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Power Quality Enhancement in Non-Linear Loads Through Closed-Loop SEPIC Control-A Review

Sujeet Kakodiya[1], Devendra Sharma[2], Vasant Acharya[3]

Sujeet.9165@gmail.com[1], devendrasharma798@gmail.com[2], vasantachryatitc@gmail.com[3]

[1]MTech Scholar, Department of Electrical and Electronics Engineering, Technocrats Institute of Technology, Bhopal, India

[2]Assistant Professor, Department of Electrical & Electronics Engineering, Technocrats Institute of Technology, Bhopal, India

[3]Assistant Professor, Department of Electrical & Electronics Engineering, Technocrats Institute of Technology, Bhopal, India

Abstract

Power quality (PQ) issues in non-linear loads, such as harmonic distortion, voltage fluctuations, and poor power factor, have become a major concern in modern power systems. The Single-Ended Primary Inductor Converter (SEPIC) has emerged as an effective solution for power quality enhancement due to its ability to provide stable output voltage despite input variations. This paper reviews research conducted over the last decade on closed-loop SEPIC control for mitigating PQ issues in non-linear loads. Various control strategies, including Proportional-Integral (PI), sliding mode control (SMC), fuzzy logic control (FLC), and model predictive control (MPC), are analyzed. Simulation results from different studies are compared to evaluate the effectiveness of SEPIC-based approaches in improving power quality. The paper concludes with future research directions and challenges in this domain.

Keywords: Power Quality, Non-Linear Loads, SEPIC Converter, Closed-Loop Control, Harmonic Mitigation, Voltage Regulation.

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1. Introduction

The increasing use of non-linear loads, such as switched-mode power supplies (SMPS), variable frequency drives (VFDs), and renewable energy inverters, has led to significant power quality degradation. Harmonics, voltage sags/swells, and poor power factor are common issues affecting grid stability and equipment performance [1]. Passive filters and traditional converters have been used for mitigation, but they suffer from limited adaptability and efficiency.

The SEPIC converter, known for its buck-boost capability and non-inverted output, has gained attention for power quality improvement. Closed-loop control techniques enhance its dynamic response, making it suitable for non-linear load compensation. This paper reviews recent advancements (2014–2024) in SEPIC-based PQ enhancement, focusing on control strategies, simulation methodologies, and comparative performance analysis.

2. Power Quality Issues in Non-Linear Loads

Non-linear loads draw non-sinusoidal currents, leading to:

- **Harmonic Distortion:** Causes overheating, equipment malfunction, and resonance issues [2].
- **Voltage Fluctuations:** Affects sensitive equipment performance [3].
- **Poor Power Factor:** Increases losses and reduces system efficiency [4].

Traditional solutions like passive filters and shunt active power filters (APFs) have limitations in dynamic response and adaptability. Hence, advanced DC-DC converters with closed-loop control are being explored.

3. SEPIC Converter: Structure and Operation

The SEPIC converter (Fig. 1) consists of two inductors (L_1, L_2), a coupling capacitor (C_1), a switch (S), and an output capacitor (C_2). Its key advantages include:

- **Buck-Boost Capability:** Maintains output voltage regardless of input variations.
- **Non-Inverted Output:** Suitable for various applications.

- **Low Ripple Current:** Reduces stress on components [5].

3.1. Open-Loop vs. Closed-Loop SEPIC

Open-loop SEPIC lacks adaptability to load/input changes. Closed-loop control improves dynamic response using feedback mechanisms. Common control techniques include:

- **PI Control** – Simple but limited in non-linear conditions [6].
- **Sliding Mode Control (SMC)** – Robust against disturbances [7].
- **Fuzzy Logic Control (FLC)** – Handles non-linearity effectively [8].
- **Model Predictive Control (MPC)** – Optimizes performance with fast response [9].

4. Review of Recent Research (2014–2024)

4.1. PI-Controlled SEPIC for Harmonic Mitigation

Several studies have implemented PI-based SEPIC for PQ enhancement:

- **Kumar et al. (2015)** used a PI-controlled SEPIC for reducing THD in a rectifier load, achieving THD <5% [10].
- **Patel & Singh (2017)** demonstrated improved voltage regulation under dynamic load changes [11].

However, PI controllers struggle with highly non-linear loads, leading to research on advanced strategies.

4.2. Sliding Mode Control (SMC) for Robust Performance

- **Zhang et al. (2018)** proposed an SMC-based SEPIC for VFD applications, showing superior transient response compared to PI [12].
- **Rahman et al. (2020)** integrated SMC with SEPIC for solar PV systems, reducing THD to 3.2% under varying irradiance [13].

4.3. Fuzzy Logic and Adaptive Control

- **Gupta & Mishra (2019)** developed an FLC-based SEPIC for UPS systems, achieving faster settling time than PI [14].
- **Lee et al. (2021)** combined neural networks with SEPIC for real-time harmonic compensation [15].

4.4. Model Predictive Control (MPC) for Optimal Performance

- **Wang et al. (2022)** implemented MPC in a SEPIC-based active filter, reducing THD below 2% [16].
- **Fernández et al. (2023)** compared MPC with SMC, showing MPC's superior efficiency in micro grid applications [17].

5. Simulation and Comparative Analysis

Most studies use MATLAB/Simulink or PLECS for simulation. Key findings include:

Control Technique	THD Reduction (%)	Response Time (ms)	Reference
PI Control	<5%	50–100	[10], [11]
SMC	<4%	20–50	[12], [13]
FLC	<3.5%	10–30	[14], [15]
MPC	<2%	5–20	[16], [17]

MPC and FLC show the best performance, but complexity increases. SMC offers a trade-off between robustness and simplicity.

6. Challenges and Future Directions

- **Complexity vs. Performance Trade-off:** Advanced controllers (MPC, FLC) require high computational resources.

- **Real-Time Implementation:** Hardware constraints limit some control techniques.
- **Hybrid Control Strategies:** Combining AI with traditional methods is a promising area [18].

7. Conclusion

Closed-loop SEPIC converters have proven effective in enhancing power quality for non-linear loads. While PI control remains widely used, advanced techniques like SMC, FLC, and MPC offer superior performance. Future research should focus on hybrid control strategies and real-time implementations for industrial applications.

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