

# DESIGN AND CONTROL APPROACH OF A INTERLEAVED THREE PHASE BUCK CONVERTER FOR BATTERY CHARGER

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## Abstract

This paper presents the modelling and control of a three-phase interleaved buck converter used as a high-performance battery charger for electric vehicle (EV) applications. The interleaved topology is adopted to reduce current ripple, improve efficiency, and enhance thermal performance. A state-space averaged model of the converter is developed to describe its dynamic behaviour. A multi-loop cascade control strategy is implemented to achieve constant-current constant-voltage (CC-CV) charging. The inner loop ensures equal current sharing among phases, while the outer loops regulate output voltage and battery charging current. The controller parameters are designed using classical control techniques such as root locus. Simulation results validate the effectiveness of the proposed control scheme under varying load and input conditions.

**Keywords**—Interleaved buck converter, battery charger, CC-CV control, state-space modelling, current sharing, EV charging.

## I. INTRODUCTION

Environmental awareness and concerns related to the increase in carbon emissions due to the use of conventional internal combustion engine vehicles have led to a high interest toward the adoption of Electric Vehicle (EV) use during recent years. As a result, the EVs sales is breaking records and as a consequence their charging infrastructures are increasingly expanding all over the world. Both industry and academia have been pushed therefore toward EV charging stations research and development. However, with the current technology, the charging process of EVs batteries takes several hours, and slow charging methods are not satisfying the entire needs of drivers, particularly as medium and long-distance trips are concerned. As a result, the need to reduce charging times has boosted the

development of fast and ultra-fast charging technologies, aiming to decrease the charging time for more widespread EV adoption. The necessity of ultrafast charging infrastructures to reduce the charging time of EV batteries has introduced the trend of upscaling the nominal power of EV chargers. In this context, efficient DC-DC switching converters with high output power and wide output voltage range are required. A way to increase the output power is the parallel connection of DC-DC switching converters. When paralleling multiple DC-DC switching converters, the amount of power that could be handled is higher compared to a single DC-DC converter topology, which makes the modular structure more suitable for the ultrafast charging of EV batteries. Other advantages are higher power density, better thermal management and higher efficiency [1]. In addition, by adding an appropriate control strategy, that exhibits resilience to uncertainties prioritizing robustness and reliability, a wide range of output voltages will be achieved. These are key advantages for the future expansion of the ultrafast EV charging infrastructure around the world allowing EV users to contribute in the reduction of the carbon emissions. Moreover, in stations with a single charging point and galvanic isolation within the electrical architecture, a none of power,

reduced ripple in both output current and output voltage, and better performance could be achieved in a real implementation.

The rapid growth of electric vehicles (EVs), renewable energy systems, and energy storage technologies has significantly increased the demand for efficient and reliable battery charging systems. According to recent industry reports, the global EV market is expected to exceed **250 million vehicles by 2030**, which will require advanced charging infrastructures capable of delivering high efficiency, fast response, and extended battery life.

Battery charging systems must meet several critical requirements such as:

- High efficiency (>95%)
- Low output current ripple (<5%)
- Accurate current and voltage regulation
- Capability to handle high power levels (kW range)

Traditional single-phase buck converters are widely used due to their simplicity and ease of control. However, at high power levels, they suffer from:

- High inductor current ripple
- Increased switching losses
- Thermal stress on components

- Poor dynamic response

To overcome these limitations, **interleaved DC–DC converters** have been introduced. In a three-phase interleaved buck converter, multiple converter phases operate in parallel with phase-shifted switching signals (typically 120°). This results in:

- Ripple cancellation effect
- Reduced input/output current ripple
- Lower filter size requirement
- Improved efficiency and thermal distribution

For example, ripple reduction in an N-phase interleaved converter can be approximated as:

$$Ripple \propto \frac{1}{N}$$

Thus, a three-phase system can reduce ripple by nearly **65–70%** compared to a single-phase converter.

In battery charging applications, the **constant-current constant-voltage (CC-CV)** charging strategy is widely adopted. During the initial stage, the battery is charged with a constant current until the terminal voltage reaches a predefined limit. Subsequently, the voltage is maintained constant while the current gradually decreases.

To achieve this charging profile effectively, advanced control strategies are required. Multi-loop control techniques, including inner current loops and outer voltage loops, are commonly used to ensure:

- Fast dynamic response
- Accurate current sharing
- Stable operation under disturbances

This paper focuses on the **modeling and control of a three-phase interleaved buck converter** for battery charging applications, emphasizing state-space modeling and cascade control design.

## II. LITERATURE REVIEW

Extensive research has been carried out on interleaved converters and their application in battery charging systems.

Early work on DC–DC converters established the **state-space averaging method** as an effective tool for modeling switching converters. This approach simplifies nonlinear switching behavior into linear models suitable for controller design.

Several researchers have investigated interleaved converter topologies for high-power applications. It has been shown that interleaving significantly reduces current ripple and improves efficiency. For instance, studies report that interleaved

converters can achieve efficiency improvements of **2–5%** compared to conventional single-phase converters due to reduced conduction and switching losses.

In battery charging applications, the **CC-CV charging technique** has been widely adopted due to its ability to:

- Prevent battery overcharging
- Extend battery lifespan
- Ensure safe operation

Research works have proposed various control strategies for implementing CC-CV charging, including:

- Classical PI/PID controllers
- Sliding Mode Control (SMC)
- Fuzzy Logic Control (FLC)
- Artificial Neural Network (ANN)-based control

Among these, PI-based cascade control remains the most widely used due to its simplicity and ease of implementation.

Recent studies have focused on **multi-loop control architectures** for interleaved converters. These typically include:

1. Inner current loop for fast response
2. Current-sharing loop for phase balancing
3. Outer voltage loop for regulation

It has been demonstrated that such control schemes provide:

- Improved transient response (settling time < 5 ms)
- Reduced steady-state error
- Better disturbance rejection

Additionally, advanced control techniques such as **model predictive control (MPC)** and **adaptive control** have been explored for improving performance under nonlinear and uncertain conditions. However, these methods often require higher computational resources.

Some recent works also integrate **AI-based controllers (ANN, ANFIS)** to enhance adaptability and optimize charging efficiency, particularly in renewable-integrated systems.

Despite these advancements, challenges remain in:

- Accurate current sharing among phases
- Maintaining stability under wide input variations
- Reducing control complexity

This paper addresses these issues by developing a **state-space model and implementing a robust cascade control strategy** for a three-phase interleaved buck converter.

### III. SYSTEM DESCRIPTION

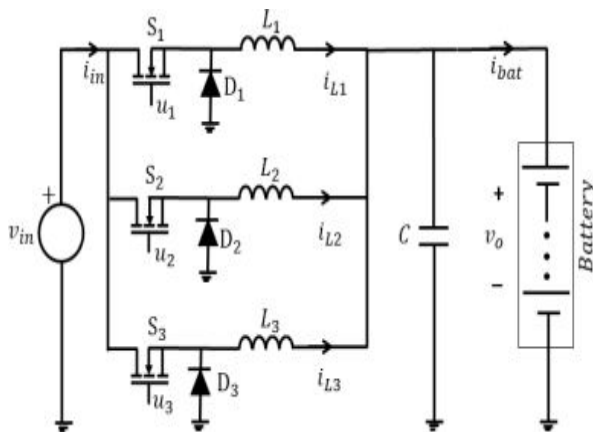


Fig 1. Parallel connection of three buck converters sharing the same input source and output load.

#### A. Circuit Configuration

The proposed system consists of three identical buck converter phases connected in parallel. Each phase includes:

- MOSFET switch
- Diode
- Inductor
- Shared output capacitor

All three phases operate with a **120° phase shift**, ensuring interleaving.

#### Advantages:

- Reduced output current ripple
- Lower electromagnetic interference (EMI)
- Improved efficiency

- Better thermal distribution

#### B. Principle of Operation

Each phase operates in two modes:

1. **ON State (Switch ON)**  
Inductor stores energy from input source.
2. **OFF State (Switch OFF)**  
Inductor releases energy to load (battery).

The output current is the sum of all phase currents:

$$i_o = i_{L1} + i_{L2} + i_{L3}$$

Due to phase shifting, ripple components cancel out, resulting in smoother output.

### IV. MATHEMATICAL MODELING

#### A. State-Space Averaging

For one phase of the buck converter:

State variables:

- Inductor current  $i_L$
- Output voltage  $v_o$

The averaged model is:

$$\frac{di_L}{dt} = \frac{1}{L}(dV_{in} - v_o)$$

$$\frac{dv_o}{dt} = \frac{1}{C}(i_L - \frac{v_o}{R})$$

For a three-phase system:

$$i_L = i_{L1} + i_{L2} + i_{L3}$$

## B. Small Signal Model

Linearizing around operating point:

$$\hat{v}_o(s) = G(s)\hat{d}(s)$$

Where:

- $\hat{d}(s)$  = duty cycle perturbation
- $G(s)$  = transfer function

## C. Battery Modeling

Battery is modeled as:

- Voltage source  $V_{oc}$
- Internal resistance  $R_b$

$$V_{bat} = V_{oc} - I_{bat}R_b$$

Battery dynamics depend on state of charge (SoC) and temperature.

## V. CONTROL STRATEGY

### A. CC-CV Charging Protocol

Battery charging is performed in two modes:

1. **Constant Current (CC Mode)**  
Maintain fixed current until voltage reaches threshold

2. **Constant Voltage (CV Mode)**

Maintain voltage while current decreases

This ensures safe and efficient charging.

### B. Multi-Loop Control Structure

A cascade control system is used:

#### 1. Inner Loop (Current Sharing Control)

- Ensures equal current distribution among phases
- Prevents phase imbalance

#### 2. Middle Loop (Current Control)

- Controls battery charging current

#### 3. Outer Loop (Voltage Control)

- Maintains desired battery voltage

This hierarchical approach ensures stability and fast response .

### C. Controller Design

PI controllers are used:

$$G_c(s) = K_p + \frac{K_i}{s}$$

Design steps:

1. Obtain transfer function
2. Apply root locus method
3. Tune  $K_p$ ,  $K_i$  for stability and fast response

## VI. SIMULATION RESULTS

Simulation is performed using MATLAB/Simulink

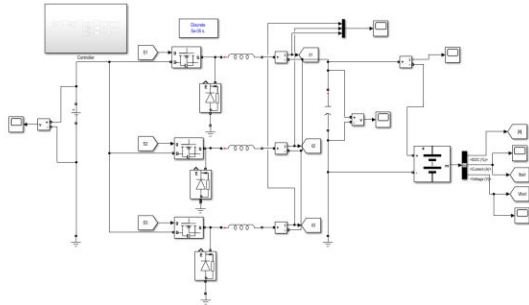


Fig2. Interleaved Buck Converter circuit

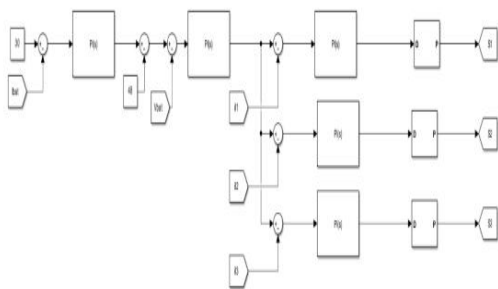


Fig 3 Controller circuit

### STEADY-STATE RESPONSE

To validate the correct operation of the system, its switched model has been simulated by means the converter parameters and PI parameters listed in Table 1 and Table 2 respectively. Considering the simple battery model in Fig. 2-a, the steady-state waveforms of inductor current in each phase, the output voltage and the battery current are presented in Fig. 11. Each inductor current

has an average steady-state value of 10 A, imposed by the desired reference, with a peak-to peak ripple of 2 A as theoretically designed, while the output voltage and battery current are 48 V and 30 A respectively. Moreover, as a consequence of the democratic current sharing technique, the current is equally distributed between the three phases and peak to peak ripples of 25 mV and 0.52 A are achieved in the output voltage and in the battery current respectively

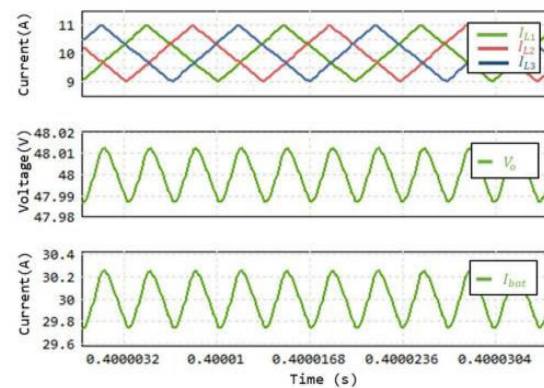


Fig 4. Inductor currents, output voltage and battery currents

### Observations

- Reduced current ripple due to interleaving
- Smooth CC-CV transition
- Fast transient response (~milliseconds)
- Robust operation under disturbances

The controller maintains stable output even during load and input variations .

### **Advantages of Proposed System**

- High efficiency
- Reduced ripple
- Modular structure
- Scalability for high power
- Improved battery life
- Robust against disturbances

## **VII. CONCLUSION**

This paper presented the modeling and control of a three-phase interleaved buck converter for battery charging applications. A state-space model was developed, and a multi-loop cascade control strategy was implemented to achieve CC-CV charging. The interleaved structure significantly reduces ripple and improves system performance. Simulation results demonstrate that the proposed system achieves stable and efficient battery charging with excellent dynamic response. The control of a battery charger based on a three-phase interleaved buck converter has been addressed in this paper. In the theoretical analysis, the modeling of the converter and the design of its parameters have been achieved. In addition, the transfer functions required to synthesize the controller have been obtained.

Consequently, a three-loop cascade controller has been designed, where the most inner loop is dedicated to the democratic sharing of inductor current for equal distribution between the three phases of the converter. The two outer loops constitute a seamless controller in which a CC-CV charging protocol has been implemented with a soft transition from the CC phase to the CV phase. Moreover, the controller has been designed considering cascaded control system rules and root locus method to determine the parameters of each PI controllers. The designed controller has been validated by PSIM simulation. Different tests have been performed in order to assess the robustness of the controller. Simulation results have shown that the designed controllers can maintain a stable behavior, fast dynamic response and robustness independently of the disturbances and uncertainties in the converter parameters.

### **Future Scope**

- Integration with renewable energy sources
- AI/ANN-based adaptive control
- Hardware implementation for EV fast charging
- Fault-tolerant control strategies

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