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Design and Analysis of a Buck-Boost Converter for a Photovoltaic Electric Vehicle System

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Abstract— The Electric Vehicle (EV) sector uses rechargeable batteries to power up their vehicles. However, these batteries are made from resources that are quickly depleting. To solve this issue the use of renewable energy sources is crucial. Along with that, systems that boost the existing voltage are necessary to save space and energy resources. This study proposes systems that will help power up the EV using Photo Voltaic (PV) solutions. Firstly, buck, boost and buck-boost converters are designed to fulfil the industry requirements of EV applications. The varying voltage (8V-18V) from the solar panel is converted to a steady voltage source (12V) using a buck-boost converter. This is used to charge the 12V LiFePo4 battery. Using a buck converter, the 12V source is converted to 5V to power the car's dashboard. The boost converter is used to convert 120V to 420V which powers the car. The buck-boost converter uses a closed loop PI control system. This increases its efficiency significantly. The buck and boost converters are simulated and analyzed in LT Spice while the buck-boost converter is simulated using MATLAB/SIMULINK. The power efficiencies of the buck, boost and buck-boost converters are over 96%.

Keywords- buck boost converter, dc-dc converter, electric vehicles, PI control, power electronics, solar power, sustainable energy

I. INTRODUCTION

A promising solution today to overcome the environmental challenges are EVs. The increased usage of EVs has the ability to reduce a significant amount of carbon emissions as well as greenhouse gases. EVs are paving the way for a more sustainable future for planet earth as well as clean air for all to breathe [1]. The integration of PV systems with EVs provides effective innovation. This concept will amplify the existing environmental benefits of EVs. By harnessing the abundant solar energy EVs can partially or even fully charge their batteries. The solar panels can be placed strategically on the exterior of the vehicle or it can even be seamlessly integrated into the very design of the EV [2]. This will not only extend the driving range of EVs, but also substantially decrease EVs dependence on grid electricity. As a result, further reducing their overall carbon footprint [3].

Vehicles will become mobile energy units, capable of generating and storing power to meet their own needs. They might also be able to contribute back to the grid during peak demand [4]. As technology continually advances, the efficiency and affordability of both EVs and PV systems will increase. This integrated approach of both systems will help revolutionize our transportation and energy landscapes [5].

As EVs become more prevalent on our roads, their ability to harness the sun's energy enhances their practicality and reduces their environmental impact. This gives us a glimpse into a future where vehicles play an active role in supporting our energy needs.

The current challenges of EVs include increasing the range and reducing the size of the battery pack of an EV. PV systems shall play and integral role in this industry moving forward.

II. LITERATURE REVIEW

This work describes the construction of a buck-boost converter. The work claims that this converter does not generate heavy switching losses. Soft switching technology is used to reduce the switching losses as well as the electromagnetic interference. This increases the efficiency of the converter. A buffer circuit is appended to the standard buck-boost converter circuit. The circuit is simulated using MATLAB/SIMULINK. The specifications of the converter used are, switching frequency of 40kHz, pulse width of 40%, the input voltage of 100V, the resonant inductor Lr of 100uH, resonant capacitor Cr of 50nF. The buffer resistance R is 50Ω, the buffer capacitor Cs is 0.47uF. This new buck-boost circuit is better than the previous version in terms of improved conversion efficiency. This reduces the electromagnetic induction and switching losses. After running the final simulation, it has been found that the system's output efficiency has significantly increased. The power losses of the new buck-boost model are lesser than the standard buck-boost circuit [6].

This study features a diverse range of PV system models alongside DC-DC converter technologies. These include buck and boost converters. These are used by changing the distance between the PV array and the load. The parameters that are used are Maximum Power Point Tracking (MPPT) and the duty cycle. The primary PV module construction involves it being managed and connected to a buck-boost converter. The system's incremental conductance MPPT algorithm incorporates a PID controller to lower output error voltage. Without PID, the second model is identical to the first controller. The final two systems, which use boost MPPT-controlled and PWM-equipped converter. Simulink/MATLAB is the software used for simulations. [7].

The construction of a three-phase interleaved parallel bidirectional buck–boost converter is mentioned in this paper. This converter converts voltage in both directions. It is the primary regulator. It is the manager of electrical energy flow between the motor drive inverter and the battery pack in the high voltage direct current bus. The charging buck mode, discharging boost mode and the electric energy interaction modes of operation are studied together with the mathematical model, corresponding circuit layout and control approach. This model uses power feedforward compensation, double closed loops, and bidirectional switching logic. The Infineon Technologies AG's XDPTM Digital Power Controllers XDPP1100-Q040 are used to realize the digital implementation. The results obtained by testing this converter demonstrate that goals such as the viability and applicability of a system are met [8].

The non inverting buck-boost converter application in the study is used to control the non-linear converter's output voltage in real time applications. There has been a significant amount of research done to enhance the dynamic behavior of converters by using intelligent control techniques. The decrease of ripple over voltage and the occurrence of transient overshoots have not been studied in this paper, however, they mention that this can be fixed by choosing filter capacitance values. This article suggests a PID control system for the same. This controller has been optimized using algorithms such as Non-Dominated Sorting Genetic Algorithm (NSGA) and Enhanced Non-Dominated Solutions Algorithm (ENSGA). The ENSGA has been used to achieve the homogenous distribution of non-dominated solutions. ENSGA is distance based dynamic crowding algorithm. The buck-boost mode's stability is observed using both ENSGA and NSGA. The ENSGA controller proved superior compared to the NSGA controller in parameters such as improved output voltage regulation, less transients, it minimized ripple voltage. This is based on various simulation results presented in the paper [9].

The Versatile Buck Boost (VBB) converter is explored in this study. The VBB is chosen because of its step up/step down voltage conversion ratio, high efficiency, low ripple, continuous input/output currents that can be regulated in a simple manner and the ability to manage any converter variable. It serves as a Power Electronics Building Block (PE-BB). This study discusses topological alterations, applied control methods and applications for the VBB. The results showcase the VBB's good performance in dc-dc, ac-ac, dc-ac and ac-dc applications. The results suggest that the PE-BB can be used as a ac-dc rectifier and a dc-ac inverter, in ac-ac applications and as a dc-dc converter. The VBB is controlled using PID control loops [10].

This research examines Hybrid Energy Storage System (HESS). It explores how the Electric Double Layer Capacitor (ELDC) affects stress reduction and battery lifespan. As an experiment, a 65 F, 16.2 V EDLC supercapacitor was linked to produce its charge/discharge curve at constant currents between 5 and 10 A. The mathematical parameters for the Faranda or "two branch model" of the EDLC were taken from the experimental charge/discharge curve. The Python/MATLAB/Simulink (PMS hybrid model of the EDLC was created using the retrieved parameters as inputs. The charge/discharge profiles acquired from the experimental configuration of the EDLC were then compared to the charge/discharge profiles of the simulated PMS model of the EDLC, and it was discovered that they matched [11].

In this study, it is mentioned that the dc-dc synchronous buck-boost converter can function with or without dead or overlap time. The topology of a quasi-impedance source converter is the inspiration for the converters design. This design uses two capacitors and two inductors for energy storage and second-order filtering. However, its gain is the same as that of a traditional buck-boost converter. By eliminating dead or overlap time, control complexity is decreased and higher frequency operation is made possible, necessitating the use of smaller capacitors and inductors. A 50 kHz prototype was used to successfully test the converter's operation using control signals, and its output voltage was compared to the ideal theoretical values. This study demonstrated experimental as well as simulated results. The converter can operate at higher frequencies compared to a conventional buck-boost converter. The converter saves cost and power density. The paper suggests the use of ceramic capacitors to further reduce the weight [12].

High gain DC-DC converters are particularly useful in specific RES applications, such as solar Photo-Voltaic (PV) systems, where DC-DC converters play a significant role in renewable energy systems (RES). In this chapter, a description of several solar PV-based systems' DC-DC high gain converters is first offered, followed by a demonstration of an improved high gain buck-boost converter (IHGBBC) appropriate for PV-based systems. Compared to single-cell Traditional Buck-Boost Converter (TBBC), the IHGBBC has a bigger voltage gain. By parallelizing the input side and cascading in the load side of two TBBC cells, the proposed IHGBBC is created. Here, 2 connected TBBC cells do a 180-degree phase shift during a switching interval. Due to this the converter has good voltage gain, positive output voltage, increased dynamic performances, lower ripple current and good power efficiency [13].

In order to raise the system's input power factor (IPF), the line current harmonics must be reduced. As a result, IPF correction circuits using a new buck-boost converter topology have been designed. The writers of th¬¬is article used this circuit specifically for charging the batteries of EVs using an AC source. To enhance the IPF, a passive power factor correction circuit with a new buck-boost converter (BBC) is used. Both voltage regulation and IPF correction use the PID controller and the hysteresis current control (HCC) approach. In addition to power factor correction management, this research recommends a buck-boost converter that uses hysteresis control to improve power factor and hence reduce THD. In MATLAB/Simulink, the converter was simulated both with and without a PFC controller. This led to the use of this controller to adjust the input power factor and regulate the output voltage. The simulations show what we want to see, and we draw the conclusion that the designed circuit can deliver the intended output—14 V DC—for an input range of 30 to 40 V AC with a respectable power factor of 0.99 [14].

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III. METHODOLOGY

This section discusses the methodology of the design and analysis of our system. Initially we studied the standard circuits of a buck converter, boost converter and the buck boost converter.

Figure. 1. displays the initial flowchart of the proposed system. A buck-boost converter is a DC-DC converter that has both step-up as well as step-down functionalities in the same circuit. It is a combination of both a buck converter (step-down voltage) as well as a boost converter (step-up voltage). Both these functionalities are needed in an electric vehicle.

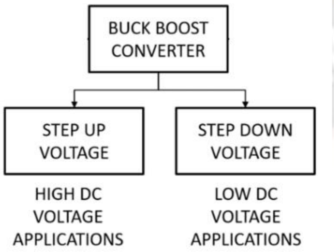

Figure 1. Flowchart of the proposed system

Figure. 2. is a flowchart that explains the various applications of the converters. These converters are used in different specifications of electric vehicles. These applications are discussed in depth, further.

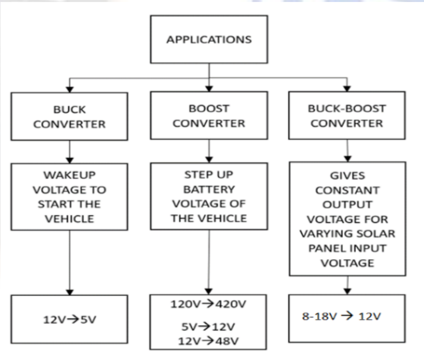

Figure 2. Flowchart of the system applications

Fig. 3. Is a block diagram showcasing the graphical representation of various applications of the system.

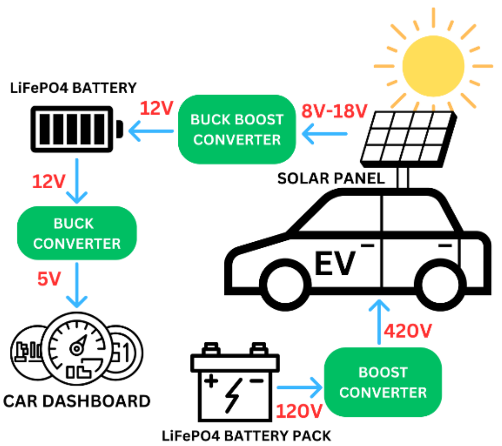

Figure 3. Flowchart of the system applications

A. *Use of Converters in Electric Vehicles*

Buck converters step down higher voltage to lower voltage. In this application a 12 V voltage source is used. This voltage will be obtained from a 12 V solar panel fitted on top of the car. Approximately, 12 V volts is sufficient voltage to start an electric car's battery. This is referred to as starting voltage. This voltage is used to start the car's battery. After the car has started, it no longer needs these 12 volts, hence we can use it for powering the dash board of the car. The dash board of the car requires only 5 V to operate [15], hence in most cars, you would need to step down these 12 V to 5 V. This is done by using a buck converter.

A boost converter steps up the input voltage. Boost converters are used in EVs to increase the voltage of the battery pack and hence reduce the number of cells. This makes it economical for the manufacturer and the customer. This also reduces the overall weight of the battery pack. The boost converter can also be used to convert the 5 V in the buck converter application back to 12 V in case the voltage needs to be used elsewhere. In this application, the buck-boost converter is used to step up a battery pack of 120 V to 420 V. Normally for operating an electric vehicle, the battery pack voltage required is in the range of 360 V to 450 V [16]. A boost of 12V to 48V is implemented to power smaller EVs.

The buck-boost converter combines the benefits of the buck and boost systems. Just one converter can be used to perform the above-mentioned operations in an electric vehicle. This will make the system lightweight and cost effective, thus optimizing resources. The buck-boost converter can perform both step-up and step-down voltage operations. This makes the system less bulky. Solar panel voltage used to charge a battery is not constant, due to the varying intensity of the sun [17]. In such a case, buck-boost converters are immensely useful. In this application the design and analysis of a buck-boost converter which can produce a constant output voltage of 12V for varying input voltages in the range of 8V to 18V is done. This output voltage of 12V can be used to charge the LiFePO4 cell as seen in Fig. 3.

B. *Selection Of Voltage Source*

This research aims to demonstrate the compatibility of photovoltaic systems as voltage sources for buck and boost converters in electric vehicles. Hence, a 12 V solar panel is used as the voltage source for the buck converter application. The manufacturer of this solar panel is Solarland. The part number is SLP020-12U. It is a multi-crystalline PV module. The voltage output is in DC and the nominal voltage is 12V. Its weight is 2.8kg and it can be mounted on the roof of an electric car. Its operating temperature is from -40°C to 85°C making it robust for outdoor applications.

For a boost converter, the voltage source selected are lithium phosphate iron batteries. These batteries are commonly used in electric cars. A 120V battery pack will be boosted to produce 420V. These 420V will be used to power the car. Using the 5V voltage obtained from the buck converter, it is boosted its initial 12V for further applications and control of this voltage. Additionally, a 12V solar panel is boosted to 48V. A 12V battery pack can also be used. 48V battery packs are generally used to power electric scooters [18].

A 12V solar panel will be used as a voltage source for the buck-boost converter. Due to the variation in voltage due to varying intensity of the sunlight, the voltage fluctuates between ranges 8V to 18V. When the input voltage is less than 12V the converter will act as a boost (step up) converter and when the input voltage is more than 12V, it will act as a buck converter (step down).

C. Selection of components

The MOSFET that is selected for the switching application is Si7336ADP. It is manufactured by Vishay Siliconix. The drain-source voltage is 30V and the drain current is 30A. It is an N-Channel MOSFET. It has low thermal resistance due to the PowerPAK® mounting. Its turn on delay time for a load resistance of 15 Ω id 24ns and turn off delay time is 90ns.This MOSFET can be used for low-side DC/DC conversion. This MOSFET is used for switching applications in the buck and the boost converter. For the high voltage (120V → 420V) application of the boost converter, a high voltage MOSFET is used. The SPA15N60C3 by Infineon Technologies is a good fit. It has a maximum drain source voltage of 600V and drain current of 15A.

The diode that is selected for buck and boost converter circuits is 1N4148. This is a silicon diode that is manufactured by Vishay Semiconductors. Its reverse voltage is 75V. Its forward voltage is 1V for a forward current of 10mA. Its breakdown voltage is 100V.

D. Simulation Platforms

The simulation platform that is used is LTspice. LTspice is a widely used, accessible, and powerful electronic circuit simulation software developed by Linear Technology which is now a division of Analogue Devices. It is used to create, analyze, and test electronic circuits. It is a flexible and potent tool for electronic circuit simulation. It has a user-friendly interface, an extensive component library, and precise simulation capabilities. This software is used for designing the buck and boost converters.

Matlab Simulink is a powerful tool used for modeling, simulating, and analyzing multidomain dynamical systems. It is an extension of Matlab, a popular programming language and software environment for technical computing. Simulink provides a graphical user interface that allows users to design and simulate dynamic systems using block diagrams, making it particularly useful for engineers and scientists in various fields. The blocks in Simulink represent system components, and users can connect these blocks to create models that depict the behavior of the system. MATLAB/SIMULINK is used for applications of PI control for the buck-boost converter.

E. Design of the Buck Converter

The Buck Converter is designed in such a way that it takes an input voltage of 12V and gives an output voltage of 5V.

Duty cycle is an important metric that indicates how much of a system's operational cycle is spent operating or performing a task.

Calculation of the duty cycle:

$$D = \frac{Ton}{T} \qquad (1)$$

$$Vout = D \times Vin \qquad (2)$$

Where,
D = Duty Cycle
T = Total Time Period
Ton = Time Period for which System is ON
Vout = Output Voltage
Vin = Input Voltage

Equation (1) represents the value of the duty cycle. From equation (2) we can obtain the value of the duty cycle with respect to the output voltage.

By performing these calculations, since our Vin = 12V and Vout = 5V, we can infer that the duty cycle is 0.4167.

$$D = \frac{5}{12}$$

$$D = 0.41666666666667$$

$$D \approx 0.4167$$

Calculation of inductor values:
Equation (3) gives us the value of the inductor.

$$L = \frac{Vout(1-D)}{Fs \times \Delta I} \qquad (3)$$

Where,
L = Inductance
Vout = Output Voltage
D = Duty Cycle
Fs = Switching Frequency
ΔI= Ratio of Ripple Current

The standard value of ΔI range between 0.2 to 0.4. We are setting the switching frequency to 500kHz and 1000kHz to check which frequency rate provides us with the highest frequency. Considering these two variables gives rise to values of inductors. These are mentioned in Table 1.

TABLE I. VALUES OF INDUCTANCE (BUCK)

Fs (kHz)	ΔI	L (µH)
500	0.2	29
1000	0.2	14.6
500	0.3	20
1000	0.3	10
500	0.4	14.6
1000	0.4	7.3

Calculation of capacitance values:
Equation (4) gives us the values of capacitance.

$$C = \frac{Vout(1-D)}{8 \times \Delta V \times L \times Fs} \qquad (4)$$

Where,
C = Capacitance
Vout = Output Voltage
D = Duty Cycle
L = Inductance
Fs = Switching Frequency
ΔV = Ripple Voltage Ratio

The ripple voltage is generally considered equal to or less than 0.01. Considering the varying values of the switching frequency and the inductance as calculated in Table 1, capacitance values are calculated in Table 2. For calculating the values of capacitance, we consider the value of ripple voltage ratio as 0.01.

TABLE II. VALUES OF CAPACITANCE (BUCK)

L (µH)	Fs (kHz)	C (µF)
29	500	5
14.6	1000	2.5
20	500	7.5
10	1000	4
14.6	500	10
7.3	1000	5

Circuit Simulation:

The circuit simulation is done in the LT Spice software. Fig. 4. is the completed circuit design of the buck converter in the LT Spice Simulator.

Where,
V1 = Input Voltage
V2 = Driver Voltage for Switching
M1 = MOSFET (Si7336ADP)
D1 = Diode (1N914)
L1 = Inductor
C1 = Capacitor
R1 = Load Resistance

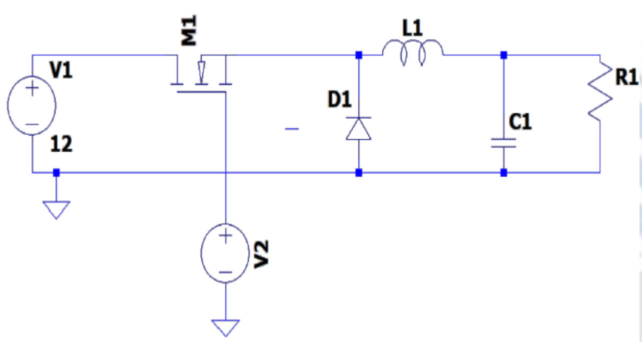

Figure 4. Buck Converter Circuit Simulation

F. *Design of boost converter*

The boost converter is designed to step up the input voltage by a certain factor.

Calculation of the Duty Cycle:

$$D = \frac{Ton}{T} \quad (5)$$

$$Vout = \frac{Vin}{1-D} \quad (6)$$

Where,
D = Duty Cycle
T = Total Time Period
Ton = Time Period for which System is ON
Vout = Output Voltage
Vin = Input Voltage

Equations 5 and 6 represent the calculation of the duty cycle. We have 3 test cases for the duty cycle. The detailed calculations are mentioned in Table 3.

TABLE III. VALUES OF DUTY CYCLE (BOOST)

Vin (V)	Vout (V)	D
120	420	0.7
5	12	0.6
12	48	0.75

Calculation of inductor values:

$$L = \frac{(Vout-Vin) \times D}{Fs \times \Delta I} \quad (7)$$

Calculation of inductor values:
Where,
L = Inductance
Vout = Output Voltage
D = Duty Cycle
Fs = Switching Frequency
ΔI = Ratio of Ripple Current

TABLE IV. VALUES OF INDUCTANCE (BOOST)

Duty Cycle	Fs (kHz)	ΔI	L (µH)
0.7	500	0.2	2143
	1000	0.2	1071
	500	0.3	1428
	1000	0.3	714
	500	0.4	1071
	1000	0.4	536
0.6	500	0.2	41
	1000	0.2	20
	500	0.3	27
	1000	0.3	14
	500	0.4	20
	1000	0.4	10
0.75	500	0.2	270
	1000	0.2	135
	500	0.3	180
	1000	0.3	90
	500	0.4	135
	1000	0.4	67.5

Since we have 3 cases of duty cycles, there will be a total of (3 x 6) = 18 values of inductance. These are mentioned in Table 4. Values of ripple current and switching frequency are the same as seen in the buck converter.

Calculation of capacitance values:
Equation 8 gives us the values of capacitance.

$$C = \frac{D}{\Delta V \times R \times Fs} \quad (8)$$

Where,
C = Capacitance
D = Duty Cycle
Fs = Switching Frequency
ΔV=Ripple Voltage Ratio
R = Load Resistance

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As mentioned in the buck converter capacitance calculations the value of ripple voltage ratio will be considered 0.01. For the 3 cases of duty cycles the load resistance will be 10 ohms as mentioned in Table 5.

TABLE V. VALUES OF CAPACITANCE (BOOST)

D	Fs (kHz)	C(μF)
0.7	500	14.3
	1000	7
0.6	500	11.67
	1000	5.834
0.75	500	15
	1000	7.5

Circuit Simulation:

Fig. 5. is the completed circuit design of the boost converter in the LT Spice Simulator.

Where,
V1 = Input Voltage
V2 = Driver Voltage for Switching
M1 = MOSFET (Si7336ADP)
D1 = Diode (1N914)
L1 = Inductor
C1 = Capacitor
R1 = Load Resistance

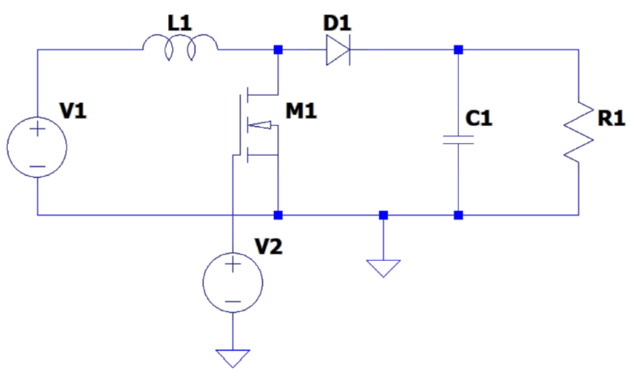


Figure 5. Boost Converter Circuit Simulation

G. Design of the buck-boost converter

A buck-boost converter controls the voltage coming from the solar panel in solar power systems with battery storage to make sure that the batteries are charged efficiently. It steps up the panel's output voltage to match the battery charging voltage when the panel voltage is too low, or steps down when the panel voltage is too high to prevent overcharging. In our project, the input voltage will vary from 8V-18V and the constant output voltage required is -12V.

Specifications:

Below are certain specifications mentioned which are required for the buck-boost converter system.
Output Power = 250W
Output Current = 20.83A
Output Voltage = -12V
Minimum Input Voltage = 8V
Maximum Input Voltage = 18V
Nominal Voltage = 13V
Switching Frequency = 10kHz
ESRCi = 0.008 (equine series resistance for input capacitor)
ESRCo = 0.005 (equine series resistance for output capacitor)

Calculation of the Duty Cycle:

Equations 9 and 10 denote formulae to calculate the duty cycle values for the buck-boost converter.

$$D = \frac{Ton}{T} \qquad (9)$$

$$Vout = \frac{D \times Vimin}{D-1} \qquad (10)$$

Where,
D = Duty Cycle
T = Total Time Period
Ton = Time Period for which System is ON
Vout = Output Voltage
Vimin = Minimum Input Voltage
Therefore, the duty cycle is 0.6.

Calculation of inductance values:

Equation (11) gives us the formula to calculate inductance value for the buck-boost converter.

$$L = \frac{Vnom \times D}{Fs \times \mathrm{ir}I} \qquad (11)$$

Where,
L = Inductance
D = Duty Cycle
Fs = Switching Frequency
ir = Ripple Current of Inductor
Vnom = Nominal Voltage
Therefore, the value of inductor is 0.04056H.

Calculation of capacitance values:

Equation (12) is the formula for calculating capacitance of a buck-boost converter. I_0

$$C = \frac{I_0 \times D}{fs \times V0r - (\frac{I_0}{1-D} + \frac{Ir}{2}) \times ESRC_0} \qquad (12)$$

Where,
C = Capacitance
Vout = Output Voltage
Fs = Switching Frequency
Vor=Output Ripple Voltage
R = Load Resistance
Iout = Output Current
ir= Ripple Current
ESRCo = 0.005 (equine series resistance for output capacitor)
Therefore, the value of capacitance is 0.004587749532402451 F.

Calculation of Minimum Load Resistance:

The value of minimum load resistance is given by the equation 13:

$$R_L \min = \frac{v_o{}^2}{p} \qquad (13)$$

Where,
RLmin = Minimum Load Resistance
Vo = Output Voltage
P = Output Power

Therefore, the value of minimum load resistance is 0.576 ohms. The system is stable up to 75ohms load resistance as seen in simulation testing.

Circuit Simulation:

Fig. 6. is the completed circuit design of the buck-boost converter in MATLAB/SIMULINK.

Where,
V = Input Voltage
D = Diode
L = Inductor
C = Capacitor
R = Load Resistance
CB = Constant Value (Duty Cycle)
Scope = Oscilloscope

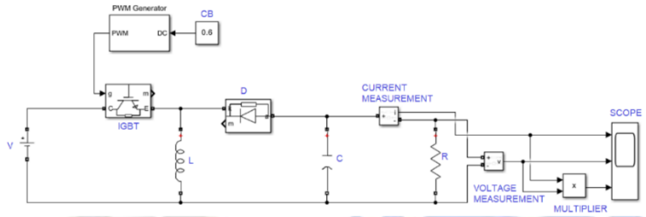


Figure 6. Buck-Boost Converter Simulation

Here the duty cycle is supplied through a PWM generator. To measure the output current and output voltage, measuring devices which are connected to the oscilloscope have been used. A multiplier to multiply the values of current and voltage to find out the output power generated is used. This is a typical application of a buck-boost converter.

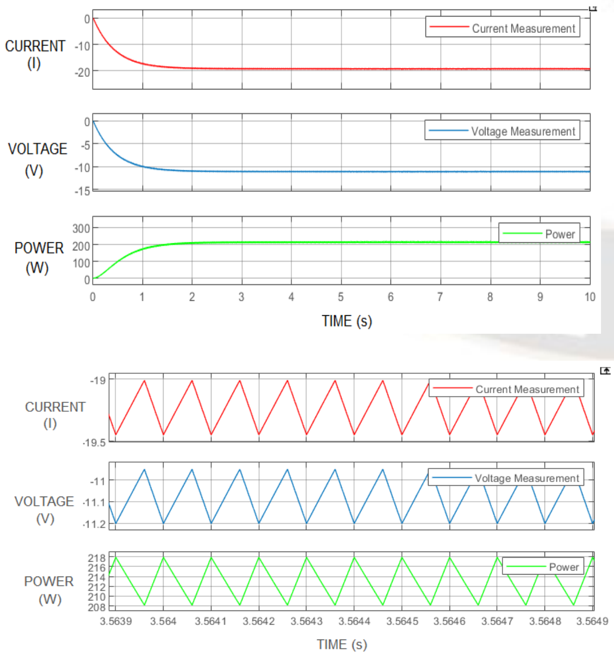


Figure 7. Output of Buck Boost Converter with Input of 9V (Boost Mode)

In the boost mode in Fig. 7. it can be seen that the maximum power produced is 218W, whereas, we need 250W.

In the buck mode in Fig. 8., it can be seen that the output power and voltage exceed our specification.

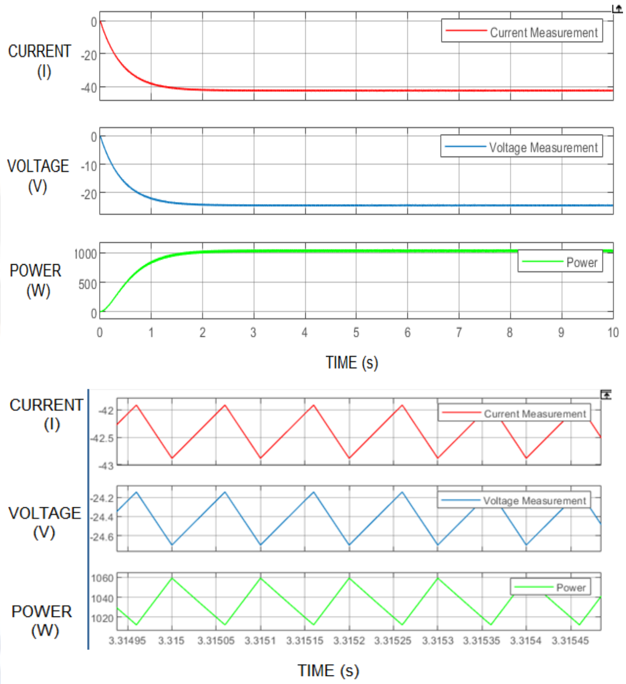


Figure 8. Output of Buck Boost Converter with Input of 18V (Buck Mode)

Hence, we need to create a system for controlling the duty cycle to produce a constant output voltage of -12V and output power of 250W.

PI Control Circuit:

In order to fix the above problem, Fig. 9. shows us the modified buck-boost converter circuit with PI control.

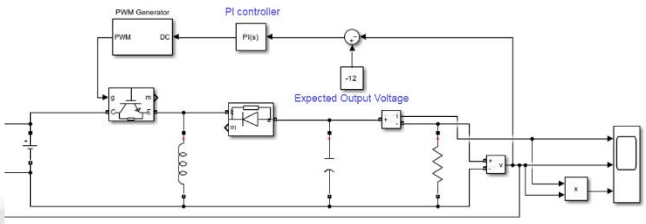


Figure 9. Buck Boost Converter PI Control

Ziegler Nichols Method Algorithm:

The critical gain (Kc) is the gain at which the system just starts to oscillate without exponentially growing or decaying.

The ultimate period (Pu) is the time taken for one complete oscillation cycle in the response. It's typically the time between successive peaks or troughs in the response curve.

According to the algorithm, after completing all the steps, the kc and pu values are:
kc= -0.03608387451783378
pu= -17.876501034027804
Algorithm: Ziegler-Nichols PI Tuning
Input: System to be controlled with a PI controller
Output: Tuned values of Kp (proportional gain) and Ki (integral gain)

1. Perform a step test on the system to obtain the response data.
   1.1. Apply a step input to the system and record the output response data.
2. Analyse the response data to determine the critical gain (Kc) and ultimate period (Pu).
   2.1. Identify the critical gain (Kc) when sustained oscillations begin.
   2.2. Measure the ultimate period (Pu) as the time for one complete oscillation cycle.
3. Calculate the proportional gain (Kp) and integral gain (Ki) using Ziegler-Nichols PI tuning rules.
   3.1. Kp = 0.45 * Kc
   3.2. Ki = 1.2 / Pu
4. Implement the PI controller with the calculated Kp and Ki values.
5. Test the control system with the PI controller using the calculated gains.
6. Fine-tune the gains, if necessary, based on the performance of the controlled system.
7. Iterate the testing and fine-tuning steps until the desired control performance is achieved.
8. Output the tuned values of Kp and Ki for the PI controller.

End Algorithm

Hence, by using the formulae, we can get the values of kp and ki, that are:

kp= -0.0162377435330252

ki= -0.0671272301954285

We tune the PI controller with the calculated values of kp and kc.

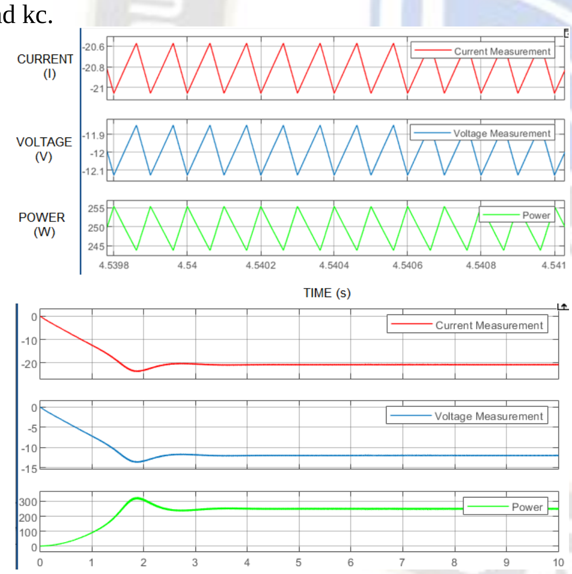
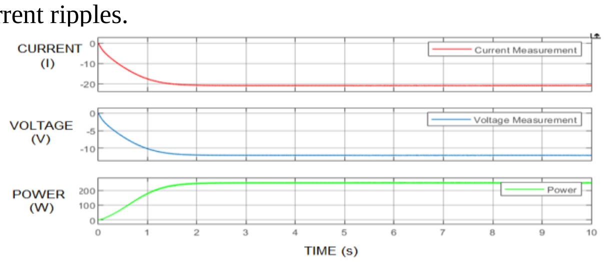


Figure 10. Output of Buck Boost Converter with Input of 9V (Boost Mode)

Fig. 10 and 11 shows the simulation of the PI tuned buck-boost converter. The results section discusses the voltage and current ripples.



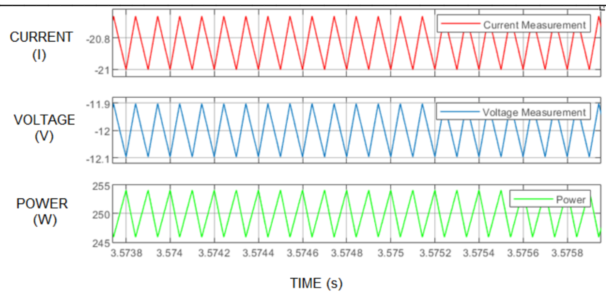


Figure 11. Output of Buck Boost Converter with Input of 18V (Buck Mode)

IV. Results

Buck Converter Results:

Table 6 represents the accuracy of the buck converter with varying parameters.

TABLE VI. Buck Converter Results

L (µH)	C (µF)	Fs (kHz)	Vin (V)	Vout (V)	Accuracy (%)
29	5	500	12	4.97	99.4
14.6	2.5	1000	12	5.04	100.8
20	7.5	500	12	4.98	99.6
10	4	1000	12	5.04	99.2
14.6	10	500	12	4.98	99.58
7.3	5	1000	12	5.03	99.4

In Table 6 we can see that the highest accuracy is for case numbers 2 and 4. We shall calculate their efficiency.

For case number 2, input current = 0.85A and output current = 1.8A. Therefore, the efficiency is 88.23%.

For case number 4, input current = 0.65A and output current = 1.5A. Therefore, the efficiency is 96.15%.

Hence, case 4 parameters are the most accurate and efficient for the buck converter system. Figure 12 represents the same.

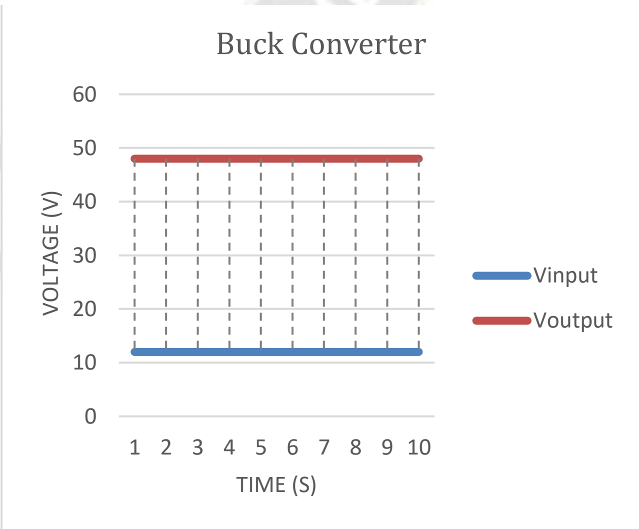


Figure 12. Buck Converter Simulation

Boost Converter Results:

For duty cycle = 0.7, the input voltage is 120V and expected output voltage is 420V.

In Table 7, the first case is the most accurate one. Hence, we shall calculate its efficiency. Input voltage is 200A and output voltage is 55A. Therefore, the efficiency is 96.25%.

TABLE VII. BOOST CONVERTER RESULTS

Duty Cycle	Fs (kHz)	C (µF)	L (µH)	Vout	Accuracy (%)
0.7	500	14.3	2142	420	100
			1428	425	98.80952
			1071	428	98.09524
	1000	7	1071	455	91.66667
			714	440	95.2381
			536	448	93.33333
0.6	500	11.67	41	12.4	96.66667
			20	12.4	96.66667
			27	12.4	96.66667
	1000	5.834	14	13.2	90
			20	13.1	90.83333
			10	13.2	90
0.75	500	15	270	46.8	97.5
			135	46.8	97.5
			180	46.5	96.875
	1000	7.5	90	48.6	98.75
			135	48.2	99.58333
			67.5	48.6	98.75

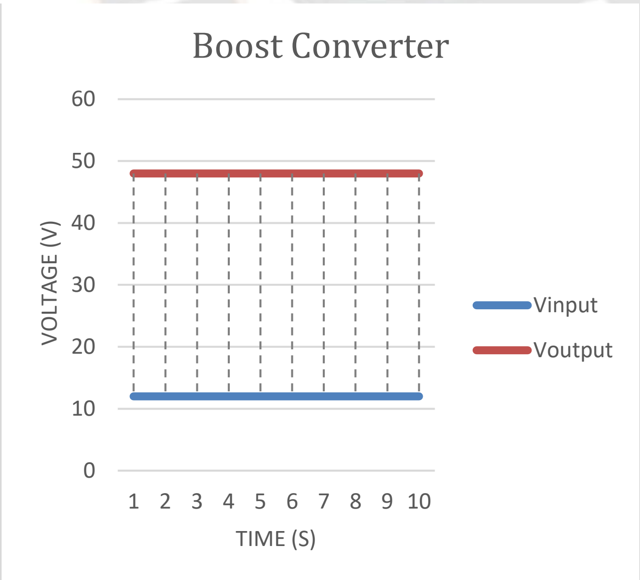


Figure 13. Boost Converter Simulation (Case 1)

Fig. 13. Depicts the boost converter simulation for the highest power efficiency where duty cycle is 0.7.

For duty cycle = 0.6, the input voltage is 5V and expected output voltage is 12V.

In Table 7, we can see that case 1,2,3 are the most accurate. Table 8 gives us an idea about their input current, output current and its efficiencies. Table 8 indicates that parameters of case 1 are the most efficient.

In table 8, the switching frequency is 500Hz and value of capacitance 11.67 micro farad for all cases.

TABLE VIII. BOOST CONVERTER EFFICIENCY

L (µH)	Vout	Accuracy (%)	Efficiency (%)	I in (A)	I out (A)
41	12.4	96.66667	93.58%	4.77	1.8
20	12.4	96.66667	84.42%	4.7	1.6
27	12.4	96.66667	91.91%	4.7	1.8

In Table 7 we can see that case 5 has the most accuracy. Hence, we calculate its efficiency. The input current is 24A and the output current is 8.4A which gives us an efficiency of 96.67%.

Buck-Boost Converter Results:

Power:

The input power of this buck-boost converter is 260W. The output power is 250W, as seen in Fig.15. 250W is the required power. Thus, the power efficiency of the PI controlled buck-boost converter is 96.15%.

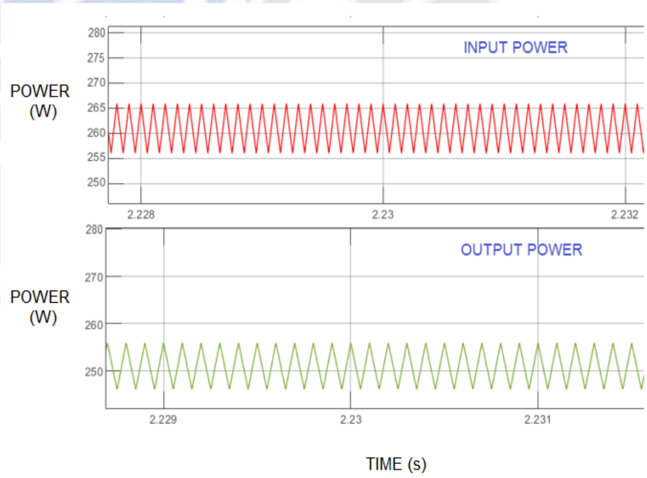


Figure 14. Power of Buck-Boost Converter

Output Ripple Voltage:

The output voltage ripple is given by equation (14):

$$V_{ripple} = V_o \max - V_o min \quad (14)$$

Where,

V_0 max = Maximum Output Voltage

V_0 min = Minimum Output Voltage

According to Fig.17, there is mimimal voltage ripple. The maximum output voltage is 12.8V and the minimum output voltage is 11.92V. Hence the voltage ripple is 0.88V.

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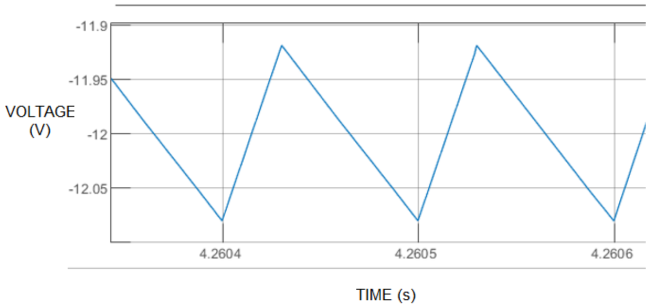

Figure 15. Voltage Ripple of Buck-Boost Converter

Fig. 15 denotes the voltage ripple. The time period is 0.0001s, therefore the frequency is 10kHz.

Output Current Ripple:
The output current ripple is given by equation (15):

$$I_{ripple} = I_o \max - I_o min \quad (15)$$

Where,
I_0 max = Maximum Output Current
I_0 min = Minimum Output Current

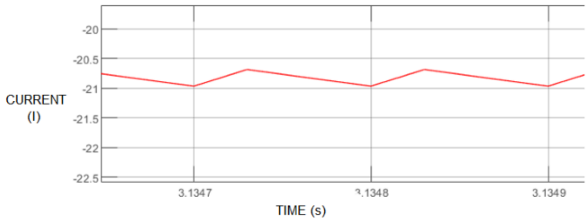

Figure 16. Current Ripple of Buck-Boost Converter

According to Fig.16, there is some current ripple. The minimum output current is 20.71V and the maximum output current is 20.945. Hence the output ripple current is 0.235A. The time period for the oscillations is 0.0001s. Therefore, the frequency is 10kHz.

Delay to Stabilise:
From Fig.17, it can be seen that, it takes approximately 2 seconds to stabilize the duty cycle.

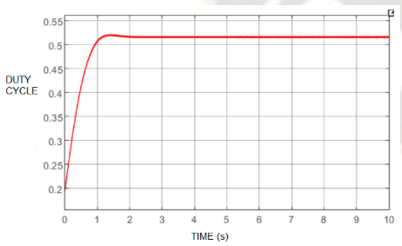

Figure 17. Delay of Converter

Thus, the delay to stabilise is 2 seconds.
PWM:
Fig. 18. shows the PWM in the boost mode. From 9V to 12V. The time period is 0.0001. Therefore the frequency is 10kHz. The duty cycle is 0.61.

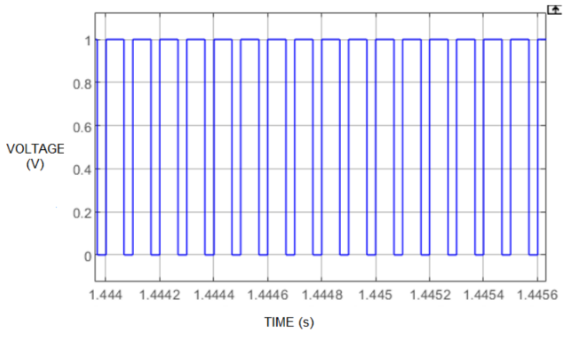

Figure 18. PWM in Boost Mode

Fig. 19. shows the PWM in the buck mode. From 18V to 12V. The time period is 0.0001. Therefore the frequency is 10kHz. The duty cycle is 0.43.

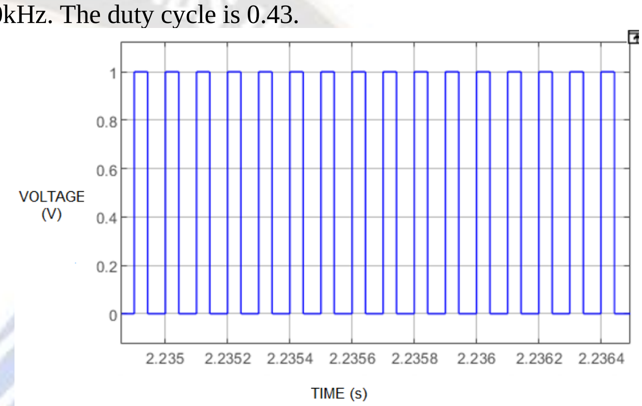

Figure 19. PWM in Buck Mode

Overall Converter Efficiencies:

Table 9 presents the summary of the best efficiencies of the system. For the buck and boost efficiencies, the power efficiencies are mentioned.

TABLE IX. OVERALL EFFICIENCIES

Converter	**Voltage (V)**	**Power Efficiency (%)**
Buck	12 → 5	96.15%
Boost	120 → 420	96.25%
	5 → 12	93.58%
	12 → 48	96.67%.

Table 10 summarises different parameters to evaluate the efficiency of a PI controlled Buck-Boost Converter.

TABLE X. BUCK-BOOST PARAMETERS

Parameters	**Value**
Power	96.67% Efficient
Output Voltage Ripple	0.0178V
Output Current Ripple	0.235A
Delay To Stabilise	2s
PWM Boost Mode (9V)	0.61
PWM Buck Mode (18V)	0.43

V. CONCLUSION AND FUTURE SCOPE

Thus, this study successfully showcased 3 dc-dc converters of the types buck, boost and buck-boost in alignment to PV systems and EVs. Specific real-world examples and voltage values have been demonstrated to present an idea regarding how these systems would work in real life. With the help of these examples, further research can be done in this area. This project has aimed to demonstrate the use of these converters in EVs with the objective of conserving resources and promoting sustainability.

The future scope of this work is to practically implement this buck, boost or buck-boost converter with hardware connected to a real-world EV. The future scope also includes the in-depth analysis of various solar panels that can be used as voltage sources. Analysis is required in this project in accordance to the electronic components available in the market today. These steps will help move this project in the direction of bringing it to reality.

In this research, a novel approach to Buck-Boost converters for EV applications is presented. By implementing a PI control system, we significantly enhance efficiency and adhere to industry standards, optimizing voltage conversion and contributing to improved EV performance and range. The analysis includes a thorough examination of the specific applications of Buck, Boost, and Buck-Boost converters, ensuring alignment with industry norms and requirements.

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