Enhancing Power Quality in Smart Grids: Coordinated Control of Voltage and Current Harmonics Using Dual-Interface Converters

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***Abstract*—Harmonic distortion, caused by the superposition of multiples of the fundamental frequency, represents a significant source of electrical noise, degrading both system stability and power quality. This distortion can exacerbate supply voltage harmonics, especially when a single Distributed Generation (DG) interface converter is used to compensate for local load harmonic currents. The issue becomes particularly challenging when the main grid voltage is severely distorted. This paper presents an innovative approach to reducing current harmonics in a distorted distribution system by employing a dual-interface converter configuration. The proposed method enhances power quality by compensating for both supply voltage and grid current harmonics simultaneously. Simulation results demonstrate the effectiveness of this technique in mitigating harmonic distortion, improving system efficiency, and maintaining the Total Harmonic Distortion (THD) of the grid voltage within permissible limits. The results underscore the potential of dual-interface converters to provide superior harmonic compensation, making them a viable solution for modern smart grid systems.**

Keywords: Active power filters, Dynamic Voltage Restorer, Microgrids, Nonlinear loads, Voltage source converters, Power quality, Harmonic mitigation, Smart grids.

I. Introduction

The growing concerns about environmental impacts and the rising costs of conventional energy sources, such as fossil fuels, have led to a significant shift toward renewable and sustainable energy. However, integrating renewable energy sources (RES) into existing utility grids has been challenging due to their intermittent and unpredictable nature. Smart microgrids have emerged as a promising solution, enabling the integration of RES while ensuring stable operation, both in grid-connected and islanded modes. This dual operational capability is especially beneficial in cases of main grid instability or power outages. To manage Smart microgrid operations efficiently, advanced control systems are essential for detecting grid disturbances, ensuring effective isolation during faults, and enabling smooth reconnection to the main grid. Moreover, sophisticated control techniques are necessary to maintain stable operations using only renewable energy, especially when RES generation fluctuates. The challenge of maintaining power quality in such systems cannot be overlooked. Power quality refers to the purity of the voltage and the sinusoidal nature of the current. Harmonic distortion, which deviates from these ideal waveforms, is one of the most significant power quality issues. Harmonics in the voltage and current waveforms can cause disruptions in power systems, affecting the operation of sensitive equipment and leading to system inefficiencies. This paper explores the causes and effects of harmonic distortion and proposes methods to mitigate its impact, particularly in systems utilizing microgrids and distributed generation.

The key contributions of this paper are as follows:

- A detailed analysis of the impact of harmonic distortion on power quality in microgrids and distributed generation systems.
- The proposal of an advanced control method for harmonics mitigation in microgrid systems that ensures both stable operation and efficient grid integration.
- Experimental results demonstrating the effectiveness of the proposed method in improving power quality and minimizing harmonic distortion.
- Insights into the role of smart microgrids in supporting the integration of renewable energy sources and enhancing grid resilience.

The structure of the paper is as follows:

- **Section 2: Background and Research Motivation** presents the background of the research, the motivation for studying power quality in microgrids, and the challenges associated with harmonics and distributed generation.
- **Section 3: Harmonics and Their Causes** discusses the nature of harmonics, their sources, and how they affect the power system.
- **Section 4: Distributed Generation** provides an overview of distributed generation systems, their role in smart microgrids, and the associated challenges related to power quality.
- **Section 5: Smart Microgrids** explores the concept of smart microgrids, their operation, and their significance in integrating renewable energy sources into the main grid.
- **Section 6: Proposed Method** introduces the proposed method for harmonic mitigation, explaining the control strategy and its implementation in a smart microgrid environment.
- **Section 7: Experimental Results and Discussion**

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presents the experimental setup, results, and a discussion of the proposed method's performance.

- **Section 8: Conclusion** summarizes the key findings of the paper and outlines potential future research directions.

II. Background and Research Motivation

Power quality (PQ) has become a critical issue for both electric utility providers and end-users in recent years, driven by the increasing reliance on sensitive electronic devices and the growing complexity of modern power systems. Power quality refers to any deviation in voltage, current, or frequency that leads to malfunction or failure of customer equipment, and it is increasingly recognized as an essential aspect of the reliability and efficiency of electrical networks. PQ problems can generally be categorized into two major sources: customer-side issues and utility-side issues. Customer-side power quality issues often arise from the use of non-linear loads, such as variable frequency drives, rectifiers, and other electronic devices, which draw current in abrupt pulses and distort the voltage waveform. This distortion leads to a range of power quality phenomena, including harmonics, voltage imbalance, and voltage sag/swell. Additionally, large loads, such as motors and industrial equipment, can cause sudden variations in power demand, contributing to PQ disturbances [1]. On the utility side, PQ problems are typically caused by faults such as short circuits, line interruptions, and lightning strikes, which result in voltage sags, swells, and power outages in transmission or distribution lines [2]. The increasing use of sensitive electronic and digital equipment, which requires high-quality, distortion-free sinusoidal supply voltages, has amplified the importance of power quality management. Over the past two decades, as industries have become more reliant on computer-based control systems, telecommunication networks, and automation technologies, the need for maintaining optimal power quality has grown significantly [3]. Modern power systems, which incorporate both traditional and renewable energy sources, face additional challenges due to the integration of non-linear loads and distributed generation (DG). As a result, even small deviations in power quality can lead to significant operational disruptions and financial losses [4]. The impact of power quality disturbances is not just limited to equipment malfunction; it also incurs considerable economic costs. According to several surveys, power outages and interruptions in the U.S. alone result in annual losses ranging from $104 billion to $164 billion, due to equipment damage, material losses, idle labor, and lost production [5]. In addition to outages, other power quality phenomena, such as harmonic distortion, also contribute to economic losses, costing between $15 billion and $24 billion annually [6]. Figure 1 highlights the most frequent types of disturbances and their primary causes, both from the customer and utility perspectives, as well as the types of equipment most affected.

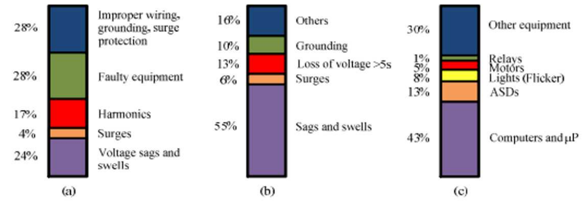

Fig. 1: Basic disturbances: (a) Causes at customer side, (b) Causes at utility side, and (c) Affected equipment

Further analysis of PQ disturbances in industrial environments, as shown in Figure 2, reveals that voltage sags/swell and harmonic distortions are the most common power issues encountered. These disturbances are particularly detrimental to sensitive equipment, leading to increased downtime, reduced productivity, and additional maintenance costs. Addressing power quality issues is not only crucial for improving system performance but also for minimizing the economic impact of electrical disturbances.

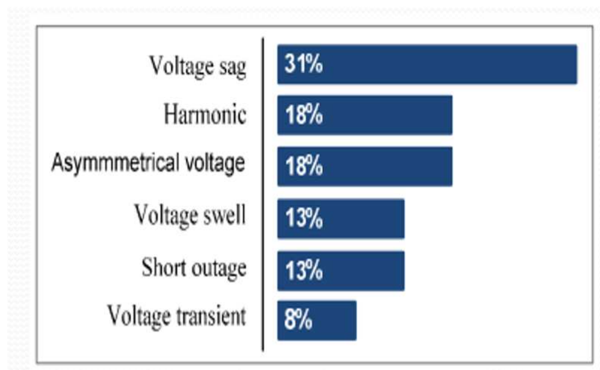

Fig. 2: Percentage occurrences of PQ disturbances in equipment interruptions

In this context, understanding the underlying causes of power quality disturbances, such as harmonics and voltage fluctuations, and developing effective mitigation strategies, becomes increasingly essential. As the power grid continues to evolve with the integration of renewable energy sources and distributed generation, the need for advanced control and monitoring systems to mitigate power quality issues will only intensify. This paper aims to explore the role of smart microgrids and advanced harmonic mitigation techniques in addressing these challenges, offering novel insights into enhancing the stability and reliability of modern power systems.

III. Harmonics and Their Causes

Harmonics, defined as spectral components at frequencies that are integer multiples of the fundamental frequency of an AC system, are a significant concern in power quality management. These harmonics arise predominantly due to non-sinusoidal load currents, establishing a strong correlation between harmonic voltage and current distortion [7]. The underlying principle is that distorted currents cause more significant losses than their sinusoidal counterparts at the same RMS values, primarily because series resistance increases with frequency. Consequently, transformers, cables, and other series components must be over-rated to withstand harmonic

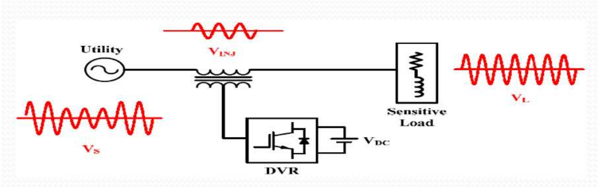

Fig. 3: Circuit of a Shunt Active Power Filter

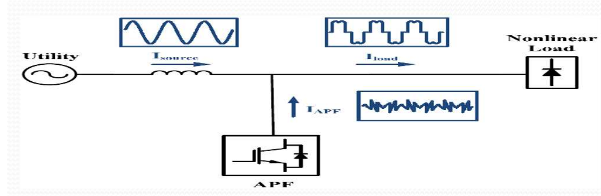

Fig. 4: Dynamic Voltage Restorer Circuit

distortions. Nonlinear loads, such as power converters including rectifiers (e.g., DC motor drives, adjustable speed drives, uninterruptible power supplies, switched mode power supplies) and cycloconverters, are common sources of harmonic currents. Other notable sources include industrial equipment like fluorescent lighting, electrical heating furnaces, welding machines, and arc furnaces [8]. Although AC motors, generators, and transformers also contribute to harmonic currents, their impact remains relatively minor compared to their fundamental current components unless construction defects or malfunctions enhance their harmonic contributions. The severity of harmonic distortion is measured using established indices by IEEE and IEC, such as Individual Harmonic Distortion (IHD), Total Harmonic Distortion (THD), and Total Demand Distortion (TDD). IHD is the ratio of the RMS value of each harmonic component to the RMS value of the fundamental frequency, while THD and TDD offer comprehensive assessments of harmonic levels. APFs (Active Power Filters) and DVRs (Dynamic Voltage Restorers) are two proven approaches addressed further in ensuing sections to mitigate harmonics effectively [9].

A. Active Power Filter (APF)

Active Power Filters (APFs) play a crucial role in addressing reactive power and harmonics challenges that threaten the grid's stability, leading to outages and equipment failures. Historically, passive LC filters—despite their initial popularity due to low costs—faced limitations such as large size, mistuning, instability, and adverse resonance phenomena [10]. These limitations paved the way for APFs, which first emerged in the early 1970s, courtesy of pioneering work by H. Sasaki and T. Machida, and further developments in 1976 employing PWM inverters with power transistors [11]. Innovations in power electronics and microprocessors over the decades have expanded APF applications, now crucial for both low/medium voltage distribution and high-voltage systems where they manage reactive power and voltage.

APFs are instrumental in not only filtering harmonics but also addressing power quality anomalies like reactive power fluctuation, voltage flicker, and load imbalances. Among various APF configurations, shunt APFs are prevalent for current harmonics management by counteracting load-induced distortions with compensatory currents as illustrated in Figure 3. Their efficacy extends to reactive power compensation, voltage fluctuation mitigation, and system balancing.

B. Dynamic Voltage Restorer

The Dynamic Voltage Restorer (DVR) emerges as a pivotal device for mitigating voltage sags, swells, imbalances, and harmonics at the point of common coupling (PCC). As depicted in Figure 4, DVRs function by injecting compensatory voltages with precision-tuned magnitude and phase, ensuring load voltage stability. In regular operation, DVRs maintain stability without exchanging real power; however, during voltage sags or swells, they swiftly adjust the DC link to buffer real power transients, proving vital for sensitive industrial loads [12].

DVRs serve versatile roles across medium and low-voltage applications, coming in configurations like single-phase, and three-phase (three-wire/four-wire), with advanced topologies such as transformer-less designs and H-bridge converters available [13].

IV. Distributed Generation

Distributed Generation (DG) refers to the decentralized production of electricity via small-scale generation technologies located close to the point of consumption. Over the past decade, DG has gained significant traction, especially in the residential and commercial sectors. This shift is driven by advancements in renewable energy technologies, alongside growing policy support from governments worldwide. For instance, countries such as Germany and Australia have seen rapid growth in the adoption of distributed generation, particularly rooftop photovoltaic (PV) systems, which benefit from favorable geographic conditions (abundant solar radiation) and government incentives designed to encourage consumer participation [14], [15].

The proliferation of DG technologies is expected to induce substantial changes in the structure of electricity markets and grid operations [16]. Central to these changes are the sustainability and energy independence offered by DG, as it allows consumers to reduce their reliance on fossil fuels. However, in addition to these primary advantages, DG systems also offer several other benefits, such as:

- **Lower capital costs per unit of capacity**: As DG systems are typically located near the point of consumption, the need for extensive transmission and distribution infrastructure is minimized, leading to reduced capital costs [17].
- **Reduction in carbon emissions**: DG technologies, particularly those based on renewable sources like solar and wind, contribute significantly to lowering carbon

emissions, making them a key component of the global effort to combat climate change [18].

- **Reduced electricity bills**: By generating electricity locally, DG systems reduce transmission and distribution losses, as well as behind-the-meter consumption. This not only lowers the cost of electricity for end-users but can also mitigate price fluctuations associated with centralized power generation [19].
- **Increased resilience to grid disturbances**: DG systems, particularly when coupled with energy storage and smart microgrid technologies, can provide enhanced resilience against grid disturbances and voltage fluctuations. This is particularly valuable in remote or off-grid areas where reliability is crucial [20].

However, the full potential of DG is contingent upon the development of efficient and widespread network infrastructure. In many regions, the absence of advanced grid systems and the high costs associated with integrating decentralized generation sources remain significant barriers. In some countries, particularly in developing regions, these challenges are compounded by inadequate energy infrastructure, which hinders the widespread deployment of DG technologies [21]. Nevertheless, despite these obstacles, the economic and environmental incentives for DG continue to drive interest in decentralized energy generation solutions, including smart microgrids.

While many DG systems operate independently or in isolated configurations, the majority are still connected to the utility grid. Grid-connected DG systems allow for the integration of local generation into the larger electricity network, ensuring that power quality and system stability are maintained. The grid plays a vital role in supervising the interaction between distributed generators to ensure that they do not cause issues such as voltage rise or frequency instability. For example, when an uncontrolled DG system injects excess power into the grid, voltage levels may increase along distribution lines. In such cases, grid operators can adjust the tap settings of substation transformers to accommodate the voltage rise, thus maintaining system stability [22].

Furthermore, the grid is responsible for maintaining the frequency of the distribution network within prescribed limits, which is essential to prevent the adverse effects of frequency imbalances, such as system instability or equipment damage. These tasks are crucial to ensure the safe and efficient operation of the overall power system. Therefore, while DG systems reduce the need for imported grid power, they do not eliminate the necessity for transmission, distribution, and ancillary grid services, such as frequency regulation and voltage control [23].

Grid-connected DG systems offer numerous advantages, including reduced energy costs, enhanced sustainability, and increased system resilience. However, these benefits are intricately tied to the role of the grid in maintaining power quality, stability, and reliability. As such, while DG reduces dependence on traditional centralized generation, it is not a substitute for the critical infrastructure and services provided by the utility grid.

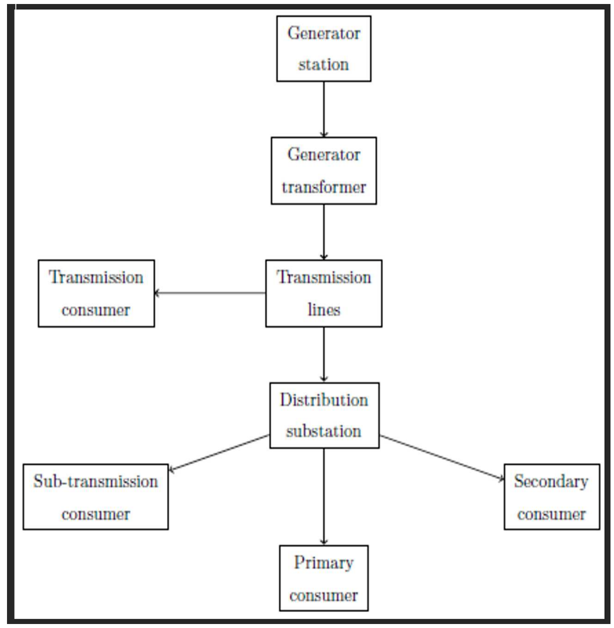

Fig. 5: Traditional grid paradigm

V. SMART MICROGRIDS

Traditional electricity grids operate on a radial power flow model, where electricity is generated at centralized power stations and transmitted through long-distance transmission lines to reach consumers, as depicted in Figure 5. This hierarchical structure, while historically effective, exhibits several inherent vulnerabilities and inefficiencies. Notably, the energy conversion efficiency of large centralized generators can be as low as one-third, excluding the waste heat recovery potential, and the environmental impact of their operation, particularly CO_2 emissions, is substantial. Moreover, the transmission and distribution (T&D) network introduces energy losses that typically account for about 8% of the total energy produced [24], translating into significant carbon emissions and energy inefficiencies.

In addition to these inefficiencies, the traditional grid struggles with issues of energy sufficiency, underutilization, and economic feasibility. A key concern is the large portion of capacity that is dedicated solely to meeting peak demand, which in many systems may only occur infrequently, often for only a few hours each year. As a result, substantial generation and transmission capacity sits idle during off-peak periods, leading to low utilization and reduced overall efficiency. For example, studies have shown that approximately 20% of the generation and transmission capacity in some networks is reserved exclusively for peak demand, which places a significant economic burden on consumers [25]. This underutilization drives up the costs of maintaining the grid, making the radial grid model increasingly untenable from both an economic and environmental perspective.

The ongoing transition to sustainable electricity generation has added further strain to traditional grid systems. While the integration of renewable energy sources such as solar, wind,

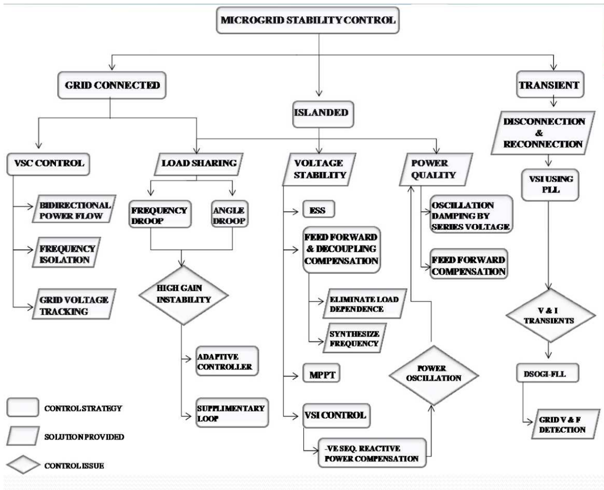

Fig. 6: Microgrid Stability Control

and hydroelectric power has become a key priority in reducing reliance on fossil fuels, these sources introduce their own set of challenges. Their intermittent and variable nature complicates their integration into the existing grid, which was originally designed for stable, continuous generation. These challenges, including grid instability and unpredictability, have limited the ability of renewable energy sources to contribute to real-time power generation [26].

To address these challenges, the concept of smart microgrids has emerged as a viable solution. Smart Microgrids are localized, small-scale energy systems that can operate independently or in conjunction with the main grid. They are designed to integrate renewable energy sources while maintaining stability, reliability, and power quality. As shown in Figure 6, smart microgrids can effectively manage renewable generation and storage, balancing supply and demand on a local level. This decentralized approach not only reduces the burden on traditional grid infrastructure but also enhances the resilience and reliability of the overall energy system.

Smart microgrids offer several key advantages over traditional grids. First, they enable the integration of renewable energy in a way that mitigates the issues of intermittency and instability. By incorporating energy storage systems and demand-side management, smart microgrids can store excess energy generated during periods of high renewable output and discharge it during times of low generation. This improves the overall reliability of the energy supply and reduces reliance on fossil-fuel-based backup power. Second, smart microgrids enhance grid resilience by providing localized energy generation and backup capacity. In the event of a larger grid failure or natural disaster, smart microgrids can operate in an islanded mode, providing continuous power to critical infrastructure such as hospitals and emergency services [20].

Furthermore, smart microgrids contribute to economic efficiency by improving the utilization of local generation resources and reducing transmission losses. By minimizing the need for long-distance transmission and distribution, smart

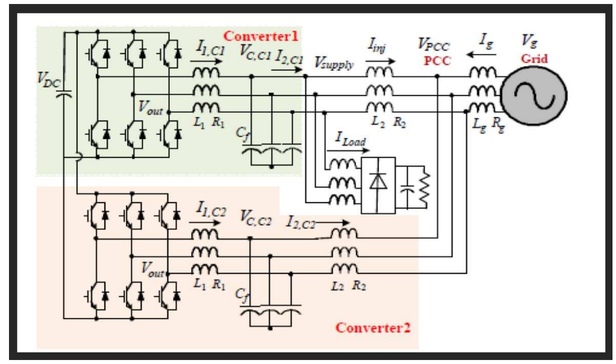

Fig. 7: Proposed Topology of the Compensation System

microgrids can significantly reduce the energy losses associated with conventional grid systems. Additionally, they can provide more efficient use of resources by enabling demand-side energy management and optimizing generation capacity based on local consumption patterns [19].

Smart microgrids represent a promising solution to many of the limitations of traditional grid systems. By enabling the efficient integration of renewable energy sources, improving system stability, and enhancing resilience to grid disturbances, smart microgrids offer a pathway toward a more sustainable, reliable, and economically efficient energy future. The continued development and deployment of smart microgrid technologies are essential in realizing the full potential of decentralized energy systems, which are increasingly critical as the world transitions toward a low-carbon energy future [17], [23].

VI. Proposed Method

This section introduces a novel compensation method aimed at alleviating harmonic distortions in both the supply voltage and grid current through a simple yet effective control scheme using two parallel interface converters. The proposed system's hardware and control strategies are illustrated in Figures 7 and 8, respectively.

The system is designed to operate at the Point of Common Coupling (PCC), where it is connected to a Distributed Generation (DG) unit. The DG unit consists of two parallel converters sharing a common DC bus. Each converter is equipped with an output LCL filter, which is crucial for filtering harmonic content. Converter 1 is responsible for controlling the harmonic components of the supply voltage, thereby improving the quality of the voltage supplied to the nonlinear load. Meanwhile, Converter 2 focuses on mitigating current harmonics, reducing their impact on the grid. This dual approach ensures that both voltage and current harmonics are effectively addressed. The specific control systems for both converters are discussed in the subsequent subsections.

A. Converter Control Strategy

The control strategy for the converters is designed to regulate the real and reactive power output to improve power quality. To begin with, the real and reactive power for Converter 1 is determined by measuring the line current I_2 of Converter 1 and the PCC voltage V_{PCC}, as shown in Figure 7. The real and reactive power are calculated in Equations 1 and 2 respectively as :

$$P_{C1} = \frac{3\tau}{2(s+\tau)} \left(V_{\text{PCC},\alpha} \cdot I_{2\alpha,C1} + V_{\text{PCC},\beta} \cdot I_{2\beta,C1}\right) \tag{1}$$

$$Q_{C1} = \frac{3\tau}{2(s+\tau)} \left(V_{\text{PCC},\beta} \cdot I_{2\alpha,C1} - V_{\text{PCC},\alpha} \cdot I_{2\beta,C1}\right) \tag{2}$$

where P_{C1} and Q_{C1} represent the real and reactive output power of Converter 1, respectively. $V_{\text{PCC},\alpha}$ and $V_{\text{PCC},\beta}$ are the PCC voltage components in the two-phase stationary reference frame, and $I_{2\alpha,C1}$ and $I_{2\beta,C1}$ represent the corresponding components of the line current for Converter 1. The time constant τ is associated with the low-pass filters used to filter the real and reactive power components. The low-pass filters serve a dual purpose: (i) filtering out power surges induced by line current noise and (ii) ensuring rapid system response, following the system's control specifications. The power reference used in the controller is based on the available power from the DG unit, and it can be adjusted if the DG unit includes a storage system or is part of a microgrid with an energy management system. The harmonic compensation is triggered once the power rating of the converters is sufficiently high, and the power reference generator output I_2 is used as the line current reference.

The line current reference for the power control term in Converter 1 is given by Equation 3 as:

$$I^{*}_{2,PQ,CI} = g_P \cdot (V_{\text{PCC},\alpha} + jV_{\text{PCC},\beta}) + g_Q \cdot (V_{\text{PCC},\beta} - jV_{\text{PCC},\alpha}) \tag{3}$$

where g_P and g_Q are two adjustable gains that control the real and reactive power outputs of Converter 1, respectively. This controller uses the instantaneous PCC voltage vector $V_{\text{PCC},\alpha} + jV_{\text{PCC},\beta}$ and its conjugate as the reference, leveraging the fact that real power is proportional to the current component orthogonal to the PCC voltage vector, while reactive power is associated with the current component orthogonal to the conjugate of the PCC voltage.

The gains g_P and g_Q are controlled using two proportional-integral (PI) controllers calculated by Equations 4 and 5 as :

$$g_P = \left(k_{p\_PQ} + \frac{k_{i\_PQ}}{s}\right) \cdot (P_{\text{ref}} - P_{C1}) \tag{4}$$

$$g_Q = \left(k_{P\_PQ} + \frac{k_{p\_PQ}}{s}\right) \cdot (Q_{\text{ref}} - Q_{C1}) \tag{5}$$

where k_{p_PQ} and k_{i_PQ} are the proportional and integral gains for the PI controllers, and P_{ref} and Q_{ref} are the reference values for real and reactive power, respectively. The power control system operates to adjust the output voltage and current to match the desired power levels while minimizing harmonic distortions. The voltage output reference for the pulse-width modulation (PWM) generation of Converter 1 is derived from Equation 6 as a combination of power control, harmonic mitigation, and active damping terms:

$$\begin{aligned} V^{*}_{\text{out},C1} = {} & H_{\text{PQ}}(s) \cdot \left(I^{*}_{2,PQ,C1} - I_{2,C1}\right) \\ & + H_{\text{Har}}(s) \cdot \left(V^{*}_{C,C1} - V_{C,C1}\right) + H_{\text{AD}}(s) \cdot I_{1,C1} \end{aligned} \tag{6}$$

where $V^{*}_{\text{out},C1}$ is the reference voltage for PWM control, $I^{*}_{2,PQ,C1}$ is the line current reference from the power control term, and $V^{*}_{C,C1}$ is the voltage reference for the harmonic mitigation term. $V_{C,C1}$ represents the filter capacitor voltage, and $I_{1,C1}$ is the output current of Converter 1.

The controllers for the power control, harmonic mitigation, and active damping terms are described in Equation 7 by the following transfer functions:

$$\begin{aligned} H_{\text{PQ}}(s) &= k_{p1,C1} + \frac{2K_{i,f,C1}\omega_c s}{s^2 + 2\omega_c s + \omega_0^2} \\ H_{\text{Har}}(s) &= k_{p2,C1} + \sum_{h=5,7,11,13} \frac{2K_{v,h,C1}\omega_c s}{s^2 + 2\omega_c s + (h \cdot \omega_0)^2} \\ H_{\text{AD}}(s) &= k_{\text{AD},C1} \end{aligned} \tag{7}$$

where $k_{p1,C1}$ and $k_{i,f,C1}$ are the proportional and integral gains for the power control loop, $k_{p2,C1}$ is the gain for the harmonic mitigation term, and $k_{\text{AD},C1}$ is the gain for the active damping loop. The harmonic mitigation term is specifically designed to focus on selected harmonic frequencies, ensuring that only those harmonics are filtered out, leading to a decoupling between the voltage and current control loops. This control strategy provides several advantages, such as improved dynamic response to harmonic distortions and better stability, compared to conventional controllers. It also eliminates the need for stage-locked loops, making the system more efficient and robust against disturbances.

The proposed method leverages a coordinated control strategy for two parallel converters to mitigate both voltage and current harmonics in the system. The decoupling of power control and harmonic mitigation ensures that the system can dynamically adjust to varying load conditions and disturbances, resulting in improved power quality and stability.

VII. Experimental Results and Discussion

This section presents the experimental results of the proposed mitigation system for harmonics in the supply voltage and grid current. The Simulink-based model was implemented to evaluate the effectiveness of the coordinated control of two parallel interface converters. The system performance was validated using various renewable energy sources, including wind, photovoltaic (PV) panels, and battery storage, with results compared to a baseline model using a single interfacing converter.

The system model, shown in Figure 9, is based on the coordinated operation of two parallel converters for simultaneous harmonic compensation of both supply voltage and grid current. The detailed circuitry and control diagrams of the proposed system are depicted in Figure 10. The model

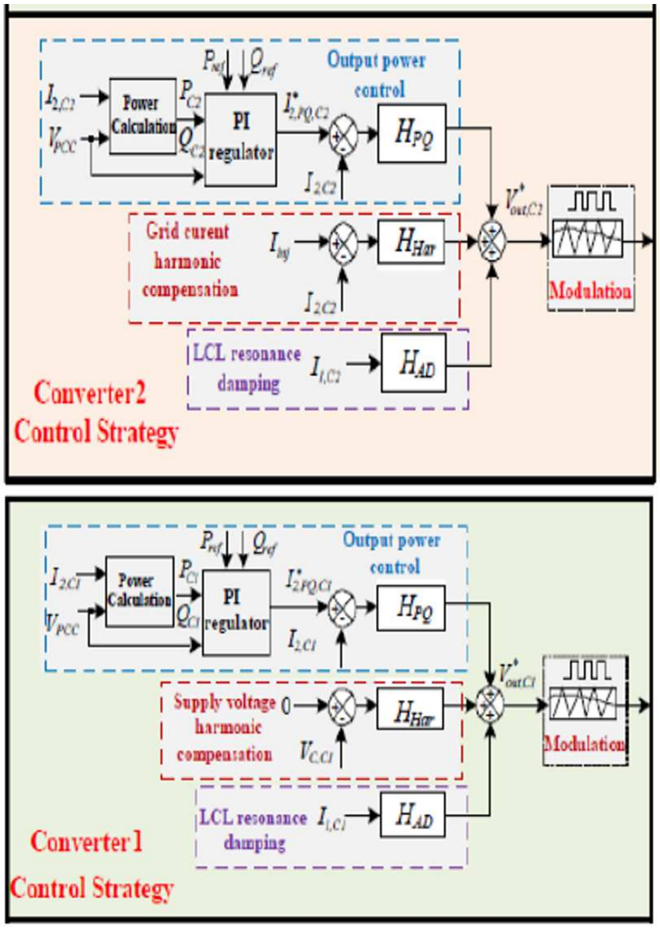

Fig. 8: Control Strategy for the Interface Converters: (a) Converter 1, (b) Converter 2

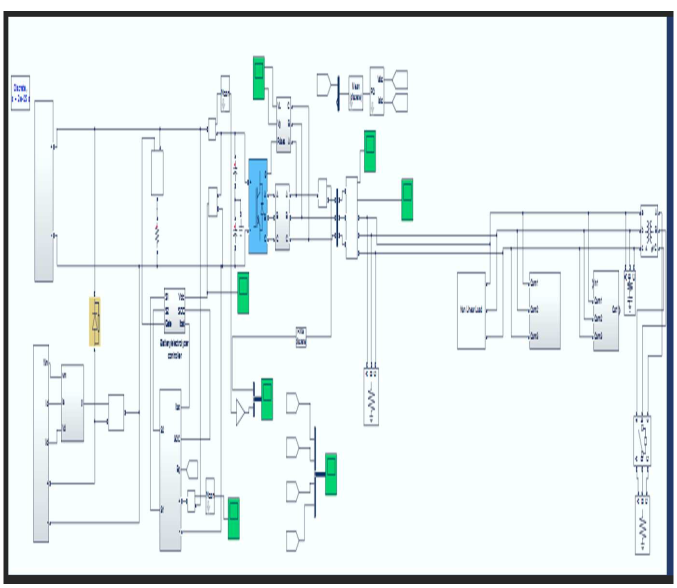

Fig. 9: Proposed Model for the Compensation System

consists of three key components: the wind turbine system, the photovoltaic (PV) array, and the battery energy storage system, each playing a critical role in providing power to the load.

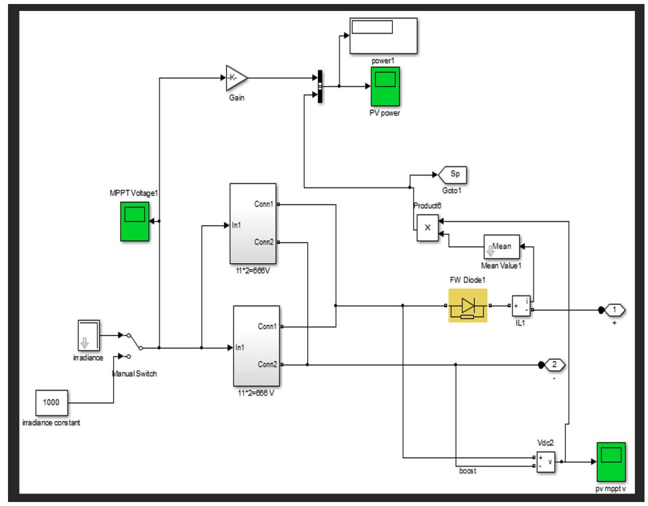

Fig. 10: Photovoltaic (PV) Subsystem: Simulation Model of the PV Panel Configuration and Power Conversion System in Simulink.

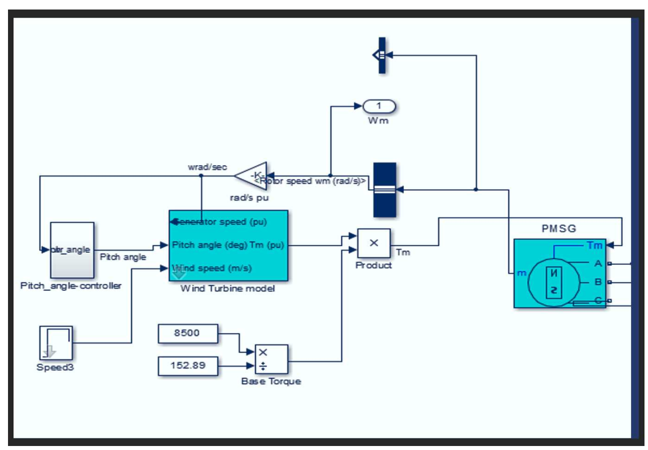

Fig. 11: Wind Energy Subsystem: Simulation Model of the Wind Turbine and Permanent Magnet Synchronous Generator (PMSG) in Simulink.

The wind energy subsystem, shown in Figure 11, is connected to a permanent magnet synchronous generator (PMSG), which is directly driven by the wind turbine. The generator power output is regulated by adjusting the pitch angle of the rotor, which is controlled based on the wind speed. The PV subsystem, depicted in Figure 12, is made up of several PV panels arranged in series or parallel to convert solar energy into DC power, with their orientation and tilt playing a vital role in optimizing energy production.

The output voltages for PV and wind systems are relatively low when compared to the expected operating levels, particularly under varying environmental conditions. System

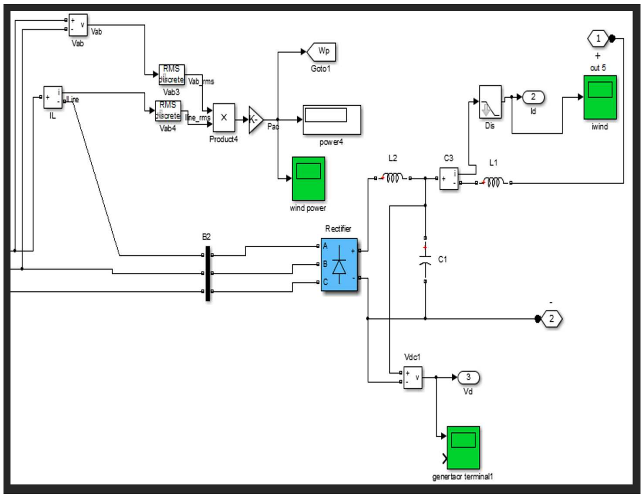

Fig. 12: Wind Energy Subsystem: Detailed Simulation of Wind Turbine Control and Power Conversion System in Simulink (Part 2).

TABLE I: Input Parameters for Simulink Model

Component	Configuration	Voltage (V)	Power (W)
PV Array	11×2×2 panels	666	80 kW
Wind Turbine	-	-	3125
Battery	-	200	-

performance is demonstrated by the outputs shown in Figure 13, where the DC voltage from wind and PV systems is illustrated with minor speckle noise due to fluctuations in wind speed and irradiance. Figure 14 shows the output voltages for the PV system and load. In the waveform, blue represents battery power, pink represents wind power, and yellow represents PV power. The Maximum Power Point Tracking (MPPT) algorithm is employed to determine the maximum available power for both the wind and hybrid battery systems, ensuring that the battery is charged efficiently while meeting the load requirements.

Figures 15 and 16 illustrate the results of the power management simulation for different operating scenarios. Figure 15 shows the situation when both PV and wind power generation meet the load demand, with the battery charging from excess wind energy. In this waveform, cyan indicates battery power, pink represents wind power, yellow represents PV power, and red indicates load power. In contrast, Figure 16 shows a case where the PV power output is close to its maximum while the wind power output is minimal. In this scenario, the fuzzy logic controller (FLC) optimally adjusts the battery charging switches, the wind selector switch, and the photovoltaic selection switch to ensure adequate power is supplied to the load. Figure 17 shows the variation in the rotor speed in response to changes in wind speed. The data demonstrate the dynamic response of the wind turbine's rotor to fluctuating wind conditions, which influences the power generated.

TABLE II: Output Parameters from the Simulink Experimentation

Parameter	Voltage (V)	Current (A)
DC Voltage, V_{dc}	629.6	-
Load Voltage, V_L	133.1	-
Battery Voltage	16.31	-
Load Current, I_L	-	3125

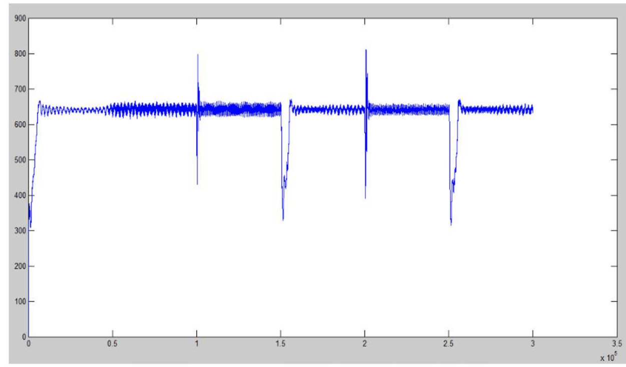

Fig. 13: DC Voltage Response of the Proposed System

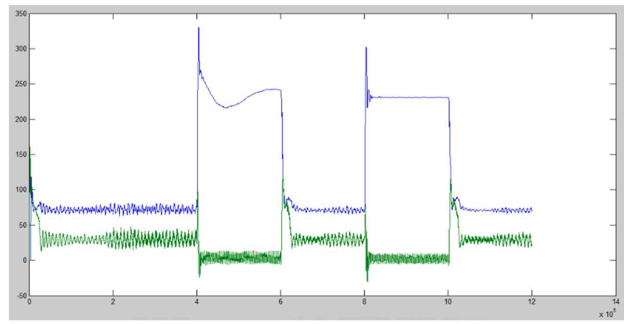

Fig. 14: Output Voltage Levels of Load and PV Cell

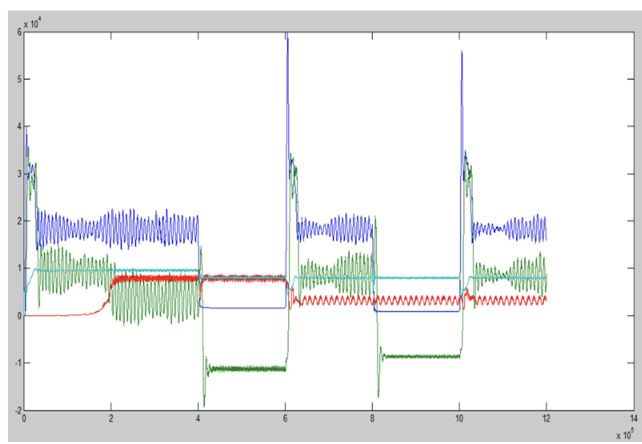

Fig. 15: Simulation Result of Power Management with PV and Wind Supplies

The dynamic response of the photovoltaic output power at constant isolation level and constant temperature is shown in Figure 18. Power produed by PV and wind are very low, load

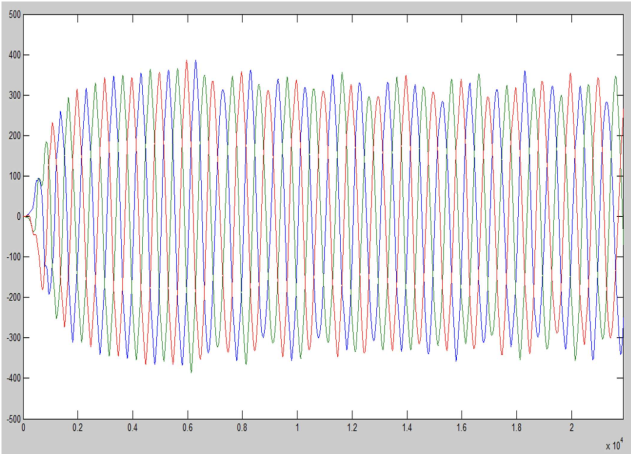

Fig. 16: Simulation Result of Power Management with Battery Alone

demand is medium and battery state of charge is high enough to run the load. Figures 19 and 20 present the output voltages in the load and PV cell, respectively, illustrating the system's voltage regulation capabilities under varying conditions where the power fluctuates as a result of changing temperatures and irradiation levels where blue color shows the battery power, pink color shows wind power and yellow shows PV power. During conditions of low wind and PV output, the battery remains sufficiently charged to provide power to the load.

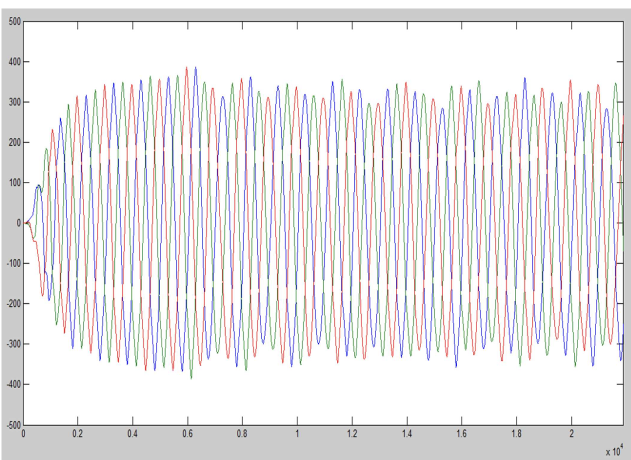

Fig. 17: Rotor Speed Variation with Time

The harmonic distortion performance of the proposed system is compared to that of a baseline system with a single interfacing converter in Table III. The results show a significant reduction in Total Harmonic Distortion (THD) for the supply voltage, grid voltage, and grid current when dual interfacing converters are used in the proposed approach. These improvements highlight the effectiveness of the coordinated control strategy in mitigating harmonic distortions.

Table IV presents the harmonic distortion magnitude concerning frequency. The results indicate that the proposed system outperforms the baseline model in terms of both

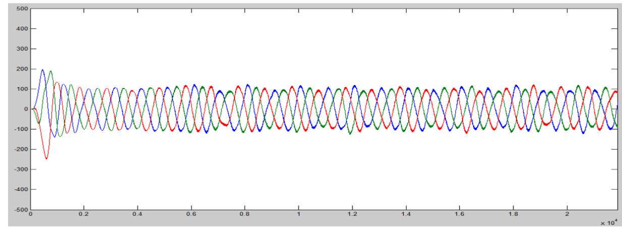

Fig. 18: PV Output Power under Varying Conditions

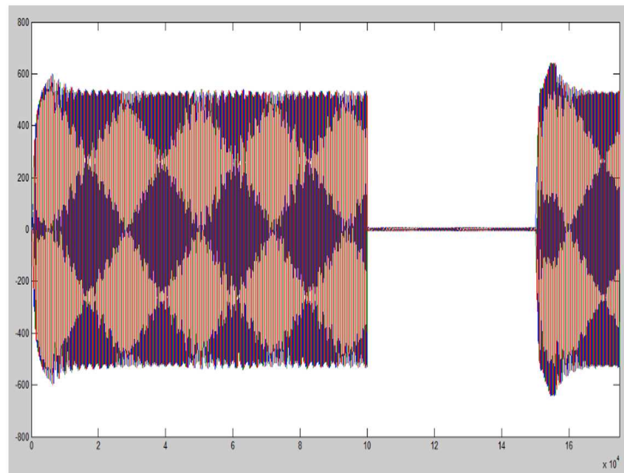

Fig. 19: Output Voltage Levels at Load

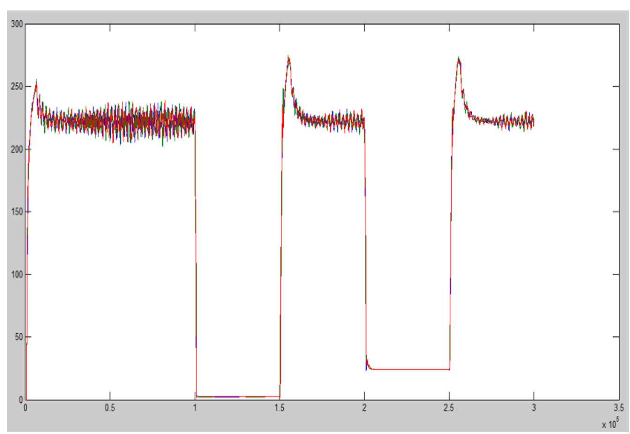

Fig. 20: Output Voltage Levels at PV Cell

TABLE III: Harmonic Distortion Comparison: Base vs Proposed Approach

THD (%)	Base Model	Proposed Model
Supply Voltage	6.45	5.78
Grid Voltage	4.57	4.21
Grid Current	12.28	11.25

TABLE IV: Harmonic Distortion Magnitude vs Frequency

THD (%)	Base Model	Proposed Model
Supply Voltage	2.28	2.21
Grid Current	3.54	3.08

supply voltage and grid current THD, demonstrating superior harmonic filtering capabilities. The experimental results confirm that the proposed method significantly reduces harmonic distortion, improves power quality, and provides effective load management. It is a viable solution for integrated renewable energy systems with hybrid power sources.

VIII. Conclusion

This paper presents a novel approach to mitigating harmonic distortion in power systems using a coordinated voltage and current control strategy for a dual-interface converter system. The main challenge with using a single Distributed Generation (DG) interface converter is the difficulty in effectively compensating for local load harmonic currents, particularly when the grid voltage is highly distorted. The proposed dual-converter system addresses this by integrating a shunt capacitor in the primary converter, directly connected to the nonlinear load. A direct feedback loop for harmonic voltage control of the filter capacitor enhances the quality of the supply voltage. Meanwhile, the second converter compensates for harmonic currents from both the nonlinear load and the primary converter, optimizing both supply voltage and grid current. This coordinated control scheme eliminates the need for complex harmonic extractions or stage-bolted loops, simplifying the control architecture and reducing the computational load on DG-interfacing converters. The simulation results confirm that the proposed method reduces harmonic distortion and improves overall system performance, including power factor correction and efficiency, making it a promising solution for modern smart grids.

Future research directions include the exploration of real-time implementation of this dual-converter system in dynamic and highly variable grid conditions, as well as the integration of machine learning algorithms for adaptive harmonic compensation. Additionally, further investigation into the scalability of this approach for large-scale smart microgrids and its compatibility with renewable energy sources, such as wind and solar, could offer significant advancements in smart grid stability and power quality.

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