

PSO-Based Optimal PI Controller Tuning for Two-Stage EV Battery Charger Using High-Gain Buck-Boost PFC Converter

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Abstract

The rapid growth of electric vehicle adoption has increased the demand for efficient, compact, and intelligent onboard charging systems. Conventional battery chargers suffer from poor power factor, high total harmonic distortion (THD), reduced efficiency, and complex control implementation under varying operating conditions. This paper presents a two-stage electric vehicle battery charger employing a bridgeless high-gain buck-boost power factor correction (PFC) AC-DC converter at the front-end and an isolated Cuk DC-DC converter at the back-end. The front-end converter operates in discontinuous conduction mode (DCM) to achieve inherent power factor correction with simplified control architecture and reduced sensor requirement. The isolated Cuk converter performs constant current and constant voltage battery charging with reduced ripple and galvanic isolation. Mathematical modelling of the converter stages is carried out using volt-second balance and state-space analysis. To improve the dynamic response of the charger, Particle Swarm Optimization (PSO) based optimal PI controller tuning is implemented for DC-link voltage regulation and charging control loops. The proposed charger is validated in MATLAB/Simulink under steady-state and dynamic operating conditions. Simulation results demonstrate near unity power factor operation, reduced source current THD, stable DC-link voltage regulation, improved transient response, and enhanced charger efficiency. Comparative analysis confirms that the PSO optimized controller significantly improves harmonic performance, settling time, overshoot, and efficiency compared to conventional PI controllers.

Keywords: *Electric vehicle charger, bridgeless buck-boost converter, power factor correction, isolated Cuk converter, Particle Swarm Optimization, PI controller tuning, harmonic reduction.*

I. INTRODUCTION

The rapid depletion of fossil fuel resources and increasing environmental concerns have accelerated the development of electric vehicle (EV) technology worldwide [1]–[3]. Electric vehicles provide several advantages including high efficiency, reduced maintenance, and zero

tailpipe emissions compared to conventional internal combustion engine vehicles [4]. Consequently, modern transportation systems increasingly rely on efficient and intelligent EV charging infrastructure.

Battery charging systems play a critical role in determining EV performance, charging speed, reliability, and battery lifespan [5]. Modern EV chargers are expected to satisfy stringent power quality requirements while ensuring high efficiency and stable charging operation. Conventional battery chargers generally employ diode bridge rectifiers followed by DC-DC converter stages, resulting in poor power factor, high harmonic distortion, increased conduction losses, and complex control implementation [6].

To overcome these limitations, bridgeless power factor correction (PFC) converter topologies have gained significant attention because of their reduced conduction losses and improved efficiency [7]. High-gain converter structures are also increasingly utilized in EV charging applications to accommodate wide battery voltage variations. Moreover, discontinuous conduction mode (DCM) operation enables inherent power factor correction and reduces sensor requirements by eliminating complex current control loops [8].

The isolated DC-DC converter stage performs constant current (CC) and constant voltage (CV) battery charging while providing galvanic isolation and reduced ripple current characteristics [9]. Among isolated converter topologies, the isolated Cuk converter offers continuous input-output current characteristics, improved dynamic response, and reduced ripple content.

Conventional PI controllers are widely used for charger control because of their simplicity and ease of implementation. However, fixed PI gains may not provide satisfactory performance under varying operating conditions due to nonlinear converter dynamics. Therefore, artificial intelligence-based optimization techniques are increasingly employed for optimal controller tuning [10].

This paper presents a PSO-based optimal PI controller tuning approach for a two-stage EV battery charger employing a bridgeless high-gain buck-boost PFC converter and isolated Cuk converter. The proposed charger achieves improved power quality, reduced harmonic distortion, stable charging characteristics, and enhanced dynamic response under varying operating conditions.

II. LITERATURE REVIEW

Electric vehicle charging systems have attracted extensive research attention in recent years due to increasing EV penetration and stringent power quality requirements [11]. Early EV chargers mainly employed uncontrolled diode bridge rectifiers followed by DC-DC converters. Although simple and economical, these chargers produced severe harmonic distortion and poor power factor characteristics [12].

Conventional boost PFC converters became widely popular because of their continuous input current characteristics and improved power factor correction capability [13]. However,

conventional boost converters require dual-loop control structures and exhibit increased conduction losses under varying operating conditions.

Bridgeless converter topologies were proposed to eliminate the diode bridge rectifier and improve overall efficiency [14]. Jang and Jovanovic proposed a bridgeless boost converter that reduced conduction losses and improved thermal performance. Researchers subsequently developed bridgeless buck-boost and bridgeless SEPIC converter structures for low-voltage EV charging applications [15].

Single-stage EV chargers integrate AC-DC and DC-DC conversion into one power processing stage, thereby reducing component count and overall system size [16]. However, single-stage chargers suffer from increased low-frequency ripple propagation and limited charging flexibility.

Two-stage EV chargers employ separate AC-DC and DC-DC conversion stages and provide improved charging control, reduced ripple current, and enhanced power quality [17]. Singh *et al.* proposed a two-stage charger employing a bridgeless high-gain buck-boost converter and isolated Cuk converter for low-voltage EV applications.

DCM operation has emerged as an effective technique for achieving inherent power factor correction with simplified control implementation [18]. In DCM operation, converter current naturally follows the input voltage waveform, thereby reducing the need for current sensing and inner current control loops.

Artificial intelligence-based optimization techniques such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), fuzzy logic, and neural networks have been increasingly applied for converter controller tuning [19]. PSO provides fast convergence and improved optimization capability for nonlinear converter systems.

Research Gap

Existing EV charger topologies suffer from high conduction losses, poor harmonic performance, and complex dual-loop control implementation. Several high-gain converters exhibit discontinuous input current characteristics and reduced efficiency under dynamic conditions. AI-based controller optimization techniques remain insufficiently explored in low-voltage onboard EV charging applications employing DCM-based bridgeless converter structures.

Main Contributions of the Paper

The major contributions of this work are summarized as follows:

- Design of a bridgeless high-gain buck-boost PFC converter for EV charging applications.
- Implementation of DCM-based inherent power factor correction.

- Design of isolated Cuk converter for CC-CV battery charging.
- Mathematical modelling of converter stages and charging dynamics.
- PSO-based optimal tuning of PI controller parameters.
- MATLAB/Simulink validation under steady-state and dynamic operating conditions.

III. PROPOSED SYSTEM AND MATHEMATICAL MODELLING

A. Proposed Charger Configuration

The Fig 1 shows the proposed charger employs a two-stage power conversion architecture consisting of:

- Front-end bridgeless high-gain buck-boost PFC AC-DC converter
- Back-end isolated Cuk DC-DC converter

The front-end converter performs power factor correction and DC-link voltage regulation, whereas the back-end converter regulates battery charging current and voltage.

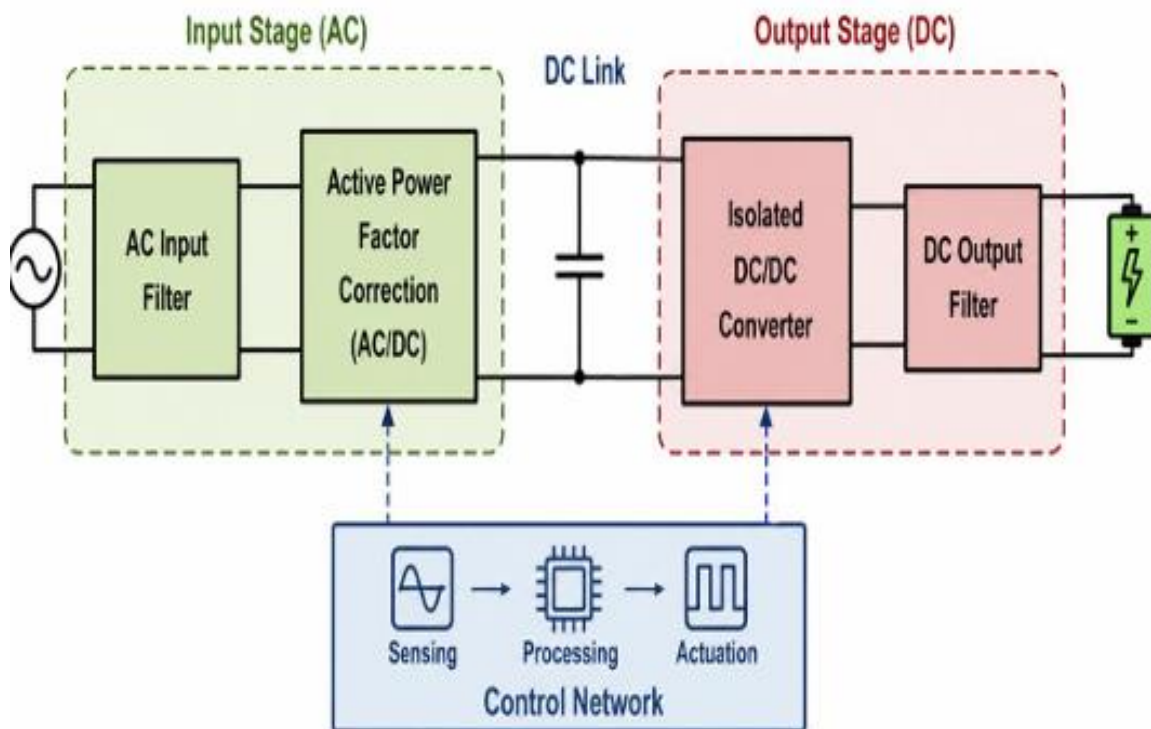


Fig. 1 Overall configuration of the proposed charger

B. Front-End Converter Operation

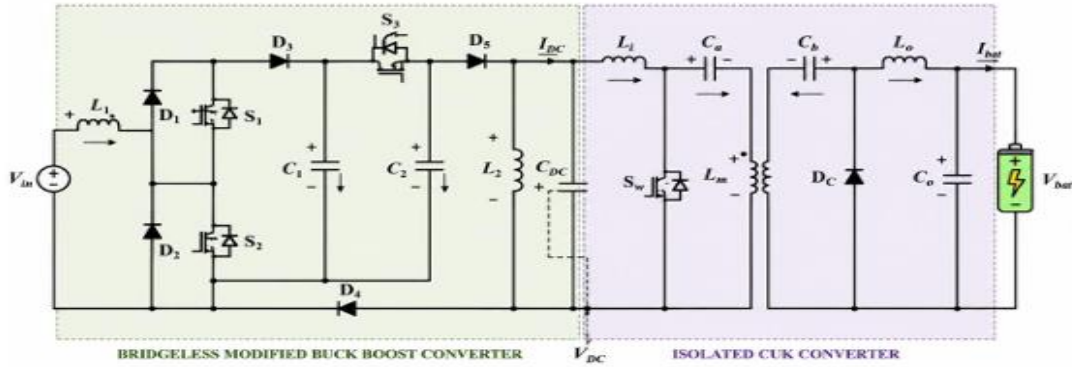


Fig.2 Circuit topology of the front-end bridgeless high-gain buck-boost converter with cuk converter used for battery charging

The front-end converter shown in Fig 2, operates in three modes during one switching period under DCM operation.

Mode I

During Mode I, switches S1, S2, and S3 are turned ON simultaneously and inductors store energy.

The inductor voltage equation is represented as:

$$v_{L1} = L_1 \left(\frac{di_{L1}}{dt} \right) = v_{in} \quad (1)$$

$$v_{L2} = L_2 \left(\frac{di_{L2}}{dt} \right) = v_{C1} + v_{C2} \quad (2)$$

Mode II

During Mode II, switches are turned OFF and stored inductor energy is transferred to the load.

$$v_{L1} = L_1 \left(\frac{di_{L1}}{dt} \right) = v_{in} - v_{C1} \quad (3)$$

$$v_{L2} = L_2 \left(\frac{di_{L2}}{dt} \right) = -v_o \quad (4)$$

Mode III

During Mode III, the inductor current becomes zero and capacitors continue supplying energy to the load.

C. Voltage Gain Analysis

Applying volt-second balance principle:

$$M = \frac{V_{DC}}{V_{in}} = \frac{2D_1}{(1 - D_1)D_2} \quad (5)$$

where:

- M = voltage gain
- D_1 = duty ratio
- D_2 = discontinuous interval duty ratio

D. DCM Operating Condition

The converter operates in discontinuous conduction mode when $D_1 + D_2 < 1$

The critical inductance is determined as:

$$L_{2critical} = \frac{R_L(1 - D_{1critical})^2 T_s}{2} \quad (6)$$

E. Isolated Cuk Converter Modelling

The isolated Cuk converter regulates battery charging voltage and current.

The voltage conversion ratio is expressed as:

$$\frac{V_o}{V_{dc}} = N \frac{D}{1 - D} \quad (8)$$

where:

- N = transformer turns ratio
- D = duty ratio

F. Battery Charging Equations

The battery charging power is represented as:

$$P_{total(t)} = P_{base(t)} + P_{EV(t)} + P_{loss(t)} \quad (9)$$

The battery state-of-charge estimation equation is:

$$SOC(t) = SOC(0) + \left(\frac{1}{C_b}\right) \int i_{b(t)} dt \quad (10)$$

G. PI Controller Equation

The DC-link voltage controller equation is expressed as:

$$m_f = K_p e_v + K_i \int e_v dt \quad (11)$$

where:

- K_p = proportional gain

- K_i = integral gain
- e_v = DC-link voltage error

H. PSO Optimization

The objective function used for PI controller optimization is:

$$J = w_1 e_v + w_2 e_i + w_3 THD + w_4 t_s \quad (12)$$

where:

- e_v = voltage error
- e_i = current error
- THD = source current harmonic distortion
- t_s = settling time

The PSO velocity update equation is:

$$v_i(k+1) = wv_i(k) + c_1 r_1(p_i - x_i(k)) + c_2 r_2(g - x_i(k)) \quad (13)$$

The particle position update equation is:

$$x_i(k+1) = x_i(k) + v_i(k+1) \quad (14)$$

IV. CONTROL STRATEGY IMPLEMENTATION

The proposed control strategy is developed to achieve:

- Near unity power factor operation
- Stable DC-link voltage regulation
- Reduced harmonic distortion
- Effective CC-CV battery charging
- Improved transient response

The overall control structure of the proposed two stage EV battery charger is shown in the Fig 3. The front-end bridgeless converter operates in DCM to achieve inherent power factor correction without requiring an inner current control loop. The DC-link voltage controller continuously compares the sensed DC-link voltage with the reference voltage and generates the modulation signal for PWM pulse generation.

The switching frequency is expressed as:

$$f_s = 1/T_s \quad (15)$$

The PWM pulse generation is implemented using carrier comparison technique.

The isolated Cuk converter regulates battery charging current and voltage using CC-CV charging strategy.

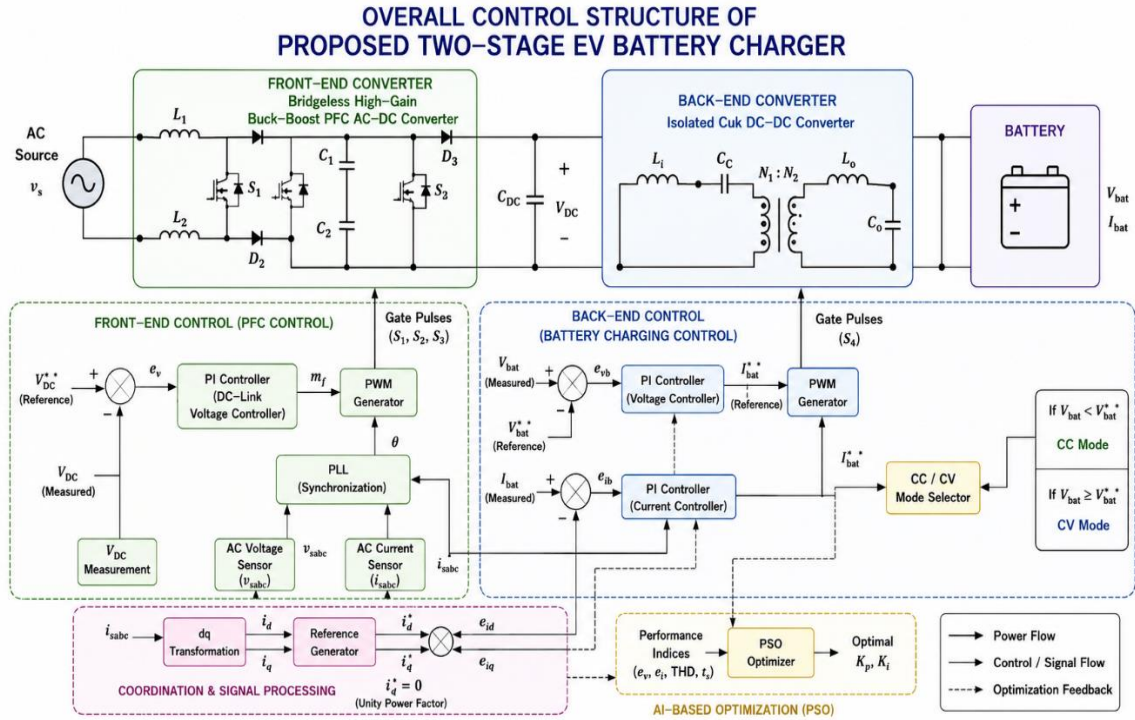


Fig.3 Overall control structure of the proposed charger

Initially, the charger operates in constant current mode where charging current is maintained constant. Once battery voltage reaches the rated value, the controller automatically shifts to constant voltage mode.

The battery voltage error equation is represented as:

$$e_v = V_{ref} - V_b \quad (16)$$

The charging current error equation is:

$$e_i = I_{ref} - I_b \quad (17)$$

PSO is employed for optimal tuning of PI controller gains to minimize overshoot, settling time, THD, and voltage regulation error.

The proposed control strategy is implemented in MATLAB/Simulink using:

- Front-end converter subsystem
- Back-end isolated cuk converter
- PI controllers
- PWM pulse generation

- PSO optimization block
- Battery model

V. RESULTS AND DISCUSSION

Simulation studies were carried out in MATLAB/Simulink under steady-state and dynamic operating conditions.

A. Steady-State Performance

The proposed charger demonstrated sinusoidal source current characteristics with near unity power factor operation.

The obtained power factor was:

$$PF=0.998$$

The source current remained nearly in phase with the source voltage waveform, confirming effective power factor correction capability.

B. DC-Link Voltage Regulation

The DC-link voltage was maintained at: $V_{dc}=300V$

The obtained waveform confirmed stable voltage regulation and reduced voltage ripple under varying operating conditions.

C. Front-End Converter Performance

The front-end bridgeless converter successfully operated in DCM mode and achieved:

- Reduced conduction losses
- Continuous input current characteristics
- Stable converter operation

D. Battery Charging Characteristics

The isolated cuk converter successfully implemented CC-CV charging operation.

During constant current mode:

$$I_b = 16A$$

The battery voltage gradually increased until rated voltage was achieved. During constant voltage mode, charging current gradually decreased while battery voltage remained constant.

E. Harmonic Analysis

FFT analysis confirmed reduced source current harmonic distortion.

The obtained THD was 3.12 %

The obtained THD satisfied IEEE-519 harmonic standards.

F. Dynamic Performance

The dynamic performance of the proposed charger was evaluated under source voltage sag conditions.

Input voltage was reduced from:

220V→180V

The charger maintained:

- Stable DC-link voltage
- Controlled charging current
- Fast transient recovery

G. PSO-Based PI Controller Performance

The optimized PI controller gains obtained using PSO are summarized below:

Table 1: PSO Optimized controller gains

Controller	K_p	K_i
DC-link controller	0.82	36
Current controller	0.65	24
Voltage controller	0.91	42

The optimized controller demonstrated:

- Reduced settling time
- Reduced overshoot
- Improved harmonic performance
- Enhanced dynamic stability

Table 2: Comparative Analysis

	THD	Power Factor	Settling Time	Overshoot	Efficiency
Conventional PI	5.84%	0.972	0.42s	8.7%	91.4%
PSO Optimized PI	3.12%	0.998	0.18s	2.1%	94.2%

The comparative analysis confirms that the PSO optimized controller significantly improves charger performance compared to conventional PI control.

VI. CONCLUSION

This dissertation presented the design, mathematical modelling, control strategy implementation, and performance evaluation of a two-stage electric vehicle battery charger employing a bridgeless high-gain buck-boost PFC AC-DC converter and an isolated Cuk DC-DC converter for low-voltage electric vehicle applications.

The front-end bridgeless high-gain converter was operated in discontinuous conduction mode to achieve inherent power factor correction with simplified control implementation and reduced sensor requirement. The bridgeless topology effectively reduced conduction losses and improved converter efficiency. The back-end isolated Cuk converter successfully implemented constant current and constant voltage battery charging with reduced charging current ripple and galvanic isolation.

Detailed mathematical modelling of the proposed charger was carried out using converter operating principles, voltage gain derivation, power balance equations, and passive component design analysis. A comprehensive control strategy consisting of DC-link voltage regulation, battery charging control, PWM pulse generation, was implemented.

To improve the dynamic performance of the charger, Particle Swarm Optimization based AI tuning technique was employed for optimal tuning of PI controller parameters. The optimized controller significantly improved transient response, reduced settling time, minimized overshoot, and reduced source current harmonic distortion.

The proposed charger was implemented in MATLAB/Simulink environment and evaluated under steady-state and dynamic operating conditions. The simulation results demonstrated:

- Near unity power factor operation
- Reduced source current THD
- Stable DC-link voltage regulation
- Effective CC-CV battery charging
- Improved dynamic response
- Reduced converter losses

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