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Three-Phase CUK-Derived Bridgeless PFC Converter for On-Board EV Charger

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ABSTRACT: In recent years, considerable research has been dedicated to the development of efficient Power Factor Correction (PFC) converters aimed at improving overall power supply performance. Conventional PFC Cuk converters often utilize full-bridge rectifiers, which contribute to higher conduction losses and reduced efficiency. Additionally, electric vehicle (EV) charging typically takes between 4 to 10 hours under standard conditions, creating limitations for long-distance travel due to factors such as available grid power, battery capacity, and the battery's state of charge (SOC).To address these challenges, this work introduces a novel three-phase bridgeless Cuk-derived PFC converter designed specifically for on-board EV charging applications. A key innovation in the proposed design is the operation of the output inductor in discontinuous conduction mode (DCM) across the entire power range, enabling inherent PFC at the AC input without the need for input voltage or current sensing. This significantly reduces system complexity and cost, while also enhancing power density and robustness against high-frequency noise. The control strategy is simplified using a single-sensor voltage control loop, eliminating the need for complex control algorithms. The converter achieves balanced current distribution across all three phases and can function effectively with or without a neutral line. Furthermore, the design minimizes the number of components compared to other three-phase topologies, leading to reduced cost, improved reliability, and a more compact form factor. Voltage stress on semiconductor devices is also lower than that observed in traditional Cuk converters. Simulation results from MATLAB/Simulink confirm the converter's ability to improve key power quality parameters, including power factor and total harmonic distortion (THD). A hardware prototype further substantiates the high performance and suitability of the proposed bridgeless PFC converter for electric vehicle charging applications.

KEYWORDS: Electric Vehicle Charging, Bridgeless Converter, Power Factor Correction (PFC), Cuk Converter, Discontinuous Conduction Mode (DCM), MATLAB Simulation, Power Quality.

I.INTRODUCTION

The global rise in environmental awareness and concerns over climate change have significantly accelerated the transition from fossil fuel-based transportation to cleaner alternatives, such as electric vehicles (EVs). The increasing urgency of addressing the energy crisis, air pollution, and greenhouse gas emissions has driven the widespread development and adoption of EVs. As this transition continues, the evolution of EV charging infrastructure plays a crucial role in enhancing user experience, ensuring grid compatibility, and promoting broader adoption.

Recent innovations in EV charging systems reflect a continuous effort to improve efficiency, reduce environmental impact, and simplify the user interface. Currently, EV charging solutions are broadly categorized into **on-board chargers** and **off-board chargers** [1], [2]. On-board chargers are integrated within the vehicle and are designed to convert AC power from the grid into DC power to charge the battery. These systems are further divided based on their power capacity and charging speed—most notably, into Level 1 and Level 2 charging systems [3].

Level 1 Charging utilizes a standard 120V AC household outlet and typically provides 1 to 2 kilowatts (kW) of power. While cost-effective and simple to implement, Level 1 charging is relatively slow, making it suitable for overnight charging or extended parking periods but impractical for users needing quick battery replenishment.



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Level 2 Charging offers faster performance by utilizing a 240V AC power source and a dedicated wall-mounted charging unit. Power delivery can range from 3.3 kW to 22 kW, depending on the equipment and the EV's specifications. These systems are widely used in residential garages, commercial facilities, public parking lots, and workplaces, offering a practical balance between speed and cost for everyday EV users.

REVIEW OF POWER CONVERSION AND BATTERY CHARGING METHODS

Various power electronic topologies have been developed to improve the performance and efficiency of EV chargers. One widely researched configuration is the **single-phase Cuk-derived bridgeless Power Factor Correction (PFC) converter** [6]. These topologies are especially useful in on-board charging systems, where space and thermal constraints limit the complexity and size of power electronics. More advanced **three-phase converters** have also been introduced for high-power applications, enhancing power quality and enabling faster charging [7], [8], [9].

A common architecture in modern EV chargers is the **two-stage converter**, consisting of an active PFC circuit as the first stage, followed by an isolated DC-DC converter. This arrangement ensures high power conversion efficiency and compliance with grid standards regarding total harmonic distortion (THD) and power factor.

In addition to power conversion, effective battery charging strategies are vital for both performance and battery lifespan. Lithium-ion batteries, which dominate EV markets, are thermally sensitive, particularly under high charging currents. **Constant Current (CC)** charging applies a fixed current until a predefined battery voltage is reached. While effective, this method introduces significant thermal stress due to continuous high current flow.

Alternatively, the **Constant Voltage (CV)** method maintains a fixed voltage across the battery terminals. In this approach, the current gradually increases during the early phase and then decreases as the battery approaches full charge. This method offers simpler control and faster charging but may lead to undercharging if not properly managed [10].

ROLE OF POWER FACTOR CORRECTION (PFC)

Power Factor Correction is critical in EV chargers, especially in grid-connected applications. PFC circuits ensure that the input current remains in phase with the voltage, thereby minimizing reactive power, improving power factor, and reducing energy losses. This not only enhances overall charger efficiency but also ensures better utilization of electrical infrastructure and compliance with international standards.

Conventional PFC converters typically use diode bridge rectifiers, which introduce significant conduction losses. To address this, **bridgeless PFC topologies** have gained attention. These configurations eliminate the input diode bridge, directly connecting the power converter to the grid. As a result, conduction losses are reduced, voltage drops are minimized, and overall power conversion efficiency is improved.

II. CUK-DERIVED BRIDGELESS PFC CONVERTER

The Cuk-derived bridgeless Power Factor Correction (PFC) converter is an advanced power electronic topology that merges the benefits of the conventional Cuk converter with the efficiency of a bridgeless configuration. Designed primarily for AC-DC conversion, this topology aims to improve power factor and reduce harmonic distortion while simultaneously enhancing system efficiency and compactness.

Unlike traditional PFC circuits that rely on a full-bridge diode rectifier at the input, the bridgeless design eliminates the diode bridge, thereby reducing conduction losses and minimizing voltage drops. This not only improves overall power quality but also contributes to better thermal performance and increased system reliability.

The core of the Cuk converter consists of inductors, capacitors, and switching devices—typically MOSFETs. It is a non-isolated, bi-directional DC-DC converter capable of both voltage step-up and step-down operations. When combined with a bridgeless configuration, the circuit achieves lower component stress, greater efficiency, and smoother input current shaping. Depending on the load conditions, the converter can operate in either Discontinuous Conduction Mode (DCM) or Continuous Conduction Mode (CCM). Both modes allow for effective shaping of the input current to



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closely follow the input voltage waveform, thereby achieving near-unity power factor and complying with international power quality standards.Key advantages of the Cuk-derived bridgeless PFC converter include:

Reduced Conduction Losses: The absence of the input diode bridge leads to higher efficiency.

Lower Voltage Stress: Voltage across components such as MOSFETs and diodes is minimized, which extends their operational life.

Improved Power Quality: Active current shaping significantly reduces harmonic distortion.

Compact Design: Fewer components and improved thermal behavior enable higher power density and reduced size.

Flexible Control: The topology supports various control strategies, including analog and digital implementations, allowing for enhanced performance tuning.

Applications of this converter are:

Electric Vehicle (EV) Charging: Enhances power factor and efficiency in on-board charging systems.

Renewable Energy Systems: Suitable for photovoltaic (PV) inverters and wind energy converters to meet grid compliance.

Industrial Power Supplies: Used in high-power industrial applications for improving power quality and reducing harmonics.

III. THREE-PHASE CUK-DERIVED BRIDGELESS PFC CONVERTER

The three-phase Cuk-derived bridgeless Power Factor Correction (PFC) converter is an evolution of the single-phase bridgeless topology, adapted to meet the demands of high-power electric vehicle (EV) charging systems. This advanced configuration extends the performance benefits of its single-phase counterpart [6] to three-phase AC input systems, allowing for greater power handling, improved power quality, and better system efficiency.

The converter consists of three Cuk converter stages, each assigned to one of the input phases. It simplifies the traditional architecture by replacing back-to-back bidirectional switches with single switches, reducing the overall number of components. Operating in Discontinuous Conduction Mode (DCM), the system naturally shapes the input current waveform, eliminating the need for complex sensing and control circuits. Only one sensor and a single control loop are required to maintain power factor correction, offering benefits such as lower cost, higher reliability, reduced system weight, and enhanced efficiency.

One of the key limitations of single-phase chargers is their restricted power handling capability. When used extensively, these systems can impose significant strain on the electrical grid, especially during fast charging. A large number of single-phase chargers and other electronic devices can result in phase imbalance, increased neutral currents, and harmonic distortion within the power distribution network. In contrast, the proposed three-phase design distributes power across all three phases, mitigating these issues and enabling higher power throughput—making it ideal for rapid EV charging.

In terms of power quality, single-phase systems are known to generate high harmonic currents that may lead to transformer overheating, losses, and premature failure. The three-phase configuration, however, offers superior power quality with lower voltage ripple and reduced harmonic content. This not only improves transformer life but also ensures a more stable and clean power supply for EVs. Additionally, current is evenly distributed among all phases, reducing electrical stress on individual components and improving the converter's operational lifespan.

The proposed converter adopts Pulse Width Modulation (PWM) for gate control, which simplifies the control strategy while ensuring precise switching of power semiconductor devices like MOSFETs or IGBTs. The combination of a bridgeless layout, reduced switch count, and simplified control results in a compact, cost-effective, and high-efficiency power conversion system suitable for modern EV applications. The proposed Three-phase BL Cuk- based PFC power converter is represented in Fig. 1.

IV. SYSTEM ARCHITECTURE ANDDESIGN

The increasing demand for efficient, compact, and reliable electric vehicle (EV) charging systems has led to the evolution of advanced converter topologies. One such innovation is the three-phase Cuk-derived bridgeless Power Factor Correction (PFC) converter, designed to optimize performance while reducing complexity and component count.



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This topology builds on the advantages of the single-phase Cuk-derived PFC converter and extends its functionality to three-phase systems for high-power EV charging.

Fig. 1 Proposed three phase cuk derived PFC converter



CONVERTER STRUCTURE AND OPERATING PRINCIPLE

The proposed converter architecture includes a unidirectional switch, two output diodes, one input inductor, one output inductor, and one input capacitor per phase, along with two shared output capacitors. This results in a total of **twenty components**, which is significantly fewer than in traditional three-phase converter implementations. Each phase contributes to a combined regulated DC output used to charge the EV battery.

All three unidirectional switches are connected in a star configuration, with each switch tied to a different AC phase on one side and the common star point on the other. These switches are driven by a **single gate signal**, enabling synchronized switching across all phases and eliminating the need for complex gate driver circuits or intricate control algorithms.

When the switches are activated simultaneously, the AC source is shorted through the input inductors. Because of the symmetry, the instantaneous current from each phase balances at the star point, resulting in **zero net current** at that node. Upon switch release, the stored energy in the inductors is transferred to the intermediate capacitor, and current completes its path either through the **neutral wire** or, if unavailable, through the other two phases.

This design also offers **fault-tolerant operation**. In the case of a missing phase or switch failure, the converter can continue operating using the remaining two phases. In such a scenario, it effectively transforms into a single-phase converter, using a back-to-back switch configuration across the active phases. Additionally, the system supports **operation without a neutral wire**, making it adaptable to both three-wire and four-wire AC systems.

CONVERTER VOLTAGE STRESS AND THERMAL BENEFITS

The topology ensures reduced voltage stress on semiconductor switches and diodes. During normal operation, the voltage appearing across each switch is approximately $(\sqrt{3}Vin + Vo)/2$, where *Vin* is the phase voltage and *Vo* is the output DC voltage. This is significantly lower than in conventional Cuk converters, where the voltage stress typically reaches Vin + Vo. The reduced voltage stress leads to lower switching losses, simplifies heat dissipation, and enhances the converter's thermal performance.



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Moreover, because each switching cycle allows only one active path of current conduction per phase—either through the switch or one of the output diodes—**conduction losses are minimized**, and thermal management becomes simpler.

STEADY-STATE OPERATION MODES

Due to the converter's symmetric phase design, a single-phase analysis suffices to describe its steady-state operation. The converter functions in three distinct modes within a single switching cycle.

Mode 1 (t₀-t₁): The switch S is turned ON, and both output diodes are OFF. In this mode, the input inductor *Lin* stores energy from the AC source, while the output inductor *Lo* draws energy from the intermediate transfer capacitor Ct. The current through both inductors increases linearly, driven by the input voltage.

Mode 2 (t_1-t_2) : The switch S is turned OFF, and output diode *Dol* becomes active. The energy stored in both inductors is transferred to the output load through the output capacitor *Col* and transfer capacitor *Ct*. The currents through *Lin* and *Lo* begin to decay.

Mode 3 (t_2-t_3): All active devices are OFF. The output capacitors *Col* and *Ct* discharge, supplying power to the load. This interval ensures voltage stability and continuity during the non-conduction period.

This operation, particularly the Discontinuous Conduction Mode (DCM), allows the converter to**achieve natural power factor correction**without requiring complex current sensing or feedback control.

CONTROL STRATEGY AND SENSOR REDUCTION

A key advantage of operating in DCM is that it requires only a **single control loop** and **one voltage sensor** to maintain output voltage regulation. The converter's output voltage is compared to a reference, and the resulting error signal determines the **duty cycle** for switching. Since the duty cycle depends only on this error, it remains **constant for a given output power**, further simplifying the control algorithm. This minimalist approach to sensing and control results in several benefits as Lower system cost, Reduced control circuit complexity, Improved reliability and robustness, and Simplified diagnostics and maintenance

COMPONENT SELECTION CONSIDERATIONS

To ensure optimal converter performance, the selection of semiconductor devices and magnetic components is crucial. **Silicon Carbide (SiC) MOSFETs** or **IGBTs** are recommended for switching devices due to their ability to handle high voltage and current levels efficiently while maintaining low switching losses. The inductors must be designed to support the three-phase current profiles while ensuring proper demagnetization during Mode 2. The capacitors, especially the transfer capacitor Ct and output capacitors Co1/Co2, should be chosen for low equivalent series resistance (ESR) and high ripple current endurance to enhance stability and longevity.

ADVANTAGES OF THE PROPOSED TOPOLOGY

The proposed three-phase Cuk-derived bridgeless PFC converter offers numerous benefits over traditional topologies like, fewer components reduce the physical size and weight of the converter, which is ideal for space-constrained EV applications, Lower voltage and conduction losses result in superior conversion efficiency, Simplified gate control and a lower number of components directly reduce manufacturing costs, Fewer parts mean fewer failure points. Additionally, the ability to operate under fault conditions (e.g., missing phase or neutral) adds resilience.Reduced conduction paths and lower losses ease thermal management challenges.A common PWM gate signal for all switches removes the need for sophisticated digital controllers.Natural PFC through DCM operation ensures compliance with harmonic and power quality standards.The three-phase Cuk-derived bridgeless PFC converter presents a highly efficient, compact, and fault-tolerant solution for on-board electric vehicle charging. Its innovative design minimizes component count, simplifies control, and improves thermal and electrical performance. Capable of operating in three-wire and four-wire configurations, and tolerant of phase loss, this topology is well-suited for modern EV applications demanding high performance and reliability. Future work may explore experimental validation, real-time control implementation, and integration with smart grid interfaces.

V. PROTOTYPE MODEL

The hardware setup as in fig 2 for the proposed three-phase Cuk-derived bridgeless PFC converter integrates carefully selected components to ensure high efficiency, reliability, and effective battery charging control. The input and output inductors used in the circuit are rated at 1.5 mH and 29 µH, respectively. These inductors are constructed by winding copper wire on ferrite toroidal cores, which are chosen for their high magnetic permeability and low core losses at



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switching frequencies. The core material and winding technique directly influence the inductance values and performance, particularly in minimizing core saturation and maximizing energy storage. Three MOSFETs, housed in TO-247AC packages, are employed as switching devices in the power stage. These MOSFETs are selected for their fast switching capabilities, low on-resistance, and high thermal efficiency. The TO-247AC package offers excellent thermal dissipation, making it ideal for low to medium power applications where effective heat management is critical.

Capacitors used in the circuit are selected based on standard commercial availability and circuit requirements. These include electrolytic, ceramic, or film types, depending on their intended role—such as filtering, decoupling, or energy storage. The specific capacitance values are chosen to ensure stable voltage levels, reduced ripple, and proper operation during switching transitions.

The control system features a closed-loop mechanism supporting both Constant Current (CC) and Constant Voltage (CV) charging modes. For feedback, an ACS712 Hall Effect current sensor is used to monitor current flow through the charging circuit. This sensor outputs an analog voltage proportional to the current, which is fed into an Analog-to-Digital Converter (ADC) in the microcontroller. A voltage divider circuit provides real-time voltage feedback.

An optically isolated TLP250F gate driver is used to deliver PWM signals to the MOSFETs. It ensures safe electrical isolation between the high-voltage power stage and the low-voltage control circuitry, protecting the microcontroller from electrical surges. The DSPIC30F2010 microcontroller acts as the central controller. It generates PWM signals based on the feedback from the current and voltage sensors, adjusting the duty cycle dynamically to maintain desired CC or CV operating conditions. Due to the unavailability of a full EV battery and laboratory-scale infrastructure, the prototype is tested using a 12V lead-acid battery. The charging parameters are set with a maximum current of 0.9A for CC mode and a target voltage of 14.5 V for CV mode.



Fig. 2 Hardware Test circuit



Fig.3 Experimental Gate pulse signal

VI. RESULTS AND DISCUSSIONS

The simulation results (Fig 4) demonstrated that the output voltage remained consistently stable under various operating conditions. The output voltage ripple was minimal, recorded at less than 1%, indicating strong voltage regulation. Analysis of the input voltage and current waveforms revealed a low input current ripple, maintained below 3%, which contributes to improved power quality and reduced electromagnetic interference as in Fig 6.

Measurements of gate signals (fig 3), input power, and output power confirmed that all operating parameters were within the expected design range. Notably, the Total Harmonic Distortion (THD) of the input current (Fig 5) was calculated to be 2.71%, reflecting a low level of harmonic distortion and compliance with standard power quality requirements. The diode currents are as shown in Fig 7.

These simulation outcomes suggest that the proposed converter design is capable of delivering stable output voltage, minimal ripple, efficient power conversion, and high-quality power. These characteristics are essential for the reliable and effective operation of electric vehicle (EV) chargers, especially in grid-connected environments where power factor and harmonics are critical performance indicators.

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Fig.4 Output voltage and current- simulation



Fig 6Experimental Output V&I of converter



Fig. 5 THD of input phase current



VII. CONCLUSIONS

The shift toward transportation electrification offers a practical pathway to reduce carbon emissions associated with internal combustion engine vehicles. One of the key challenges for electric vehicle (EV) manufacturers is reducing charging time while ensuring that power quality remains uncompromised. Although considerable research has been dedicated to addressing the complexities of fast charging, several challenges still persist. The adoption of fast-charging technology for EVs is closely tied to the efficiency, cost-effectiveness, safety, reliability, compactness, and control simplicity of the power converter topology used. In response to these demands, a novel single-sensor-based bridgeless (BL) three-phase Cuk-derived PFC converter is proposed, simulated, prototyped, and analyzed as a grid-to-vehicle (G2V) on-board charger. This proposed topology features a reduced component count compared to conventional three-phase converter configurations, which translates into lower manufacturing cost, enhanced reliability, and a more compact design. The output inductor is specifically designed to operate in Discontinuous Conduction Mode (DCM) across the full power range, facilitating natural Power Factor Correction (PFC) at the AC input without the need for complex control mechanisms. One of the notable advantages of the proposed system is its simplified control structure— all switches are driven using a common gate signal, significantly reducing the control effort and complexity. Additionally, the converter ensures balanced loading across all three phases and offers operational flexibility, supporting two-phase or three-phase operation, with or without a neutral connection.

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