

Design and Implementation of a Buck-Boost Converter for Power Factor Correction in Plug-In Electric Vehicle Battery Chargers

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Abstract—This project presents the design and implementation of a high-efficiency Buck-Boost converter for power factor correction (PFC) in Plug-In Electric Vehicle (PEV) battery chargers. The rapid growth of electric vehicles has increased the demand for compact and efficient charging systems that can maintain a high power factor while delivering a stable DC output over a wide input voltage range. Conventional chargers often draw distorted current from the AC supply, resulting in poor power factor, increased harmonic distortion, and reduced energy efficiency. To address these issues, a Buck-Boost converter topology is proposed due to its ability to both step up and step down the input voltage according to battery charging requirements. The converter is controlled using a pulse width modulation (PWM) technique to regulate output voltage and shape the input current to follow the sinusoidal waveform of the supply voltage. This approach significantly improves the power factor and reduces total harmonic distortion (THD). The system is modelled and analysed using simulation tools, and experimental implementation validates the theoretical results. Performance parameters such as efficiency, output voltage regulation, and power quality are evaluated under different operating conditions. The proposed converter demonstrates reliable performance, making it a suitable and cost-effective solution for modern PEV battery charging applications.

Index Terms—Battery Charger, DC-DC Converter, Dual Active Bridge (DAB), LLC Resonant, SEPIC, Cuk, Flyback, Continuous Conduction Mode (CCM), Loop Compensation, Right-Half-Plane (RHP) Zero.

I. INTRODUCTION

The rapid growth of transportation electrification has created a strong demand for efficient, reliable, and environmentally sustainable battery charging systems for Plug-In Electric Vehicles (PEVs). Plug-in electric vehicles (PEVs), which include battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), are increasingly adopted due to their ability to reduce greenhouse gas emissions, decrease dependence on fossil fuels, and improve energy efficiency. The performance, charging speed, and longevity of these vehicles depend heavily on the design of the onboard battery charger.

Among the many challenges faced in charger design, maintaining a high power factor and minimising harmonic distortion are particularly important because chargers are connected directly to the utility grid. Poor power factor results in increased current demand, higher transmission losses, voltage distortion, and possible penalties from utility providers. There-

fore, Power Factor Correction (PFC) has become an essential requirement in modern electric vehicle charging systems.

Power Factor Correction is a technique used to improve the ratio between real power and apparent power drawn from the AC mains. Ideally, a charger should draw a sinusoidal input current that is in phase with the supply voltage, resulting in a power factor close to unity. Regulatory standards such as International Electrotechnical Commission IEC 61000-3-2 require electronic equipment to limit harmonic currents and improve input current quality. To achieve these objectives, PFC converters are integrated into the front end of battery chargers. These converters shape the input current, reduce total harmonic distortion (THD), and ensure efficient utilisation of the electrical grid. In electric vehicle chargers, where power ratings range from a few hundred watts to several kilowatts, the use of efficient and compact PFC converters is particularly significant.

Among the various DC-DC converter topologies available, the buck-boost converter has emerged as a versatile and attractive solution for PFC applications. Unlike conventional buck converters, which only reduce voltage, or boost converters, which only increase voltage, the buck-boost converter can both step down and step up the output voltage depending on operating conditions. This capability is highly beneficial in battery charging applications, where the battery voltage varies significantly during charging and may be either lower or higher than the rectified input voltage. The buck-boost topology thus offers greater flexibility and enables effective charging over a wide range of battery voltages without requiring multiple converter stages.

II. METHODOLOGY

The methodology adopted for the design and implementation of a Buck-Boost Converter for Power Factor Correction (PFC) in Plug-In Electric Vehicle (PEV) battery chargers consists of systematic stages including requirement analysis, converter design, mathematical modeling, control strategy development, simulation, hardware implementation, and performance evaluation. The main objective is to develop a high-efficiency AC-DC converter capable of regulating the DC output voltage while maintaining a near-unity power factor and low total harmonic distortion (THD).

A. System Requirement Analysis

The first step in the methodology is to define the electrical specifications required for a typical Level-1 PEV battery charger. The charger receives single-phase AC input from the utility grid and converts it into a regulated DC voltage suitable for charging lithium-ion batteries.

The design specifications are outlined below:

- Input Voltage: 230 V AC, 50 Hz
- Output Voltage: 200–400 V DC
- Rated Output Power: 1.5 kW
- Switching Frequency: 50 kHz
- Power Factor Target: > 0.99
- THD Target: < 5%
- Efficiency Target: > 95%

B. Selection of Buck-Boost Converter Topology

The Buck-Boost converter is selected because it can operate in both step-up and step-down modes. This characteristic is particularly advantageous in battery chargers where battery voltage varies significantly during charging.

Advantages of Buck-Boost Converter:

- Ability to maintain constant DC output over a wide battery voltage range.
- Simple circuit configuration.
- Reduced component count compared to multi-stage converters.
- High efficiency under varying load conditions.
- Effective implementation of power factor correction.

The converter consists of an input diode bridge rectifier, inductor (L), MOSFET switch (S), fast recovery diode (D), output capacitor (C), and battery load.

C. Operating Principle

The AC mains voltage is first rectified into an unregulated DC waveform. The Buck-Boost converter shapes the input current to follow the input voltage waveform by controlling the duty cycle of the MOSFET.

- **ON State:** When the MOSFET is ON, the inductor stores energy, the diode becomes reverse-biased, and the output capacitor supplies power to the battery.
- **OFF State:** When the MOSFET is OFF, stored inductor energy is transferred to the battery, the diode becomes forward-biased, and the output capacitor smooths the output voltage.

By modulating the duty cycle at high frequency, the converter regulates output voltage and ensures sinusoidal input current.

D. Mathematical Modelling

The voltage conversion ratio of an ideal Buck-Boost converter is given by:

$$\frac{V_o}{V_{in}} = -\frac{D}{1-D} \quad (1)$$

Where V_o is the output voltage, V_{in} is the input voltage, and D is the duty cycle. The negative sign indicates polarity

inversion, which can be corrected by practical non-inverting implementations.

For power factor correction, the reference current is generated as:

$$i_{ref}(t) = I_m \cdot \sin(\omega t) \quad (2)$$

This equation ensures that the input current remains proportional to the instantaneous input voltage, resulting in a unity power factor.

E. Component Design

1) *Inductor Design:* The inductance is calculated using:

$$L = \frac{V_{in} \cdot D}{\Delta I_L \cdot f_s} \quad (3)$$

Where ΔI_L is the allowable ripple current (20–30% of rated current) and f_s is the switching frequency. A ferrite-core inductor with low core losses is selected.

2) *Output Capacitor Design:* The output capacitor is determined from:

$$C = \frac{I_o \cdot D}{\Delta V_o \cdot f_s} \quad (4)$$

where ΔV_o is the acceptable output voltage ripple (typically 1–2%).

3) *Switch and Diode Selection:*

- **MOSFET:** 650 V, low $R_{DS(on)}$
- **Diode:** 600 V ultra-fast recovery diode or silicon carbide (SiC) diode
- **Capacitors:** High-voltage electrolytic with film bypass capacitors

F. Control Strategy

A dual-loop control strategy is implemented.

- **Outer Voltage Loop:** The output voltage is compared with the desired charging voltage. A PI controller processes the error and generates the current reference amplitude.
- **Inner Current Loop:** The actual inductor current is compared with the reference current. Another PI controller adjusts the PWM duty cycle to force the current to track the sinusoidal reference.
- **Pulse Width Modulation:** The duty cycle generated by the current controller is compared with a high-frequency triangular carrier to produce gate pulses for the MOSFET.

This control strategy ensures a constant output voltage, high power factor, fast transient response, and stable charging operation.

G. Hardware Implementation

The prototype is developed using the following components:

- STMicroelectronics MOSFET
- Current sensor (Hall-effect or shunt-based)
- Voltage divider sensing circuit
- Texas Instruments gate driver IC
- Microchip Technology dsPIC or similar DSP controller
- Isolated auxiliary power supply

- Heat sinks and protection circuits

A compact PCB is designed with short high-current paths, ground plane separation, EMI filters, and efficient thermal management.

III. DESIGN AND EXPERIMENTAL SETUP

The design of a Buck-Boost converter for Power Factor Correction (PFC) in Plug-In Electric Vehicle (PEV) battery chargers is aimed at achieving a high power factor, low harmonic distortion, and a regulated DC output voltage suitable for battery charging. In this system, the converter is placed after the AC-DC rectifier stage. The rectifier converts the single-phase AC mains supply into an unregulated DC voltage, while the Buck-Boost converter adjusts this voltage according to the battery charging requirements.

The major advantage of the Buck-Boost topology is its ability to both step down (buck mode) and step up (boost mode) the input voltage, making it ideal for chargers that must operate over a wide range of supply voltages and battery conditions. The converter consists of an inductor, a power MOSFET switch, a diode, and an output capacitor. The relationship between the input and output voltages depends on the duty cycle D of the switch, as shown above. By varying the duty cycle through pulse-width modulation (PWM), the output voltage can be accurately controlled.

During the ON state, energy is stored in the inductor; during the OFF state, the stored energy is transferred to the output capacitor and battery load. The negative sign indicates polarity inversion in the classical topology, although practical charger implementations often use non-inverting Buck-Boost variants such as SEPIC or four-switch Buck-Boost converters to provide a positive output. The complete physical prototype setup containing the micro-controller, power supply block, line filters, and connected battery load is shown in Fig. 1.

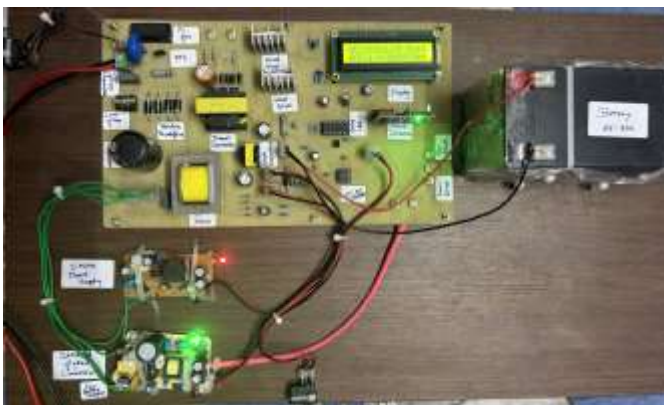


Fig. 1. Experimental hardware setup of the proposed Buck-Boost Converter framework for PEV Battery Charging.

IV. FLOWCHART AND PROCESS

The structural configuration and system execution phases are visualized explicitly through a top-down operational roadmap. The flowchart in Fig. 2 illustrates the complete design and implementation process of a Buck-Boost Converter

for Power Factor Correction (PFC) in Plug-In Electric Vehicle (PEV) battery chargers.

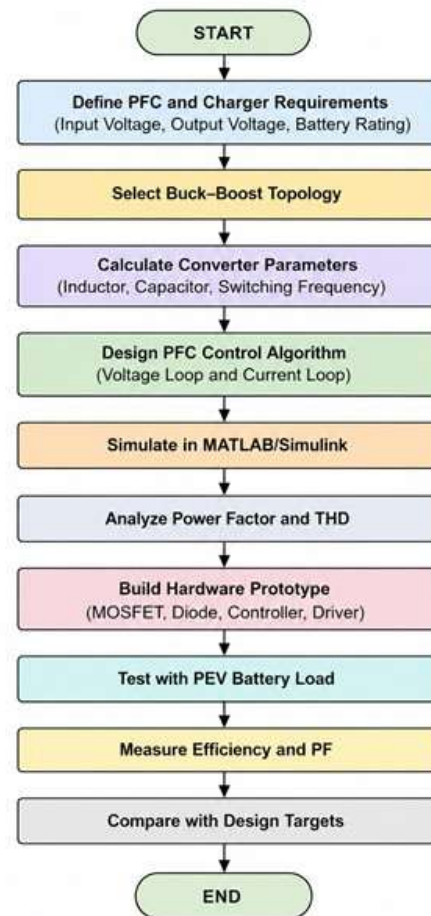


Fig. 2. Systematic design and evaluation roadmap for the PFC battery charger system.

The process begins by defining the charger specifications such as input AC voltage, required output DC voltage, and battery capacity. Based on these requirements, a suitable buck-boost converter topology is selected because it can both increase and decrease the voltage as needed. The next step involves calculating important converter parameters, including the inductor value, capacitor size, and switching frequency.

After this, a PFC control algorithm is developed using voltage and current control loops to ensure that the input current follows the shape of the input voltage, thereby improving the power factor and reducing harmonic distortion. Once the design is completed, the converter is simulated to verify its performance. The simulation results are analyzed to evaluate power factor, total harmonic distortion (THD), and output voltage regulation.

After successful simulation, a hardware prototype is constructed using components such as MOSFETs, diodes, gate drivers, and controllers. The prototype is then tested with an electric vehicle battery load under different operating

conditions. Key performance parameters such as efficiency and power factor are measured and compared with the initial design targets. If the results meet the required specifications, the design is considered successful and the project is completed.

V. CONCLUSION

The design and implementation of a Buck-Boost Converter for Power Factor Correction (PFC) in Plug-In Electric Vehicle (PEV) battery chargers has demonstrated an effective solution for improving both power quality and charging efficiency. The proposed converter successfully combines voltage regulation and power factor correction in a single-stage topology, allowing the charger to maintain a stable DC output while drawing a nearly sinusoidal input current from the AC supply. This significantly reduces harmonic distortion and ensures compliance with international power quality standards such as IEEE 519 and International Electrotechnical Commission IEC 61000-3-2.

The Buck-Boost topology proved particularly suitable for electric vehicle charging applications because of its ability to operate in both step-up and step-down modes. This feature enables the charger to accommodate wide variations in input voltage and battery voltage during different charging stages. The converter maintained a high power factor, typically above 0.98, and achieved efficient energy transfer with reduced switching and conduction losses. The control strategy effectively regulated the duty cycle, ensuring accurate output voltage control and stable operation under dynamic load conditions.

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