Design of a Buck-Boost Converter

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I. Introduction

Buck-books converters are dc to dc converters that are widely used in applications such as variable dc power supplies, automotive start-stop systems, point of sale (POS) systems and industrial personal computers (IPCs). All these applications require input voltages that can either be higher or lower than the desired output voltage.

Several topologies for buck-boost converter designs have long been established. Many of these reverse the polarity of the output voltage and are hence termed inverting. The single-end primary inductor converter (SEPIC), Zeta converter, and two switch buck-boost converters have positive or non-inverting outputs. However, compared with a basic inverting buck-boost converter, all three non-inverting topologies have additional power components and reduced efficiency. This report presents operational principles, current stress and power-loss analysis of these buck-boost converters, and presents design criteria for an efficient non-inverting buck-boost converter.

This document discusses the design of a basic IPS and tests its output voltage waveforms supplied to a resistive load.

Figure: An example of buck-boost application

A. Background

For high efficiency, the switched-mode power supply (SMPS) switch must turn on and off quickly and have low losses. The advent of a commercial semiconductor switch in the 1950s represented a major milestone that made SMPSs such as the boost converter possible. The major DC to DC converters were developed in the early 1960s when semiconductor switches had become available. The aerospace industry's need for small, lightweight, and efficient power converters led to the converter's rapid development.

Switched systems such as SMPS are a challenge to design since their models depend on whether a switch is opened or closed. R. D. Middlebrook from Caltech in 1977 published the models for DC to DC converters used today. Middlebrook averaged the circuit configurations for each switch state in a technique called state-space averaging.

This simplification reduced two systems into one. The new model led to insightful design equations which helped the growth of SMPS.

B. Motivation

Battery-powered systems, where the input voltage can vary widely, starting at full charge and gradually decreasing as the battery charge is used up. At full charge, where the battery voltage may be higher than actually needed by the circuit being powered, a buck regulator would be ideal to keep the supply voltage steady.

However as the charge diminishes, the input voltage falls below the level required by the circuit, and either the battery must be discarded or re-charged; at this point the ideal alternative would be the boost regulator.

By combining these two regulator designs it is possible to have a regulator circuit that can cope with a wide range of input voltages both higher and lower than that needed by the circuit. Fortunately both buck and boost converters use very similar components; they just need to be re-arranged, depending on the level of the input voltage.

C. Objective

The object of this report is to design and buck-boost converter that is able to convert the ac mains supply to 24V dc and then step it up and down to 48V and 16V respectively for a load of 1 kΩ.

II. Literature Review

The buck-boost converter is a form of switch mode power supply (SMPS) that combines the principles of buck and boost converter to provide an output that can either be greater or smaller than the input voltage.

Battery power systems often stack cells in series to achieve higher voltage. However, sufficient stacking of cells is not possible in many high voltage applications due to lack of space. Boost converters can increase the voltage and reduce the number of cells. Two battery-powered applications that use boost converters are used in hybrid electric vehicles (HEV) and lighting systems.

The NHW20 model Toyota Prius HEV uses a 500 V motor. Without a boost converter, the Prius would need nearly 417 cells to power the motor. However, a Prius actually uses only 168 cell and boosts the battery voltage from 202 V to 500 V. Boost converters also power devices at smaller scale applications, such as portable lighting systems. A white LED typically requires 3.3 V to emit light, and a boost converter can step up the voltage from a single 1.5 V alkaline cell to power the lamp.

An unregulated boost converter is used as the voltage increase mechanism in the circuit known as the 'Joule thief'.

This circuit topology is used with low power battery applications, and is aimed at the ability of a boost converter to 'steal' the remaining energy in a battery. This energy would otherwise be wasted since the low voltage of a nearly depleted battery makes it unusable for a normal load. This energy would otherwise remain untapped because many applications do not allow enough current to flow through a load when voltage decreases.

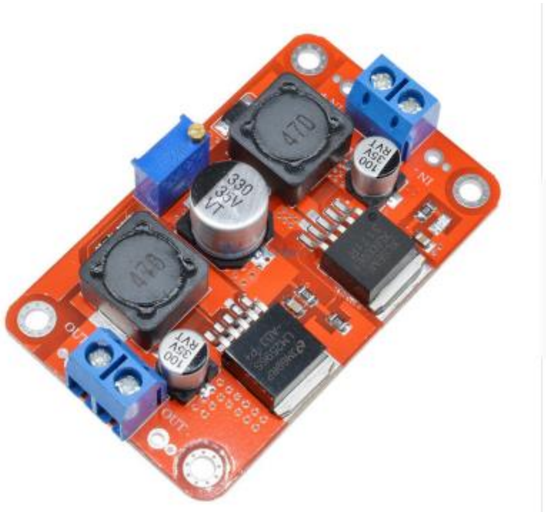

Figure: A low cost buck-boost converter module

The working principle of an inverting buck-boost converter is briefly discussed below.

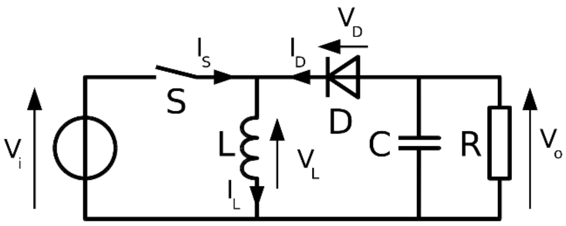

Figure: An inverting buck-boost converter

The above circuit operation can be broken down in two modes as shown below.

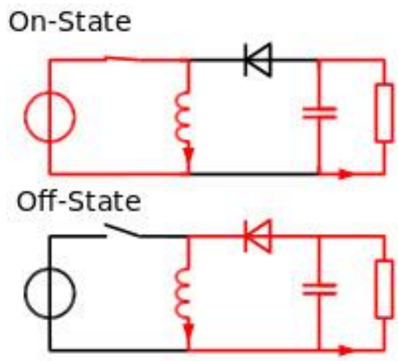

Figure: Operating modes of the buck-boost converter

Mode -1: Switch ON

In this mode, the switch (for example a MOSFET) is kept on and thereby (representing a short circuit) offers zero resistance to the flow of current so when the switch is ON all the current will flow through the switch and the inductor and back to the DC input source. The inductor stores charge during the time the switch is on and when the solid state switch is off the polarity of the inductor reverses so that current flows through the load and through the diode and back to the inductor. So the direction of current through the inductor remains the same.

Mode – 2: Switch Closed

In this mode the polarity of the inductor is reversed and the energy stored in the inductor is released and is ultimately dissipated in the load resistance and this helps to maintain the flow of current in the same direction through the load and also step-up the output voltage as the inductor is now also acting as a source in conjunction with the input source.

The change in the inductor current in both modes can be equated and, for a particular input voltage V_{IN} and duty cycle of the switch *k*, the following equation is derived for the output voltage:

$$Vo = -\frac{k}{1-k} \times Vin$$

It can be seen that the output voltage is stepped up for the $k > 0.5$ and is stepped down for $k < 0.5$.

The values of the inductor and capacitor were chosen such that the inductor was kept in continuous conduction mode (CCM) using the equations shown below.

III. Methodology

The following methodology was adapted to achieve the outcomes of this project.

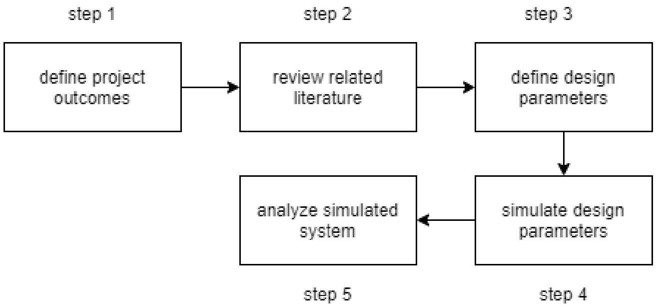

Figure: Project methodology

IV. Proposed Method

The object of this report is to design and buck-boost converter that is able to convert the ac mains supply to 24V dc and then step it up and down to 48V and 16V respectively for a load of 1 kΩ. The figure below shows the block diagram that will satisfy the objectives of our project.

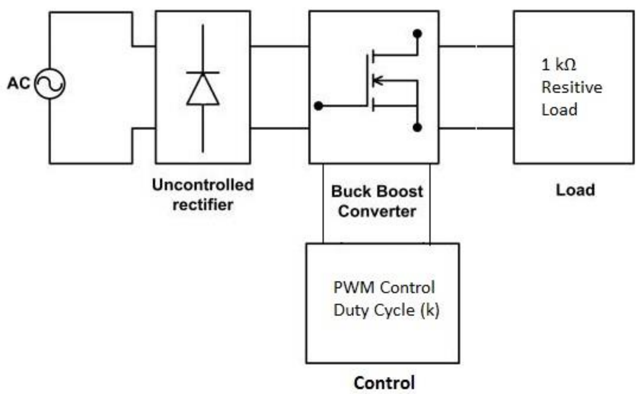

Figure: Block diagram on an IPS

The following components specifications were in this project.

Component	*Description*
Diode	1N4007
Inductor	Core type
Capacitor	Ceramic, 100V
Schottky Diode	1N5822
MOSFET switch	IRF250
Microcontroller	Arduino Uno
Op-Amp	LM741
Resistor	1 kΩ, 10W
Potentiometer	100K, logarithmic
Transformer	Step down, 220-24V

V. SIMULATION & RESULTS

The following figure shows the simulated system.

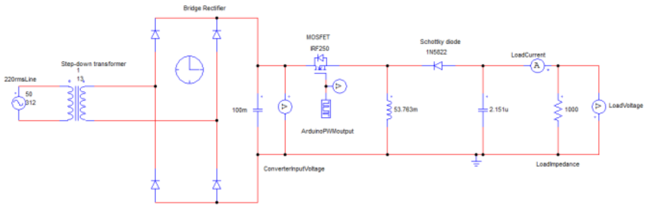

Figure: Design of an inverting buck-boost converter

The table below summarizes the design specification of the simulated system.

Symbols	*Meaning*	*Value*
V_L	Mains voltage	220V AC
V_{in}	Converter input	24V DC
f	Switching frequency	31 kHz
k	Duty cycle	0.667
V_{OUT}	Output voltage	48 V
R	Load	1 kΩ
I_O	Output current	48 mA
ΔI	Change in inductor current, 20% of I_o	9.6 mA
ΔV_C	Output ripple voltage, 1% of V_{OUT}	0.48 V

The values of the inductor and capacitor were calculated using the equations below.

$$L = \frac{Vin \times k}{\Delta I \times f} = 53.7\ mH$$

$$C = \frac{Io \times k}{\Delta Vc \times f} = 2.2\ \mu F$$

The MOSFET switch was provided with a pulse width modulated (PWM) gating pulse generated by an Arduino microcontroller. The duty cycle of the modulated signal is physically controlled via potentiometer attached to the micro controller. To be able to drive the MOSFET switch, the 5V output of the microcontroller is fed to an operational amplifier (LM741) to generate a 20V signal as shown in the figure below.

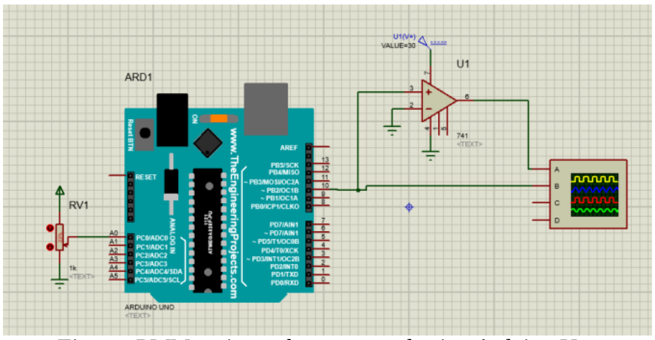

Figure: PWM gating pulse generated using Arduino Uno

The waveform obtained in the oscilloscope is shown below.

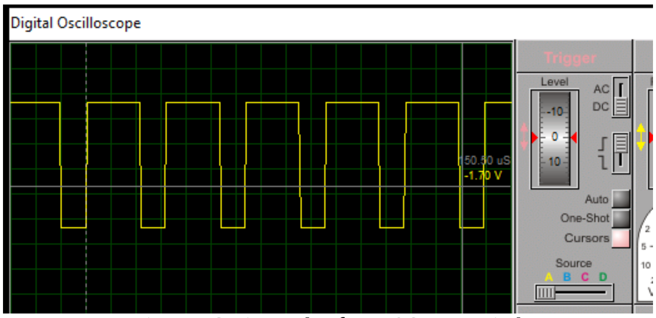

Figure: Gating pulse for MOSFET switch

The simulation results for a duty cycle of 66.7% is shown below. (V_{OUT} = 48V, k= 0.667).

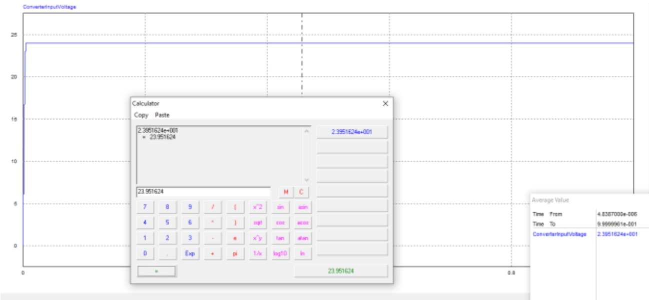

Figure: Rectified voltage V_{IN} of 24V

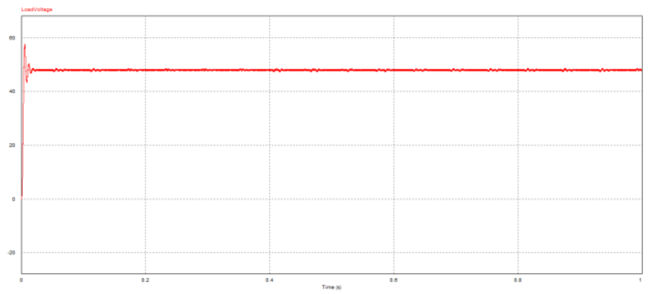

Figure: Load output voltage of 48V

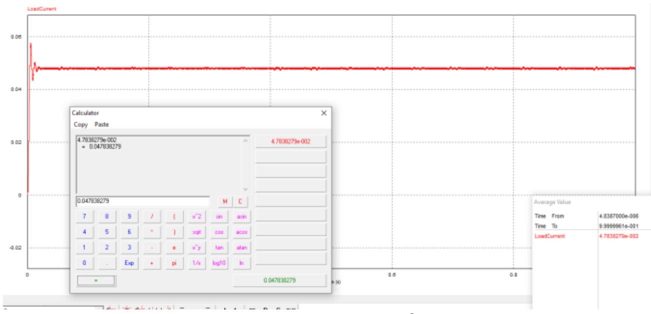

Figure: Load current of 0.05A

The duty cycle k was then varied by varying the potentiometer and the output voltages obtained were as shown.

Duty Cycle %	*Output Average Voltage*
70	55.927867 V
66.7	47.916774 V
60	35.967505 V
50	23.988192 V
40	15.994136 V
30	10.282616 V

It is seen that the output voltage was stepped up for duty cycle values greater than 50% and stepped down for values less than 50%. For a duty cycle of 50% the average output voltage was nearly the same as input.

All the values obtained corresponded closely with their theoretical estimations made using the previously stated formula.

$$Vo = -\frac{k}{1-k} \times Vin$$

VI. PCB Design

The following circuit was used to design a PCB in Proteus.

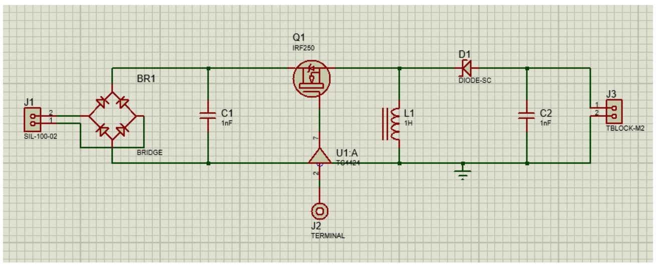

Figure: Proteus Schematic

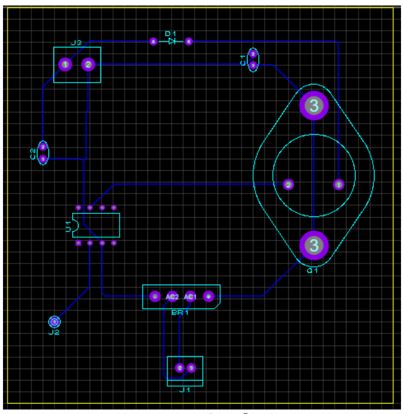

Figure: PCB design

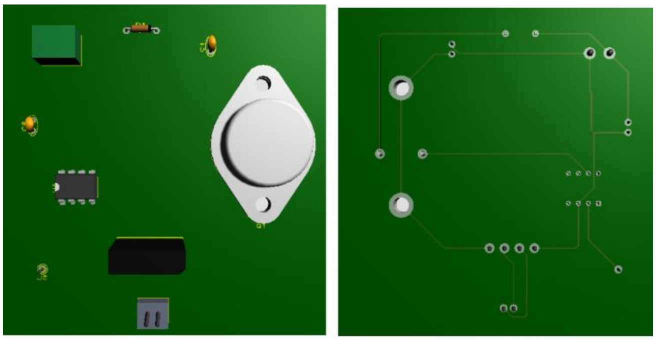

Figure: 3D top and bottom view of PCB

VII. Discussions

The simulations of the buck-boost converter was seen to provide the stepped up or stepped down voltages corresponding to its duty cycle. Both PSIM and Proteus simulation environments were used. There were slight discrepancies in simulation results in both environments for equivalent circuit.

In high voltage designs, silicon diodes may be used in preference to Schottky types due to their high reverse voltage capabilities. The control unit may also carry out over current and over voltage protection, as well as the normal oscillator and pulse width modulation functions to regulate the output voltage.

Buck-boost converter ICs are commonly used to carry out the control unit functions. These range from very low power, high efficiency ICs for portable devices such as mobile phones and automotive applications

Another commonly used facility is ‘pulse skipping’ where the control unit prevents charging on one or more oscillator pulses when it senses that the load current is low. This reduces the overall current drawn from the (typically battery) supply, prolonging battery life

VIII. Conclusion

The simulated design of the buck-boost converter can provide the required output voltage to the load as determined by the duty cycle provided to the switch.

IX. References

[1] Texas Intruments, “How to design efficient non-inverting buck-boost Converter” http://www.ti.com/lit/an/slyt584/slyt584.pdf

[2] Texas Instruments, “Basic calculations of an inverting buck-boost converter” http://www.ti.com/lit/an/slva721a/slva721a.pdf

[3] Electrical4u, “Buck-Boost Converter” https://www.electrical4u.com/buck-boost-converter/.