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DESIGN AND ANALYSIS OF A PV-BASED CASCADED BUCK-BOOST CONVERTER

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Abstract - *This paper presents the design and analysis of a cascaded buck-boost converter for electric vehicle battery charging. The converter enhances efficiency, reduces inductor current ripple, and achieves fast switching speeds, ideal for high-performance applications. MATLAB simulations with closed-loop control and PWM generation show significant improvements in ripple reduction and faster switching speeds, validating the potential of the cascaded buck-boost converter in modern EV charging systems.*

Key Words: Electric Vehicle (EV), Cascaded buck-boost converter (CBB) Photo Voltaic (PV), Maximum power point tracking (MPPT), Inductor current ripple reduction, Fast switching speed, MATLAB simulation, Closed-loop control (CLC), Pulse Width Modulation (PWM) generation, Renewable energy technologies.

1. INTRODUCTION

This project aims to develop an off-board EV battery charger using grid electricity and solar power. Leveraging India's solar resources, the initiative promotes decentralized electricity generation. Integrating solar PV technology with EV charging stations encourages energy independence and reduces reliance on fossil fuels. The system's automatic buck and boost configuration enhances energy management, ensuring a reliable energy supply even during grid fluctuations. Simulations in MATLAB validate the feasibility of this Cascaded Buck-Boost converter (CBB), marking a significant advancement in EV charging technology and renewable energy utilization.

2. PROJECT OVERVIEW

Photovoltaic (PV) generation offers advantages like no fuel costs, low maintenance, and no pollution. However, PV modules have low efficiency, necessitating a high-efficiency power conditioning system (PCS). A single-phase PV PCS consists of DC-DC and DC-AC conversion stages. The DC-DC converter controls maximum power point tracking (MPPT) via duty ratio modulation. Though commonly used, the Cuckoo algorithm has limitations. A cascaded converter improves efficiency for high-power applications, reducing conduction loss and voltage ripple. The proposed topology predicts the optimal duty ratio based on solar irradiation. MATLAB simulations with closed-loop control and WM generation enhance performance. Initially, power is sourced from the grid, converted to 12V DC, and boosted to 24V if needed. A four-channel relay selects the best power source, interfacing with an Arduino Nano for regulation. The cascaded converter maintains constant voltage, reducing ripple and switching loss. This project demonstrates the advantages of using a cascaded buck-boost converter for PV modules, improving efficiency and performance.

2.1 Objectives of the study

The primary objectives of this study are to design, to analyze the performance of a Cascaded Buck & Boost converter using a PV panel. To develop the prototype model of the Cascaded Buck & Boost converter. This approach not only enhances system efficiency but also guarantees a dependable power supply for diverse applications, with the output power utilized for battery charging.

2.2 Problem Formulation

A comparison between a conventional DC-DC converter and a cascaded Buck & Boost converter is done based on various parameters like manual feedback, input current ripple & output voltage ripple. The main aim is to obtain a high-accuracy converter with reduced input current ripple and reduced output voltage ripple as shown in Table 1.

2.3. Importance of work

The cascaded converter provides continuous load output. For higher current applications, it is preferable. It will improve the efficiency and reduce the maintenance needed for any photovoltaic system. It provides a faster switching speed and reduces inductor current ripple.

Table-1: Comparison between conventional DC-DC converter and cascaded Buck & Boost converter

S.No	Conventional Buck-Boost Converter	Cascaded Buck-Boost Converter
1	Efficiency is low	Improved efficiency
2	Buck or Boost conversion works in either one topology	Simultaneous Buck Boost operation is achieved
3	Increase in inductor current ripple	Reduced Inductor current ripple
4	Slow switching speed	Fast switching speed

3. EXISTING SYSTEM

The conventional DC-DC converter faces limitations like input/output ripple and efficiency. The Cascaded Buck-Boost (CBB) converter addresses these issues, offering high-gain conversion, reduced ripple, and better performance for EV charging systems. Its design enhances voltage boost/buck capabilities, making it ideal for high step-up/down power conversion.

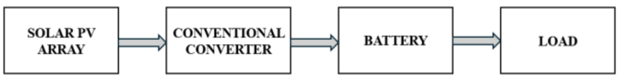

Fig -1: Existing boost converter system

3.1 Limitations of the existing system

The existing system's limitations impact efficiency and reliability. Firstly, the total current flowing through a single switch increases voltage stress. Additionally, high input ripple current and output voltage ripples cause performance issues. Significant switching losses lead to inefficient energy use, and overall voltage stability is low, making the system less reliable. These factors collectively limit effectiveness and efficiency, highlighting the need for improvements.

4. PROPOSED SYSTEM

The cascaded buck & boost concept is used in this work to obtain noninverting output to run the constant DC load as shown in Fig.1.The design equations have been presented, and performance parameters have been related using theoretical calculations and simulation. The operation principle and steady-state performance are analyzed and finally, the experimental results are given, moreover, the derivation of the proposed converter is also presented.

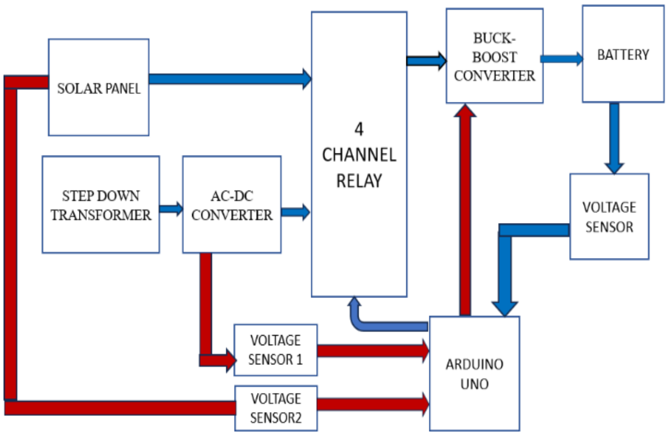

Fig -2: The proposed system operation

5. METHODOLOGY & DESIGN

Initially, power is sourced from the grid and routed through a step-down transformer to convert the 230V AC voltage to 12 V AC. Subsequently, a 12 V AC to 12 V DC conversion is achieved using an AC-DC Converter. A 12 V solar panel is employed, with a boost converter enhancing the voltage to 24 V when necessary. Outputs from both the solar panel and the step-down transformer are directed to a four-channel relay. The relay interfaces with a voltage and current sensing circuit, as well as an Arduino Nano for regulation and control. The relay selects the best power source that is available and disables another source. The relay output is connected to voltage voltage-sensing circuit to measure and modify the voltage. The output from the four-channel relay is connected to the cascaded buck-boost converter, which bucks or boost automatically the voltage if the voltage level decreases or increases from the solar panel or grid making it constant and preventing it from varying. The converter is connected to the battery which charges from the cascaded converter and it has a voltage sensor to check if the required voltage is achieved. The Arduino governs the circuit operations and initiates the signaling process. A dedicated circuit for voltage and current sensing measures these parameters from both sources for display purposes. Utilizing Arduino code, the system selects the power source with the higher voltage. Values can be monitored via a serial monitor or an LCD. The output voltage received can be used to charge the load through the battery.

5.1. THEORETICAL ANALYSIS

Fig 3 shows the circuit diagram of a cascaded Buck-Boost converter and Table 1 shows the Comparison between a conventional DC-DC converter with a cascaded buck-boost converter.

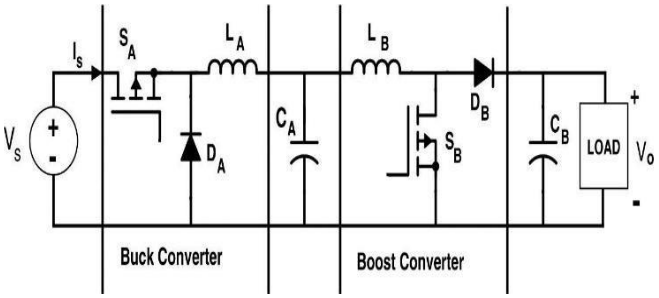

Fig -3: Circuit Diagram of CBB converter

4.2. Selection of Converter Components

1. Input voltage ranges:

Input Voltage $V_{in}(min)$ = 8.00 V

Input Voltage $V_{in}(max)$ = 11.0 V

Input Voltage $V_{in}(avg)$ = 9.50 V

2. Output voltage & current ranges:

Output Voltage Vo (Boost) = 12.0 V

Output Voltage Vo (Buck) = 4.0 V

Output Current Io = 1.0 A

3. Calculation of Duty Cycle (Boost):

$$\text{Duty Cycle } D1 = 1 - \frac{Vin(avg)}{Vout} = 20.83\ \%$$

4. Calculation of Duty Cycle (Buck):

$$\text{Duty Cycle } D2 = \frac{Vout}{Vin(avg)} = 42.10\ \%$$

5. Calculation of inductor (Boost):

$$\text{Inductance } L1 = \frac{D1(Vout - Vin(avg))}{Fs \times \Delta IL1} = 564\ \mu H$$

6. Calculation of inductor (Buck):

$$\text{Inductance } L2 = \frac{D2(Vout - Vin(avg))}{Fs \times \Delta IL2} = 78\ H$$

7. Calculation of inductor ripples current (Boost):

Inductor Ripple Current $\Delta I\ (L1)$ =

20% to 40% of Io = 0.03 A

8. Calculation of inductor ripples current (Buck):

Inductor Ripple Current $\Delta I\ (L2)$ =

20% to 40% of Io = 0.118 mA

9. Output Capacitor selection (Boost):

$$\text{Output Capacitance Co} = \left[\frac{I_{O \times D1}}{Fs \times \Delta Vout}\right] = 22\ \mu F$$

Where,
Output voltage ripple

$$\Delta Vout = ESR\left[\frac{Io}{1-D1} + \frac{\Delta I_L}{2}\right] = 0.378v$$

10. Output Capacitor selection (Boost):

$$\text{Output Capacitance Co} = \left[\frac{\Delta I_{L2}}{8 \times Fs \times \Delta Vout}\right] = 22\ \mu F$$

Where,
Output voltage ripple

$$\Delta Vout = ESR\left[\frac{Io}{1-D2} + \frac{\Delta I_L}{2}\right] = 0.378\ V$$

Table-2: Hardware specifications

S.No	Values	Parameters
1	Input voltage *Vin(avg)*	9.5V
2	Converter efficiency *(η)*	99%
3	Buck Inductor *(L1)*	0.78H
4	Boost Inductor *(L2)*	564µH
5	Buck Capacitor *(C1)*	220µF
6	Boost Capacitor *(C2)*	22µF
7	Switching frequency *(Fs)*	25 kHz
8	Buck Duty cycle *(D1)*	42.10%
9	Boost Duty cycle *(D2)*	20.83%
10	Load Resistance *(RR)*	1000Ω
11	Output Voltage ripple	1.63v
12	Inductor ripple current *(ΔIL)*	1.350v
13	Output voltage *(Vout)*	12v(Boost)

6. SIMULATION ANALYSIS

This project outlines the circuit design of the Cascaded Buck-Boost converter-based controller, including a solar panel, voltage measurement circuit, and cascaded converter design with MOSFET switches. The MATLAB model consists of inductors, output capacitors, blocking diodes, and resistive loads. For verification, simulations were done with a 7.5 Ω resistive load, 1.5mH inductors, 500μF output capacitors, a 10 kHz switching frequency, and a 1e−6 sampling time. The system operates in Buck mode when the input is 24V and the reference is 12V, and Boost mode when the input is 12V and reference is 24V, adjusting the duty cycle accordingly.

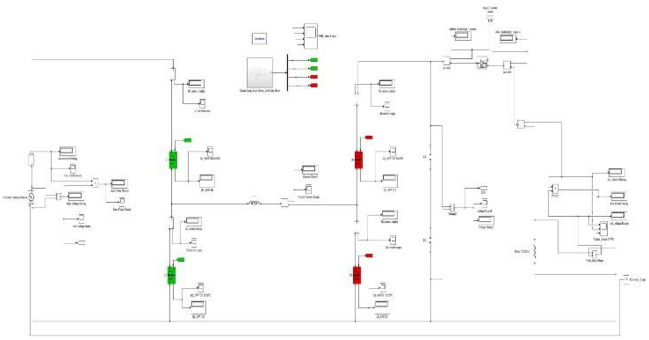

Fig -4: MATLAB Model of Cascaded Converter

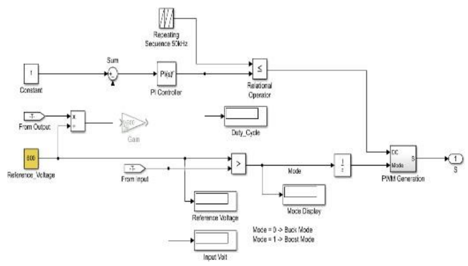

Fig -5: Closed loop buck-boost controller block

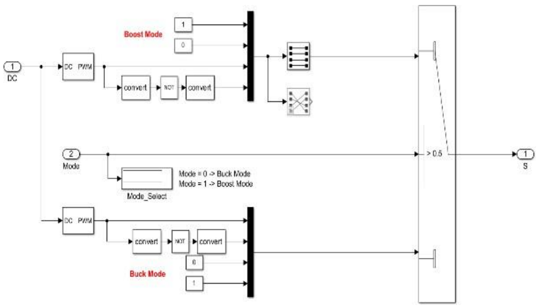

Fig -6: PWM generation block

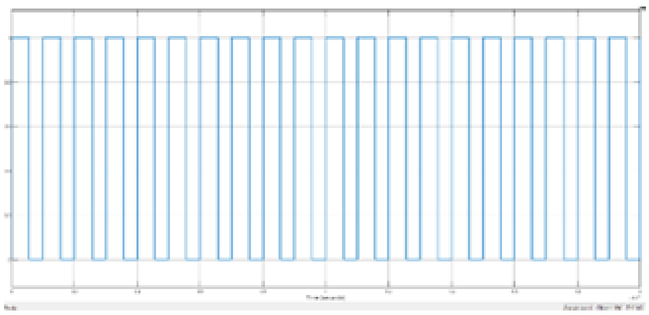

Fig -7: PWM signals

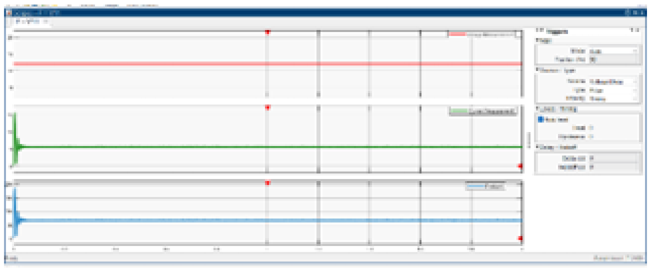

Fig -8: Input voltage, current, and power during Boost operation.

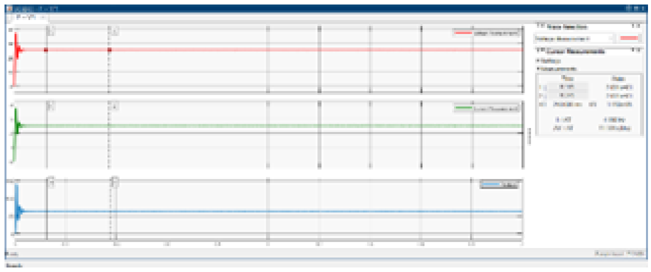

Fig -9: Output voltage, current, and power during Boost operation.

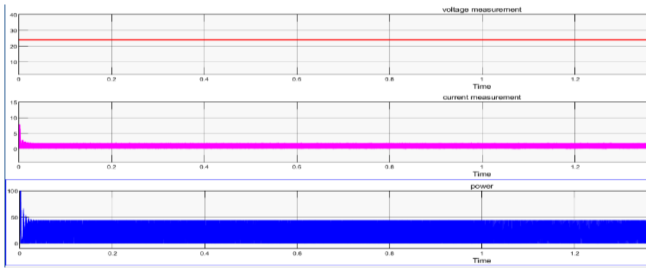

Fig -10: Input voltage, current, and power during Buck operation.

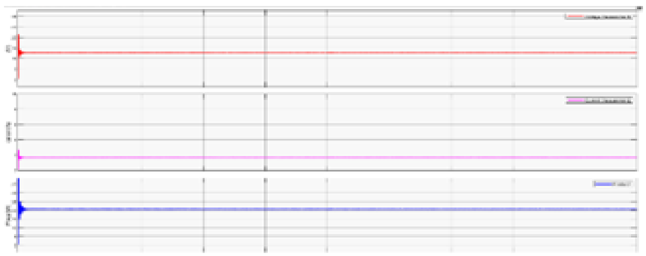

Fig -11: Output voltage, current, and power during Buck operation.

7. HARDWARE ANALYSIS

When varying the input voltage of the solar panel manually using a potentiometer from (8-12) V the constant output of 12V is given by the converter in order to maintain the constant voltage for the battery charging. If the voltage of the batteries drops below 20 v, the battery won't get charged. Since we developed the prototype model of the Cascaded converter, we can also verify the results using MATLAB Simulation.

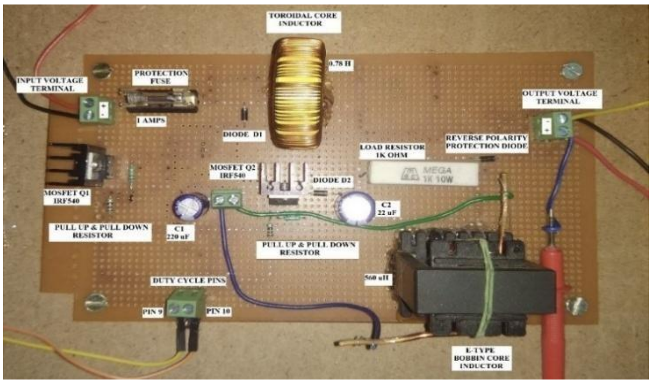

Fig -12: Cascaded Buck-Boost converter

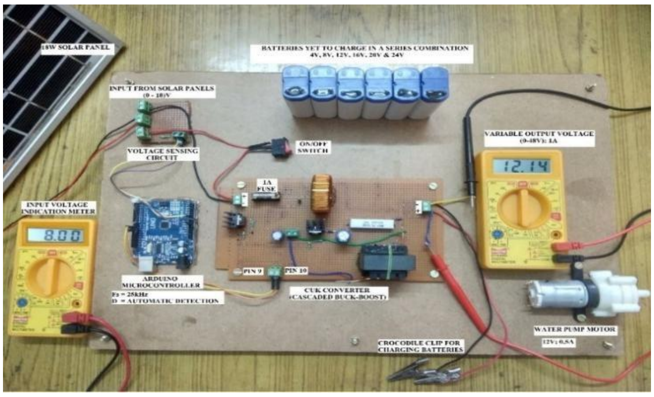

Fig -13: Input voltage 8.00V with constant 12V output voltage

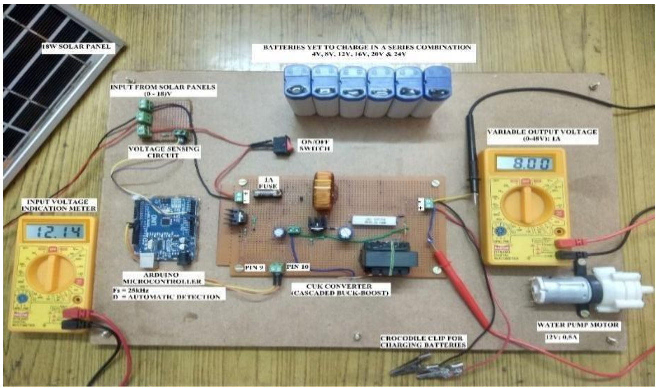

Fig -14: Input voltage 12V with constant 8V output voltage

8. RESULT

The following tabulations show the results from hardware system validation and simulation results from MATLAB. As we can see in both cases, we get the constant DC voltage required for charging the battery. This work increases the efficiency of the system, reduces inductor ripple current, and provides a faster switching speed.

Table-3: Input Output Tabulation of Hardware Implementation

S.No	Input Voltage (Variable Input)	Output Voltage (Constant Output)	Mode of Operation
1	8.00V	12.14V	Boost Mode
2	8.49V	12.35V	
3	10.01V	12.41V	
4	11.94V	12.39V	
5	24V	12.20V	Buck mode
6	23.67V	12.45V	
7	22.88V	12.67V	
8	22.00V	12.44V	

Table-4: Results from the simulation

S.No	Input Voltage (Variable Input)	Output Voltage (Constant Output)	Mode of Operation
1	(24-20) V	12.25V	Buck mode
2	(22-19) V	12.40V	
3	(8-12) V	12.3V	Boost Mode
		16.5V	
		20.4V	
		24.6V	
4	Less than 8V	Cut off Mode	

9. SUSTAINABLE DEVELOPMENT GOALS

Goal 7:Affordable and Clean Energy

The project aims to harness solar energy for charging EV batteries. Solar energy is a renewable and abundant resource, significantly reducing greenhouse gas emissions compared to traditional fossil fuels. By utilizing solar power, the project not only supports the adoption of clean energy but also makes EV charging more affordable for consumers, thereby encouraging the widespread use of sustainable energy sources.

Goal 11: Sustainable Cities and Communities

Encouraging the use of electric vehicles (EVs) supports cleaner and more sustainable urban development. EVs produce zero tailpipe emissions, leading to improved air quality and reduced noise pollution in cities. By reducing the carbon footprint of transportation, the project contributes to the development of smart and sustainable cities.

Goal 13: Climate Action

Reducing dependence on fossil fuels through the use of renewable energy sources helps mitigate climate change. The project addresses the urgent need to cut down on greenhouse gas emissions by promoting the use of solar energy for EV charging.

Goal 12: Responsible Consumption and Production

Promoting resource and energy efficiency within the project fosters sustainable consumption and production patterns. The use of solar energy for EV charging minimizes the depletion of non-renewable resources and reduces environmental impact. The project encourages responsible use of resources by optimizing energy consumption and promoting sustainable production practices.

10. CONCLUSION

In this work, a Cascaded Converter was designed and the simulation results obtained for the proposed system and the performance of the same are validated using experimental results [6]. The performance of the converter was analyzed using prototype by both buck & boost operation where rated input voltage of solar panel value from (8-12) V is boosted to 12V, 16V & 24 V then also reduced to 4V & 8 V under 1 kΩ load condition to charge the battery. In conclusion, EV charging is an essential aspect of electric vehicle ownership and the transition to sustainable transportation.

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