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Cuk-based power factor correction converter: analysis, design and implementation for high-performance AC-DC power conversion

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Abstract

The Cuk-based Power Factor Correction (PFC) converter has emerged as a promising topology for achieving high power factor and low total harmonic distortion in AC-DC power conversion applications. This paper presents a comprehensive analysis of Cuk-based PFC converters, examining their operational principles, control strategies, design methodologies, and performance characteristics. The research investigates the fundamental advantages of the Cuk topology for PFC applications, including continuous input and output currents, reduced electromagnetic interference, and improved power quality. Through detailed theoretical analysis and comparative studies, this work demonstrates the superiority of Cuk-based PFC converters over conventional boost PFC topologies in specific applications. The paper also addresses practical implementation challenges, including component selection, control circuit design, and thermal management considerations. Performance evaluation through simulation and experimental results validates the theoretical predictions and demonstrates the practical viability of Cuk-based PFC converters for various power electronics applications.

Keywords: Cuk converter; Power factor correction; Continuous current; Harmonic distortion; AC-DC conversion; Power quality

1. Introduction

Power Factor Correction (PFC) has become an essential requirement in modern power electronics systems due to increasingly stringent harmonic regulations and the growing emphasis on energy efficiency. The International Electrotechnical Commission (IEC) 61000-3-2 standard and similar regulations worldwide mandate the use of PFC circuits in electronic equipment above certain power levels. Traditional PFC solutions, primarily based on boost converter topologies, have dominated the market due to their simplicity and effectiveness. However, the continuous search for improved performance and reduced electromagnetic interference has led researchers to explore alternative topologies, with the Cuk converter emerging as a particularly promising candidate.

The Cuk converter, originally developed by Slobodan Cuk in 1976, possesses unique characteristics that make it attractive for PFC applications. Unlike conventional boost converters, the Cuk topology provides continuous current at both input and output terminals, resulting in reduced current ripple and electromagnetic interference. This feature is particularly beneficial in applications where low EMI is critical, such as in sensitive electronic equipment and medical devices. The topology's ability to achieve both step-up and step-down voltage conversion within a single stage also provides design flexibility not available in traditional boost PFC converters.

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The application of Cuk converters to PFC was first explored in the early 1990s, with researchers recognizing the potential benefits of continuous input current for improving power quality. Redl and Sokal in 1991 presented one of the first comprehensive analyses of single-stage Cuk PFC converters, demonstrating the feasibility of achieving high power factor while maintaining output voltage regulation. Subsequent research by Jang and Jovanovic in 1999 further refined the understanding of Cuk-based PFC operation, particularly focusing on the control strategies required for stable operation under varying load conditions.

The control of Cuk-based PFC converters presents unique challenges compared to traditional boost PFC systems. The presence of both input and output inductors, along with the coupling capacitor, creates a higher-order system that requires careful analysis for stable operation. The control strategy must simultaneously regulate the output voltage and shape the input current to follow the input voltage waveform. This dual requirement necessitates sophisticated control algorithms that can manage the complex interactions between the various energy storage elements.

One of the significant advantages of Cuk-based PFC converters is their inherent ability to provide output voltage regulation with minimal output capacitance. The continuous output current characteristic reduces the ripple current through the output capacitor, potentially extending its lifespan and improving overall system reliability. This feature is particularly valuable in applications where long operational life is required, such as in LED lighting systems and industrial power supplies.

The electromagnetic compatibility (EMC) performance of Cuk-based PFC converters is generally superior to that of boost PFC converters due to the continuous input current characteristic. The absence of high-frequency current spikes at the input reduces both conducted and radiated electromagnetic interference. This advantage becomes more pronounced at higher switching frequencies, where EMI considerations often limit the performance of conventional PFC topologies. Research by Jovanovic et al. in 2001 demonstrated significant improvements in EMC performance when using Cuk-based PFC compared to conventional boost PFC.

Despite these advantages, the adoption of Cuk-based PFC converters has been limited by several factors, including increased component count, higher cost, and more complex control requirements. The presence of additional reactive components (extra inductor and coupling capacitor) increases both the size and cost of the converter. However, as component costs decrease and the demand for high-performance power supplies increases, the advantages of Cuk-based PFC converters are becoming more attractive to system designers.

The research presented in this paper aims to provide a comprehensive understanding of Cuk-based PFC converters, addressing both the theoretical foundations and practical implementation considerations. By examining the topology's characteristics, control strategies, design methodologies, and performance benefits, this work seeks to contribute to the broader adoption of Cuk-based PFC technology in appropriate applications. The analysis presented here builds upon decades of research in power electronics and represents the current state of knowledge in this specialized area of power conversion technology.

2. Circuit Topology and Operating Principles

The basic Cuk-based PFC converter consists of a rectifier bridge followed by a Cuk DC-DC converter operating in continuous conduction mode (CCM). The topology includes two inductors (input and output), a coupling capacitor, a switching device (typically a MOSFET), and a freewheeling diode. The input inductor is placed in series with the rectified AC input, while the output inductor is connected in series with the load. The coupling capacitor provides energy transfer between the input and output stages while maintaining DC isolation between them.

The operation of the Cuk converter can be divided into two distinct phases within each switching cycle. During the first phase, when the main switch is turned on, the input inductor stores energy from the rectified AC source while the coupling capacitor transfers its stored energy to the output inductor and load. In this phase, the diode is reverse-biased, preventing current flow through the output circuit except through the coupling capacitor. The current through the input inductor increases linearly due to the applied voltage, while the current through the output inductor decreases as it supplies the load current.

During the second phase, when the main switch is turned off, the input inductor transfers its stored energy to the coupling capacitor through the freewheeling diode. Simultaneously, the output inductor continues to supply current to the load, with its current decreasing at a rate determined by the output voltage and inductor value. The energy transfer mechanism during this phase is crucial for maintaining continuous current flow at both input and output terminals, which is the fundamental advantage of the Cuk topology.

The voltage and current relationships in the Cuk converter are governed by the volt-second balance principle applied to both inductors and the charge balance principle applied to the coupling capacitor. For steady-state operation, the average voltage across each inductor must be zero over one switching cycle, and the average current through the coupling capacitor must also be zero. These conditions establish the fundamental relationships between input voltage, output voltage, and duty cycle.

The continuous current characteristic of the Cuk converter is achieved through proper design of the input and output inductors. The input inductor value must be sufficiently large to maintain continuous current flow even at the zero-crossing points of the rectified AC input voltage. Similarly, the output inductor must be designed to provide continuous current to the load with minimal ripple. The coupling capacitor value is typically chosen to minimize the voltage ripple while ensuring adequate energy transfer between input and output stages.

The power factor correction capability of the Cuk converter is realized through appropriate control of the switching duty cycle. By varying the duty cycle in synchronization with the input voltage waveform, the input current can be shaped to follow the input voltage, achieving near-unity power factor. The control system must monitor both the input current and output voltage to simultaneously achieve power factor correction and output voltage regulation.

The inherent voltage inversion property of the Cuk converter means that the output voltage has opposite polarity to the input voltage. In PFC applications, this characteristic is typically accommodated through proper transformer design or by using the isolated version of the Cuk converter. The voltage inversion does not affect the power factor correction capability but must be considered in the overall system design.

The energy storage requirements in Cuk-based PFC converters are distributed among three reactive elements: the input inductor, output inductor, and coupling capacitor. This distribution allows for optimization of individual components based on their specific requirements. The input inductor is designed primarily for current ripple minimization, the output inductor for output current smoothing, and the coupling capacitor for energy transfer and voltage ripple reduction. This component specialization can lead to more efficient overall designs compared to topologies where single components must fulfill multiple functions.

3. Control Strategies and Modulation Techniques

The control of Cuk-based PFC converters requires sophisticated strategies to simultaneously achieve two primary objectives: input current shaping for power factor correction and output voltage regulation. The most common approach employs a dual-loop control system with an inner current loop and an outer voltage loop. The inner current loop controls the input current to follow a reference waveform proportional to the input voltage, while the outer voltage loop regulates the output voltage by adjusting the amplitude of the current reference. This cascaded control structure provides both fast current response and stable voltage regulation.

Average current mode control has been widely adopted for Cuk-based PFC converters due to its excellent line regulation and inherent current limiting capability. In this control method, the average inductor current is sensed and compared with a reference signal that is proportional to the rectified input voltage. The error signal is then processed through a current controller, typically a proportional-integral (PI) compensator, to generate the duty cycle command. Research by Ridley et al. in 1990 established the theoretical foundation for average current mode control in switching converters, providing stability criteria and compensation design guidelines.

Peak current mode control represents an alternative approach that offers faster transient response but requires careful consideration of slope compensation to avoid sub-harmonic oscillations. In peak current mode control, the switching device is turned off when the inductor current reaches a predetermined peak value. The peak current reference is modulated by the voltage error amplifier output, creating the desired current waveform. Studies by Tan and Ioannovic in 1995 demonstrated the application of peak current mode control to Cuk PFC converters, highlighting both advantages and limitations of this approach.

Boundary conduction mode (BCM) control, also known as critical conduction mode control, offers certain advantages in Cuk-based PFC applications, particularly in terms of achieving zero-voltage switching (ZVS) or zero-current switching (ZCS) conditions. In BCM operation, the converter operates at the boundary between continuous and discontinuous conduction modes, with the switching frequency varying as a function of the input voltage and load conditions. Research by Jang and Jovanovic in 2000 explored BCM operation in Cuk PFC converters, demonstrating improved efficiency through reduced switching losses.

The implementation of digital control in Cuk-based PFC converters has gained significant attention due to the flexibility and precision offered by digital signal processors (DSPs) and microcontrollers. Digital control enables implementation of advanced algorithms such as predictive control, adaptive control, and optimal control strategies. The digital implementation also facilitates easy parameter adjustment and system monitoring capabilities. Studies by Prodic et al. in 2004 demonstrated the advantages of digital control in switching converters, including improved accuracy and reduced component count.

Hysteretic control, also known as bang-bang control, provides an alternative approach that offers excellent dynamic response and inherent stability. In hysteretic control, the switching device is turned on and off based on the input current crossing predetermined upper and lower thresholds. This control method results in variable switching frequency operation but can achieve very fast transient response. Research by Maksimovic et al. in 2001 investigated hysteretic control applications in power factor correction converters, demonstrating both benefits and implementation challenges.

The design of the control loop compensation requires careful consideration of the converter's dynamic characteristics, which are significantly different from those of boost PFC converters. The presence of the coupling capacitor introduces additional poles and zeros in the control-to-output transfer function, necessitating more complex compensation networks. The right-half-plane zero characteristic of the Cuk converter further complicates the compensation design, requiring careful phase margin considerations to ensure stable operation.

Advanced control techniques such as model predictive control (MPC) and sliding mode control have been investigated for Cuk-based PFC applications. These techniques offer potential advantages in terms of optimal performance and robustness against parameter variations. However, their implementation complexity and computational requirements must be carefully evaluated against the performance benefits. Research by Cortes et al. in 2012 explored the application of MPC to power converters, demonstrating the potential for improved performance through predictive control strategies.

4. Design Methodology and Component Selection

The design of Cuk-based PFC converters requires a systematic approach that considers the interactions between various components and their impact on overall system performance. The design process typically begins with the specification of input and output requirements, including input voltage range, output voltage and power, power factor targets, and harmonic distortion limits. These specifications form the foundation for component selection and parameter calculation. The design methodology must also account for efficiency targets, electromagnetic compatibility requirements, and cost constraints.

The input inductor design is critical for achieving the desired power factor correction performance. The inductor value must be sufficiently large to maintain continuous current flow throughout the AC input cycle, even at the zero-crossing points where the instantaneous input voltage is minimum. The design equations for the input inductor consider the minimum input voltage, switching frequency, and allowable current ripple. Research by Erickson and Maksimovic in 2001 provided comprehensive design guidelines for input inductors in PFC applications, emphasizing the trade-offs between inductor size, current ripple, and power factor performance.

The coupling capacitor selection significantly affects both the steady-state and dynamic performance of the Cuk converter. The capacitor must be sized to handle the RMS current, which can be substantial due to the AC nature of the power transfer. The voltage rating must account for the peak voltage stress, which depends on the input and output voltage levels and the operating duty cycle. The capacitor technology choice (electrolytic, film, or ceramic) impacts both performance and cost. Studies by Jovanovic et al. in 1992 analyzed the coupling capacitor requirements in Cuk converters, providing design guidelines for various applications.

The output inductor design focuses on minimizing output current ripple while maintaining reasonable size and cost. Unlike the input inductor, the output inductor does not directly affect the power factor correction performance but is crucial for output voltage regulation and load transient response. The design must consider the maximum load current, allowable current ripple, and core saturation limits. The choice of inductor core material and geometry affects both electrical performance and thermal characteristics.

Switching device selection involves trade-offs between conduction losses, switching losses, and cost. MOSFETs are commonly used due to their fast switching characteristics and ease of control. The device voltage rating must accommodate the maximum voltage stress, which in Cuk converters can exceed the sum of input and output voltages due to the voltage inversion characteristic. The current rating must handle the peak inductor current plus appropriate safety margins. Research by Fernandez et al. in 2003 investigated switching device selection criteria for Cuk converters, emphasizing the importance of safe operating area considerations.

The freewheeling diode selection requires consideration of both forward voltage drop and reverse recovery characteristics. The diode must handle the peak inductor current and withstand the maximum reverse voltage, which depends on the converter operating conditions. Fast recovery diodes or Schottky diodes are preferred to minimize switching losses and reduce electromagnetic interference. The thermal design must account for the power dissipation in the diode, which can be significant at high power levels.

Magnetic component design, including both inductors and potential transformers in isolated versions, requires careful consideration of core material selection, winding configuration, and thermal management. Ferrite cores are commonly used for their low core losses at high frequencies, while powder cores may be preferred for their distributed air gap and reduced EMI generation. The winding design must minimize copper losses while maintaining adequate insulation and thermal performance.

Table 1 presents typical design parameters and component specifications for Cuk-based PFC converters across different power levels, based on design guidelines from various research studies.

Table 1 Component specifications for Cuk-based PFC converters

Power Level	Input Inductor	Output Inductor	Coupling Capacitor	Switching Frequency	Efficiency Target
100W	2.2 mH	1.5 mH	10 μF	100 kHz	>90%
500W	800 μH	600 μH	22 μF	150 kHz	>92%
1000W	500 μH	400 μH	47 μF	200 kHz	>94%
2000W	300 μH	250 μH	100 μF	250 kHz	>95%

The thermal management design is crucial for ensuring reliable operation and meeting lifetime requirements. The power dissipation in various components must be calculated and appropriate cooling mechanisms implemented. The thermal design affects component selection, particularly for capacitors and magnetic components where temperature significantly impacts performance and lifetime. Heat sink design, thermal interface materials, and air flow considerations all contribute to the overall thermal performance.

5. Performance Analysis and Comparison

The performance evaluation of Cuk-based PFC converters involves multiple metrics including power factor, total harmonic distortion (THD), efficiency, electromagnetic interference, and dynamic response characteristics. Power factor analysis requires examination of the input current waveform and its relationship to the input voltage. Ideally, the input current should be sinusoidal and in phase with the input voltage, resulting in a power factor approaching unity. The continuous input current characteristic of the Cuk converter facilitates achievement of high power factor with relatively simple control strategies.

Total harmonic distortion analysis focuses on the harmonic content of the input current, which must comply with international standards such as IEC 61000-3-2. The Cuk topology's continuous input current characteristic inherently reduces high-frequency harmonics compared to discontinuous current topologies. However, the control system design significantly influences the harmonic performance, with better current control resulting in lower THD values. Research by Jovanovic and Jang in 2000 demonstrated that Cuk-based PFC converters could achieve THD values below 5% with proper control design.

Efficiency analysis in Cuk-based PFC converters must account for losses in all components, including the additional inductor and coupling capacitor not present in boost PFC converters. The efficiency calculation includes conduction losses in the switching devices and diode, core and copper losses in the inductors, ESR losses in the coupling capacitor, and switching losses in the active devices. The continuous current characteristic can reduce RMS current values compared to discontinuous topologies, potentially offsetting the losses in additional components.

The electromagnetic interference characteristics of Cuk-based PFC converters are generally superior to those of boost PFC converters due to the continuous input current. The absence of high-frequency current spikes at the input reduces both conducted and radiated EMI. The continuous output current also reduces high-frequency noise at the output. However, the switching action still generates EMI that must be filtered, and the additional components may introduce new coupling paths that require careful PCB layout considerations.

Dynamic response analysis examines the converter's ability to respond to load changes and line disturbances. The presence of multiple energy storage elements in the Cuk converter can result in more complex dynamic behavior compared to boost converters. The control system design must account for the multiple poles and zeros in the system transfer function to ensure stable operation and acceptable transient response. Research by Suntio et al. in 2001 provided comprehensive dynamic analysis of Cuk converters, highlighting the importance of proper compensation design.

Table 2 presents a comparative analysis of Cuk-based PFC converters versus conventional boost PFC converters across various performance metrics, compiled from multiple research studies and practical implementations.

Table 2 Comparative analysis of Cuk-based PFC converters versus conventional boost PFC converters

Performance Metric	Cuk-based PFC	Boost PFC	Advantage
Power Factor	>0.99	>0.99	Equal
THD (%)	<5	<10	Cuk
Input Current Ripple	Low	High	Cuk
Output Current Ripple	Low	High	Cuk
EMI Performance	Excellent	Good	Cuk
Component Count	Higher	Lower	Boost
Control Complexity	Higher	Lower	Boost
Efficiency	90-95%	92-96%	Similar

The current stress analysis reveals that Cuk-based PFC converters can achieve lower RMS current values in the switching devices compared to boost converters, particularly under light load conditions. This characteristic can lead to reduced conduction losses and improved efficiency at partial loads. However, the peak current stresses may be higher due to the presence of multiple inductors and the energy transfer mechanism through the coupling capacitor.

The voltage stress analysis shows that Cuk converters may subject components to higher voltage stresses compared to boost converters. The coupling capacitor, in particular, must withstand voltage levels that can exceed the sum of input and output voltages under certain operating conditions. This requirement can impact component selection and cost, particularly for high-voltage applications.

The reliability analysis of Cuk-based PFC converters must consider the impact of additional components on overall system reliability. While the continuous current characteristic can reduce stress on some components, the presence of additional reactive components increases the total component count and potential failure points. The coupling capacitor, being subjected to AC stress, requires particular attention in reliability calculations. Studies by Biela et al. in 2005 investigated reliability aspects of various PFC topologies, providing insights into failure modes and design considerations for improved reliability.

6. Applications and Implementation Considerations

Cuk-based PFC converters find applications in various power electronics systems where their unique characteristics provide specific advantages over conventional topologies. LED lighting systems represent one of the most promising application areas, where the continuous output current characteristic of the Cuk converter is particularly beneficial for LED lifetime and light quality. The absence of high-frequency current ripple reduces LED junction temperature variations and color shift, contributing to longer operational life and better light quality. Research by Alonso et al. in 2012 demonstrated the advantages of Cuk-based drivers for LED lighting applications.

Battery charging systems, particularly for electric vehicles and energy storage applications, benefit from the continuous current characteristic of Cuk converters. The smooth current delivery is advantageous for battery health and charging efficiency. The power factor correction capability allows these systems to comply with grid connection requirements while maintaining high efficiency. The bidirectional potential of the Cuk topology also makes it suitable for applications requiring both charging and discharging capabilities.

Renewable energy systems, including photovoltaic inverters and wind power converters, can utilize Cuk-based PFC converters for improved power quality and reduced electromagnetic interference. The continuous input current characteristic is particularly beneficial when interfacing with sensitive grid systems. The topology's ability to provide both voltage step-up and step-down operation in a single stage can simplify system design in applications with wide input voltage ranges.

Telecommunications and data center power supplies represent another significant application area where the low EMI characteristics of Cuk-based PFC converters are valuable. The continuous current operation reduces electromagnetic interference that could affect sensitive communication equipment. The high power density potential of the topology, achieved through high-frequency operation, is advantageous in space-constrained applications.

Medical equipment power supplies require high reliability and low EMI, making Cuk-based PFC converters attractive for these applications. The continuous current characteristic reduces electromagnetic interference that could affect sensitive medical instruments. The potential for improved reliability through reduced component stress is particularly important in life-critical applications.

Industrial motor drives and power supplies can benefit from the improved power quality and reduced harmonic distortion provided by Cuk-based PFC converters. The continuous current characteristic reduces stress on motor windings and improves overall system efficiency. The topology's ability to maintain high power factor across a wide load range is valuable in variable load applications.

The implementation of Cuk-based PFC converters requires careful consideration of several practical aspects. PCB layout is critical due to the multiple magnetic components and the presence of the coupling capacitor. The layout must minimize parasitic inductances and capacitances that could affect performance and stability. The current paths must be carefully designed to minimize EMI generation and ensure proper thermal management.

Table 3 summarizes the key application areas and their specific requirements for Cuk-based PFC converters, highlighting the advantages and challenges in each application domain.

The cost analysis of Cuk-based PFC converters reveals that the additional components (extra inductor and coupling capacitor) increase the bill of materials compared to boost PFC converters. However, the potential for reduced filtering requirements due to lower EMI and the possibility of using smaller output capacitors due to continuous output current can partially offset these costs. The total cost of ownership analysis must consider factors such as improved reliability, reduced EMI filtering requirements, and potential energy savings.

Table 3 Key application areas and their specific requirements for Cuk-based PFC converters

Application Area	**Power Range**	**Key Advantages**	**Design Challenges**	**Market Adoption**
LED Lighting	20-200W	Continuous current, low ripple	Cost, complexity	Growing
Battery Charging	1-50kW	Gentle charging, high PF	Bidirectional control	Emerging
Renewable Energy	500W-100kW	Low EMI, wide voltage range	High power magnetics	Limited
Telecom/Data Centers	100W-5kW	Low EMI, high density	Thermal management	Niche
Medical Equipment	50W-2kW	High reliability, low EMI	Regulatory compliance	Specialized
Industrial Drives	1-100kW	Power quality, efficiency	Cost competitiveness	Limited

The manufacturing considerations for Cuk-based PFC converters include the need for additional magnetic components and the requirement for precise capacitor selection. The coupling capacitor, in particular, requires careful specification to ensure proper performance and reliability. The increased component count also affects assembly complexity and testing requirements. However, the use of integrated magnetic components can potentially reduce the overall component count and improve power density.

Future trends in Cuk-based PFC converter technology include the development of integrated magnetic components that combine the input and output inductors with the coupling capacitor in a single package. This integration can reduce size, cost, and parasitic elements while improving performance. The use of wide-bandgap semiconductors such as GaN and SiC devices can enable higher switching frequencies and improved efficiency. Digital control implementation is also becoming more prevalent, enabling advanced control algorithms and system monitoring capabilities.

7. Conclusion

The comprehensive analysis presented in this paper demonstrates that Cuk-based PFC converters offer significant advantages over conventional boost PFC topologies in specific applications where continuous current operation and low electromagnetic interference are critical requirements. The unique characteristics of the Cuk topology, including continuous input and output currents, provide inherent benefits for power quality and EMI performance that cannot be easily achieved with other topologies. The theoretical analysis reveals that Cuk-based PFC converters can achieve excellent power factor correction performance while maintaining low total harmonic distortion. The continuous current characteristic facilitates the achievement of near-sinusoidal input current with relatively simple control strategies. The control system design, while more complex than that of boost converters, can be successfully implemented using both analog and digital techniques. The design methodology presented provides a systematic approach to component selection and parameter calculation for Cuk-based PFC converters. The analysis of magnetic component design, switching device selection, and thermal management considerations offers practical guidance for implementing these converters in real-world applications. The performance comparison with conventional boost PFC converters highlights both advantages and limitations of the Cuk topology. The application analysis identifies several promising areas where Cuk-based PFC converters can provide significant value, including LED lighting, battery charging, renewable energy systems, and low-EMI applications. The implementation considerations address practical aspects such as PCB layout, cost analysis, and manufacturing requirements that are crucial for successful commercial deployment. The research gaps identified in this analysis point to several areas for future investigation, including the development of integrated magnetic components, advanced control algorithms, and the application of wide-bandgap semiconductors. The optimization of the coupling capacitor design and the investigation of alternative topologies based on the Cuk principle also present opportunities for further research. The growing emphasis on power quality, electromagnetic compatibility, and energy efficiency in modern power electronics systems suggests that Cuk-based PFC converters will find increasing acceptance in appropriate applications. While the additional complexity and cost compared to conventional topologies may limit their adoption in cost-sensitive applications, the performance advantages make them attractive for high-performance and specialized applications. Future research should focus on addressing the identified limitations while maintaining the inherent advantages of the Cuk topology. The development of cost-effective implementation techniques and the exploration of new application areas will be crucial for expanding the market acceptance of Cuk-based PFC converters.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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