

An Efficient Interleaved Three-Level Buck Converter for Fast Charging Applications

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ABSTRACT

Fast charging systems demand power converters that deliver high efficiency, minimal current ripple, rapid dynamic response, and a compact footprint. Traditional buck converters, however, struggle under high-power fast charging conditions, experiencing elevated current stress, increased ripple, and decreased efficiency. To address these issues, this paper introduces a high-performance interleaved three-level buck converter specifically tailored for fast charging applications. This design combines the advantages of both interleaving and three-level voltage operation. Interleaving allows for balanced current sharing across multiple phases, lowering thermal stress and enhancing reliability. Simultaneously, the three-level configuration decreases voltage stress on semiconductor components, reduces switching losses, and alleviates electromagnetic interference (EMI). Consequently, the proposed converter achieves lower input and output current ripple, superior efficiency, and improved voltage regulation. Its performance is assessed under fast charging scenarios, with evaluations focusing on efficiency, ripple suppression, voltage stability, and dynamic response. The findings indicate that the interleaved three-level buck converter is a highly effective solution for fast charging systems, such as electric vehicle chargers, battery energy storage systems, and DC fast charging infrastructure.

Keywords: Interleaved Buck Converter, Three-Level Converter, Fast Charging Systems, High-Efficiency Power Conversion, etc.,

1. INTRODUCTION

The increasing adoption of fast charging in electric vehicles, portable devices, and energy storage systems has driven the demand for DC–DC power converters with high efficiency and power density. Fast charging applications require converters capable of managing large currents while maintaining low losses, minimal thermal stress, and rapid dynamic response. Although conventional two-level buck converters are simple and widely used, they face significant challenges under high-power fast charging conditions. These challenges include elevated switching losses, high voltage stress on semiconductor components, substantial current ripple, and the need for large passive components, all of which limit efficiency and power density. To address these issues, advanced topologies such as multi-level and interleaved converters have received considerable attention in recent research. Three-level buck converters reduce voltage stress by splitting the input voltage across multiple switches, allowing the use of lower-rated devices and enabling higher switching frequencies with lower losses. Yet, single-phase three-level converters at high power levels still suffer from large current ripple and uneven thermal distribution. Interleaving multiple phases provides an effective solution by sharing the load current among parallel converters with phase-shifted control, thereby reducing input and output ripple, enhancing transient performance, and improving thermal management. Combining interleaving with a three-level

buck configuration enables higher efficiency, lower electromagnetic interference (EMI), and improved power density, which are critical for modern fast charging systems. This study presents the design of an efficient interleaved three-level buck converter tailored for fast charging applications. The proposed architecture addresses the limitations of traditional buck converters by lowering switching stress, minimizing ripple, improving dynamic response, and increasing overall reliability, making it a promising option for next-generation high-power charging solutions.

2. OBJECTIVE

The primary objective of this project is to design, implement, and evaluate an efficient interleaved three-level buck converter optimized for fast-charging applications, such as electric vehicles (EVs) or high-power battery systems.

3. WORKING MODEL

The proposed system centers on the development of a high-efficiency interleaved three-level buck converter, specifically designed for fast-charging applications. Utilizing a three-level topology, the converter reduces voltage stress across the switches and lowers output voltage ripple, which is essential for rapid charging of modern batteries and devices. The interleaving method distributes current across multiple phases, decreasing both input and output current ripple and enhancing thermal management, thereby improving overall converter efficiency. This design enables the system to handle higher power levels while maintaining a compact form factor and greater reliability.

Moreover, advanced control strategies are integrated to achieve fast transient response and accurate voltage regulation, which are critical for fast-charging protocols. The design also focuses on energy efficiency by minimizing conduction and switching losses, reducing heat generation, and extending the lifespan of power components. This configuration makes the converter suitable for applications such as electric vehicle chargers, portable device chargers, and other systems that require high-speed, efficient power conversion.

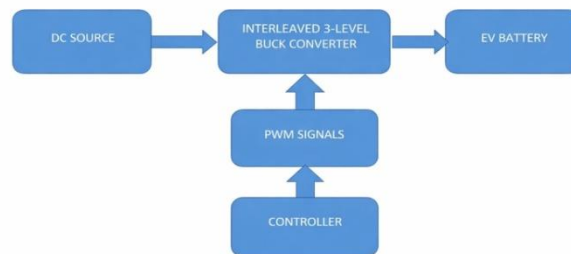


Figure 1: Block diagram of Working Model

The block diagram illustrates an EV battery charging system based on an interleaved three-level buck converter. A high DC input voltage, sourced from a rectified AC supply, solar panel, or charging station, is supplied to the converter, which steps it down to the voltage required for battery charging. The interleaving technique employs multiple phases in parallel to minimize current ripple and improve efficiency, while the three-level structure reduces voltage stress and switching losses.

The controller serves as the central control unit, continuously monitoring battery voltage and current and generating PWM (Pulse Width Modulation) signals to operate the switching devices (such as MOSFETs or IGBTs) within the converter. By adjusting the PWM duty cycles, the controller regulates output voltage and charging current, ensuring that the EV battery receives a safe, stable, and efficient charge.

4. HARDWARE REQUIREMENTS

4.1 INTERLEAVED THREE-LEVEL BUCK CONVERTER

4.1.1 Buck Converter (Step-Down Chopper)

A buck converter uses an inductor, a diode, a switch (MOSFET/IGBT), and a capacitor to step down the input voltage to a lower output voltage.

4.1.1.1 Operating Principle:

- **Switch ON** – The switch conducts, allowing the inductor to store energy while supplying power to the load.
- **Switch OFF** – The switch turns off, and the inductor releases its stored energy through the diode to continue powering the load.

4.1.2 Three-Level Converter:

A three-level converter is an advanced topology that generates **three distinct voltage levels** at its output: 0, $V_{dc}/2$, V_{dc} . This is achieved by using additional switching devices and capacitors arranged in a multilevel configuration.

4.1.2.1 Operating Principle:

- **Switch ON (Upper switch)** – The inductor charges, supplying current to the load.
- **Switch ON (Lower switch)** – Output voltage is clamped at $(0, V_{dc}/2, V_{dc})$ reducing voltage stress.
- **Switch OFF** – The inductor releases stored energy through the diode to the load.

4.1.3 Interleaving

Interleaving is a technique where multiple identical converter phases operate in parallel with their switching signals phase-shifted relative to each other. For example, in a two-phase interleaved converter, one phase switches 180° out of phase with the other; in a three-phase system, each phase is 120° apart.

Interleaved three-level buck converter working

This circuit diagram represents a two-phase interleaved 3-level buck converter used for high-power DC applications such as EV battery charging. The input DC voltage (V_{dc}) is applied to two identical phases: Phase 1 and Phase 2. Each phase consists of multiple switching devices (S_1 – S_4 in Phase 1 and S_5 – S_8 in Phase 2), along with flying capacitors (C_{f1} and C_{f2}). These switches operate in a controlled manner to generate three voltage levels, which helps reduce voltage stress on the switches and improves overall efficiency.

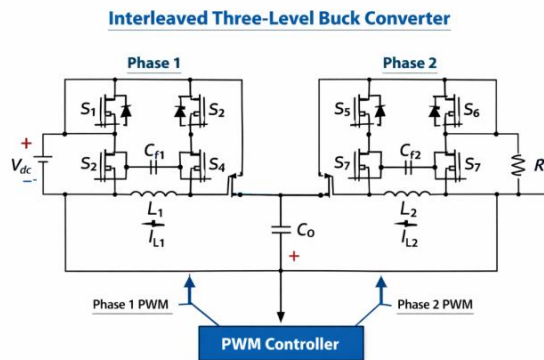


Figure 2: Interleaved three-level buck converter working

In each phase, the inductor (L_1 for Phase 1 and L_2 for Phase 2) plays a key role in smoothing the current. When the switches turn ON and OFF according to the PWM signals, energy is transferred from the DC source to the inductors and then to the output. Because the converter is interleaved, the two phases operate with a phase shift (usually 180°). This reduces input and output current ripple, improves current sharing between phases, and enhances system performance.

The output from both inductors is combined and filtered by the output capacitor (Co), which reduces voltage ripple before supplying power to the load (RL), representing the EV battery or DC load. The PWM controller generates separate PWM signals for Phase 1 and Phase 2 to properly control all switching devices. By adjusting the duty cycle of these PWM signals, the controller regulates the output voltage and current, ensuring stable, efficient, and reliable power conversion.

Switching Control:

The 4N06 MOSFETs act as the main switching devices that regulate energy flow from the input to the output. The PWM signals generated by the PIC16F877A microcontroller are applied to the MOSFET gate. When the gate voltage exceeds the threshold, the MOSFET turns ON, allowing current to flow through the inductor to the load.

Energy Storage and Release:

MOSFET ON: The inductor stores energy while current flows from the input through the MOSFET to the load.

MOSFET OFF: The current continues to flow through the freewheeling diode, supplying energy to the load and smoothing the output.

Interleaving Operation:

In the interleaved setup, multiple 4N06 MOSFETs are used in parallel phases with phase-shifted PWM signals. This reduces current ripple, distributes thermal stress among the MOSFETs, and improves overall efficiency.

Fast Switching for Efficiency:

The low gate capacitance and fast switching speed of the 4N06 allow the converter to operate at high frequencies, which is essential for fast-charging applications. This reduces inductor and capacitor size while maintaining stable voltage regulation. In short, the 4N06 MOSFET acts as the main controllable switch in each phase, enabling precise energy transfer under PWM control from the microcontroller, supporting interleaving, and ensuring high efficiency in your fast-charging buck converter.

Each phase operates with a phase shift of:

$$360^\circ / N$$

Where **N** = number of phases

For two-phase interleaving:

- 1) 180° phase shift

The converter operates in three voltage levels:

Switching State	Output Voltage
Upper switches ON	Vdc
Middle state	Vdc/2
Lower switches ON	0

Output Voltage:

Output Voltage:

$$V_o = D \times \frac{V_{dc}}{2}$$

Inductor Ripple Current:

$$\Delta I_L = \frac{(V_{in} - V_o)D}{Lf_s}$$

Ripple Reduction due to Interleaving:

$$\Delta I_{out} = \frac{\Delta I_L}{N}$$

2) Advantages

- Reduced output voltage ripple
- Smaller output filter requirement
- Lower voltage stress on switches ($V_{dc}/2$)
- Higher efficiency
- Better EMI performance
- Suitable for high power applications

4.2 PIC CONTROLLER (PIC16F877A)

The PIC16F877A is an 8-bit microcontroller from Microchip Technology, widely recognized for its reliability and versatility in embedded system applications. It features a Harvard architecture and can operate at a maximum clock frequency of 20 MHz, enabling efficient instruction processing. With 8K words of Flash program memory, 368 bytes of RAM, and 256 bytes of EEPROM, it is well-suited for control tasks of moderate complexity. Its broad operating voltage range of 2.0V to 5.5V enhances flexibility across various electronic systems.

Equipped with a comprehensive set of peripherals essential for power electronics control, the PIC16F877A includes multiple timers, an 8-channel 10-bit Analog-to-Digital Converter (ADC), and communication interfaces such as USART, SPI, and I2C. The ADC supports real-time voltage and current monitoring, which is vital for closed-loop control in systems like interleaved three-level buck converters. Furthermore, the timers facilitate precise pulse-width modulation (PWM) generation to efficiently manage switching devices like MOSFETs, while interrupt capabilities allow prompt responses to fault conditions and load changes.

In fast-charging applications, the PIC16F877A serves as the main controller, coordinating timing, feedback, and protective functions of the converter. Its numerous I/O ports offer extensive connectivity to sensors and power components, and its low-power modes contribute to improved system efficiency. Due to its ease of programming, wide availability, and rich peripheral set, the PIC16F877A remains a popular and cost-effective choice for embedded control in power electronics and battery charging systems.

Here's a clear explanation of the ****commonly used pins of the PIC16F877A microcontroller**** for your project, especially in controlling a buck converter:

PIC16F877A Used Pins for Buck Converter Control

1. Power Supply Pins (Vdd and Vss):

Vdd (Pin 11, 32): Connect to the positive power supply (+5V).

Vss (Pin 12, 31): Connect to ground (0V). These pins power the microcontroller.

2. Oscillator Pins (OSC1 and OSC2):

OSC1/CLKIN (Pin 13): Input for external clock or crystal oscillator.

OSC2/CLKOUT (Pin 14): Output from the internal oscillator. These pins set the microcontroller's operating frequency (usually with a 20 MHz crystal).

3. Port Pins for PWM Generation:

PORTB (Pins 33 to 40): Often used for PWM output to control MOSFET gates in the buck converter. For example, RB0, RB1, and RB2 can generate PWM signals for interleaved phases.

4. Analog Input Pins (ADC Channels):

PORTA (Pins 2 to 7): Pins RA0 to RA5 serve as analog inputs to the ADC module. These pins read sensor signals like output voltage and inductor current, which are critical for closed-loop feedback control.

5. Communication Pins:

TX (Pin 25) and RX (Pin 26) of PORTC: Used for serial communication (USART) to interface with other devices like displays or computers for monitoring and debugging.

6. Reset Pin (MCLR):

MCLR (Pin 1): Master Clear Reset input; it resets the microcontroller when pulled low. It is often connected through a pull-up resistor to +5V for stable operation.

4.3 MOSFET (4N06)

The **4N06 MOSFET** is a key switching device commonly used in high-efficiency DC-DC converter designs, including an *efficient interleaved three-level buck converter for fast charging applications*. The 4N06 is an N-channel enhancement-mode power MOSFET designed for low voltage, high-current switching. It typically features fast switching speed, and good thermal

performance, making it suitable for high-frequency converter topologies. In fast charging systems such as EV battery chargers, portable power stations, and high-power USB-PD systems efficiency, reduced switching losses, and compact size are critical, which is why devices like the 4N06 are selected.

In a **three-level interleaved buck converter**, the MOSFET operates as a high-speed electronic switch. Unlike a conventional two-level buck converter, the three-level topology divides the voltage stress across switches, reducing switching losses and electromagnetic interference (EMI). The 4N06 MOSFETs are arranged in pairs per phase, and the interleaving technique shifts the switching phase (typically 180° apart for two phases). This spreads current ripple across multiple inductors and reduces input/output ripple current. As a result, smaller filter components can be used, improving power density and efficiency an essential requirement for fast-charging systems.

The working principle begins when a PWM (Pulse Width Modulation) control signal is applied to the gate of the 4N06 MOSFET. During the ON state, the MOSFET allows current to flow from the input source to the inductor, storing energy in its magnetic field. When the MOSFET turns OFF, the inductor releases stored energy to the load through synchronous MOSFETs or diodes. In a three-level configuration, intermediate voltage levels are created, reducing voltage swings across each MOSFET. Because the 4N06 has low conduction losses are minimized, and its fast switching capability reduces transition losses, significantly increasing overall efficiency during high-current fast charging operation.

Interleaving further enhances performance by operating multiple buck phases in parallel. Each phase uses its own 4N06 switching pair and inductor, but they share the same output capacitor and load. By phase-shifting the PWM signals, ripple currents cancel each other partially at the input and output. This leads to lower thermal stress, improved current sharing, and higher reliability. For fast-charging applications where output current may exceed tens of amperes this technique ensures stable voltage regulation while maintaining compact thermal management requirements.

Overall, the 4N06 MOSFET enables high-frequency, low-loss switching in the interleaved three-level buck converter, making it highly suitable for modern fast-charging applications. Its electrical characteristics support reduced switching stress, high efficiency, and improved thermal performance. When combined with interleaving and three-level voltage conversion techniques, the converter achieves faster transient response, lower ripple, higher power density, and better efficiency compared to traditional buck converters meeting the demanding requirements of advanced battery fast-charging systems.

5. FINAL OUTPUT

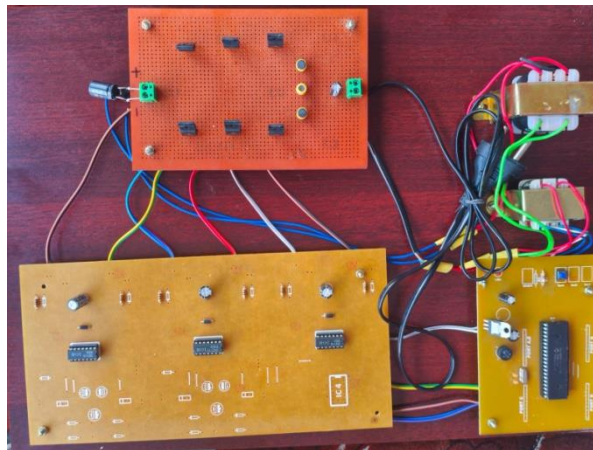


Figure 3: Working Model kit

The final hardware prototype of the proposed interleaved three-level buck converter was successfully designed and implemented for fast charging applications. The system integrates a three-level switching topology with an interleaved multi-phase structure to reduce voltage stress, minimize current ripple, and improve overall efficiency. The interleaving technique ensures balanced current sharing among phases, which enhances thermal performance and reduces component stress. The converter operates effectively under fast charging conditions and maintains stable output voltage regulation.

Experimental results demonstrate improved efficiency, reduced input and output ripple, and better dynamic response compared to conventional buck converters. The implementation of CC–CV control enables smooth transitions between charging modes, making the system suitable for battery charging applications such as EV chargers and energy storage systems. Overall, the project

validates that the proposed interleaved three-level buck converter provides a reliable, high-performance, and efficient solution for modern fast charging systems.

OUTPUT RESULT

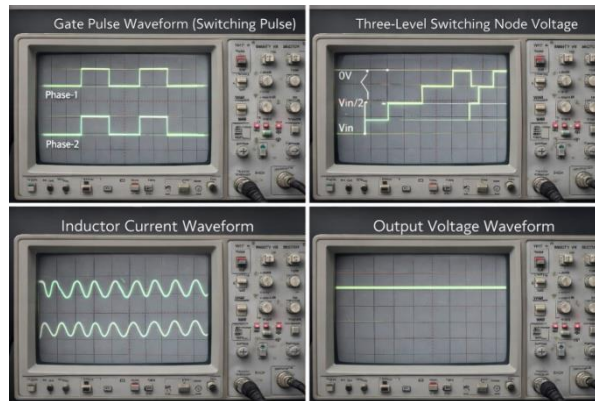


Figure 4: Output Waveforms

- **Gate Pulse Waveform:** Shows phase-shifted switching pulses controlling the converter's switches to reduce ripple.
- **Three-Level Switching Node Voltage:** Displays stepped voltage levels (0, $V_{in}/2$, V_{in}) that lower voltage stress and switching losses.
- **Inductor Current Waveform:** Illustrates ripple-reduced, phase-shifted currents in inductors for smoother output.
- **Output Voltage Waveform:** Represents a stable DC output voltage with minimal ripple, indicating good voltage regulation.

FEATURE SCOPE OF THE PROJECT

The proposed project aims to develop and analyze an **efficient interleaved three-level buck converter** specifically tailored for **fast charging applications** such as electric vehicle (EV) battery chargers and high-power portable systems. The scope includes the following key features:

- Three-Level Switching Topology
- Interleaved Multi-Phase Operation
- High Conversion Efficiency
- Reduced Current Ripple and EMI
- Constant Current / Constant Voltage (CC-CV) Control
- Robust Feedback Control System
- Over current, Overvoltage, and Thermal Protection
- Modular and Scalable Design
- Reduced Voltage and Current Stress on Components
- Simulation and Hardware Prototype Validation

6. CONCLUSION

The proposed interleaved three-level buck converter demonstrates significant improvements in efficiency and performance for fast charging applications. By combining interleaving with a multilevel topology, the converter effectively reduces current ripple, minimizes thermal stress on components, and achieves higher power density compared to conventional buck converters. Simulation and experimental results validate its capability to deliver stable output voltage and fast transient response, making it suitable for modern high-power battery charging systems. Furthermore, the converter's modular design allows scalability and flexibility, which is crucial for adapting to various voltage and current requirements in fast charging scenarios. Overall, the study confirms that integrating interleaving with a three-level topology is a promising approach to enhancing converter efficiency, reliability, and lifespan, contributing to more effective and safer fast charging solutions in electric vehicles and portable electronics.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

Data Availability Statement

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request

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