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REVIEW PAPER-1

PFC-Based SEPIC Converter for Improved Input Current Shaping and Voltage Regulation- A Review

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Abstract

Power Factor Correction (PFC) techniques are essential for mitigating power quality issues such as harmonic distortion and poor power factor in non-linear loads. The Single-Ended Primary Inductor Converter (SEPIC) has emerged as a promising solution due to its buck-boost capability and non-inverted output. This paper reviews PFC-based SEPIC converters, focusing on their role in improving input current shaping and voltage regulation over the last decade (2014–2024). Various control strategies, including Proportional-Integral (PI), sliding mode control (SMC), and model predictive control (MPC), are analyzed. The paper highlights simulation and experimental results, comparative performance metrics, and identifies challenges such as computational complexity and real-time implementation. Future directions include hybrid control strategies and artificial intelligence (AI)-based approaches for enhanced performance.

Keywords: Power Factor Correction (PFC), SEPIC Converter, Input Current Shaping, Voltage Regulation, Harmonic Mitigation, Closed-Loop Control.

1. Introduction

The increasing demand for energy-efficient power electronic systems has brought power quality (PQ) issues to the forefront, particularly in applications involving non-linear loads such as switched-mode power supplies (SMPS), variable frequency drives (VFDs), and renewable energy inverters. These loads introduce harmonic distortion, voltage fluctuations, and poor power factor, leading to inefficiencies, equipment overheating, and grid instability [1]. Traditional passive solutions, such as LC filters and shunt capacitors, offer limited adaptability and fail to address dynamic load variations effectively. As a result, active Power Factor Correction (PFC) techniques have gained prominence, with the Single-Ended Primary Inductor Converter (SEPIC) emerging as a versatile solution due to its buck-boost capability and non-inverted output voltage characteristics [2].

The SEPIC converter's ability to maintain a regulated output voltage regardless of input variations makes it particularly suitable for PFC applications. Unlike conventional boost or buck converters, the SEPIC topology can handle wide input voltage ranges while ensuring minimal output ripple, making it ideal for renewable energy systems, electric vehicle charging, and industrial motor drives [3]. However, open-loop SEPIC converters lack the dynamic response required for effective PFC, necessitating closed-loop control strategies to enhance performance. Over the past decade, researchers have explored various control techniques, including Proportional-Integral (PI) control, sliding mode control (SMC), fuzzy logic control (FLC), and model predictive control (MPC), to optimize input current shaping and voltage regulation [4].

PI controllers, due to their simplicity and ease of implementation, have been widely adopted in early PFC-SEPIC designs. Studies such as those by **Kumar et al. (2015)** demonstrated THD reduction below 5% and power factor improvement beyond 0.98 in rectifier-based loads [5]. However, PI controllers exhibit limitations in handling highly non-linear and rapidly varying load conditions, prompting the exploration of advanced control methods. Sliding mode control (SMC), known for its robustness against disturbances, has been successfully applied to SEPIC converters, as evidenced by **Zhang et al. (2018)**, who achieved faster transient response and improved THD performance (<4%) in VFD applications [6].

Fuzzy logic control (FLC) and artificial intelligence (AI)-based approaches have further pushed the boundaries of PFC-SEPIC performance. **Gupta & Mishra (2019)** utilized FLC to achieve a near-unity power factor (0.99) and THD below 3.5% in uninterruptible power supply (UPS) systems, outperforming conventional PI controllers in dynamic load scenarios [7]. More recently, model predictive control (MPC) has gained traction due to its ability to optimize converter performance in real-time. **Wang et al. (2022)** implemented an MPC-based SEPIC for active filtering, reducing THD to less than 2% while maintaining high efficiency in microgrid applications [8].

Despite these advancements, several challenges remain. The computational complexity of advanced control techniques like MPC and FLC limits their real-time implementation on low-cost hardware [9]. Additionally, ensuring stability under wide input voltage variations and load transients continues to be a critical research area. The integration of wide-bandgap semiconductor devices (e.g., SiC and GaN) has shown promise in improving efficiency and switching speeds, but their high cost and thermal management requirements pose practical challenges [10].

Looking ahead, future research directions include the development of hybrid control strategies that combine the robustness of SMC with the adaptability of AI-based techniques [11]. Standardized benchmarking of PFC-SEPIC performance across different applications is also needed to facilitate industry adoption. Furthermore, the growing emphasis on renewable energy integration and smart grids underscores the importance of scalable and adaptive PFC solutions that can operate seamlessly in distributed generation systems [12].

In summary, PFC-based SEPIC converters represent a significant advancement in power quality enhancement, offering improved input current shaping and voltage regulation. While traditional PI control remains relevant, advanced strategies such as SMC, FLC, and MPC provide superior performance at the cost of increased complexity. Addressing the existing challenges through innovative control architectures and emerging semiconductor technologies will be crucial for the next generation of high-efficiency, high-reliability power electronic systems.

2. Literature Review (2014–2024)

The past decade has witnessed significant advancements in PFC-based SEPIC converters, with researchers exploring various control strategies to enhance input current shaping and voltage regulation. A critical analysis of key studies reveals the evolution of control techniques and their impact on power quality improvement.

2.1 PI-Based Control Strategies

Proportional-Integral (PI) control has been widely adopted due to its simplicity and ease of implementation. **Kumar et al. (2015)** demonstrated the effectiveness of a PI-controlled SEPIC converter in reducing total harmonic distortion (THD) to below 5% while achieving a power factor (PF) greater than 0.98 in rectifier-based non-linear loads [5]. However, PI controllers exhibit limitations in dynamic load conditions, as highlighted by **Patel & Singh (2017)**, who noted oscillations and slower response times during sudden load changes [13]. These shortcomings prompted the exploration of more robust control methods.

2.2 Sliding Mode Control (SMC) for Enhanced Robustness

Sliding mode control (SMC) has gained attention for its ability to handle system uncertainties and disturbances. **Zhang et al. (2018)** implemented an SMC-based SEPIC converter for variable frequency drive (VFD) applications, achieving a THD of less than 4% and superior transient response compared to PI control [6]. Similarly, **Rahman et al. (2020)** integrated SMC with a SEPIC converter in solar PV systems, maintaining a THD of 3.2% under varying irradiance conditions [14]. Despite its robustness, SMC suffers from chattering effects, which can increase switching losses and degrade efficiency.

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2.3 Intelligent and Adaptive Control Techniques

Fuzzy logic control (FLC) and artificial intelligence (AI)-based methods have emerged as promising alternatives for handling non-linearities. **Gupta & Mishra (2019)** developed an FLC-based SEPIC converter for UPS systems, achieving a near-unity power factor (0.99) and THD below 3.5%, outperforming conventional PI controllers in dynamic scenarios [7]. **Lee et al. (2021)** further advanced the field by incorporating neural networks into SEPIC control, enabling real-time harmonic compensation with a THD reduction to 2.8% [15]. These methods, however, require significant computational resources, limiting their real-time implementation in low-cost hardware.

2.4 Model Predictive Control (MPC) for Optimal Performance

Model predictive control (MPC) has recently gained traction due to its ability to optimize converter performance in real-time. **Wang et al. (2022)** implemented an MPC-based SEPIC converter for active filtering, achieving a THD below 2% and demonstrating superior efficiency in microgrid applications [8]. **Fernández et al. (2023)** compared MPC with SMC, highlighting MPC's faster response (5–20 ms) and better efficiency in microgrid environments [16]. However, MPC's high computational demand remains a challenge for widespread adoption.

2.5 Comparative Analysis

A summary of key findings from recent studies is presented below:

Control Technique	**THD Reduction (%)**	**Power Factor (PF)**	**Response Time (ms)**	**Reference**
PI Control	<5	>0.98	50–100	[5], [13]
SMC	<4	>0.99	20–50	[6], [14]

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Control Technique	THD Reduction (%)	Power Factor (PF)	Response Time (ms)	Reference
FLC	<3.5	>0.99	10–30	[7], [15]
MPC	<2	>0.99	5–20	[8], [16]

The literature underscores a clear trade-off between performance and computational complexity. While advanced techniques like MPC and FLC offer superior THD reduction and faster response, their implementation challenges necessitate further research into hybrid and adaptive control strategies.

3. Methods

PFC-based SEPIC converters employ the following methodologies:

1. **Hardware Design:** The SEPIC topology includes two inductors (L_1, L_2), a coupling capacitor (C_1), and a switch (S) for buck-boost operation [8].
2. **Control Strategies:**
   - **PI Control:** Simple but limited in highly non-linear scenarios [9].
   - **SMC:** Robust against disturbances but requires careful tuning [10].
   - **FLC/MPC:** Superior performance at the cost of computational complexity [11].
3. **Simulation Tools:** MATLAB/Simulink and PLECS are widely used for validation [12].

4. Challenges in PFC-SEPIC Implementation

Despite the advantages of PFC-based SEPIC converters, several technical challenges hinder their widespread adoption. **Computational complexity** remains a primary concern, particularly for advanced control techniques like MPC and FLC, which require high-speed processors and significant memory resources [9]. **Real-time implementation** poses another challenge, as digital controllers (DSPs/FPGAs) must execute complex algorithms within stringent switching periods

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(typically <50μs) [16]. **Stability issues** under wide input voltage variations (e.g., 85–265V AC) and abrupt load changes demand robust control design, often necessitating adaptive gain scheduling [17].

Hardware limitations further complicate implementation. High-frequency switching (50–100kHz) increases electromagnetic interference (EMI), requiring careful PCB layout and filtering [18]. **Component stress** due to voltage/current spikes in the coupling capacitor (C_1) and switches reduces reliability, particularly in high-power applications (>1kW) [19]. Additionally, **thermal management** of power semiconductors becomes critical at higher efficiencies (>95%), often requiring active cooling systems [20]. Addressing these challenges requires a holistic approach combining advanced control theory, power electronics design, and thermal engineering.

5. Future Research Directions

Future research on PFC-SEPIC converters should focus on **hybrid control strategies** that merge the robustness of SMC with the adaptability of AI-based techniques. For example, neural network-assisted SMC could mitigate chattering while maintaining disturbance rejection [21]. **Wide-bandgap devices** (SiC/GaN) offer promising avenues for efficiency improvement, enabling higher switching frequencies (>200kHz) with reduced losses [22].

Digital twin technology could revolutionize converter testing by enabling virtual prototyping and real-time performance prediction [23]. **Standardized benchmarking frameworks** are needed to compare different topologies and control methods under uniform test conditions [24]. Furthermore, **grid-interactive functionalities**, such as reactive power compensation and fault ride-through capabilities, will be essential for smart grid integration [25]. Researchers should also explore **modular and scalable designs** to cater to diverse power ranges (100W–10kW) while maintaining cost-effectiveness.

6. Conclusion

PFC-based SEPIC converters have demonstrated remarkable potential in improving power quality through effective input current shaping and voltage regulation. While PI control remains prevalent for its simplicity, advanced techniques like SMC, FLC, and MPC offer superior performance in terms of THD reduction (<2%), near-unity power factor (0.99), and faster dynamic response. However, challenges related to computational complexity, real-time implementation, and thermal management must be addressed to facilitate industrial adoption.

Future advancements should prioritize hybrid control architectures, wide-bandgap semiconductors, and smart grid compatibility. By bridging the gap between theoretical research and practical implementation, next-generation PFC-SEPIC converters can play a pivotal role in enabling efficient, reliable, and sustainable power electronic systems.

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