad (1)$$

The average voltage $V_o = \frac{k}{1-k}V_s$ (2)

The converter is ideal, the loss in the switches are zero.

$\therefore \int_T p_s(t)\,dt = \int_T p_o(t)\,dt \Rightarrow$ The average source current is $I_s = \frac{k}{1-k}I_o$ (3)

The range of $k$ is o to 1. For $0 \le k \le 0.5$, the converter operates as buck regulator and $0.5 \le k \le 1$, the converter operates as boost regulator.
From Fig.3(a), the slope of the inductor current gives ripple current of the inductor.

The current ripple of the inductor is $\Delta I_L = \frac{kV_s}{f_s L}$ (4)

The ripple current in equation (4) depends on inductance $L$ and switching frequency $f_s$. Let assume that the switching frequency of the converter is constant and the ripple current is depending only on value of inductance.The boundary of the continuous conduction occurs at critical value of inductance. At critical inductance, the ripple inductor current is maximum i.e. $I_2$.The value of inductance in the converter should be more than $L_c$ for continuous conduction[11].

From equation (4)

$$\Delta I_L = I_2 = \frac{kV_s}{f_s L_c} \Rightarrow 2I_L = \frac{kV_s}{f_s L_c} \quad (5)$$

Average inductor current is $I_L = \frac{I_o}{(1-k)}$ (6)

From equations (5) and (6)

The value of critical inductance is $\therefore L_c = \frac{(1-k)^2 R}{2 f_s}$ (7)

When switch is on state i.e. mode 1, the capacitor stored energy will transfer the energy to the load, so that capacitor current is equal to the load current. From Fig.3(b), the ripple capacitor voltage can be calculated as

$$\Delta V_c = \frac{kI_o}{Cf_s} \quad (8)$$

The ripple voltage depends on the capacitance and switching frequency. For smaller value ripple voltage large value of switching frequency. The boundary for continuous capacitor voltage the capacitance must be equal to critical capacitance and maximum ripple voltage is $V_2$ and $V_2 = 2V_o$ [11].

The critical capacitance is $\Delta V_c = 2V_o = C_c = \frac{k}{2Rf_s}$ (9)

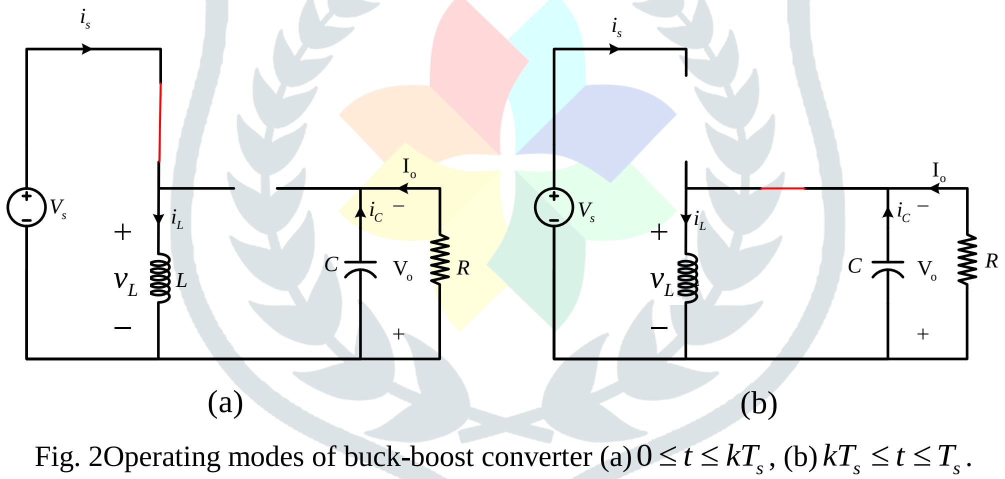



Fig. 2Operating modes of buck-boost converter (a) $0 \le t \le kT_s$, (b) $kT_s \le t \le T_s$.

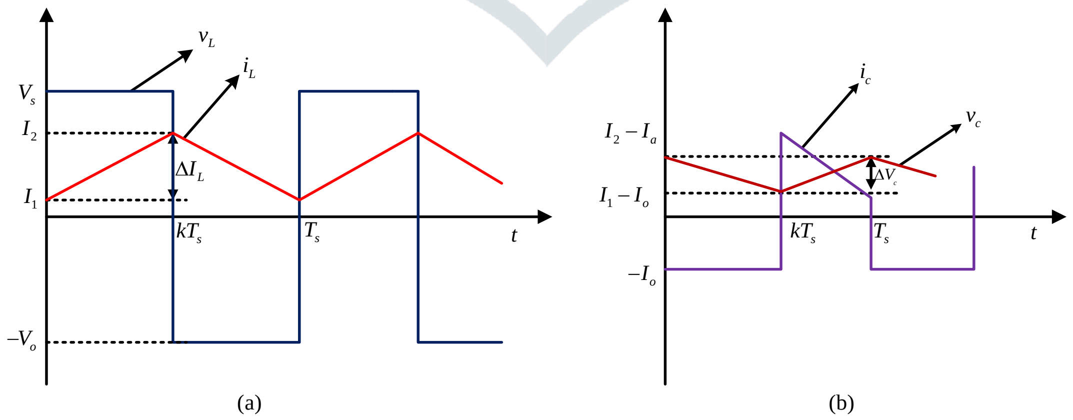



Fig. 3 Voltage and current waveforms(a) inductor, (b) capacitor

## 3. Analysis and simulation study of buck-boost converter

As discussed in section.2, the equations would be used for designing prototype buck-boost converter in matlab simulink. The supply voltage, switching frequency and load resistance are 12V, 100kHz and 50Ω respectively. The converter provides output voltage from 2 to 28V. The selection of the components is mentioned below in the table.1, for just continuous conduction mode. The converter should provide 2V with small ripple voltage 42mV. The output filter capacitance required as per the equation (8) is 20µF. The value of the inductor must select to provide at least just continuous conduction for small duty cycle. The minimum value of inductance is 180.625µH. The selected components for simulating converter areshown in Table.2. The open-loop control of converter simulink model for the verification analysis is designed as shown in Fig.1(c). As per the table1, the waveforms are shown in Fig.5 and 6 for output voltage 2 and 28V respectively.

| Output voltage ($V_o$) | Load current ($I_o$) | Duty cycle ($k$) | Critical inductance ($L_c$) in µH | Critical capacitance ($C_c$) in nF | Inductor ripple currentat $L_c$ ($\Delta I_L$) | Capacitor ripple voltageat $C_c$ ($\Delta V_C$) |
|---|---|---|---|---|---|---|
| 2V | 0.04A | 0.15 | 180.625 | 15 | 99.7mA | 4V |
| 28V | 0.56A | 0.7 | 22.5 | 70 | 3.73A | 56V |

Table 1. Design parameters for buck-boost converter

| Output voltage ($V_o$) | Load current ($I_o$) | Duty cycle ($k$) | Inductance in µH | capacitance in µF | Inductor ripple current ($\Delta I_L$) in mA | Capacitor ripple voltage at $C_c$ ($\Delta V_C$) in mV |
|---|---|---|---|---|---|---|
| 2V | 0.04A | 0.15 | 190 | 20 | 94.7 | 3 |
| 28V | 0.56A | 0.7 | 190 | 20 | 442 | 196 |

Table 2. The selected components for buck-boost converter for satisfactory operation

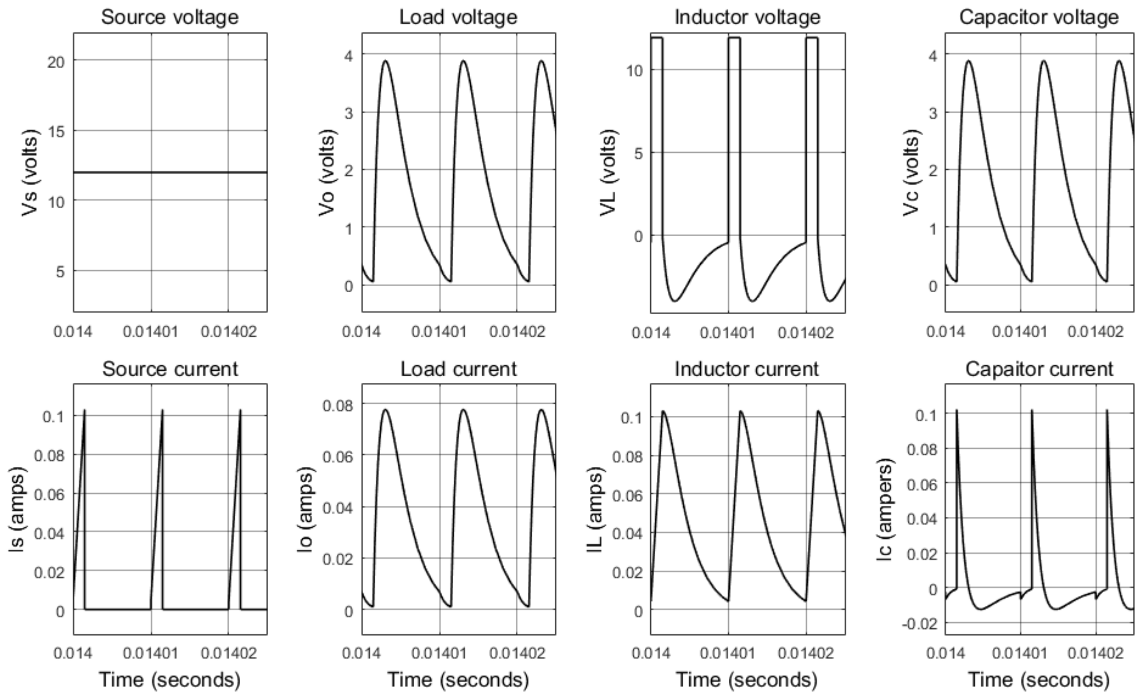



Fig. 4 Waveformsfor average output voltage is 2V as per table1

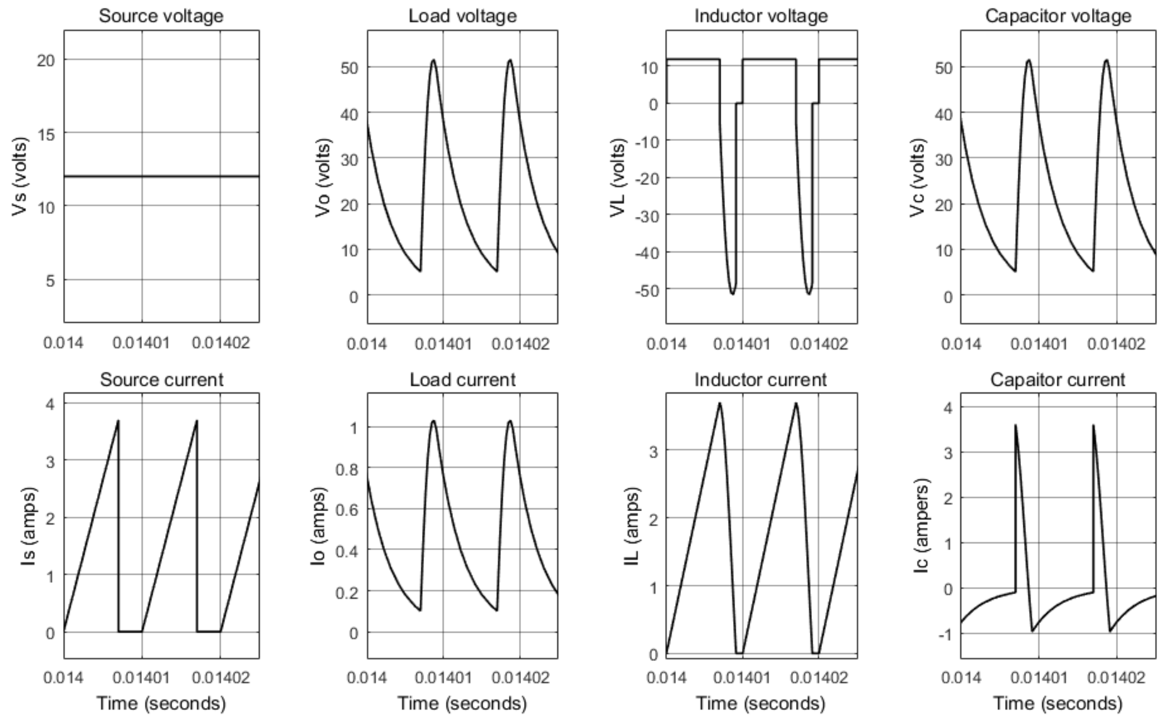



Fig. 5Waveforms for average output voltage is 28V as per table1

The ripple voltage of capacitor and ripple current of inductor are 56V and 3.7 A.The load ripple voltage and current approximately 56V and 3.7A. The core of the inductor will undergo saturation for large current. The converter has a poor performance when load average voltage is increased from 5 to 28V. To improve performance of the converter, the ripple voltage of the load must be less than 1% of average load voltage and inductor ripple current must be small so that core will not saturate. The selected components as per the analysis mentioned in table2, is simulated shown the waveforms in Fig.6 and 7.

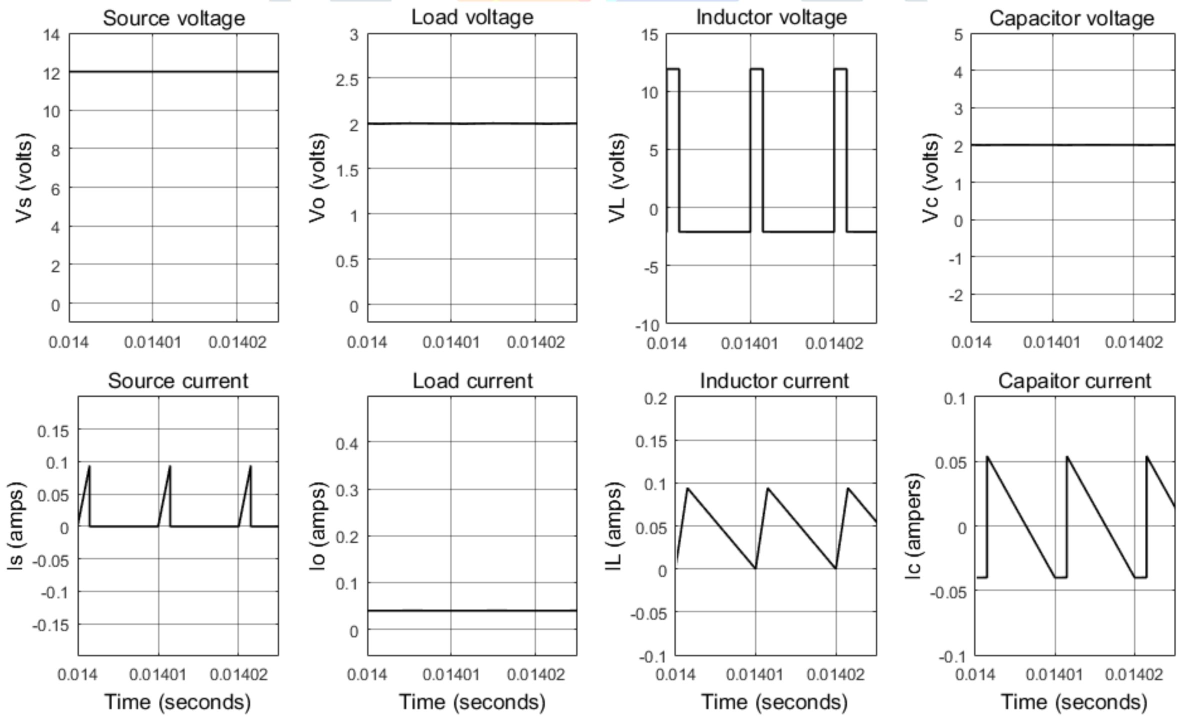



Fig. 6Waveforms for average output voltage is 2V as per table2

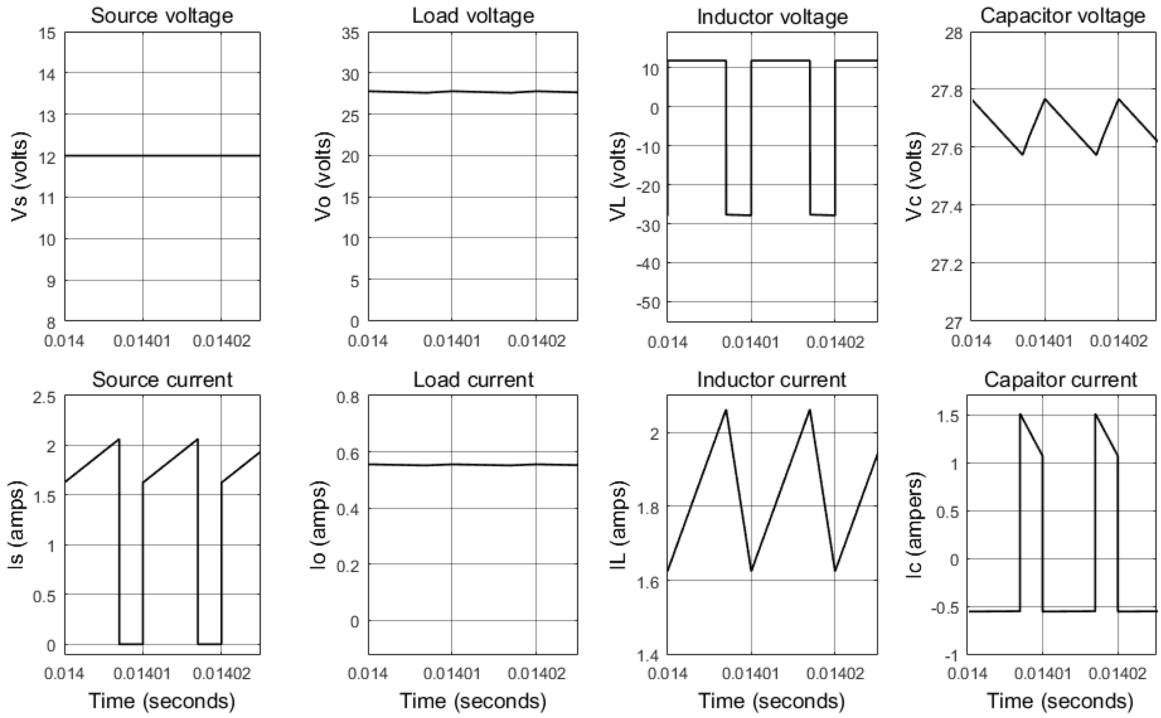



Fig. 7Waveforms for average output voltage is 28V as per table2

## 4. Closed loop control technique

The closed loop control technique will be implemented to maintain load voltage constant [11]. The sensing voltage on the load side compared with constant reference voltage from 2 to 28V, the error is produced is further amplified and feedback to the PI controller. The output of PI controller is then compared with high frequency sawtooth signal, the generated pulse is given to IGBT. The feedback circuit implemented for buck-boost converter is shown in Fig.8. A variable source voltage is used to test circuit model in simulink. The variation of voltage is given at 0.05 sec from 12 to 15V and at 0.07 sec from 15 to 5V. The spike of in the load voltage for rising voltage is much larger than falling voltage. The response controller is 6.26ms to change load voltage to reference magnitude voltage error amplifier. The waveforms for load voltage of 2 and 28V are shown in Fig.9(a) and (b).

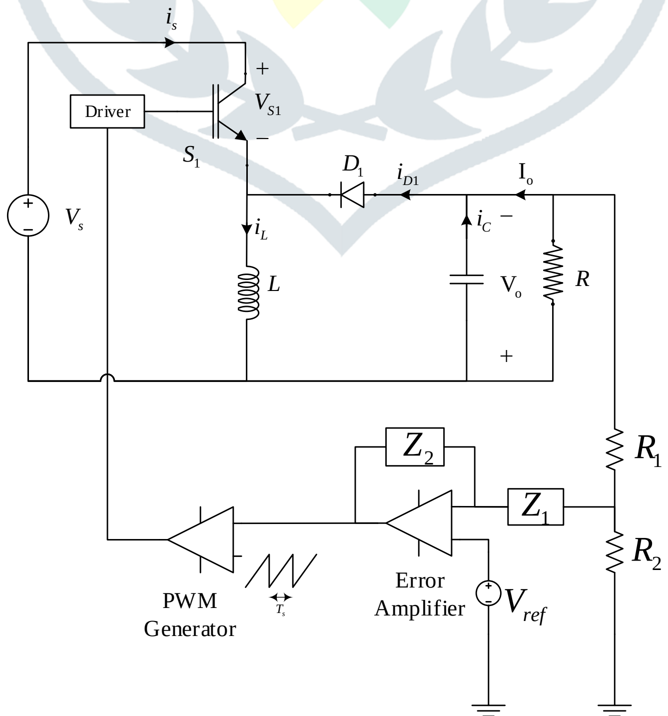



Fig. 8 Constant voltage control method using feedback control technique

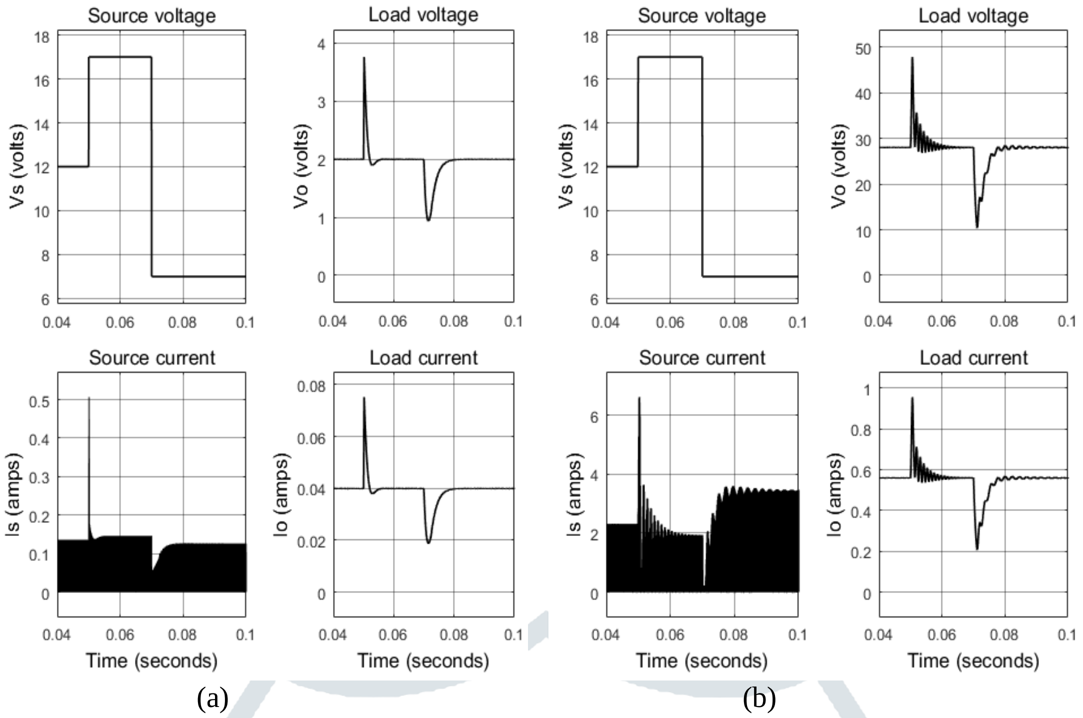



Fig. 9 Load voltage and current waveforms for 2V and 28V reference load voltage

## 5. Hardware testing

The hardware circuit of buck-boost converter with closed-loop control technique is shown in Fig.10. The 555-timer circuit is used to generate a sawtooth signal with a frequency of 6.45kHz as shown in Fig.11. The error amplifier signal is then compared with sawtooth signal, the generated pulse given to IGBT switch. The output voltage waveforms are shown in Fig.12 and 13. The voltage waveform across the inductor is shown in Fig.14.

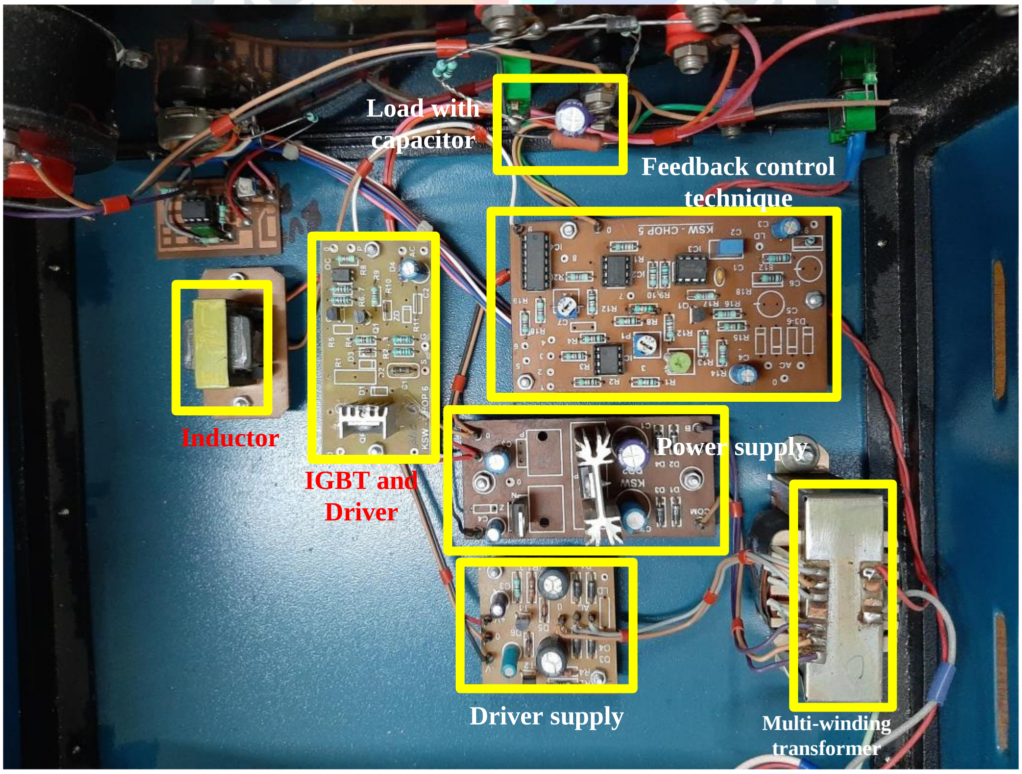



Fig. 10 Hardware circuit model of buck-boost converter

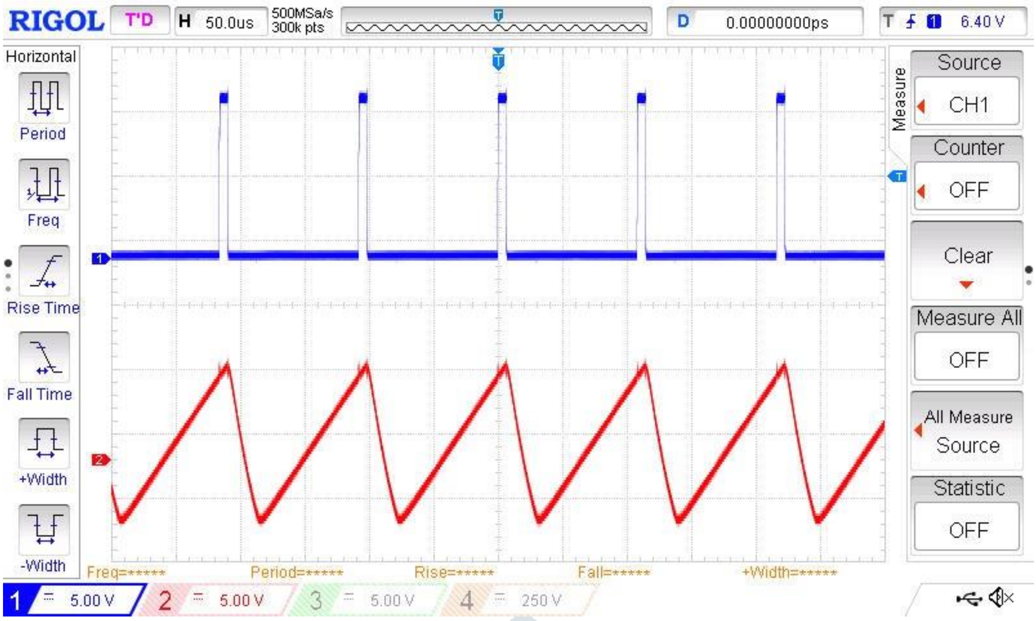



Fig. 11 Sawtooth signal generation with a frequency of 6.45kHz

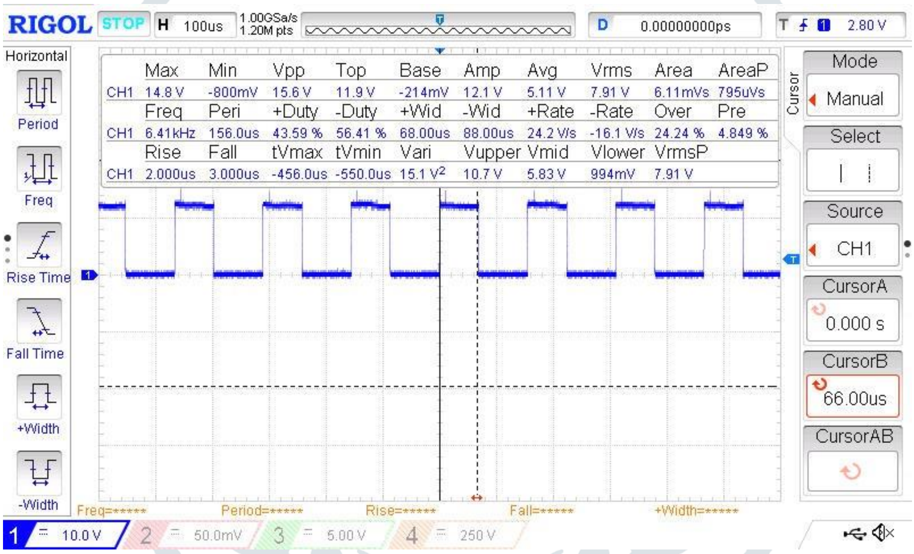



Fig. 12 Switch voltage waveform

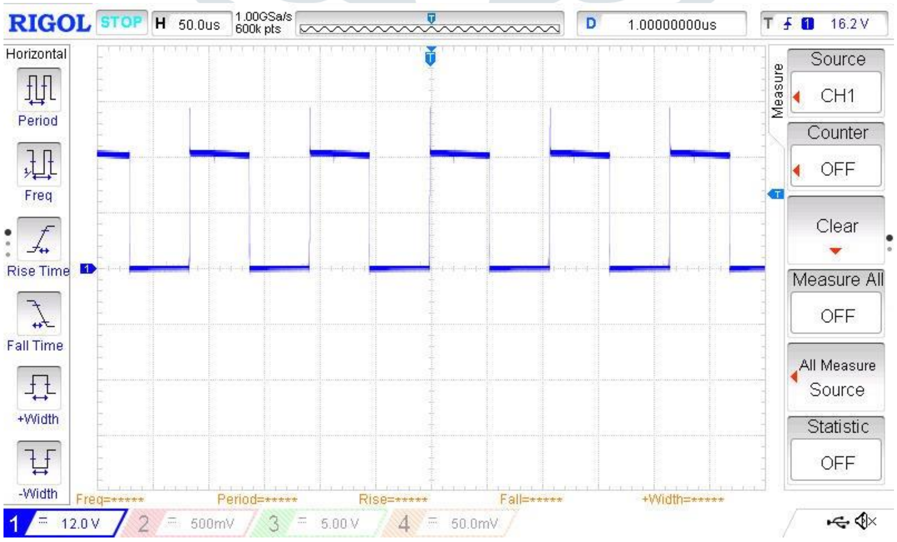



Fig. 13 Switch voltage waveform

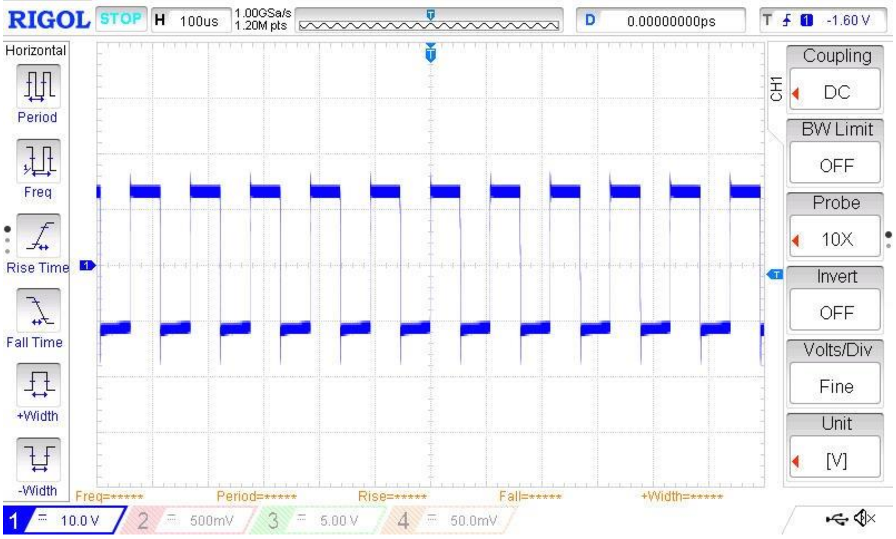


Fig. 14 Inductor voltage waveform

## 6. Conclusion

The low-power buck boost converter with variable output voltage from 2 to 28V simulated and designed for a fixed input voltage of 12V. The analysis is made for continuous conduction mode. The simulation results are performed at switching frequency of 100kHz but in hardware model the switching frequency of 6.45kHz. The inductance used in the hardware circuit is 3mH with small ripple current.

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