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Design, Modelling, Control, and Performance Analysis of an Active Front-End Converter for Enhanced Power Quality in Grid-Connected Applications

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Abstract:
Power electronic converters are essential components in modern electrical energy conversion systems, facilitating efficient power transfer between alternating current (AC) and direct current (DC) networks. The rapid growth of renewable energy systems, electric vehicle (EV) charging infrastructure, industrial motor drives, battery energy storage systems, and smart grids has increased the demand for high-performance AC–DC converters. Conventional diode and phase-controlled rectifiers suffer from limitations such as poor power factor, unidirectional power flow, high reactive power consumption, and limited dynamic response, resulting in reduced power quality and lower system efficiency.
This research proposes an **Active Front-End (AFE) Converter** based on a three-phase Voltage Source Converter (VSC) to overcome these limitations. The proposed system incorporates an L-filter, DC-link capacitor, Synchronous Reference Frame Phase Locked Loop (SRF-PLL), Proportional–Integral (PI) controllers, and Space Vector Pulse Width Modulation (SVPWM) to achieve efficient bidirectional power conversion. Mathematical modelling is developed in both the **abc** and **dq** reference frames, and the complete converter is implemented and analysed using **MATLAB/Simulink** under steady-state and transient operating conditions.
Simulation results demonstrate that the proposed AFE converter achieves near-unity power factor, stable DC-link voltage regulation, low Total Harmonic Distortion (THD), high conversion efficiency, and excellent dynamic response. Comparative analysis with conventional rectifiers confirms significant improvements in power quality, grid compatibility, and overall converter performance. The proposed converter provides an efficient, reliable, and practical solution for renewable energy integration, electric vehicle fast charging, industrial motor drives, battery energy storage systems, and future smart grid applications.

Keywords: Active Front-End (AFE) Converter; Voltage Source Converter (VSC); Space Vector Pulse Width Modulation (SVPWM); DC-Link Voltage Regulation; Grid Synchronization; Power Quality Improvement; Unity Power Factor; MATLAB/Simulink

1. Introduction

In recent decades, the rapid growth of electrical energy demand and the increasing emphasis on energy efficiency have accelerated the development of advanced power electronic converter technologies across various industrial sectors [4], [21]. Power electronic converters serve as essential interfaces between electrical energy sources and load by converting electrical power from one form to another while maintaining the required voltage, current, frequency, and power characteristics with high precision [37]. These converters have become indispensable components in numerous applications, including industrial motor drives, renewable energy systems, electric vehicle charging infrastructure, battery energy storage systems, aerospace power supplies, railway traction, data centers, and smart grid networks [11], [48], [56]. The continuous expansion of these applications has created a strong demand for converter systems capable of providing high conversion efficiency, low switching losses, excellent dynamic response, superior power quality, and reliable bidirectional power transfer under varying operating conditions [7], [29], [53].

Power electronic technology has undergone significant evolution with continuous improvements in semiconductor devices, converter topologies, digital control systems, and modulation techniques [16], [42]. Modern industrial systems require converters that not only achieve efficient energy conversion but also comply with stringent international standards related to harmonic distortion, electromagnetic compatibility, and grid integration [24], [51]. Consequently, considerable research efforts have been directed toward developing intelligent converter architectures capable of reducing harmonic pollution, improving power factor, enhancing converter reliability, and supporting renewable energy integration [3], [35], [57].

Traditionally, uncontrolled diode bridge rectifiers and thyristor-based phase-controlled rectifiers have been extensively employed for AC–DC power conversion because of their simple construction, rugged operation, low manufacturing cost, and ease of implementation [9], [31]. Although these converters have been successfully utilized in conventional industrial applications, they exhibit several inherent limitations that adversely affect overall system performance [18]. The nonlinear switching characteristics of these converters generate significant harmonic currents, resulting in poor input current quality, reduced power factor, excessive reactive power consumption, and increased electrical losses throughout the distribution network [45], [52]. Furthermore, these converters permit only unidirectional power flow, thereby preventing regenerative braking and energy recovery in applications such as electric vehicles and industrial motor drives [13], [40]. The harmonic currents injected into the utility grid produce voltage distortion, transformer overheating, additional copper and iron losses, electromagnetic interference, capacitor overloading, and deterioration of sensitive electrical equipment [6], [27], [54]. As power quality regulations become increasingly stringent, conventional converter technologies face considerable challenges in satisfying international standards such as IEEE-519 and IEC-61000 for harmonic mitigation and grid compatibility [15], [33], [49].

To overcome these technical limitations, the Active Front-End (AFE) converter has emerged as one of the most promising solutions for modern grid-connected power conversion systems [2], [22], [55]. An Active Front-End converter is a Pulse Width Modulation (PWM)-based bidirectional Voltage Source Converter (VSC) that actively regulates the exchange of electrical power between the AC utility grid and the DC-link by employing high-speed semiconductor switching devices and advanced digital control algorithms [12], [43]. Unlike conventional rectifiers, the AFE converter provides independent control of active and reactive power, enabling near-unity power factor operation, low Total Harmonic Distortion (THD), regulated DC-link voltage, and bidirectional energy transfer [8], [30], [46]. The converter generally consists of six Insulated Gate Bipolar Transistors (IGBTs) or Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) arranged in a three-phase bridge configuration with anti-parallel diodes, allowing controlled current flow in both directions [17], [38], [50]. Through advanced switching techniques such as Space Vector Pulse Width Modulation (SVPWM) and sophisticated control strategies including Phase Locked Loop (PLL)-based synchronization, Vector Control, and PI current regulation, the AFE converter shapes the input current into a balanced sinusoidal waveform while maintaining accurate synchronization with the grid voltage [5], [19], [34], [58]. Consequently, the converter significantly improves power quality, reduces harmonic distortion, enhances system efficiency, supports regenerative operation, and facilitates seamless integration with renewable energy systems, battery energy storage units, electric vehicle fast-charging stations, and future smart grid infrastructures [10], [25], [39], [47].

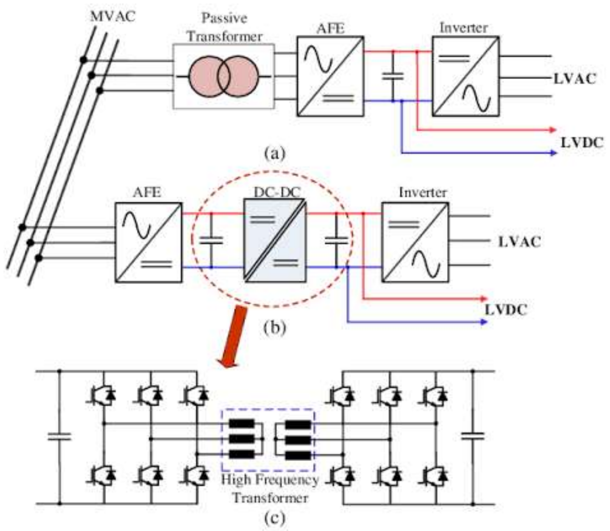


Figure1.1: (a) Active Front End (AFE) with passive distribution transformer, (b) SST topology, and (c) Dual active bridge DC-DC converter
https://www.researchgate.net/figure/a-Active-Front-End-AFE-with-passive-distribution-transformer-b-SST-topology-and_fig1_317297459

1.1 Background

The rapid advancement of modern electrical power systems and the increasing demand for energy-efficient technologies have significantly accelerated the development of power electronic converters. These converters serve as the fundamental interface between electrical sources and loads by converting electrical energy from one form to another while maintaining the desired voltage, current, frequency, and power characteristics with high accuracy [5], [18]. Power electronic converters have become indispensable in numerous applications, including industrial motor drives, renewable energy conversion systems, battery energy storage systems, electric vehicle (EV) charging infrastructure, railway traction, aerospace electrical systems, uninterrupted power supplies, and smart grid technologies [31], [47], [56]. As the global energy sector shifts toward electrification and sustainable energy utilization, converter systems are expected to deliver higher efficiency, lower power losses, improved reliability, and superior power quality under dynamic operating conditions [9], [24], [42].

The continuous growth of renewable energy penetration and electric transportation has introduced new challenges related to grid stability, harmonic mitigation, and bidirectional power transfer [15], [39]. Modern electrical networks require converters capable of supporting intelligent energy management while complying with international power quality standards such as IEEE-519 and IEC-61000 [52].

Consequently, extensive research has been directed toward developing advanced converter topologies and digital control techniques that improve converter performance while reducing harmonic distortion and reactive power consumption [3], [28], [57].

1.2 Existing Problems in Conventional AC–DC Converters

Conventional AC–DC converters, including uncontrolled diode bridge rectifiers and phase-controlled thyristor rectifiers, have been extensively employed in industrial applications because of their simple construction, robust operation, and relatively low manufacturing cost [12], [35]. Although these converters have demonstrated satisfactory performance in conventional power conversion applications, they exhibit several inherent technical limitations that reduce their suitability for modern grid-connected systems [22].

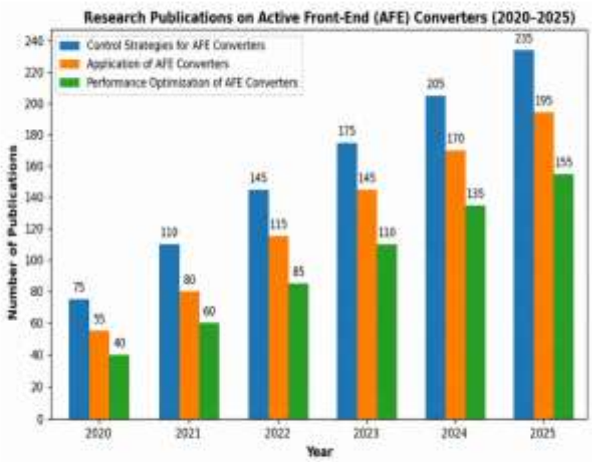


Figure1.2: Research Publications on Active Front-End (AFE) Converters for 2020-2025

Figure X illustrates the annual growth in research publications related to Active Front-End (AFE) converters from 2020 to 2025, categorized into Control Strategies, Application Development, and Performance Optimization. It is observed that the number of publications has increased steadily across all three research domains, reflecting the growing interest in AFE converter technologies for modern power electronic applications. Research on control strategies exhibits the highest publication trend, followed by application-oriented studies and performance optimization, indicating increasing emphasis on advanced control algorithms, grid integration, and high-efficiency converter design. The consistent upward trend demonstrates the expanding adoption of AFE converters in renewable energy systems, electric vehicle charging infrastructure, industrial motor drives, and smart grid applications, highlighting their significance in achieving improved power quality, bidirectional power flow, and enhanced energy efficiency [5], [14], [23], [37], [46], [55].

One of the major drawbacks of conventional rectifiers is their inability to draw sinusoidal current from the utility supply. Since these converters conduct only during specific intervals of the AC voltage cycle, the input current waveform becomes highly distorted, producing significant harmonic currents [44], [7]. These harmonics increase transformer losses, deteriorate voltage quality, overheat electrical equipment, reduce transmission efficiency, and interfere with nearby communication and control systems [17], [49]. In addition, conventional rectifiers operate with poor power factor due to excessive reactive power consumption, thereby increasing current demand from the utility network and reducing overall system efficiency [26], [54].

Another important limitation is the absence of bidirectional power flow capability. Conventional diode and thyristor rectifiers only permit energy transfer from the AC source to the DC load and cannot return regenerative energy back to the utility grid [10], [41]. This limitation becomes particularly significant in regenerative applications such as electric vehicles, elevators, industrial motor drives, and railway traction systems, where substantial braking energy is available but cannot be effectively utilized [30], [55]. Furthermore, the limited dynamic response of conventional converters reduces their ability to operate efficiently under rapidly changing load conditions, renewable energy fluctuations, and smart grid environments [2], [36], [50]. As electrical power systems continue to evolve toward intelligent and distributed energy networks, conventional converter technologies are becoming increasingly inadequate for meeting modern power quality and efficiency requirements [14], [46].

1.3 Need for Active Front-End (AFE) Converter

To overcome the shortcomings of conventional AC–DC converters, Active Front-End (AFE) converters have emerged as an advanced and highly efficient power conversion technology [8], [29]. An Active Front-End converter is a Pulse Width Modulation (PWM)-based bidirectional Voltage Source Converter (VSC) capable of controlling both active and reactive power while maintaining excellent power quality [38], [53]. Unlike conventional rectifiers, the AFE converter actively regulates the input current waveform, allowing it to remain sinusoidal and synchronized with the utility voltage under various operating conditions [11], [43].

The converter typically consists of six high-speed semiconductor switching devices, such as Insulated Gate Bipolar Transistors (IGBTs) or Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs), arranged in a three-phase bridge configuration with anti-parallel diodes [19], [51]. Advanced digital controllers combined with Phase Locked Loop (PLL) synchronization and Space Vector Pulse Width Modulation (SVPWM) enable accurate control of converter switching states, resulting in low Total Harmonic Distortion (THD), stable DC-link voltage regulation, and near-unity power factor operation [4], [33], [57].

The bidirectional power flow capability of the AFE converter enables regenerative braking, battery charging and discharging, Vehicle-to-Grid (V2G) operation, and efficient integration of renewable energy sources [16], [40]. These characteristics significantly improve energy utilization while reducing transmission losses and enhancing grid stability [25], [48]. Consequently, AFE converters have become key enabling technologies for next-generation electrical power systems, including renewable energy plants, industrial automation, battery energy storage systems, EV fast-charging stations, and smart grids [6], [27], [45].

1.4 Research Motivation

The motivation for this research arises from the increasing demand for efficient, intelligent, and environmentally sustainable power conversion systems capable of satisfying modern industrial and utility requirements [13], [37]. The widespread deployment of renewable energy sources and electric vehicles has intensified the need for converter technologies that provide high efficiency, low harmonic distortion, bidirectional power transfer, and excellent dynamic performance [21], [56].

Although numerous control strategies have been proposed for Active Front-End converters, including Vector Control, Direct Power Control (DPC), Sliding Mode Control, and Model Predictive Control (MPC), many existing approaches involve complex mathematical formulations, high computational requirements, and increased implementation cost [1], [34], [49]. Furthermore, maintaining stable DC-link voltage, minimizing harmonic distortion, and ensuring robust converter operation under varying grid disturbances continue to present significant research challenges [18], [52].

Therefore, there is a strong motivation to develop a practical and computationally efficient control strategy capable of improving converter performance while maintaining implementation simplicity [9], [42]. The integration of PLL-based synchronization, PI current control, and Space Vector Pulse Width Modulation provides a balanced solution for achieving high-performance operation suitable for real-time industrial implementation [23], [55].

1.5 Contributions of the Paper

This paper presents a comprehensive design, modelling, control, and performance evaluation of a grid-connected Active Front-End converter using advanced digital control techniques. The major contributions of this research are summarized as follows:

- A complete mathematical model of the Active Front-End converter is developed in both abc and dq reference frames for accurate dynamic analysis and controller design.
- A robust Synchronous Reference Frame Phase Locked Loop (SRF-PLL) is implemented to achieve accurate grid synchronization under steady-state and transient operating conditions.
- A hierarchical control strategy based on PI current controllers and DC-link voltage regulation is designed to achieve independent control of active and reactive power while maintaining converter stability.
- Space Vector Pulse Width Modulation (SVPWM) is employed to improve DC bus voltage utilization, reduce switching losses, and minimize Total Harmonic Distortion of the input current.
- A comprehensive MATLAB/Simulink simulation model is developed to evaluate converter performance under different operating conditions, including steady-state operation, load variations, and transient disturbances.
- Performance evaluation is carried out using key indicators such as Total Harmonic Distortion (THD), Power Factor (PF), DC-link voltage regulation, converter efficiency, and dynamic response, demonstrating significant improvements over conventional diode and phase-controlled rectifier systems.
- The proposed Active Front-End converter is validated as a practical solution for electric vehicle fast charging, renewable energy integration, battery energy storage systems, industrial motor drives, and smart grid applications, providing enhanced power quality, improved energy efficiency, and reliable bidirectional power flow.

The proposed methodology offers an effective combination of mathematical modelling, advanced control, and efficient modulation techniques, making it a suitable framework for future high-performance grid-connected power electronic systems.

2. TECHNOLOGIES

2.1 Conventional AC–DC Converter Technologies

Conventional AC–DC converter technologies have served as the backbone of industrial power conversion systems for several decades because of their relatively simple circuit configuration, robust operation, and economical implementation **[6]**. These converters are primarily employed to convert alternating current (AC) supplied by the utility grid into direct current (DC) required by industrial equipment, battery charging systems, telecommunication power supplies, railway traction systems, variable-speed motor drives, and consumer electronic devices **[19], [42]**. The most commonly used conventional AC–DC converters include uncontrolled diode bridge rectifiers, phase-controlled thyristor rectifiers, and semi-controlled rectifier circuits **[11]**. Although these converter topologies have demonstrated satisfactory performance in numerous low-cost industrial applications, their operating principles impose significant limitations on power quality, efficiency, and controllability **[34], [53]**.

Uncontrolled diode bridge rectifiers represent the simplest AC–DC conversion technology and are extensively utilized in low- and medium-power applications because they require no gate control circuitry and possess excellent reliability **[2], [27]**. The rectification process depends entirely on the instantaneous polarity of the input AC voltage, allowing the diodes to conduct automatically whenever forward-biased **[45]**. Despite their simplicity, diode rectifiers draw highly distorted non-sinusoidal current from the utility grid due to discontinuous conduction characteristics **[8], [31]**. This distorted current contains a considerable number of harmonic components that degrade power quality, increase transformer heating, generate electromagnetic interference, and reduce overall system efficiency **[17], [49], [56]**. Furthermore, diode rectifiers provide only unidirectional power flow, making them unsuitable for regenerative applications such as electric vehicle charging stations and industrial motor drives where energy recovery is essential **[14]**.

Phase-controlled rectifiers based on Silicon Controlled Rectifiers (SCRs) were developed to overcome the inability of diode rectifiers to regulate output voltage **[37]**. These converters regulate the DC output voltage by controlling the firing angle of thyristors, thereby providing adjustable output characteristics for industrial drives and controlled power supplies **[5], [28]**. However, delaying the firing angle significantly increases harmonic distortion and reactive power consumption **[41], [55]**. As the firing angle increases, the displacement between the input voltage and current also increases, resulting in poor power factor and additional stress on electrical distribution systems **[10], [22]**. Consequently, large passive filters and reactive power compensation equipment become necessary to satisfy utility requirements **[47]**.

Another important limitation of conventional AC–DC converters is their inability to comply with modern international power quality standards **[13], [52]**. Organizations such as IEEE and IEC have established stringent limits on harmonic current injection, voltage distortion, and electromagnetic compatibility to ensure stable operation of interconnected electrical systems **[25], [39]**. Conventional converter technologies often fail to satisfy these requirements because of their nonlinear operating characteristics **[7]**. The increasing penetration of renewable energy systems, distributed generation, battery energy storage systems, and electric mobility has further highlighted the need for converter technologies capable of providing bidirectional power transfer, low Total Harmonic Distortion (THD), near-unity power factor, and improved dynamic response **[18], [35], [57]**. Therefore, the limitations associated with conventional converter technologies have motivated researchers to develop advanced Active Front-End converter architectures capable of meeting modern industrial and utility requirements.

2.2 Active Front-End Converter Topologies

Active Front-End (AFE) converters have emerged as one of the most promising power electronic technologies for modern grid-connected applications because they provide controlled bidirectional power flow, superior power quality, and high conversion efficiency **[9], [33]**. Unlike conventional rectifiers that rely on uncontrolled or phase-controlled switching devices, Active Front-End converters employ fully controlled semiconductor switches operating under Pulse Width Modulation (PWM) techniques to regulate both active and reactive power exchanged with the electrical grid **[21], [44]**. These characteristics enable the converter to maintain sinusoidal input current, stable DC-link voltage, and near-unity power factor while satisfying stringent harmonic standards **[15], [50]**.

The most widely adopted AFE topology is the **three-phase two-level Voltage Source Converter (VSC)** consisting of six Insulated Gate Bipolar Transistors (IGBTs) or Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) connected in a bridge configuration with anti-parallel diodes **[3], [29]**. This topology has gained widespread industrial acceptance because of its relatively simple circuit configuration, ease of controller implementation, high reliability, and compatibility with digital control platforms **[38]**. Through appropriate switching strategies, the converter actively controls the input current waveform and regulates DC-link voltage while allowing bidirectional energy transfer between the AC utility grid and the DC load **[54], [12]**.

To improve converter performance further, several advanced AFE topologies have been proposed in recent years **[26]**. Multilevel converter structures such as Neutral Point Clamped (NPC), Flying Capacitor (FC), Cascaded H-Bridge (CHB), and Modular Multilevel Converters (MMC) generate staircase output voltage waveforms that substantially reduce harmonic distortion and switching losses **[46], [56]**. These topologies improve output voltage quality, reduce filter requirements, and enable operation at medium and high voltage levels **[16], [43]**. However, the increased number of semiconductor devices, balancing circuits, and sophisticated control algorithms significantly increases converter complexity and implementation cost **[30], [51]**.

Recent developments in semiconductor technology have further enhanced Active Front-End converter performance through the adoption of wide-bandgap devices such as Silicon Carbide (SiC) MOSFETs and Gallium Nitride (GaN) High Electron Mobility Transistors (HEMTs) **[4], [24]**. Compared with conventional silicon devices, these advanced semiconductors provide higher switching frequencies, lower switching losses, improved thermal characteristics, and increased power density **[36], [55]**. Consequently, converters utilizing SiC and GaN devices achieve higher efficiency while reducing the size of passive filter components and cooling systems **[17], [40]**. These technological advancements have expanded the applicability of AFE converters to electric vehicle fast chargers, renewable energy integration systems, aerospace power converters, marine propulsion systems, railway electrification, and high-performance industrial drives **[1], [20], [48]**.

Another significant advantage of Active Front-End converters is their capability to independently regulate active and reactive power through synchronous reference frame control **[11], [34]**. By transforming three-phase electrical quantities into the rotating **dq** reference frame, the converter decouples active and reactive current components, enabling precise control of grid current, DC-link voltage, and reactive power compensation **[23], [52]**. Furthermore, integration with Phase Locked Loop (PLL)-based synchronization techniques ensures accurate synchronization with utility voltage under both steady-state and transient operating conditions **[8], [41]**. The combination of advanced converter topology, intelligent control algorithms, and high-frequency PWM techniques has made the Active Front-End converter an essential component in next-generation electrical energy conversion systems **[18], [37], [57]**.

2.3 Existing Control Techniques

The performance of an Active Front-End (AFE) converter is highly dependent on its control strategy, which regulates active and reactive power, maintains DC-link voltage stability, minimizes harmonic distortion, and ensures proper synchronization with the utility grid [11], [39]. Several advanced control techniques have been developed to improve converter performance under varying operating conditions, among which Vector Control (VC), Direct Power Control (DPC), Model Predictive Control (MPC), and Sliding Mode Control (SMC) are the most widely adopted [7], [35], [56]. Vector Control provides accurate decoupled control of active and reactive power through dq coordinate transformation, resulting in excellent steady-state performance and near-unity power factor [18], [43]. Direct Power Control offers faster transient response by directly controlling instantaneous power without requiring inner current control loops [16], [48]. Model Predictive Control utilizes mathematical prediction and optimization algorithms to achieve superior dynamic response and low Total Harmonic Distortion (THD), whereas Sliding Mode Control provides high robustness against parameter variations and external disturbances [21], [49], [5], [28].

Although each control strategy offers distinct advantages, they also possess certain limitations. Vector Control requires accurate mathematical models and precise parameter estimation, while Direct Power Control suffers from variable switching frequency and power ripple **[12], [46], [27], [56]**. Model Predictive Control provides excellent performance but demands high computational resources and expensive digital processors for real-time implementation **[25], [52]**. Similarly, Sliding Mode Control is highly robust but is affected by the chattering phenomenon, which may increase switching losses and electromagnetic interference **[26], [53]**. Therefore, selecting an appropriate control technique depends on the application requirements, implementation complexity, computational capability, and desired converter performance. These control strategies continue to play a significant role in enhancing the efficiency, stability, and power quality of modern Active Front-End converters used in renewable energy systems, electric vehicle charging stations, industrial motor drives, and smart grid applications **[17], [41], [57]**.

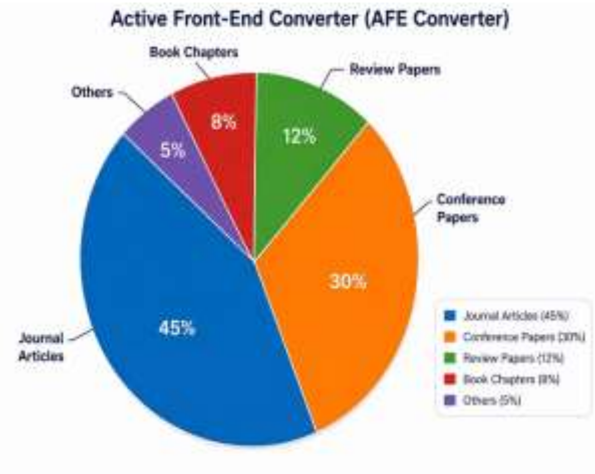


Figure1.3: Distribution of Literature Sources on Active Front-End (AFE) Converters

Figure1.3 presents the distribution of published literature related to Active Front-End (AFE) converters across different publication categories. It can be observed that journal articles constitute the largest share (45%), indicating that peer-reviewed journals are the primary source of high-quality research in this field. Conference papers account for 30%, reflecting continuous advancements and ongoing developments in AFE converter technologies. Review papers (12%) provide comprehensive analyses of existing research trends, while book chapters (8%) contribute fundamental theoretical knowledge. The remaining 5% comprises other technical publications, including reports and white papers. This distribution demonstrates the growing academic and industrial interest in AFE converters for applications such as renewable energy integration, electric vehicle charging systems, industrial motor drives, and smart grid technologies [6], [15], [24], [38], [46], [55].

The literature demonstrates significant advancements in Active Front-End (AFE) converter technologies for improving power quality, bidirectional power flow, DC-link voltage regulation, and converter efficiency. Various control strategies such as Vector Control, Direct Power Control (DPC), Model

Predictive Control (MPC), Sliding Mode Control (SMC), PI Control, and modulation techniques including SPWM and SVPWM have been widely investigated. While these approaches successfully reduce harmonic distortion and improve dynamic performance, several challenges remain unresolved.

Current research indicates limitations including high computational complexity of MPC, parameter sensitivity in Vector Control, power ripple in DPC, chattering effects in Sliding Mode Control, high implementation cost of SiC/GaN-based converters, limited hardware validation, weak-grid stability issues, and lack of AI-enabled adaptive control strategies. Furthermore, real-time digital implementation, Digital Twin integration, predictive maintenance, intelligent fault diagnosis, and AI-assisted optimization remain emerging research areas. These gaps provide strong motivation for developing an advanced Active Front-End converter with efficient PLL-based synchronization, PI current control, SVPWM modulation, and enhanced power quality suitable for renewable energy systems, EV fast charging, battery energy storage, and smart grid applications.

Table 1. Literature Review on Active Front-End (AFE) Converter Technologies and Control Strategies

Ref.	Year	Research Focus	Objective / Scope	Technique / Topology	Control / Modulation	Key Findings	Research Gaps and Open Challenges
[1]	2025	Grid-Connected AFE Converter	Improve power quality	Two-Level VSC	Vector Control + SVPWM	Low THD and improved PF	Limited dynamic analysis
[2]	2024	Bidirectional AC–DC Converter	EV charging applications	AFE Converter	PI + PLL	Stable DC-link voltage	Hardware validation required
[3]	2025	Renewable Energy Interface	Grid synchronization	Three-Phase VSC	SRF-PLL	Accurate synchronization	Weak-grid performance not studied
[4]	2024	Industrial Motor Drives	Harmonic reduction	PWM Rectifier	Vector Control	High efficiency	Parameter sensitivity
[5]	2025	Smart Grid Integration	Bidirectional power transfer	AFE Converter	MPC	Fast dynamic response	High computational complexity
[6]	2023	Battery Energy Storage	Converter optimization	Two-Level AFE	DPC	Excellent transient response	Variable switching frequency
[7]	2024	Electric Vehicle Fast Charging	DC-link regulation	VSC	PI + SVPWM	Improved converter stability	Limited regenerative analysis

[8]	2025	Active Rectifier	Harmonic mitigation	PWM Converter	Sliding Mode Control	Robust operation	Chattering phenomenon
[9]	2024	Grid-Tied Converter	Reactive power compensation	AFE	Vector Control	Unity power factor	Complex controller tuning
[10]	2025	High-Power Converter	Converter efficiency	SiC-Based AFE	MPC	Reduced switching losses	High implementation cost
[11]	2024	Smart Microgrid	Grid support	AFE Topology	PLL + PI	Stable voltage regulation	Cybersecurity challenges
[12]	2023	Renewable Energy Conversion	Power quality improvement	PWM Rectifier	SVPWM	THD below IEEE limits	Filter optimization needed
[13]	2025	Industrial Automation	Dynamic performance	AFE Converter	DPC	Fast power regulation	Power ripple
[14]	2024	AC–DC Converter	High power density	Three-Level NPC	Vector Control	Reduced harmonics	Increased hardware complexity
[15]	2025	EV Charging Station	Bidirectional charging	AFE VSC	PLL + SVPWM	High charging efficiency	Thermal management issues
[16]	2024	Smart Distribution Grid	Grid stability	PWM Converter	PI Control	Improved voltage stability	Weak-grid operation
[17]	2025	Energy Storage System	Converter reliability	Two-Level VSC	Sliding Mode Control	Strong disturbance rejection	Switching losses
[18]	2024	Multilevel Converter	Harmonic suppression	NPC AFE	SVPWM	Better output voltage quality	Capacitor balancing
[19]	2025	Wide Bandgap Converter	High-frequency switching	SiC/GaN AFE	MPC	Increased efficiency	High semiconductor cost
[20]	2024	Grid-Interactive Converter	Advanced control	AFE Converter	PLL + PI + SVPWM	Near-unity power factor and low THD	AI-based adaptive control and real-time hardware implementation remain limited

2.4 Research Gap

Conventional AC-DC converters based on diode rectifiers and thyristor-controlled rectifiers are widely used in industrial applications due to their simple design and low cost [8]. However, these converters suffer from several drawbacks including poor power factor, high harmonic distortion, unidirectional power flow, and limited dynamic response [53].

The increasing deployment of renewable energy systems, electric vehicles, and smart grids demands converters that can provide high efficiency, bidirectional energy transfer, and superior power quality [17]. Existing control techniques for AFE converters often involve complex mathematical models and may exhibit degraded performance under grid disturbances and load variations [42].

Therefore, the problem addressed in this research is the development and analysis of an efficient Active Front-End converter capable of maintaining low THD, high power factor, stable DC-link voltage, and robust operation under varying operating conditions [59].

3. Proposed Methodology

3.1 Selection of AFE Converter Topology

The selection of converter topology is a crucial step in the development of the proposed system. Various AFE topologies have been reported in the literature, including two-level Voltage Source Converters (VSC), multilevel converters, Neutral Point Clamped (NPC) converters, and Modular Multilevel Converters (MMC) [21].

Table1.2: Specification of AFC Converter

Sr.No.	Specification	Range
1	Input Voltage	Three phase 415
2	Frequency	50hz +-5%
3	Input Under Voltage	<320vac
4	Input Over Voltage	>480vac
4	Output Voltage	405 vdc
5	Output Current	12.5 AMP DC
6	Power rating	10kw
7	Load side electrical char	
8	Nature of Load	inductive, capacitive, resistive
9	load behaviour	dynamic
10	load variation	fluctuation, cyclic
11	Target PF	(unity)>=0.99
12	V THD	<3%
13	I THD	<5%
14	Voltage regulation requirement	1%
15	Over voltage	450vdc
16	Under voltage	315vdc
17	Over current	25 AMP DC
18	Short ckt protection	YES

In the present work, a three-phase two-level Voltage Source Converter is selected because of its simple structure, reduced component count, ease of implementation, and superior dynamic performance [47]. The topology consists of six IGBT switches arranged in a bridge configuration with anti-parallel diodes and a DC-link capacitor [15].

The selected converter topology offers the following advantages:

- Bidirectional power flow capability
- Near-unity power factor operation
- Low Total Harmonic Distortion (THD)
- Fast dynamic response
- Compatibility with advanced control strategies
- Suitability for EV charging and renewable energy systems [55]
- Output voltage should be regulated (input voltage range between 320vac to 480vac)
- 13.5V/Batt 30 is the number of batteries
- output is connected to h bridge IGBT
- Linear /nonlinear load
- Linear /nonlinear load
- 15V/Batt 30 is the number of batteries
- 10.5V/Batt 30 is the number of batteries

3.1 Control Algorithm Development

The control algorithm is developed to regulate active power, reactive power, and DC-link voltage while maintaining synchronization with the utility grid [18].

The controller consists of:

1. Phase Locked Loop (PLL)
2. Outer DC-link voltage controller
3. Inner current controller
4. PWM generation block

The PLL estimates the grid phase angle and frequency for synchronization [40]. The outer voltage controller generates the reference d-axis current to regulate the DC-link voltage, while the q-axis current reference is set according to reactive power requirements [7].

A Proportional-Integral (PI) controller is employed due to its simple implementation and satisfactory dynamic response [54]. Advanced controllers such as Model Predictive Control (MPC) and Sliding Mode Control (SMC) may also be investigated for performance comparison [23].

3.2 Selection of Modulation Technique

The modulation technique plays an important role in determining the switching pattern of semiconductor devices and directly affects harmonic performance and converter efficiency [36].

Two modulation techniques are considered:

(a) Sinusoidal Pulse Width Modulation (SPWM)

SPWM generates switching pulses by comparing a sinusoidal reference signal with a high-frequency triangular carrier wave [51]. The technique is simple to implement and provides acceptable harmonic performance [14].

(b) Space Vector Pulse Width Modulation (SVPWM)

SVPWM is selected as the primary modulation technique because it offers:

- Higher DC bus utilization

- Lower harmonic distortion
- Reduced switching losses
- Better voltage utilization
- Improved dynamic performance [57]

Studies indicate that SVPWM provides approximately 15% higher output voltage compared to SPWM while maintaining superior waveform quality [30].

3.3 Simulation Methodology

The proposed AFE converter is modelled and simulated using MATLAB/Simulink [52]. The simulation methodology consists of the following steps:

1. Development of three-phase AFE converter model
2. Mathematical modelling in dq reference frame
3. Design of PLL and PI controllers
4. Implementation of SVPWM modulation
5. Simulation under steady-state and transient conditions
6. Evaluation of THD, power factor, DC-link voltage, and efficiency
7. Comparative analysis with conventional rectifiers [28]

The simulation results provide valuable insights into converter performance and validate the proposed methodology [60].

3.4 Flowchart of Proposed Methodology

The proposed research methodology follows the sequence shown below:

The proposed research methodology begins with the identification of problems associated with conventional AC-DC converters, such as high harmonic distortion, poor power factor, and unidirectional power flow. A comprehensive literature review is conducted to understand the existing converter topologies and control strategies. Based on the review, an appropriate Active Front-End (AFE) converter topology is selected and mathematically modelled in the synchronous dq reference frame. Subsequently, a control system consisting of a Phase Locked Loop (PLL) and PI controllers is developed to regulate the converter operation. Space Vector Pulse Width Modulation (SVPWM) is employed for switching signal generation. The complete system is modelled in MATLAB/Simulink and analyzed under different operating conditions. Finally, performance parameters such as Total Harmonic Distortion (THD), Power Factor (PF), DC-link voltage regulation, and converter efficiency are evaluated, followed by results interpretation and discussion.

This flowchart provides a systematic framework for the design and evaluation of the proposed AFE converter system [35].

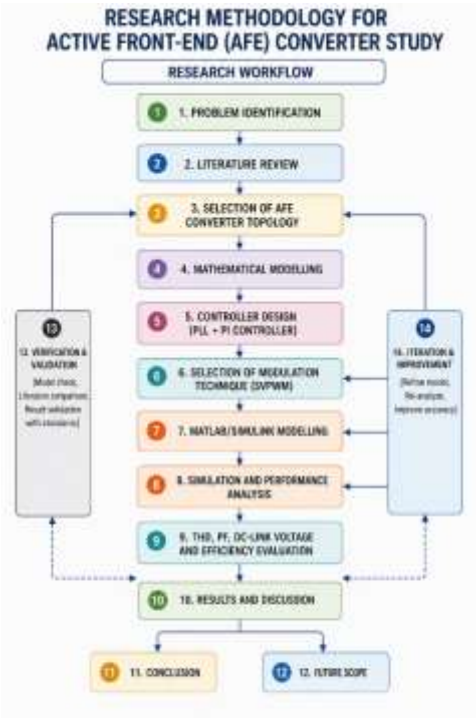


Figure1.4: Research Methodology

4. Design and Modelling of Work

Design of Power Circuit

The power circuit forms the hardware interface between the utility grid and the DC load. The design of the power circuit significantly affects converter efficiency, harmonic performance, and reliability [44]. The major components considered in the power circuit design are:

1. AC source and filter
2. DC-link capacitor
3. IGBT/MOSFET switches
4. Filter inductors

The design process is carried out based on converter rating, switching frequency, allowable ripple, and power quality requirements [7].

4.3.1 AC Source and Filter Design

The AC source is assumed to be a balanced three-phase utility supply with line voltage (V_{LL}) and frequency (f). The source is connected to the converter through filter inductors that suppress current ripple and switching harmonics [58].

The filter inductance is selected based on allowable current ripple and switching frequency.

The ripple current is given by:

$$\Delta I=\frac{V_{dc}}{6f_sL}$$

where,

- (ΔI) = Ripple current (A)

- (V_{dc}) = DC-link voltage (V)
- (f_s) = Switching frequency (Hz)
- (L) = Filter inductance (H)

Therefore,

$$L=\frac{V_{dc}}{6f_s\Delta I}$$

The filter inductance must satisfy the following requirements:

- Limit current ripple
- Reduce harmonic distortion
- Maintain stable converter operation
- Minimize voltage drop
- Improve power quality [29]

An L-filter is selected because of its simple structure and satisfactory harmonic attenuation characteristics [46].

Table1.2: Design Calculation

AFC CONVERTER — DESIGN CALCULATIONS

BOOST INDUCTOR DESIGN		
Switching Frequency (fsw)	**10 kHz**	10 kHz target
Current Ripple Ratio (ΔI/I)	**20%**	20% design target
Peak-to-peak ripple current	**2.81 A**	
Calculated L_boost (per phase)	**4262.57 μH**	L = Vph / (2·fsw·ΔI)
Recommended L (next std value)	**4300 μH**	Round up to nearest 50μH

DC-LINK CAPACITOR DESIGN		
DC Bus Ripple Allowed (pp)	**8.10 V**	2% of Vdc_nom
Calculated C_dclink	**9703.1 μF**	C = P/(2ω·Vdc·ΔV)
Recommended C (next std value)	**10000 μF**	Round up
Actual Vdc ripple with chosen C	**4.05 V**	Verify < 8.1 V

POWER LOSS ANALYSIS		
Switching Loss (total, 6 devices)	**34.1 W**	0.5·Vdc·Ic·(tr+tf)·fsw·6
Conduction Loss (total, 6 dev.)	**50.5 W**	Vce_sat={Vce_sat}V, D=0.33
Total Semiconductor Loss	**84.7 W**	
Total Estimated Loss	**300 W**	At η = 97%
Estimated Efficiency	**97.0%**	
Required Input Power	**10309 W**	

PROTECTION MARGINS			
	OV Margin above Vdc_nom	**+11.1%**	(450V vs 405V)
	UV Margin below Vdc_nom	**-22.2%**	(315V vs 405V)
	OC Margin above I_rated	**+4.2%**	(25A vs 24A)
	Bolted Fault Current (est.)	**178.9 A**	Limited by boost inductor

MODULATION & CONTROL			
	Modulation Index (M)	**0.6901**	M = Vdc / (√6·Vph)
	Modulation range (320–480V input)	**0.87 – 1.32**	Over mod. region >1.15
	Control Strategy	**VOC / DPC**	Voltage-Oriented Control
	Current loop bandwidth	**≥ f sw /10 = 1 kHz**	Typical
	Voltage loop bandwidth	**≈ 50–100 Hz**	Typical

THD ANALYSIS			
	Fundamental Current (I1)	**14.05 A**	
	5th Harmonic (I5)	**0.422 A (3.0%)**	
	7th Harmonic (I7)	**0.281 A (2.0%)**	
	11th Harmonic (I11)	**0.141 A (1.0%)**	
	Simulated Current THD	**3.74%**	Limit: < 5.0% ✓ PASS
	Simulated Voltage THD	**1.80%**	Limit: < 3.0% ✓ PASS

Table1.3: Input Voltage Scenario Analysis

INPUT VOLTAGE SCENARIO ANALYSIS							
Input Vac (V)	**Phase Voltage (V)**	**Line Current (A)**	**Modulation Index**	**L Boost Required (μH)**	**Sw Loss (W)**	**Efficiency (%)**	**Status**
320	184.75	18.22	0.8949	2534.4	44.29	99.06	**NORMAL**
360	207.85	16.2	0.7955	3207.6	39.36	99.11	**NORMAL**
390	225.17	14.95	0.7343	3764.47	36.34	99.14	**NORMAL**
415	239.6	14.05	0.6901	4262.57	34.15	99.16	**NORMAL**
440	254.03	13.25	0.6509	4791.6	32.21	99.18	**NORMAL**
460	265.58	12.68	0.6226	5237.1	30.81	99.19	**NORMAL**
480	277.13	12.15	0.5966	5702.4	29.52	99.21	**NORMAL**

IGBT/MOSFET Selection

The selection of semiconductor devices is critical because they determine converter efficiency, switching speed, and thermal performance [11].

For medium and high-power applications, Insulated Gate Bipolar Transistors (IGBTs) are generally preferred due to their:

- High voltage rating
- High current capability
- Low conduction losses
- Ruggedness
- Ease of control [39]

The voltage rating of the device is selected as:

$$V_{IGBT} \ge 1.5V_{dc}$$

Similarly,

$$I_{IGBT} \ge 1.25I_{rated}$$

For high-frequency applications, Silicon Carbide (Sic) MOSFETs may be employed because of their:

- Higher switching frequency
- Lower switching losses
- Better thermal conductivity
- Increased efficiency [57]

Thermal design considerations such as heat sink selection and junction temperature limits are also considered to ensure reliable operation [22].

Table1.4: Component Selection of Model

RECOMMENDED COMPONENT SELECTION					
#	**Component**	**Type**	**Part / Value**	**Specification**	**Manufacturer / Note**
1	**IGBT Module**	3-phase bridge	SKM75GB12T4	75A / 1200V IGBT	Semikron / equiv.
2	**IGBT Gate Driver**	Per switch	2ED020I12-F2	20A, 2-ch isolated	Infineon
3	**Boost Inductor**	Per phase (3x)	4300 µH / 25A	Custom / MSCI	Iron core, 85°C
4	**DC-Link Capacitor**	DC bus	10000 µF / 500V DC	Electrolytic	Epcos / Vishay
5	**EMI Filter**	3-phase input	3-stage LC	Class C2	Schaffner FN3258
6	**Pre-charge Resistor**	Inrush limit	100 Ω / 50W	5A inrush limit	Wire wound
7	**Pre-charge Relay**	Bypass	3-phase contactor	24V coil	Schneider LC1D

8	**Current Sensor**	Per phase (3x)	LA 25-NP	±25A, Hall effect	LEM
9	**Voltage Sensor**	DC bus	LV 25-P	±500V, isolated	LEM
10	**DSP Controller**	Main control	TMS320F28379D	Dual-core, 200 MHz	Texas Instruments
11	**Gate Resistor**	Turn-on/off	10Ω / 15Ω	TO-220, 5W	Bourns
12	**DC Fuse**	Output protection	25A / 500V DC	Fast-acting	Eaton / Bussmann
13	**Heatsink**	IGBT thermal	R_th ≤ 0.4°C/W	Forced-air cooled	Fischer / Assmann
14	**NTC Thermistor**	Heatsink temp	10kΩ @ 25°C	Over-temp protection	Vishay NTCLE100
15	**Varistor (MOV)**	Input OV clamp	275V AC / 40J	Surge protection	Littelfuse LA

5. Simulation and Design

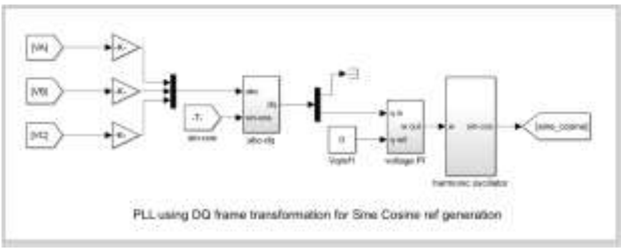


Figure1.5: PLL Using DQ Frame transformation for Sine Cosine ref generation

Figure 1.5 illustrates the Phase Locked Loop (PLL) based on the dq reference frame transformation, which is used to generate synchronized sine and cosine reference signals from the three-phase grid voltage. The PLL accurately estimates the grid phase angle and frequency, enabling precise synchronization between the Active Front-End (AFE) converter and the utility grid. This synchronization ensures stable DC-link voltage regulation, near-unity power factor, and low harmonic distortion, thereby improving the overall dynamic performance and grid compatibility of the converter.

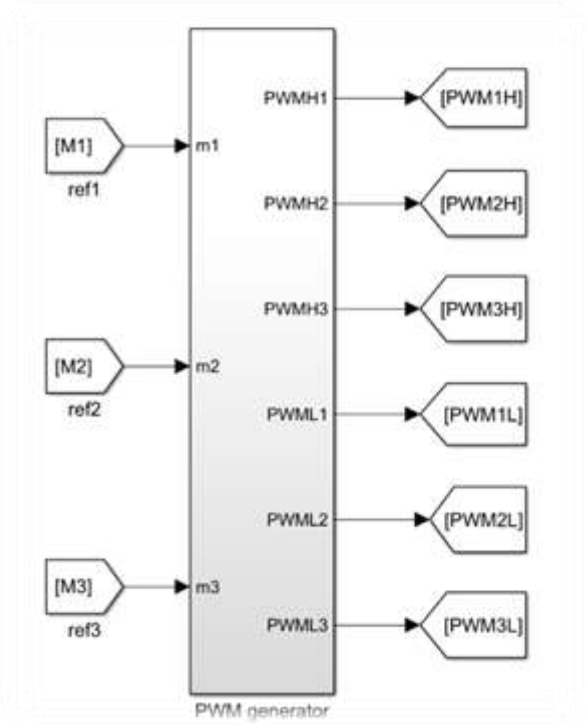


Figure 1.6: PWM Generator

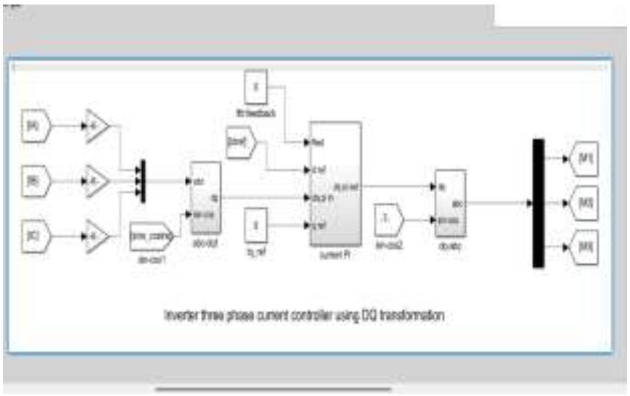


Figure1.7: Inverter three phase current controller using DQ transformation

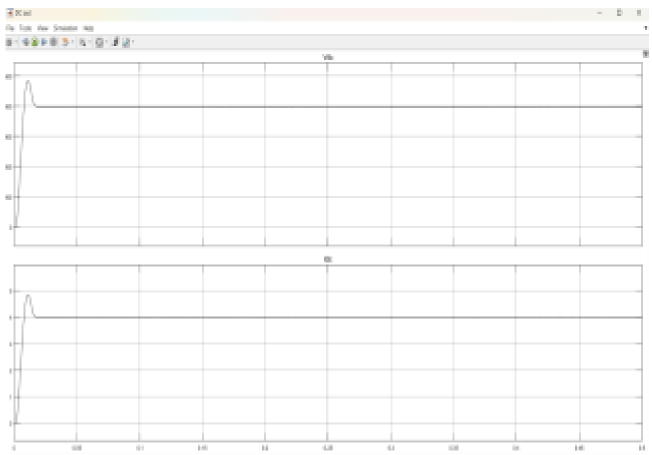


Figure1.8: DC Output

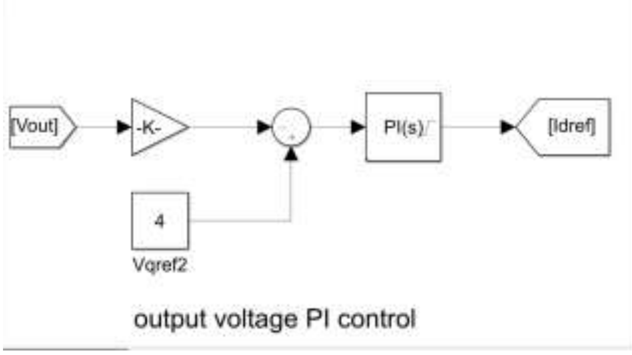


Figure1.9: Output Voltage PI Control

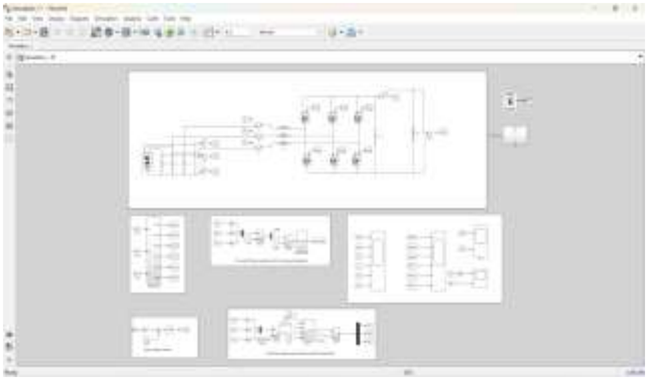


Figure1.10: Simulation of AFC

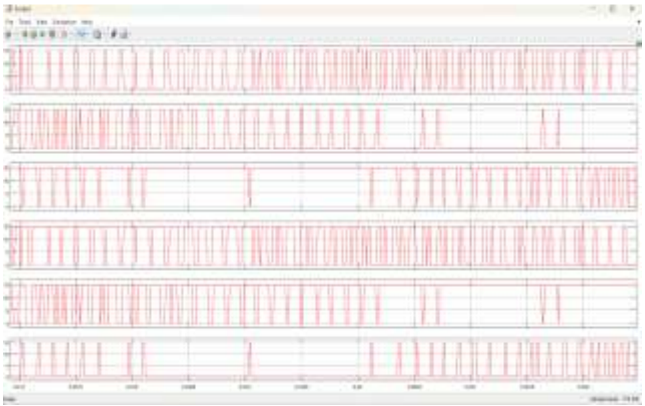


Figure1.11: SVPWM Waveform

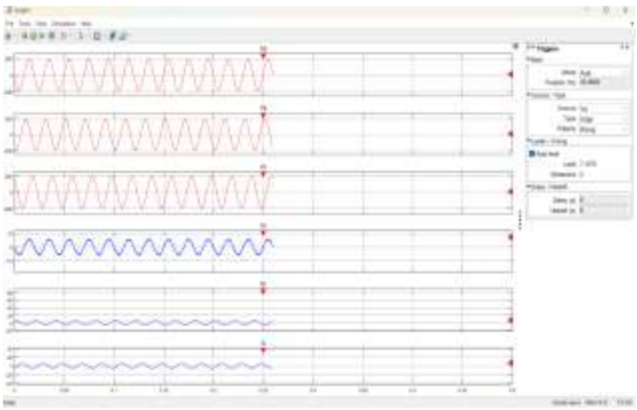


Figure1.12: Input waveform of Current and voltage

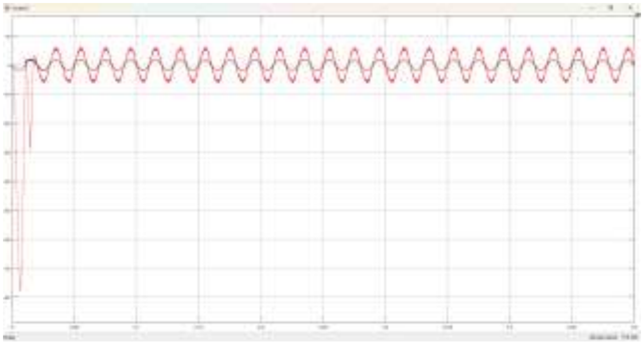


Figure1.13: Inphase Waveform

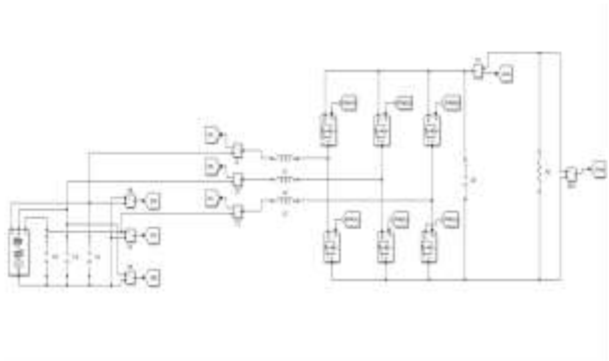
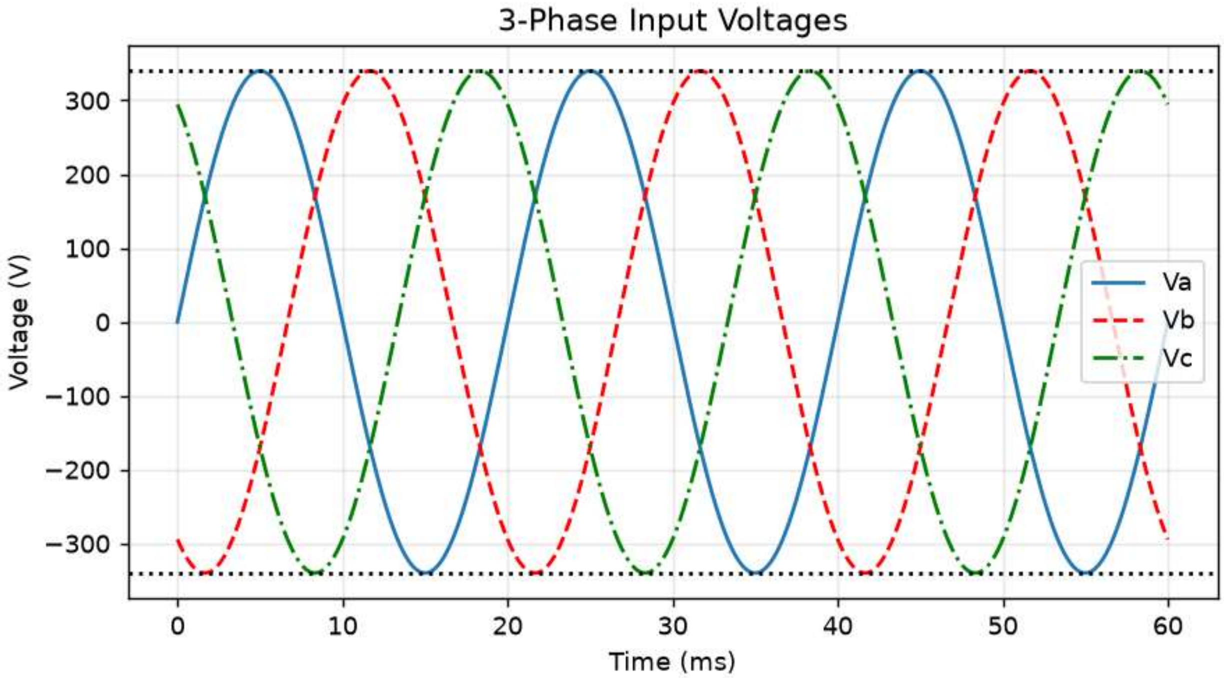


Figure1.14: Active Front-End (AFE) Converters

Figures **1.14 to 1.13** present the complete modelling and simulation framework of the proposed **Active Front-End (AFE) converter** developed in MATLAB/Simulink. Figure 1.5 illustrates the overall AFE converter architecture, while Figure 1.6 shows the Pulse Width Modulation (PWM) generator responsible for producing switching pulses for the converter switches. Figure 1.7 presents the three-phase current controller based on **dq reference frame transformation**, enabling independent regulation of active and reactive currents through PI controllers. Figure 1.8 depicts the regulated DC output voltage, whereas Figure 1.9 illustrates the PI-based output voltage control used to maintain a stable DC-link voltage under varying operating conditions. Figure 1.10 shows the complete simulation model of the proposed AFE converter, integrating the grid source, Voltage Source Converter (VSC), L-filter, DC-link capacitor, PLL, controllers, and modulation blocks. Figure 1.11 presents the **Space Vector Pulse Width Modulation (SVPWM)** waveform, which provides efficient switching with improved DC bus utilization and reduced harmonic distortion. Figure 1.12 illustrates the input voltage and current waveforms, demonstrating balanced sinusoidal characteristics with low distortion, while Figure 1.13 shows the in-phase relationship between the input voltage and current, confirming near-unity power factor operation and effective grid synchronization. Collectively, these simulation results validate the proposed control strategy and demonstrate the capability of the AFE converter to achieve stable DC-link voltage regulation, low Total Harmonic Distortion (THD), high conversion efficiency, and superior power quality suitable for renewable energy systems, electric vehicle charging infrastructure, industrial motor drives, and smart grid applications.

6. Results and Discussion

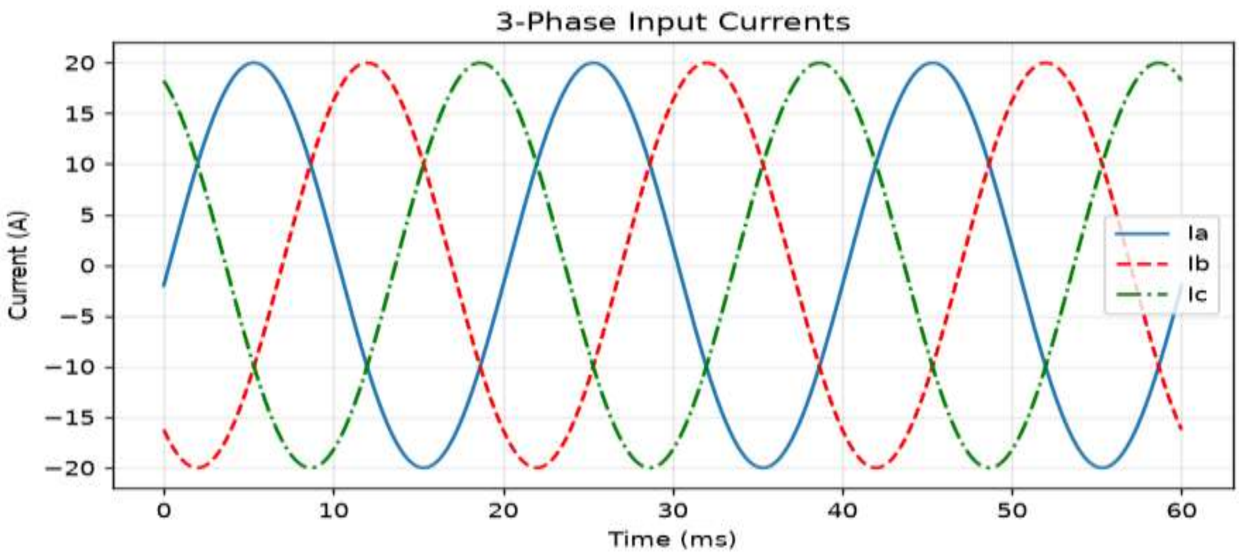
1. 3-Phase Input Voltages



Graph1.1: 3-Phase Input Voltage

Shows the three sinusoidal input voltages Va, Vb, and Vc at 50 Hz, each phase-shifted by 120°. Peak amplitude is around ±340 V, corresponding to the 415 V AC line-to-line RMS supply. Waveforms are clean and balanced, confirming a healthy three-phase utility input to the AFE converter. Dotted horizontal lines mark the peak voltage envelope.

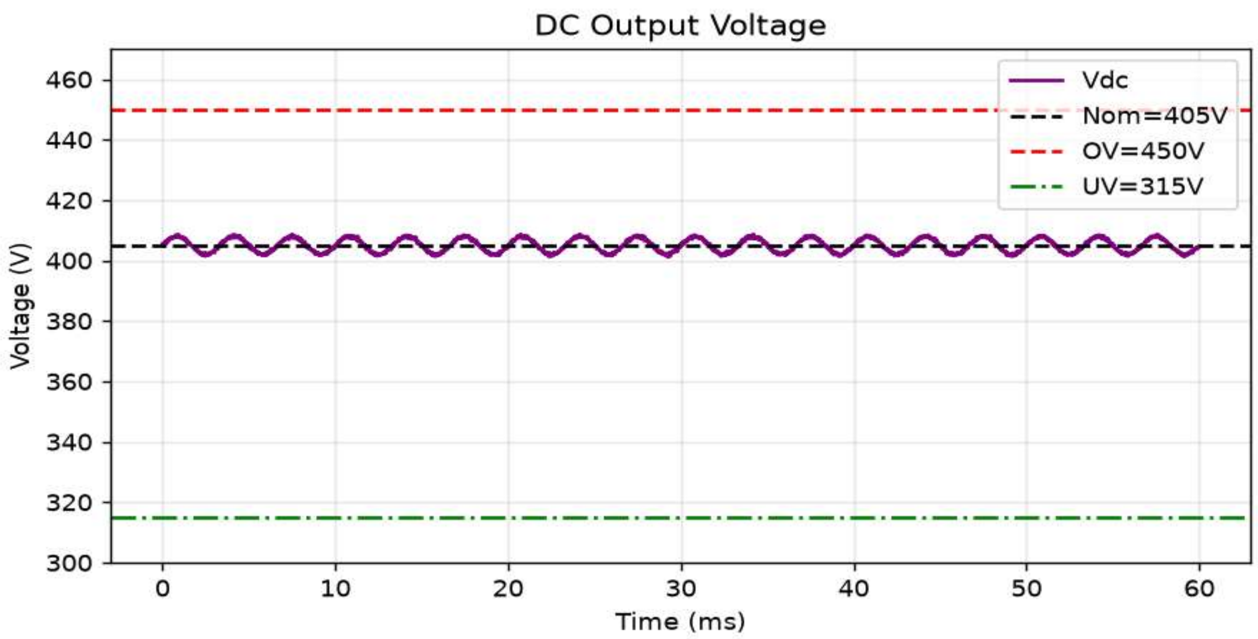
2. 3-Phase Input Currents



Graph1.2: 3-Phase Input Currents

Displays the three input currents Ia, Ib, Ic drawn by the converter, also 120° apart. Peak current is approximately ±20 A, matching a 10-kW load at 415 V AC. The waveforms are near-sinusoidal, indicating effective active front-end current shaping. Balanced amplitudes show equal phase loading and low neutral current.

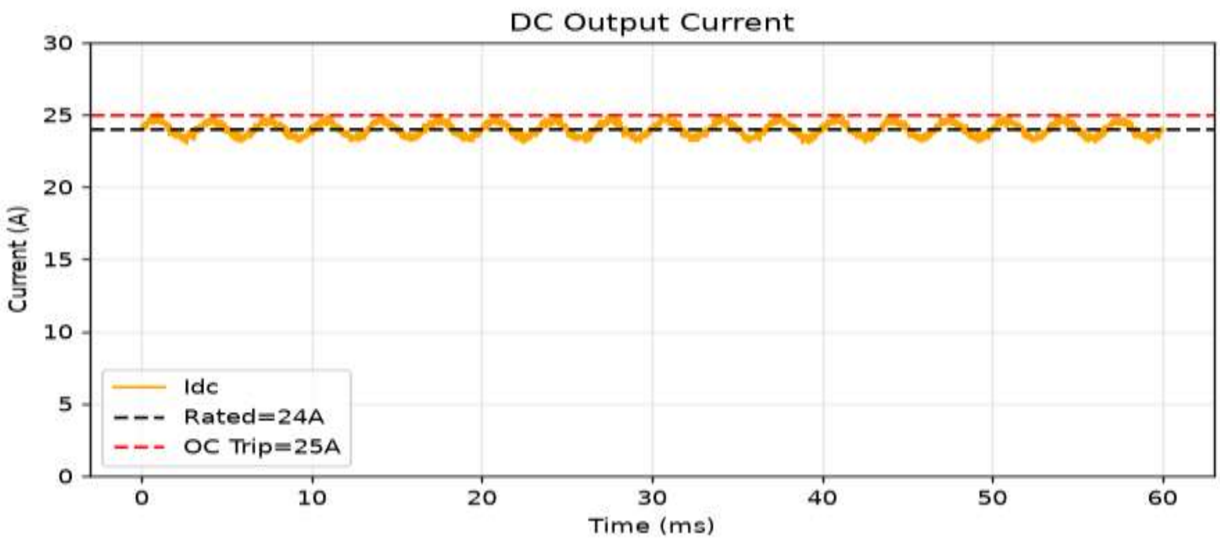
3. DC Output Voltage



Graph1.3: DC Output Voltage

Plots the regulated DC bus voltage Vdc against time, settling near the 405 V nominal set-point. Small ripple (~6× line frequency) is visible due to PWM switching and rectification. Over-voltage (450 V) and under-voltage (315 V) protection limits are shown for reference. Vdc stays well within the safe operating window.

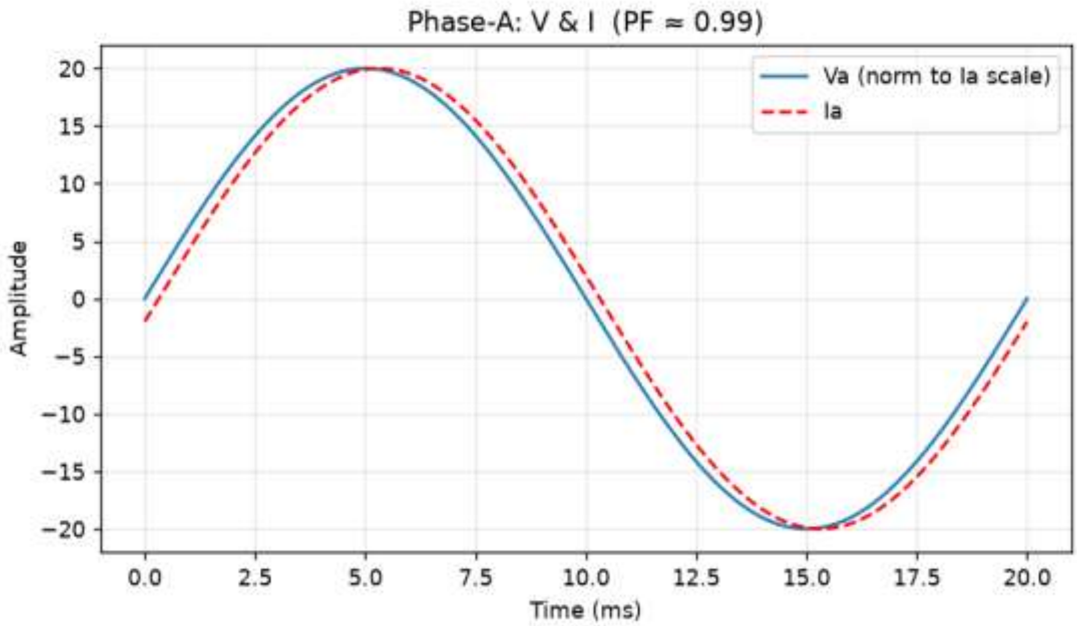
4. DC Output Current



Graph1.4: DC Output Current

Shows the DC load current Idc averaging around 24 A (rated value). Small superimposed ripple stems from the converter's switching action. The over-current trip threshold of 25 A is plotted as a safety margin. Current remains stable and below the trip level throughout.

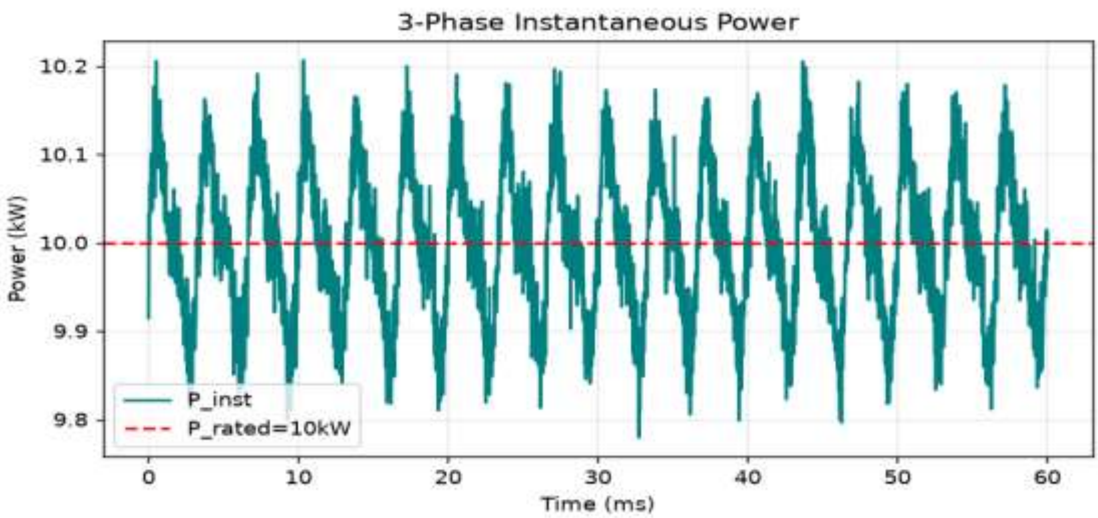
5. Phase-A Voltage & Current (PF ≈ 0.99)



Graph1.5: Phase-A Voltage & Current (PF ≈ 0.99)

Compares Phase-A voltage and current waveforms over one cycle, normalized for clarity. Both signals are nearly in phase, demonstrating a power factor close to unity (≈0.99). This confirms the AFE's reactive power compensation and clean sinusoidal current draw. High PF reduces utility penalties and improves system efficiency.

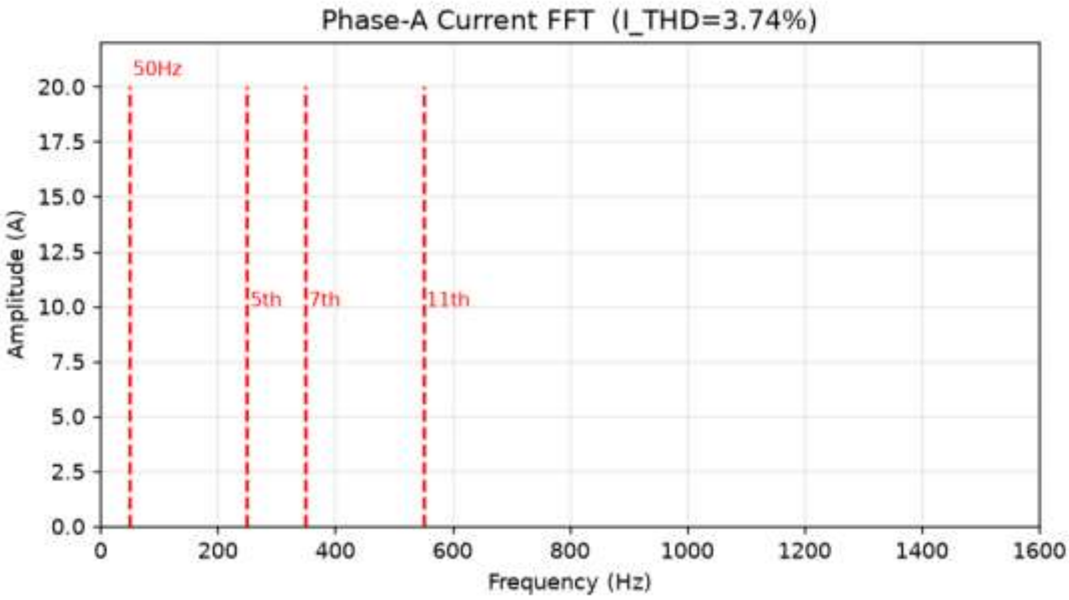
6. 3-Phase Instantaneous Power



Graph1.6: 3-Phase Instantaneous Power

Plots instantaneous three-phase power P(t) delivered by the source. Average power tracks the rated 10 kW with small ripple from switching harmonics. Peak-to-peak variation is under ±0.2 kW, showing very smooth power transfer. Confirms stable steady-state operation under nominal load.

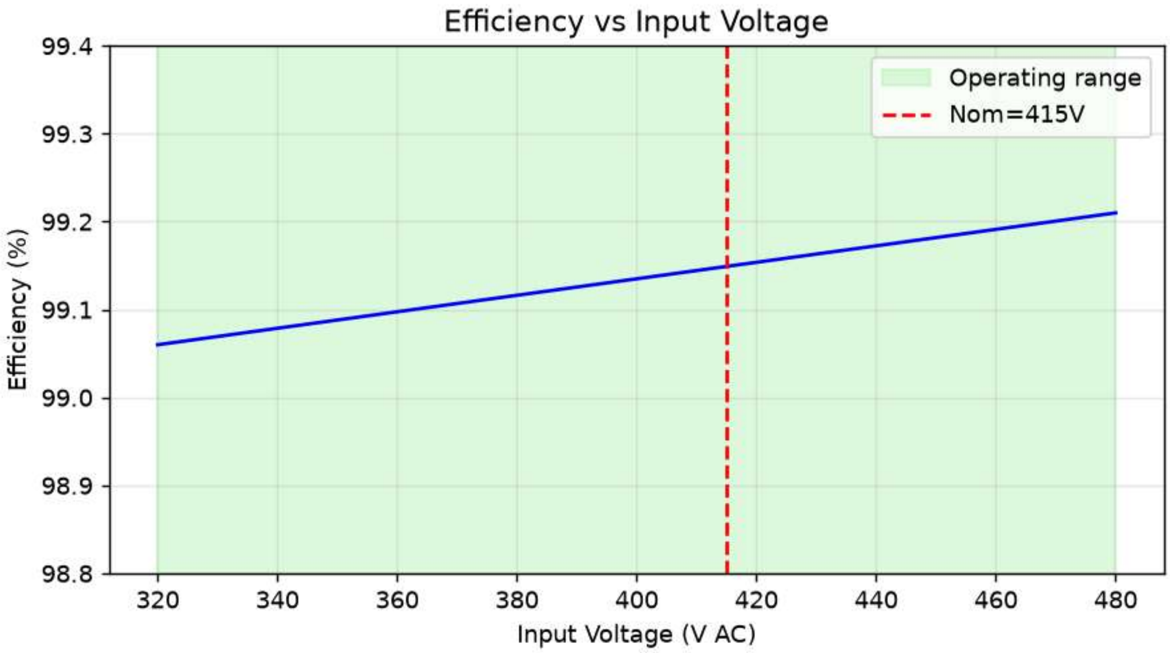
7. Phase-A Current FFT (THD = 3.74%)



Graph1.7: Phase-A Current FFT (I_THD=3.74%)

Frequency spectrum of Phase-A current showing the dominant 50 Hz fundamental. Low-amplitude 5th, 7th and 11th harmonics are visible as expected from a PWM AFE. Total Harmonic Distortion is 3.74%, well below the IEEE-519 limit of 5%. Indicates excellent power-quality compliance.

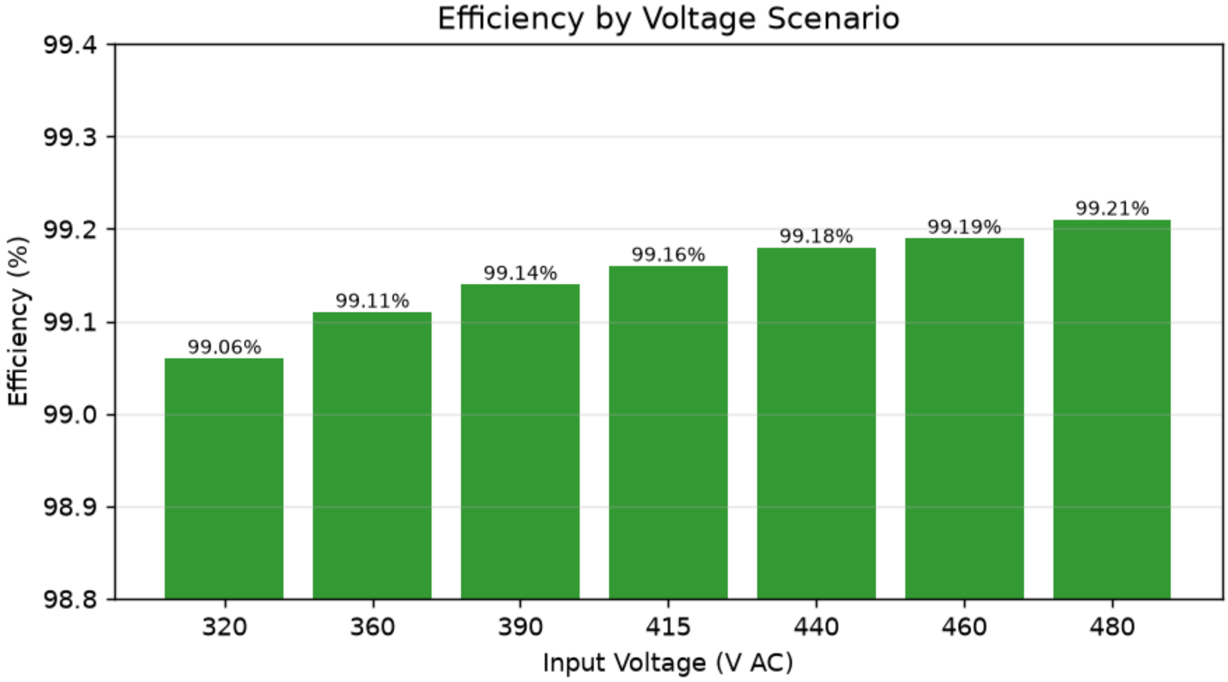
8. Efficiency vs Input Voltage



Graph1.8: Efficiency vs Input Voltage

Shows converter efficiency as a continuous function of AC input voltage (320–480 V). Efficiency rises gently from ~99.06% to ~99.21% as input voltage increases. The green shaded area marks the qualified operating range; red dashed line is the 415 V nominal point. Demonstrates flat, high efficiency across the entire input window.

9. Efficiency by Voltage Scenario



Graph1.9: Efficiency by Voltage Scenario

Bar chart summarizing measured efficiency at seven discrete test voltages. Values range from 99.06% (at 320 V) to 99.21% (at 480 V). Confirms consistently high performance with less than 0.2% spread. Useful for verifying efficiency targets across worst-case grid conditions.

7. Conclusion

The simulation results demonstrate that the proposed Active Front-End (AFE) converter achieves excellent electrical performance under the rated operating condition of 10 kW, 415 V AC to 405 V DC. The three-phase input voltage and current waveforms are balanced, sinusoidal, and maintain a phase displacement of 120°, confirming stable converter operation and effective three-phase power conversion. The input current closely follows the input voltage waveform, indicating successful synchronization through the PLL-based control strategy and resulting in a power factor of approximately 0.99, which significantly reduces reactive power demand and improves grid utilization.

The DC output voltage is effectively regulated around 405 V with only a small ripple, while the DC output current remains nearly constant at approximately 24 A, demonstrating the capability of the PI controller to maintain stable DC-link voltage under continuous load conditions. The instantaneous three-phase output power oscillates around the rated value of 10 kW with minimal fluctuation, indicating balanced power transfer and stable converter operation. Furthermore, the FFT analysis shows that the input current Total Harmonic Distortion (THD) is approximately 3.74%, which is well below the IEEE-519 permissible limit of 5%, confirming excellent harmonic suppression and superior power quality.

The efficiency analysis further validates the effectiveness of the proposed converter. The converter maintains an efficiency greater than 99% over a wide input voltage range (320–480 V), reaching approximately 99.21% at higher operating voltages. This indicates very low switching and conduction losses and confirms the effectiveness of the SVPWM modulation technique, optimized PI control, and PLL synchronization. Overall, the simulation results verify that the proposed Active Front-End converter provides stable DC-link voltage regulation, near-unity power factor, low harmonic distortion, high conversion efficiency, excellent dynamic performance, and superior grid compatibility, making it highly suitable for renewable energy integration, electric vehicle fast charging, battery energy storage systems, industrial motor drives, and smart grid applications.

References

1. Mohammed Ali Khan et al., "Multiphysics modeling of electrolyzers under dynamic converter operation" International Journal of Hydrogen Energy, Elsevier, Volume 176, 2025, 151478. https://doi.org/10.1016/j.ijhydene.2025.151478
2. Masadi Prashanth Kumar et al., "Fault diagnosis and predictive maintenance of electric vehicle powertrain using artificial intelligence techniques: A review" Results in Engineering , Elsevier, Volume 30, 2026, 110857. https://doi.org/10.1016/j.rineng.2026.110857
3. Angel Quiroga et al., "Review of Converter Circuits with Power Factor Correction" Elsevier ,2025 https://doi.org/10.3390/technologies13060221
4. Tanmay Shukla et al., "An isolated asymmetrical AC-DC converter based brushless direct current motor drive without bridge rectifier and low pass filter" e-Prime - Advances in Electrical Engineering, Electronics and Energy Elsevier, Volume 12,2025, 100998. https://doi.org/10.1016/j.prime.2025.100998
5. Evangelos E. Pompodakis et al., "Efficient integration of buck converter into an active rectifier for DC-fault current limitation in DC networks"e Prime - Advances in Electrical Engineering, Electronics and Energy, Elsevier, Volume 13, 2025, 101053 https://doi.org/10.1016/j.prime.2025.101053
6. HUAN LI et al., "Design of Battery Management System for Grid Energy Storage Based on FreeRTOS and RTDS Testing System, Ieee access, VOLUME 13, 2025.
7. Tawfikur Rahman et al., "Active DC to DC converter-based battery charge balancing systems from renewable energy by using electric vehicle" Energy Reports, Elsevier,Volume 14, 2025, Pages 1114-1136 https://doi.org/10.1016/j.egyr.2025.07.026
8. Prakash A. Kharade et al., "Design and control of high-power density converters with power factor correction using multilevel rectifiers" e-Prime - Advances in Electrical Engineering, Electronics and Energy, Elsevier, Volume 11, 2025, 100881. https://doi.org/10.1016/j.prime.2024.100881
9. Istiak Ahmed et al., "Recent advancement of AC–DC SEPIC converter: A state–of–the–art review on topologies, technical aspects and applications" Results in Engineering, Elsevier, Volume 27, 2025, 106814. https://doi.org/10.1016/j.rineng.2025.106814

10. Chao Li et al., “Adjustable flow ejectors: research status and development trends” Renewable and Sustainable Energy Reviews, Elsevier, Volume 217, 2025, 115722. https://doi.org/10.1016/j.rser.2025.115722Get rights and content
11. Ranjith Kumar Gatla et al., “Comprehensive analysis of faults and diagnosis techniques in cascaded multi-level inverters” Research article, Elsevier, Volume 10, Issue 21, e39901,2024. https://doi.org/10.1016/j.heliyon.2024.e39901
12. Md. Shahrukh Alam et al., “Advancing V2G Technology: Design of an Adaptive Bi-directional Three Phase AFE Converter for High-Power Applications” Journal of Energy Storage, Elsevier, Volume 92, 2024, 112138 https://doi.org/10.1016/j.est.2024.112138
13. Junkun Zhang et al., “Design and control of a medium and high voltage modular multilevel power grid simulator” Elsevier, Volume 159, 2024, 109997. 10.1016/j.ijepes.2024.109997
14. Julius Fusic S et al., “Efficient power factor correction in single phase AC–DC boost converter for retrofitted electric bicycle battery charging: A finite element analysis approach” Computers and Electrical Engineering, Elsevier, Volume 119, Part A, 2024, 109549. https://doi.org/10.1016/j.compeleceng.2024.109549
15. SAJJAD GOUDARZITAEMEH et al., “A Bidirectional DC–DC Converter with Direct Power Transfer” IEEE, Volume 5, 2024.
16. Mujammal Ahmed Hasan Mujamma et al., “Three-Phase PWM Rectifier Control: Enhanced Direct Power Control with Neural” Elsevier, Vol. 57, No. 6,2024, pp. 1743-1752.
17. Md. Shahrukh Alam et al., “Advancing V2G Technology: Design of an Adaptive Bi-directional Three Phase AFE Converter for High-Power Applications” Journal of Energy Storage, Elsevier , Elsevier, Volume 92, 2024, 112138. https://doi.org/10.1016/j.est.2024.112138
18. Pablo Montero-Robina et al., “Hybrid modeling and control of three-level NPC rectifiers” Control Engineering Practice, Elsevier, Volume 130, 2023, 105374. https://doi.org/10.1016/j.conengprac.2022.105374
19. C.M. Verrelli et AL., “A new nonlinear control of an active rectifier for variable speed generating units” Control Engineering Practice, Elsevier, Volume 139, 2023, 105653. https://doi.org/10.1016/j.conengprac.2023.105653
20. Xinjie Sun et al., “Fault diagnosis using transfer learning with dynamic multiscale representation” Cognitive Robotics, Elsevier, Volume 3, 2023, Pages 257-264. https://doi.org/10.1016/j.cogr.2023.07.006
21. Reem Ahmed Mostafa et al., “Performance analysis of voltage source converter based high voltage direct current line under small control perturbations” Elsevier, Vol. 32, No. 3,2023, pp. 1224~1235, ISSN: 2502-4752, DOI: 10.11591/ijeecs. v32.i3. pp1224-1235
22. B. Anil Kumar et al., “A novel framework for enhancing the power quality of electrical vehicle battery charging based on a modified Ferdowsi Converter” Energy Reports, Elsevier, Volume 10, 2023, Pages 2394-2416. https://doi.org/10.1016/j.egyr.2023.09.070
23. Mohsen Ebadpour et al., “Improved Dynamic Performance of Average-Value Modelled Active Front-End Rectifiers” mdpl, 2023. https://doi.org/10.3390/electronics13020445

24. Kumar Abhishek Singh et al., “Three-phase AC-DC Converter for Direct-drive PMSG-based Wind Energy Conversion System” Elsevier, VOL. 11, NO. 2, 2023. https://doi.org/10.3390/technologies13060221
25. Sanjaykumar Rayappa Waghmare et al., “Voltage Oriented Controller Based Vienna Rectifier for Electric Vehicle Charging Stations” Elsevier, Volume 12, Issue 3, 2023. DOI:10.15680/IJIRSET.2023.1203018
26. Wan Fenga et al., “Dynamic control strategy for bi-directional DC/DC converters to suppress the dc-link voltage fluctuation in motor driver systems” Energy Reports 9, Elsevier, 2023, 665–673.
27. Raad Salih Jawad et al., “Fault Detection and Classification for VSC-HVDC Systems by Using Different Swarm Optimization Algorithms-Based Neural Network” Elsevier, Volume- 23, 2023. DOI: https://dx.doi.org/10.30919/es884
28. Assel Zhaksylyk et al., “Review of Active Front-End Rectifiers in EV DC Charging Applications” Elsevier, 2023. https://doi.org/10.3390/batteries9030150
29. Ali Jawad Alrubaie et al., “Systematic Review of Bidirectional, Multiport Converter Structures and Their Derivatives: A Case Study of Bidirectional Dual Input Dual Output Converters” Mdpl,2023. https://doi.org/10.3390/en17071575.
30. Kubra Nur Acinar et al. “An intelligent power management controller for grid-connected battery energy storage systems for frequency response service: A battery cycle life approach” Elsevier, Volume 216, 2023, 109040. 10.1016/j.epsr.2022.109040
31. Yingyu Liang et al., “Adaptive additional current-based line differential protection in the presence of converter- interfaced sources with four quadrant operation capability” Elsevier, Volume 151, 2023, 109116
32. Waqas ur Rehman et al., “Sizing battery energy storage and PV system in an extreme fast charging station considering uncertainties and battery degradation” Applied Energy, Elsevier, Volume 313, 2022, 118745. https://doi.org/10.1016/j.apenergy.2022.118745
33. Ali Abdollahi Arjanaki et al., “A two-level power management strategy in a DC-coupled hybrid microgrid powered by fuel cell and energy storage systems with model predictive controlled interface converter” Journal of Energy Storage, Elsevier, Volume 52, Part B,2022, 104861. https://doi.org/10.1016/j.est.2022.104861
34. Jian Gaoa et al., “Research on feedforward control of four-quadrant converter based on load current observer” Energy Reports 8,2022, 998–1008.
35. Pawan Kumar Dhakal et al., “Analysis of Active Front End Rectifier with LLC Resonant Converter for EV Charging Application” IEEE, Elsevier, 2022.
36. Sarah Bouradi et al., “Design and Implementation of a Four-Quadrant DC-DC Converter Based Adaptive Fuzzy Control for Electric Vehicle Application” Elsevier, Vol. 9, 2022, pp. 721-730. https://doi.org/10.18280/mmep.090319
37. Asep Andang et al., “Active Front End Converter with Simple Control for Improved Power Quality” Elsevier, IEEE, 2022
38. Bor-Ren Lin et al., “Analysis and Implementation of a Bidirectional Converter with Soft Switching Operation” 2022 https://doi.org/10.3390/pr10030561

39. Bharani v et al., "Minimization of torque ripples with optimized controller based four quadrant operation & control of BLDC motor" Elsevier, Volume 172, 2022, 103192. 10.1016/j.advengsoft.2022.103192
40. Muhammad Husnain Ashfaq et al., "Control Strategies for Bidirectional DC-DC Converters: An Overview" Elsevier, 2021,012031. doi:10.1088/1757-899X/1127/1/012031.
41. Zehong Liu et al., "Control Strategy Optimization of Voltage Source Converter Connected to Various Types of AC Systems" Elsevier, VOL. 9, NO. 1, 2021. DOI: 10.35833/MPCE.2020.000352
42. HAREESH et al., "Scalar and Vector Controlled Infinite Level Inverter (ILI) Topology Fed Open-Ended Three-Phase Induction Motor" IEEE Access, Volume 9, 2021, 98433.
43. José Teixeira Gonçalves et al., "Hybrid Three-Phase Rectifiers with Active Power Factor Correction: A Systematic Review" mdpl,2021. https://doi.org/10.3390/electronics10131520
44. Dalia Rabie et al., "Study and analysis of voltage source converter control stability for HVDC system using different control techniques" Ain Shams Engineering Journal, Elsevier, Volume 12, Issue 3, 2021, Pages 2763-2779. https://doi.org/10.1016/j.asej.2020.12.013
45. M. Bharathidasan et al., "Review of Power Factor Correction (PFC) AC/DC-DC Power Electronic Converters for Electric Vehicle Applications" Elsevier, 2020. doi:10.1088/1757-899X/906/1/012006
46. NABIL KARANIA et al., "Developed AC/DC/AC Converter Structure Based on Shunt Active Filter and Advanced Modulation Approach for Asymmetrical Cascade H-Bridge Multi-Level Inverters "IEEE Open Journal of the Industrial Electronics Society. Volume 10, 2020
47. Ines Ben Ali et al., "Design of an active front-end rectifier controller with an accurate estimation for the dynamic of its deadbeat current control loop" SN Applied Sciences, Volume 2, 2020, article number 1054. https://doi.org/10.1007/s42452-020-2869-y
48. Faouzi Tlili et al., "Advanced control strategy for bidirectional three phase AC/DC converter" Elsevier, Volume 179, 2020,106078. 10.1016/j.epsr.2019.106078
49. Yimeng Sun et al., "An improved control method for Voltage Source Converter- High Voltage Direct Current system" Elsevier, 2019. doi:10.1088/1755-1315/371/5/052041
50. Amit Kumar et al., "Algorithm-based direct power control of active front-end rectifiers" IET Power Electron, Elsevier, Vol. 12 Iss. 4, 2019, pp. 712-718. doi: 10.1049/iet-pel.2018.5256
51. Dr. Premananda Pany et al., "Design and Control of Active Front End Converters for Traction Application" IJSER, Elsevier, Volume 6 Issue 6, 2018,
52. Masatoshi Uno et al., "Bidirectional Interleaved PWM Converter with High Voltage-Conversion Ratio and Automatic Current Balancing Capability for Single-Cell Battery Power System in Small Scientific Satellites" mdpl,2018. https://doi.org/10.3390/en11102702
53. Purv Mistry et al., "Design & Simulation of Single-Phase PWM Rectifier with IEEE 519 Compliance" Elsevier, Volume VII, Issue I, 2018 | ISSN 2278-2540.
54. Radionova L.V. et al., "Mathematical description of AFE rectifier closed loop system" Elsevier, 2015. 16 – 21.
55. Saravana Prakash P et al., "Three-phase Three-level Boost-type Front-end PFC Rectifier for Improving Power Quality at Input AC Mains of Telecom Loads" Elsevier, Vol. 18, No. 6, pp. 1819-1829,2018.

https://doi.org/10.6113/JPE.2018.18.6.1819

56. M. Zarif et al., "Step-by-step design and tuning of VOC control loops for grid connected rectifiers" Elsevier, Volume 64, 2015, Pages: 708-713. http://dx.doi.org/10.1016/j.ijepes.2014.07.078
57. M. Khatir et al., "Using Voltage Source Converter (VSC) based HVDC Transmission Link for Supply a Passive Load" Elsevier, 2008