

**Review Article** 

# High-Efficiency Power Factor Correction (PFC) Circuits: A Review of Topologies and Applications

### Swati Gupta

Student, Department of Electrical & Instrumentation Engineering, Guru Gobind Singh Indraprastha University (GGSIPU), Delhi, India

## INFO

E-mail Id: swatigupta@gmail.com Orcid Id: https://orcid.org/0009-0005-6878-6374 How to cite this article: Gupta S. High-Efficiency Power Factor Correction (PFC) Circuits: A Review of Topologies and

Applications. J Adv Res Power Electro Power Sys 2025; 12(1&2): 7-13.

Date of Submission: 2025-02-04 Date of Acceptance: 2025-03-19

### ABSTRACT

Power Factor Correction (PFC) circuits play a critical role in enhancing the efficiency and reliability of power conversion systems by reducing power losses, improving power factor, and ensuring compliance with international power quality standards. With the increasing demand for energy-efficient electronics across various industries, high-efficiency PFC topologies have gained significant attention. Traditional PFC techniques, such as passive and active PFC circuits, have been widely employed; however, recent advancements in power electronics have led to the development of more efficient topologies, including bridgeless PFC, interleaved PFC, and digital control strategies. These advanced PFC designs minimize conduction losses, optimize thermal management, and achieve near-unity power factor operation.

This review provides a comprehensive overview of different PFC topologies, their working principles, and their comparative advantages. It also explores digital control methodologies and the role of modern semiconductor materials, such as Gallium Nitride (GaN) and Silicon Carbide (SiC), in improving the efficiency and reliability of PFC circuits. Furthermore, the applications of PFC circuits in switched-mode power supplies (SMPS), electric vehicles (EVs), renewable energy systems, and LED drivers are discussed, emphasizing their contribution to energy savings and grid stability. The study highlights emerging trends, including AI-driven adaptive control techniques and wireless PFC solutions, which promise further improvements in power factor correction technology. Ultimately, this review aims to provide insights into the future of PFC circuits and their role in shaping next-generation energy-efficient power conversion systems.

**Keywords:** Power Factor Correction (PFC), Electric Vehicles (EVs), Optimize Thermal Management

#### Introduction

Power Factor Correction (PFC) is essential in modern power electronics to reduce harmonic distortion, improve power efficiency, and ensure compliance with international power quality standards. Many electrical devices, such as power supplies, motor drives, and LED drivers, operate on AC power, but without proper PFC, they draw non-sinusoidal currents, leading to increased power losses, voltage fluctuations, and grid disturbances. Poor power factor not only reduces the efficiency of electrical systems but

*Journal of Advanced Research in Power Electronics and Power Systems (ISSN: 2456-1401) Copyright (c) 2025: Author(s). Published by Advanced Research Publications* 



also results in higher electricity costs and increased stress on power distribution networks.  $^{\rm 1}$ 

To mitigate these issues, researchers have developed various PFC circuits that enhance power factor while minimizing losses. PFC circuits work by shaping the input current waveform to match the voltage waveform, ensuring that power is drawn efficiently from the grid. Traditional passive PFC methods use inductors and capacitors to filter harmonics, but they are often bulky and less effective at higher power levels. In contrast, active PFC circuits employ power electronic components such as MOSFETs, IGBTs, and controllers to dynamically regulate the input current, achieving near-unity power factor and lower total harmonic distortion (THD).

With the increasing demand for energy-efficient systems, advancements in PFC technology have led to the development of more sophisticated topologies, including bridgeless PFC, interleaved PFC, and digitally controlled PFC circuits. These designs offer improved efficiency, reduced component size, and enhanced thermal performance, making them ideal for high-power applications. Furthermore, emerging semiconductor materials like Gallium Nitride (GaN) and Silicon Carbide (SiC) are enabling higher switching frequencies, lower conduction losses, and greater reliability in PFC circuits.<sup>2,3</sup>

Given the growing adoption of electric vehicles (EVs), renewable energy systems, and high-efficiency industrial equipment, the role of PFC has become increasingly significant. This review explores the evolution of PFC topologies, their working principles, and their impact on modern power electronics. Additionally, the applications of PFC circuits in various industries will be discussed, highlighting their role in achieving sustainable and energyefficient power conversion solutions.

#### **Power Factor Correction Techniques**

Power Factor Correction (PFC) techniques are designed to improve the efficiency of electrical systems by reducing power losses and harmonics while ensuring compliance with regulatory standards. PFC circuits can be broadly classified into passive PFC and active PFC, each offering distinct advantages and limitations based on application requirements. While passive PFC is a simpler and costeffective method, active PFC provides superior performance and is widely used in modern power conversion systems. The choice of PFC technique depends on factors such as power level, cost constraints, efficiency requirements, and size limitations.<sup>4</sup>

#### **Passive PFC**

Passive PFC uses passive components such as inductors, capacitors, and transformers to shape the input current waveform and improve power factor. This approach is

simple, cost-effective, and reliable since it does not require complex control circuitry. However, passive PFC circuits have several limitations, including large component size, increased weight, and limited power factor improvement, making them unsuitable for high-power applications.

One common passive PFC method is the use of passive LC filters, which help reduce harmonics and smoothen the current waveform. However, achieving a high power factor (above 0.9) with passive PFC is challenging, as these circuits are less efficient in compensating for dynamic load variations. Additionally, the performance of passive PFC deteriorates at higher frequencies, necessitating larger inductors and capacitors, which can significantly increase system size and cost.

Due to these drawbacks, passive PFC is primarily used in low-power applications such as small power supplies, low-wattage LED drivers, and household electronic devices where cost and simplicity are more critical than achieving near-unity power factor. For more demanding applications, active PFC is the preferred solution due to its higher efficiency and superior power factor correction capabilities.<sup>5</sup>

#### Active PFC

Active PFC employs power electronic devices, such as MOSFETs, IGBTs, and diodes, along with control circuits to dynamically regulate the input current and achieve nearunity power factor. Unlike passive PFC, active PFC circuits can correct power factor over a wide input voltage range, making them suitable for high-power applications such as switching power supplies, motor drives, electric vehicles (EVs), and renewable energy systems. Active PFC circuits are more complex and require additional components, including controllers and sensors, but they provide significant benefits in terms of higher efficiency, reduced harmonic distortion, and improved voltage regulation.<sup>6</sup>

## Several active PFC topologies are commonly used in modern power systems, including:

#### **Boost PFC**

The boost converter topology is the most widely used active PFC technique. It steps up the input voltage while shaping the current waveform to follow the input voltage profile, achieving a high power factor (typically above 0.95). Boost PFC circuits are preferred in applications requiring highefficiency power supplies such as data centers, industrial equipment, and consumer electronics. However, one drawback of boost PFC is the presence of high switching losses at elevated power levels, which can reduce overall efficiency.

#### Buck PFC

The buck converter topology steps down the input voltage while maintaining power factor correction. This topology

is suitable for applications where the output voltage needs to be lower than the input voltage, such as low-voltage DC power supplies and LED drivers. While buck PFC is less common than boost PFC, it offers advantages in specific

use cases where voltage step-down is required while maintaining high power factor and efficiency.

#### Buck-Boost PFC

The buck-boost PFC topology combines the characteristics of both buck and boost converters, allowing for both voltage step-up and step-down functionality. This makes it particularly useful in applications where input voltage fluctuations are common, such as automotive power supplies, battery chargers, and off-grid renewable energy systems. Buck-boost PFC provides greater flexibility and adaptability but requires more complex control mechanisms compared to standard boost or buck PFC circuits.

With advancements in digital control strategies and the integration of GaN and SiC semiconductor devices, modern active PFC circuits have significantly improved in terms of efficiency, power density, and reliability. These advancements are driving the adoption of active PFC in next-generation power electronics, ensuring better energy utilization and compliance with stringent power quality standards.<sup>7</sup>

#### **Advanced PFC Topologies**

Recent advancements in Power Factor Correction (PFC) circuits have led to the development of high-efficiency topologies that aim to minimize losses, improve power quality, and enhance system reliability. Traditional PFC circuits, such as conventional boost converters, suffer from limitations like high conduction losses, increased switching losses, and reduced efficiency at higher power levels. To overcome these challenges, researchers have developed advanced PFC architectures, including bridgeless PFC, interleaved PFC, and digital control-based PFC, which offer significant improvements in efficiency, power density, and overall system performance.

These topologies are widely adopted in high-power applications, such as server power supplies, electric vehicles (EVs), industrial motor drives, and renewable energy systems, where energy efficiency and compliance with power quality standards are critical. This section explores key advanced PFC topologies, highlighting their working principles, benefits, and applications.<sup>8,9</sup>

#### **Bridgeless PFC**

Bridgeless PFC eliminates the traditional diode bridge rectifier, thereby reducing conduction losses, improving efficiency, and minimizing thermal stress on components. In conventional PFC circuits, the presence of a full-bridge rectifier introduces voltage drops across the diodes, leading to significant power losses, especially in high-power applications. By eliminating these diodes and integrating active switches for rectification, bridgeless PFC improves overall power conversion efficiency.

## Several bridgeless PFC topologies have been developed, including:

#### Totem-Pole PFC

The Totem-Pole PFC topology utilizes bidirectional switches (typically GaN or SiC MOSFETs) to enable efficient power conversion while achieving a near-unity power factor. This topology operates in continuous conduction mode (CCM) and critical conduction mode (CRM), allowing for lower conduction and switching losses. The adoption of widebandgap (WBG) semiconductors, such as Gallium Nitride (GaN) and Silicon Carbide (SiC), has significantly improved the performance of Totem-Pole PFC by enabling higher switching frequencies, better thermal performance, and increased power density. Due to its high efficiency, Totem-Pole PFC is widely used in high-power AC-DC power supplies, EV chargers, and data center applications.<sup>10</sup>

#### Dual-Boost PFC

Dual-Boost PFC utilizes two boost converters operating in parallel to enhance performance and minimize losses. This configuration reduces input current ripple, improves efficiency, and allows for better thermal management compared to traditional boost PFC circuits. Dual-Boost PFC is particularly advantageous in applications requiring higher power levels and is commonly used in high-power industrial drives, medical equipment, and aerospace power supplies.

Despite its benefits, bridgeless PFC introduces challenges such as increased complexity in control, electromagnetic interference (EMI) issues, and the need for advanced switching devices. However, with the advent of digital controllers and WBG semiconductors, these challenges are being effectively addressed, making bridgeless PFC a promising solution for future high-efficiency power conversion systems.<sup>11,12</sup>

#### Interleaved PFC

Interleaved PFC is a technique that employs multiple parallel power stages operating in a phase-shifted manner, reducing input current ripple, improving thermal performance, and enhancing efficiency. By distributing the power processing across multiple channels, interleaved PFC circuits can significantly reduce switching and conduction losses, making them ideal for high-power applications where efficiency and power density are critical.

#### **Working Principle and Benefits**

Interleaved PFC operates by dividing the total current among multiple parallel converter stages, each switching at a phase-shifted interval. This approach provides several benefits:

- Reduced Current Ripple: The interleaved operation minimizes current ripple at the input, leading to better electromagnetic compatibility (EMC) and reduced stress on components.
- Improved Thermal Management: By distributing power dissipation across multiple stages, interleaved PFC enhances heat dissipation, reducing cooling requirements and improving system reliability.
- Higher Efficiency: Lower conduction losses and reduced switching losses lead to improved overall power conversion efficiency.
- Scalability: Interleaved PFC can be easily scaled for higher power levels by increasing the number of interleaved phases, making it suitable for high-power industrial and automotive applications.<sup>13</sup>

#### **Applications of Interleaved PFC**

#### Interleaved PFC is commonly used in:

- High-power server and telecom power supplies, where efficiency and reliability are crucial.
- Electric vehicle (EV) onboard chargers, which require compact, lightweight, and efficient power conversion solutions.
- Renewable energy inverters, where power quality and harmonic reduction are critical.
- Medical and industrial power supplies, where stable power delivery and thermal efficiency are key factors.

Despite its advantages, interleaved PFC requires more complex control algorithms and increased component count, which can increase design complexity and cost. However, with advancements in digital control techniques and semiconductor technology, interleaved PFC remains a highly efficient solution for next-generation power electronics.<sup>14,15</sup>

#### **Digital Control PFC**

With rapid advancements in digital control techniques, modern PFC circuits now incorporate microcontrollers, digital signal processors (DSPs), and field-programmable gate arrays (FPGAs) for precise real-time control, leading to higher efficiency, improved dynamic response, and adaptive power factor correction.

#### **Advantages of Digital Control PFC**

- Adaptive Control Strategies: Digital controllers enable adaptive PFC algorithms, allowing real-time adjustment of operating parameters based on load conditions, voltage variations, and power quality requirements.
- Predictive and AI-based PFC: Machine learning (ML) and AI-driven control strategies are being integrated into PFC circuits, enabling predictive maintenance, intelligent load forecasting, and real-time power optimization.

- Improved Efficiency and Power Quality: Digital control allows advanced modulation techniques, dynamic duty cycle adjustments, and phase-shift compensation, leading to better efficiency and lower total harmonic distortion (THD).
- Simplified Implementation of Complex PFC Architectures: Digital controllers make it easier to implement multiphase interleaved PFC, bridgeless PFC, and hybrid PFC topologies, improving overall system performance.

#### **Applications of Digital Control PFC**

- Smart grid systems, where real-time power factor optimization is essential.
- Electric vehicle (EV) fast chargers, which require adaptive power regulation.
- Data center power supplies, where digital control ensures high efficiency under varying loads.
- Industrial automation systems, where power quality and reliability are critical.

While digital control PFC offers numerous benefits, it requires sophisticated programming, increased computational power, and additional cost. However, with the widespread adoption of high-performance microcontrollers and Aldriven control solutions, digital PFC is becoming the standard in next-generation power electronics.<sup>16</sup>

#### **Applications of PFC Circuits**

High-efficiency Power Factor Correction (PFC) circuits are crucial in various applications where power quality, energy efficiency, and regulatory compliance are essential. By improving power factor and reducing total harmonic distortion (THD), PFC circuits help optimize power conversion, minimize energy losses, and ensure stable operation of electrical systems. The demand for PFC solutions is increasing due to stringent power quality regulations such as IEC 61000-3-2 and IEEE 519, which enforce limits on harmonic distortion in electrical networks.

The integration of advanced PFC topologies has significantly improved efficiency, power density, and reliability in key applications, including switched-mode power supplies (SMPS), electric vehicles (EVs), renewable energy systems, and LED drivers. Each of these applications benefits from optimized PFC solutions tailored to meet their specific performance requirements.

#### Switched-Mode Power Supplies (SMPS)

Switched-Mode Power Supplies (SMPS) are widely used in consumer electronics, industrial equipment, and telecommunications infrastructure, requiring high power efficiency and compliance with power quality standards. PFC circuits play a vital role in ensuring compliance with IEC 61000-3-2 standards, which regulate harmonic emissions for electronic devices connected to the power grid.

#### Key Benefits of PFC in SMPS:

- Improved Energy Efficiency: Reduces reactive power consumption, leading to lower electricity costs and minimal heat dissipation.
- **Compliance with Regulatory Standards:** Ensures adherence to IEC 61000-3-2, IEEE 519, and Energy Star guidelines for energy efficiency.
- Enhanced Reliability: Reduces stress on components, improving the lifespan of SMPS units.
- Better Performance in High-Power Applications: Used in data centers, industrial automation, and medical equipment where high power factor and minimal harmonic distortion are critical.

Modern SMPS designs integrate active PFC techniques, such as boost PFC and interleaved PFC, to achieve power factors above 0.95 while maintaining compact size and high efficiency.

#### **Electric Vehicles (EVs) and Battery Chargers**

With the growing adoption of electric vehicles (EVs) and hybrid electric vehicles (HEVs), efficient battery charging systems are essential for reducing charging time, minimizing power losses, and improving grid stability. PFC circuits ensure that EV chargers operate efficiently, reducing harmonic pollution and optimizing power utilization from the electrical grid.

#### **Role of PFC in EVs and Charging Systems:**

- Improved Charging Efficiency: Enhances AC-DC conversion efficiency in onboard and offboard chargers, reducing power losses.
- Grid-Friendly Operation: Minimizes harmonic distortion and reactive power consumption, ensuring compatibility with utility grids.
- Higher Power Factor for Fast Charging: Modern EV fast chargers require power levels exceeding 50 kW, making active PFC a necessity for achieving high power factor and reducing energy wastage.
- Supports Bidirectional Charging: Advanced PFC circuits facilitate Vehicle-to-Grid (V2G) and Vehicle-to-Home (V2H) energy transfer, allowing EVs to supply power back to the grid or home energy systems.

PFC topologies such as Totem-Pole PFC and interleaved PFC are widely used in EV onboard chargers, ensuring compact, lightweight, and highly efficient charging solutions.

#### **Renewable Energy Systems**

As the world transitions toward sustainable energy sources, renewable energy systems such as solar photovoltaic (PV) inverters and wind energy converters require efficient power conversion solutions. PFC circuits help improve the grid integration of renewable energy sources by enhancing power quality, reducing harmonic distortion, and stabilizing voltage levels.

#### Importance of PFC in Renewable Energy Systems:

- Enhances Solar Inverter Efficiency: Solar PV inverters equipped with PFC technology can operate with higher power factors, reducing losses during DC-AC conversion.
- Improves Grid Compliance: Ensures compliance with IEEE 1547 and EN 50549 standards for grid-connected renewable energy systems.
- Minimizes Power Losses in Wind Energy Systems: Wind turbines with variable-speed generators require efficient PFC-enabled power converters to ensure stable operation.
- Supports Energy Storage Systems: PFC-based converters enable efficient integration of battery energy storage systems (BESS) with renewable power grids.

Advanced digital control PFC techniques are increasingly used in smart grids and microgrid applications, improving overall system stability and energy efficiency.

#### **LED Drivers and Smart Lighting Systems**

Power Factor Correction is essential in LED lighting systems to ensure stable operation, reduce flickering, and improve energy efficiency. LEDs are replacing traditional lighting technologies due to their higher luminous efficacy and longer lifespan, but they require efficient LED drivers with PFC to operate effectively on AC mains.

#### **Benefits of PFC in LED Drivers:**

- **Ensures Flicker-Free Lighting:** PFC reduces current fluctuations, eliminating visible flickering in LED bulbs.
- Enhances Energy Efficiency: Reduces reactive power losses, leading to lower electricity bills and better power utilization.
- Minimizes Harmonic Emissions: Compliance with IEC 61000-3-2 standards ensures minimal THD in commercial and industrial LED lighting applications.
- Extends LED Lifespan: Reduces stress on LEDs by ensuring stable voltage and current regulation.

Modern smart lighting systems integrate digital PFC techniques for adaptive power regulation, enabling intelligent dimming, energy savings, and IoT-based lighting control in smart cities, commercial buildings, and residential applications.

#### **Industrial and Medical Equipment**

Industrial machinery, automation systems, and medical devices require precise power regulation to ensure high reliability and uninterrupted operation. PFC circuits are widely used in industrial motor drives, CNC machines, welding equipment, and medical imaging systems to improve power quality and efficiency.

#### Key Advantages of PFC in Industrial and Medical Applications:

- Prevents Voltage Fluctuations: Ensures stable voltage and current supply, reducing the risk of malfunctions in sensitive medical and industrial equipment.
- Improves Power Efficiency: Reduces energy losses in high-power industrial motors and drives.
- Ensures Compliance with Power Standards: Many industrial facilities must meet IEEE 519 harmonic distortion limits to avoid penalties and maintain grid stability.

Advanced digital control PFC solutions are increasingly used in mission-critical industrial and healthcare applications to achieve precise and adaptive power factor regulation.

#### **Challenges and Future Trends**

Despite their advantages, PFC circuits face challenges such as complexity, cost, and efficiency trade-offs. Future trends include:

- Integration of GaN and SiC devices for higher efficiency.
- Development of smart PFC controllers using artificial intelligence (AI).
- Adoption of wireless PFC techniques for improved energy transfer in inductive power systems.

#### Conclusion

High-efficiency Power Factor Correction (PFC) circuits are indispensable in modern power electronics, ensuring power quality, regulatory compliance, and energy efficiency across various applications. By minimizing harmonic distortion and reactive power consumption, PFC circuits help reduce power losses, improve voltage stability, and optimize power utilization in systems ranging from switched-mode power supplies (SMPS) and electric vehicles (EVs) to renewable energy systems and industrial automation.

While traditional passive and active PFC techniques remain widely used, advanced topologies such as bridgeless PFC, interleaved PFC, and digital control PFC are setting new benchmarks in efficiency, compactness, and adaptability. These emerging solutions reduce component losses, enhance thermal management, and enable higher power densities, making them ideal for applications requiring strict power quality regulations and high-performance energy conversion.

The rapid evolution of semiconductor technologies, particularly wide-bandgap (WBG) materials like silicon carbide (SiC) and gallium nitride (GaN), is driving nextgeneration PFC innovations. These materials offer lower switching losses, higher breakdown voltage, and faster switching speeds, allowing high-frequency PFC designs with improved efficiency and reduced size. Additionally, the integration of machine learning and artificial intelligence (AI)-based control algorithms is enhancing adaptive PFC strategies, enabling real-time optimization of power factor and energy management in smart grids, IoT-enabled devices, and renewable energy systems. Looking ahead, the continued advancements in digital control techniques, Al-driven optimizations, and semiconductor materials will further enhance the performance, reliability, and adoption of PFC circuits in diverse applications. As industries move toward higher energy efficiency and sustainability goals, the role of high-efficiency PFC technologies will become even more crucial in achieving greener and more intelligent power conversion solutions.

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