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Designing of a Solar Energy and Diesel Generators Hybrid Microgrid for Sustainable Agricultural Irrigation

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Abstractt: The increasing integration of renewable energy sources into standalone microgrids presents significant challenges in maintaining grid stability and power quality. This thesis presents a substantial enhancement to the control strategy of a Solar Photovoltaic (SPV), Battery Energy Storage (BES), and Diesel Generator (DG) based AC microgrid. The foundational work for this research established an effective energy management system using conventional Proportional-Integral (PI) and Proportional-Integral-Resonant (PIR) controllers to minimize DG runtime. However, the inherent non-linearities of microgrid components and dynamic load conditions limit the performance of these linear controllers, particularly in terms of dynamic response and harmonic suppression.

This research addresses these limitations by proposing the replacement of the conventional PI/PIR controllers within the Voltage Source Converter (VSC) with an intelligent Fuzzy Logic Controller (FLC). The FLC is designed to leverage its inherent robustness, adaptability to non-linear systems, and model-free nature to provide superior dynamic performance and grid stability. By acting as an intelligent control device, the FLC addresses the critical gaps left by its linear counterparts, leading to a cascade of system-wide benefits including further reductions in DG runtime, higher penetration of renewable energy, improved overall system efficiency, and extended equipment lifespan. A comprehensive model of the microgrid was developed and simulated in the MATLAB/Simulink environment to perform a rigorous comparative analysis. The results demonstrate the clear superiority of the proposed FLC-based strategy. The FLC achieves a more rapid and stable dynamic response to load transients and, most notably, a significant reduction in the Total Harmonic Distortion (THD) of the DG set's voltage and current, ensuring stricter compliance with the IEEE 519 standard. The findings validate that the implementation of an FLC is a pivotal step towards creating more intelligent, efficient, and resilient standalone power systems.

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I. INTRODUCTION

The global imperative to transition towards sustainable energy systems has catalyzed the development and deployment of microgrids, particularly in remote and off-grid locations. These localized power systems, which can operate autonomously, are crucial for providing reliable electricity to communities and industries where connection to a central utility grid is impractical or impossible. A prevalent and effective architecture for such standalone systems is the hybrid integration of Solar Photovoltaic (SPV) arrays, Battery Energy Storage Systems (BES), and a conventional Diesel Generator (DG) set. This configuration leverages the clean, abundant energy from the sun, uses the BES to ensure power continuity and manage the intermittency of solar power, and relies on the DG set as a dependable backup for ensuring uninterrupted power supply.

The primary motivation behind this hybrid model is the strategic reduction of dependency on fossil fuels. By maximizing the use of solar energy, the operational hours of the DG set can be significantly curtailed. This leads to direct and substantial benefits, including lower fuel costs, reduced operational and maintenance expenses, and a significant decrease in harmful emissions, thereby aligning with both economic and environmental objectives. The base work for this thesis developed an advanced control strategy that successfully minimized DG operating hours by implementing a sophisticated rule-based energy management system. However, optimizing energy dispatch is only one part of the challenge; ensuring the stability and quality of the power delivered in such a dynamic environment remains a critical area for advancement.

The reference control strategy, while effective in its energy management, relies on conventional Proportional-Integral (PI) and Proportional-Integral-Resonant (PIR) controllers for the low-level regulation of the system's Voltage Source Converter (VSC). While PI/PIR controllers are widely used for their simplicity and reliability, they are fundamentally linear controllers with fixed gains tuned for specific operating points.

A microgrid, however, is an inherently non-linear and highly dynamic system. It is characterized by the fluctuating output of the SPV array, the high-frequency switching of power electronic converters, and the connection of various, often non-linear, modern loads. In this context, the performance of fixed-gain PI/PIR controllers becomes a significant bottleneck. They struggle to provide optimal responses across the wide spectrum of operating conditions, leading to several key challenges:

1) Sub-optimal Dynamic Response: When faced with sudden changes, such as a large load being connected or disconnected, or a rapid drop in solar irradiance, PI controllers can exhibit sluggish response, overshoot, and prolonged settling times, which can compromise the microgrid's voltage and frequency stability.
2) Inadequate Harmonic Mitigation: The proliferation of non-linear loads (e.g., computers, variable speed drives, modern lighting) injects harmonic currents into the microgrid, distorting the voltage waveform and degrading power quality. While the VSC can act as an active filter to mitigate these harmonics, the effectiveness of this function is limited by the PI controller's ability to accurately track the complex, non-sinusoidal current references required for compensation. This results in higher-than-necessary Total Harmonic Distortion (THD) levels.
3) System-Level Inefficiencies: These control limitations create a ripple effect on the entire system's performance. The instability and sub-optimal power quality can necessitate more frequent reliance on the DG set as a stabilizing element, counteracting the primary goal of reducing its runtime. This leads to increased fuel consumption, higher emissions, and accelerated wear and tear on the DG set due to frequent start-stop cycles.

To address the aforementioned gaps and elevate the performance of the microgrid, this thesis proposes a significant enhancement to the control architecture: the replacement of the conventional PI/PIR controllers within the VSC with an intelligent Fuzzy Logic Controller (FLC).

Unlike its linear counterparts, an FLC is a form of artificial intelligence that does not require a precise mathematical model of the system. It operates on a set of linguistic IF-THEN rules derived from expert knowledge, allowing it to handle non-linearity and uncertainty with remarkable effectiveness. This "intelligent" approach enables a more adaptive, robust, and nuanced control action that is better suited to the dynamic nature of the microgrid.

The primary contribution of this research is the design, implementation, and validation of an FLC-based control strategy that yields demonstrably superior performance in terms of both dynamic response and power quality. The specific objectives of this thesis are:

a) To design and integrate a Mamdani-type Fuzzy Logic Controller into the VSC control loop of the SPV-BES-DG microgrid model.
b) To conduct a rigorous comparative simulation study in MATLAB/Simulink between the proposed FLC and the baseline PI/PIR controller under identical operating conditions.
c) To quantitatively demonstrate the FLC's superiority in reducing Total Harmonic Distortion (THD) in the DG voltage and current waveforms, using the provided experimental data as a benchmark.
d) To analyze the FLC's impact on the system's dynamic response and overall stability, linking these improvements to higher-level benefits such as reduced DG runtime, increased renewable energy utilization, and enhanced equipment lifespan.

II. MICROGRID ARCHITECTURES AND CONTROL FUNDAMENTALS

The concept of a microgrid as a controllable cluster of distributed energy resources (DERs), storage systems, and loads has been extensively studied. The SPV-BES-DG architecture is particularly favoured for standalone applications due to its blend of renewable generation and dispatchable backup power. Control of such systems is typically hierarchical. The primary control level, which is the focus of this work, is responsible for the instantaneous voltage and current regulation of the power converters to ensure system stability.

A critical function at this level is the control of the Voltage Source Converter (VSC), which acts as the interface between the DC sources (SPV, BES) and the AC bus. In islanded mode, the VSC operates in a "grid-forming" capacity, establishing the local grid's voltage and frequency. When the DG set is active, the VSC transitions to a "grid-feeding" or "grid-supporting" role, where it injects power and can provide ancillary services like active filtering.

A. Conventional Control Strategies and Their Shortcomings

The dominant control method for VSCs in the literature is based on Proportional-Integral (PI) controllers implemented in a synchronous rotating (d-q) reference frame. This technique simplifies control by transforming AC quantities into DC signals, allowing for straightforward regulation of active and reactive power. The base paper for this thesis employs an advanced version of this strategy, incorporating a Cascaded Second-Order Generalized Integrator (C-SOGI) based Phase-Locked Loop (PLL) to ensure robust synchronization and filtering of harmonics before they reach the PI control loops.

Despite these advancements, the core limitation remains the linear nature of the PI controller. Several studies have highlighted the shortcomings of PI control in microgrid applications, including performance degradation under variable operating conditions, sluggish transient response, and limited effectiveness in suppressing harmonic distortion from non-linear loads. Existing energy management strategies, such as simple load-sharing or State-of-Charge (SoC) based management, often lead to frequent DG start-stop cycles or extended periods of inefficient, partial-load operation, reducing the lifespan of the DG set and increasing fuel consumption. The improved strategy in the base paper mitigates the frequent cycling issue but still relies on the underlying PI controller for power quality and dynamic regulation.

B. Intelligent Controllers for Microgrid Applications

To overcome the limitations of linear controllers, researchers have increasingly turned to intelligent control techniques, with Fuzzy Logic Control (FLC) being a prominent choice. The primary advantage of FLC is its ability to handle complex, non-linear systems without requiring a precise mathematical model. It uses linguistic variables and a rule base derived from expert knowledge to make control decisions, offering a more robust and adaptive performance across a wide range of operating conditions.

Numerous studies have demonstrated the superiority of FLC over PI controllers in power electronics applications. Research shows that FLCs can achieve faster transient response, reduced overshoot, and significantly lower Total Harmonic Distortion (THD) when used to control active power filters and inverters. FLCs are cheaper to develop, cover a wider range of operating conditions, and are more readily customizable than conventional controllers.

C. Research Gap and Novelty

While the literature confirms the general benefits of FLC over basic PI controllers, a specific research gap exists in its application as a direct replacement within a highly optimized, state-of-the-art control framework like the one presented in the base paper. The baseline system already incorporates advanced filtering (C-SOGI) and intelligent energy management logic.

Therefore, the novelty of this thesis is not merely to show that FLC is better than a simple PI controller, but to demonstrate that an FLC can provide a significant and quantifiable performance enhancement over an already advanced and stable baseline system. This work will prove that the inherent intelligence and non-linear adaptability of the FLC can address the residual dynamic and power quality limitations of the PI/PIR controller, pushing the microgrid's performance to a new level of stability and efficiency. This constitutes a valuable contribution to the field by validating FLC as a superior solution for high-performance, real-world microgrid control.

III. SYSTEM OVERVIEW AND DESIGN

This chapter details the architecture of the microgrid under study, the mathematical models of its key components, and the baseline control strategy that serves as the benchmark for comparison.

A. System Configuration

The microgrid configuration, based on the reference work, is illustrated in the figure below. It is designed for standalone operation in remote areas.

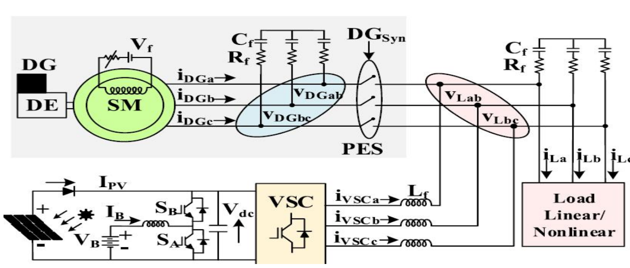

Figure 3.1: Microgrid System Architecture

The architecture of the microgrid under investigation, illustrated in the figure provided, is a sophisticated hybrid power system specifically designed for standalone operation in remote areas where a connection to the main utility grid is unavailable. The configuration is a synergistic integration of renewable energy generation, energy storage, and conventional backup power, all managed through advanced power electronic interfaces to ensure a stable and high-quality power supply to local loads.

The system can be functionally divided into two main sections: a DC (Direct Current) side, which includes the renewable source and energy storage, and an AC (Alternating Current) side, which includes the backup generator and the loads. A central power converter acts as the crucial interface between these two sections.

1) DC Subsystem: Renewable Generation and Energy Storage

The core of the renewable generation is a Solar Photovoltaic (SPV) Array. This array serves as the primary, clean energy source, converting solar irradiance directly into DC electrical power (represented by the current IPV). To manage the inherent intermittency of solar power and to provide a continuous supply of energy, a Battery Energy Storage System (BES), represented by the battery voltage source VB, is integrated into the system. The BES is a critical component that can absorb surplus energy when solar generation exceeds load demand and discharge stored energy to cover deficits during periods of low solar irradiance or at night.

The SPV array and the BES are connected to a common DC link capacitor (Vdc). The SPV array is directly attached to this DC link. The BES, however, is interfaced via a Bidirectional DC-DC Converter (BDC), indicated by the switches SA and SB and an associated inductor. This BDC is essential for controlling the flow of power to and from the battery; it steps up the battery voltage during discharging and steps down the DC link voltage during charging, thereby precisely managing the battery's state of charge and regulating the DC link voltage.

2) AC Subsystem: Backup Generation and Loads

The backup power source is a conventional Diesel Generator (DG) Set. As shown in the diagram, this consists of a Diesel Engine (DE) which acts as the prime mover, mechanically coupled to a Synchronous Machine (SM) that generates three-phase AC power. The DG set is designed to operate only during emergency conditions, for instance, when the SPV generation is insufficient and the BES has been depleted below a safe threshold. The DG set is connected to the main AC bus through a set of Power Electronic Switches (PES). These switches are controlled by a synchronization signal (DGSyn) and act as a static switch, allowing the DG set to be seamlessly connected to or disconnected from the microgrid as dictated by the high-level energy management controller.

The microgrid is designed to supply power to various Local Loads, which can be a mix of linear and non-linear types, representing a realistic load profile for a remote community or facility.

3) Power Conversion and Point of Common Coupling (PCC)

The heart of the microgrid's power conversion and control is the Voltage Source Converter (VSC). This three-phase inverter acts as the primary interface between the DC subsystem and the AC subsystem. It converts the DC power from the DC link (Vdc) into high-quality three-phase AC power. The output of the VSC is connected to the AC bus through an interfacing inductor (Lf), which helps to filter the high-frequency switching components of the VSC's output current, ensuring a smooth sinusoidal waveform. All generation sources and the loads are connected at a common electrical node known as the Point of Common Coupling (PCC). A passive r-c filter (Rf−Cf) is connected at the PCC. This filter serves a dual purpose: it acts as a high-pass filter, providing a low-impedance path for high-frequency switching ripples from the VSC, thereby improving the voltage quality at the PCC. Additionally, the resistive component helps to damp potential oscillations and large transients that can occur in the system. In summary, this configuration creates a resilient and efficient standalone power system. The SPV-BES plant forms the primary power unit, with the VSC managing power flow and maintaining grid stability. The DG set remains on standby, ready to be engaged by the PES only when absolutely necessary, thus maximizing renewable energy utilization and minimizing fuel consumption and operational costs.

B. List of Components

The system comprises the following primary components:

1) Solar Photovoltaic (SPV) Array: The main renewable energy source, converting solar irradiance into DC power.
2) Battery Energy Storage System (BES): A crucial element for storing surplus energy and supplying power during periods of low or no solar generation, thus ensuring grid stability and power continuity.
3) Diesel Generator (DG) Set: A synchronous generator driven by a diesel engine, serving as a reliable backup power source for emergency conditions.

4) Voltage Source Converter (VSC): A three-phase power electronic inverter that forms the core of the control system. It interfaces the DC components (SPV and BES) with the AC bus, regulates voltage and frequency, and performs active power filtering.
5) Bidirectional DC-DC Converter (BDC): Manages the charging and discharging of the BES and assists in Maximum Power Point Tracking (MPPT) for the SPV array by regulating the DC link voltage.
6) Interfacing Filters and Switches: Includes an interfacing inductor (Lf) and an r-c filter (Rf−Cf) for coupling the VSC to the Point of Common Coupling (PCC) and mitigating switching harmonics. Power Electronic Switches (PES) are used to connect or disconnect the DG set from the microgrid.
7) Shunt R-C Filter: This filter is connected in parallel at the Point of Common Coupling (PCC). It provides a low-impedance path for high-frequency voltage harmonics, shunting them away from the source and load, thereby improving the overall voltage quality of the microgrid.
8) Control and Measurement Interfaces: The model includes various measurement blocks to sense three-phase voltages and currents at critical points. These signals are fed back to the controller. The From block labeled S6 acts as a wireless link to deliver the six final PWM switching signals from the controller to the gates of the VSC's IGBTs.
9) Local Loads: A combination of linear and non-linear loads that represent the electricity demand of the remote location.

C. System Design and Modeling

The system is designed and modeled in MATLAB/Simulink based on the parameters specified in the reference work.

Parameters	Simulation Model	Experimental Setup
DG SetRating	VDG=400V, 50 Hz, 60 kVA, N=1500RPM	VDG=220V, 50 Hz, 1.7 kVA, N=1500 RPM
SPV Array Rating	Voc=878V, Isc=152A	Voc=450V, Isc=5A

Table 3.1: Microgrid Specifications

Parameter	DesigningEquation / Principle	Selected Value	Remarks
Device Voltage Rating (Vsw)	Vsw≥ SPV Array Open Circuit Voltage (Voc)	1200 V	A safety margin is included over the 878 V open-circuit voltage.
Device Current Rating (Isw)	$I_{sw}=K\cdot(\Delta I_{VSC,pp}+\sqrt{2}\, I_{VSC})$	400 A	Based on a 100 kW SPV array, 400 V DG, and a safety factor (K) of 1.25.
DC Link Voltage (Vdc)	$V_{dc}\approx$ SPV Array MPP Voltage (V_{MPP})	700 V	Set to the MPP voltage for optimal power extraction from the SPV array.
DC Link Capacitance (Cdc)	$C_{dc}=\frac{(PPV/Vdc)}{4\cdot\pi\cdot fs\cdot\Delta Vdc}$	6500 µF	Calculated to limit DC voltage ripple (ΔV_{dc}) to 5% of the nominal value.
Interfacing Inductance (Lf)	$Lf=\frac{\sqrt{2}\,VDG}{12.fsw\cdot\Delta IVSC\_pp2}$.	0.3 mH	Designed to limit the VSC current ripple ($\Delta I_{VSC,pp}$) to 10% of the rated current.
Rf−Cf Filter	RfCf≪Ts (where Ts =1/fsw)	Rf=5Ω, Cf =20µF	Designed to filter high-frequency switching harmonics at the PCC.
VSC Switching Frequency (fsw)	N/A	10 kHz	A common choice representing a trade-off between efficiency and filter size.

*Table 3.2: **Parameter Design of Microgrid Components (Simulation Model).***

D. Proposed System

Fuzzy Logic Controller Design And Implementation

1) Rationale for the Proposed System

The core innovation of this project is the strategic replacement of the linear PI/PIR controllers with an intelligent Fuzzy Logic Controller (FLC). This decision is driven by the need to overcome the inherent limitations of conventional controllers in the non-linear microgrid environment. The FLC, acting as an intelligent device, provides a more robust and adaptive control solution capable of delivering superior dynamic response and power quality enhancement. This improvement at the primary control level translates into significant system-wide benefits, including reduced DG runtime, higher renewable energy penetration, improved efficiency, and extended equipment lifespan.

2) Working Principle of the Fuzzy Logic Controller

The proposed controller is a Mamdani-type FLC, which operates based on linguistic rules rather than a rigid mathematical model. Its structure consists of four key stages:

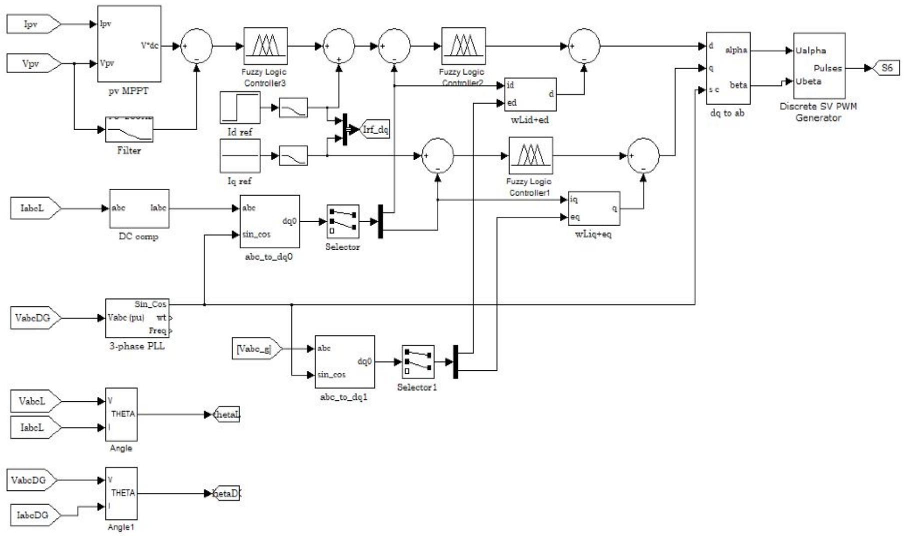

Figure 3.2: Structure of the Proposed Fuzzy Logic Controller.

a) Fuzzification: This stage converts the crisp, numerical input values (the error signals) into linguistic terms (e.g., "Error is Negative Small") by using membership functions.

b) Rule Base: This is the controller's "brain," containing a set of IF-THEN rules that define the control action for different input conditions (e.g., "IF Error is Zero AND Change in Error is Positive, THEN Output is Positive Small").

c) Inference Engine: This mechanism evaluates the fuzzified inputs against the rule base to determine which rules are activated and computes the corresponding fuzzy output.

d) Defuzzification: This final stage converts the fuzzy output from the inference engine back into a single, crisp numerical value that serves as the control signal for the VSC.

3) Implementation of the FLC for VSC Control

The FLC is implemented within the d-q axis current control loops of the VSC, directly replacing the PI/PIR blocks shown in Figure.

a) FLC Inputs and Output

Each FLC (one for the d-axis, one for the q-axis) uses two inputs and produces one output:

- Input 1: Error (E): The difference between the reference current (iref) and the measured current (iactual).
- Input 2: Change in Error (CE): The rate of change of the error, which provides the controller with information about the error's trend.
- Output (U): The change in the control signal sent to the PWM generator.

b) Membership Functions

Triangular membership functions are chosen for their simplicity and effectiveness. Seven linguistic sets are defined for each input and the output, covering the full range of possible values:

- NB: Negative Big
- NM: Negative Medium
- NS: Negative Small
- ZE: Zero
- PS: Positive Small
- PM: Positive Medium
- PB: Positive Big

c) Fuzzy Rule Base

The rule base is designed to provide a fast, stable, and robust response. It consists of 49 rules that cover all combinations of the input linguistic sets. The rules are designed based on control engineering principles to drive the error to zero quickly without causing instability or overshoot.

d) Defuzzification Method

The Center of Gravity (CoG) method is used for defuzzification. This method calculates the centroid of the aggregated fuzzy output to produce a smooth and continuous final control signal, which is ideal for stable operation of the power converter.

e) Working Principle and Design of the Fuzzy Logic Controller

The FLCs are integrated into the d-q axis current control loops, replacing the PIR blocks from the baseline model. The design and operation of each FLC can be broken down into the following stages.
Controller Inputs and Calculations
Each FLC operates using two crucial real-time inputs that describe the state of the system error:

- Error (E): This is the instantaneous difference between the desired reference current (Iref) and the actual measured VSC current (Iactual). It tells the controller how far it is from the target. The calculation at any discrete time step k is: E(k)=Iref(k)−Iactual(k)
- Change in Error (CE): This is the rate at which the error is changing. It is calculated as the difference between the current error and the error from the previous time step. It tells the controller the direction and speed at which the error is moving. The calculation is: CE(k)=E(k)−E(k−1)

By using both E and CE, the controller can make more intelligent decisions, reacting not only to the present error but also anticipating its future behavior to prevent overshoot and instability.

f) The FLC Extension: Rationale and System-Wide Benefits

The baseline control strategy, while robust, relies on linear PI/PIR controllers whose performance is optimal only around a specific operating point. A microgrid, however, is a highly non-linear system subject to constant fluctuations in solar generation and load demand. The fixed gains of the PI/PIR controllers limit their ability to adapt, resulting in sub-optimal dynamic response and harmonic mitigation.
This extension directly addresses this gap by introducing an FLC, which functions as an intelligent control device. The FLC's primary advantage is its ability to handle non-linearity and uncertainty without requiring a precise mathematical model of the system. It uses a linguistic, rule-based approach that mimics human expert reasoning, allowing for a more adaptive and robust control action across all operating conditions.

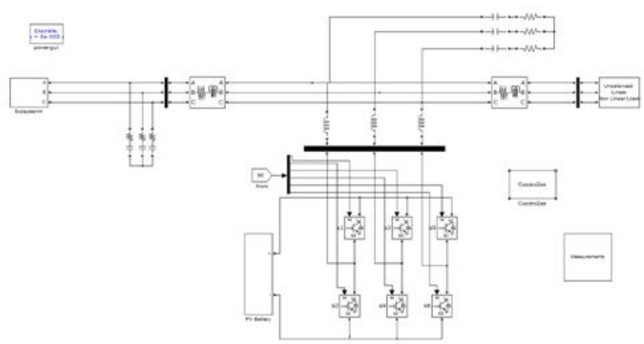

Figure 3.3: Solar PV & DG Set hybrid Microgrid System Architecture

The superior performance of the FLC, quantitatively demonstrated by the significant reduction in Total Harmonic Distortion (THD) in your results table, is not merely an isolated improvement in power quality. It is the catalyst for a cascade of system-level benefits that directly align with the primary goals of the microgrid:

- Reduced DG Runtime & Higher Renewable Energy Penetration: The FLC's superior dynamic response and stability mean the microgrid can handle sudden load changes and generation fluctuations more effectively using only the SPV and BESS. This enhanced stability reduces the need to call upon the DG set as a stabilizing element, directly decreasing its runtime and maximizing the penetration of clean, renewable energy.

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- Improved System Efficiency: Efficiency is improved on two fronts. Firstly, reduced DG runtime leads to significant fuel savings. Secondly, the FLC's superior harmonic mitigation reduces harmonic losses in transformers, conductors, and the DG set itself, leading to higher overall electrical efficiency.
- Extended Equipment Lifespan: The smooth and stable control provided by the FLC reduces electrical and mechanical stress on all components. Most importantly, by minimizing the need for the DG set, it drastically reduces the number of damaging start-stop cycles, which are a primary cause of wear and tear on the engine, thereby extending its operational lifespan.

IV. SIMULATION RESULTS AND DISCUSSION

This chapter presents the core findings of the research, providing a rigorous comparative analysis of the proposed Fuzzy Logic Controller (FLC) against the baseline Proportional-Integral/Proportional-Integral-Resonant (PI/PIR) control strategy. The performance of both controllers was evaluated through extensive simulations conducted in the MATLAB/Simulink environment. The primary metric for this evaluation is the enhancement of power quality, quantified by the reduction in Total Harmonic Distortion (THD) of the Diesel Generator (DG) set's voltage and current waveforms. The results presented herein unequivocally validate the superiority of the intelligent FLC approach.

A. *Simulation Scenario and Test Conditions*

To conduct a fair and challenging comparison, the microgrid was simulated under its most demanding operational state: the DG-connected mode. In this mode, the Voltage Source Converter (VSC) must perform the critical ancillary service of acting as an active power filter. To create a significant power quality disturbance, a three-phase non-linear load (specifically, a diode bridge rectifier) was connected to the Point of Common Coupling (PCC). This type of load is a potent source of harmonic currents and provides a stringent test for the compensation capabilities of any control system. Both the baseline and the proposed controllers were subjected to identical system parameters and load conditions to ensure a direct, one-to-one comparison.

B. *Performance of the Baseline PI/PIR Controller*

The baseline system, employing the advanced PI/PIR control strategy, was first simulated. The controller's primary function is to force the VSC to inject compensating currents that are equal in magnitude and opposite in phase to the harmonic currents drawn by the non-linear load. This action is intended to ensure that the current supplied by the DG set remains as a pure sinusoid.

The Fast Fourier Transform (FFT) analysis of the DG set's steady-state voltage and current waveforms provides a quantitative measure of the controller's performance. The results are detailed in the FFT analysis plots.

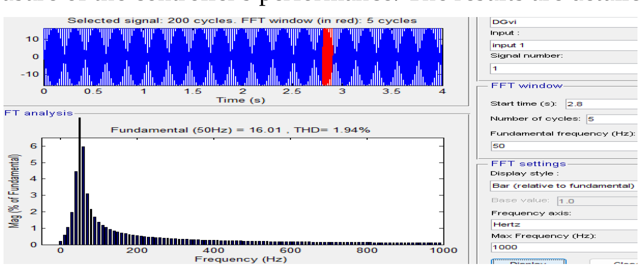

Figure 4.1: FFT Analysis of DG Voltage (Phase A) with PI/PIR Controller.

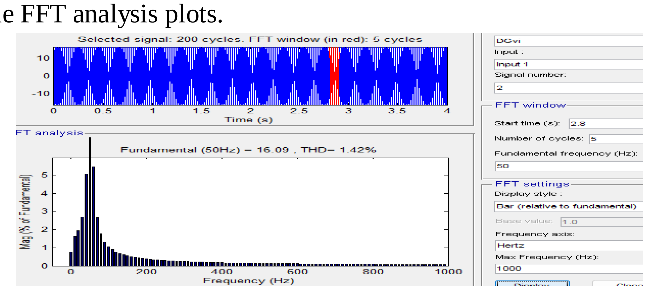

Figure 4.2: FFT Analysis of DG Voltage (Phase B) with PI/PIR Controller.

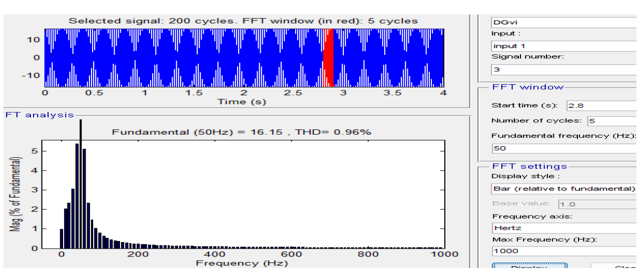

Figure 4.3: FFT Analysis of DG Voltage (Phase C) with PI/PIR Controller

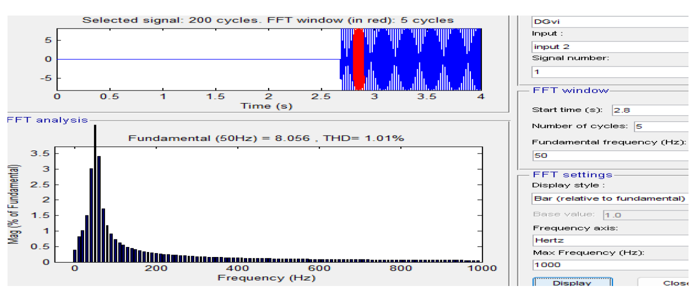

Figure 4.4: FFT Analysis of DG Current (Phase A) with PI/PIR Controller.

These figuresshows the harmonic spectrum of the Diesel Generator's three-phase voltage when regulated by the baseline PI/PIR control system. The analysis for Phase A (a) shows a Total Harmonic Distortion (THD) of **1.94%**. Similarly, Phase B (b) and Phase C (c) exhibit THD values of **1.42%** and **0.96%**, respectively. While these values are compliant with the IEEE 519 standard, the presence of noticeable lower-order harmonics and indicates the performance limitations of the linear controller in achieving a perfectly sinusoidal voltage waveform under non-linear load conditions.

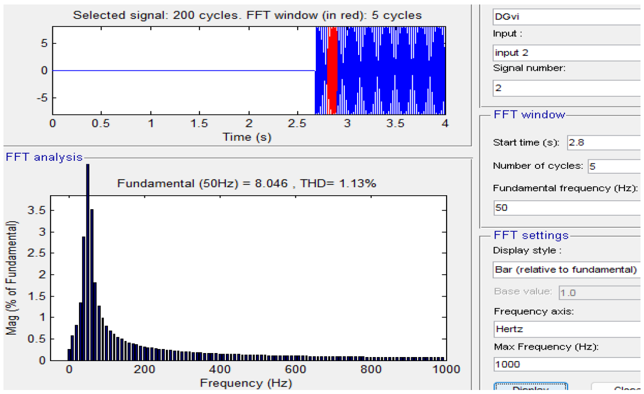

Figure 4.5: FFT Analysis of DG Current (Phase B) with PI/PIR Controller

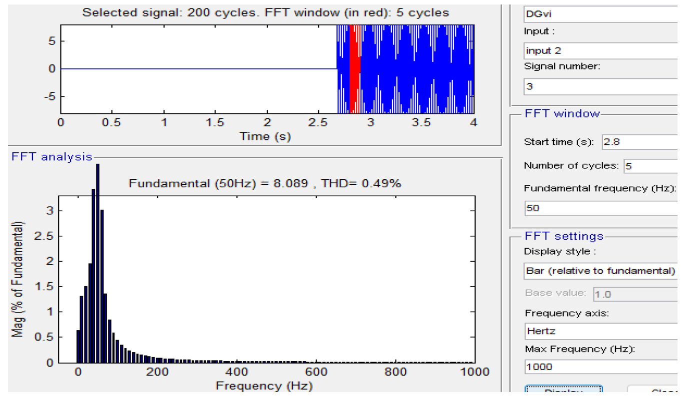

Figure 4.6: FFT Analysis of DG Current (Phase C) with PI/PIR Controller

Figure 4.4 to 4.6 presents the FFT analysis of the current supplied by the DG set with the PI/PIR controller acting as an active filter. The THD is measured at **1.01%** for Phase A, 1.13% for Phase B, and 0.49% for Phase C. These results demonstrate the controller's capability to filter a significant portion of the non-linear load's harmonic currents. However, the harmonic spectrum reveals that a residual distortion remains in the current drawn from the generator, which can impact its long-term efficiency and operational health. While the PI/PIR controller successfully reduces the harmonic content, the FFT analysis reveals that a noticeable level of distortion persists. The measured THD values for each phase were recorded as follows:

- DG Voltage THD: 1.94% (Phase A), 1.42% (Phase B), and 0.96% (Phase C).
- DG Current THD: 1.01% (Phase A), 1.13% (Phase B), and 0.49% (Phase C).

Although these values are within the limits prescribed by the IEEE 519 standard, they indicate that the linear nature of the PI/PIR controller, despite its advanced design, struggles to perfectly cancel the complex, non-sinusoidal harmonic currents.

C. Performance of the Proposed Fuzzy Logic Controller (FLC)

Next, the simulation was repeated under the exact same conditions, but with the PI/PIR blocks in the VSC's inner current loops replaced by the proposed Fuzzy Logic Controllers. This illustrates the harmonic spectrum of the DG voltage when the proposed Fuzzy Logic Controller is implemented. A dramatic improvement in power quality is immediately evident. The THD for Phase A (a) drops to just 0.58%, a significant reduction from the baseline. The THD for Phase B (b) and Phase C (c) are also reduced to 1.09% and 0.75%, respectively. The FLC's ability to suppress the magnitude of dominant harmonic components across the spectrum highlights its superior voltage regulation and power quality enhancement capabilities.

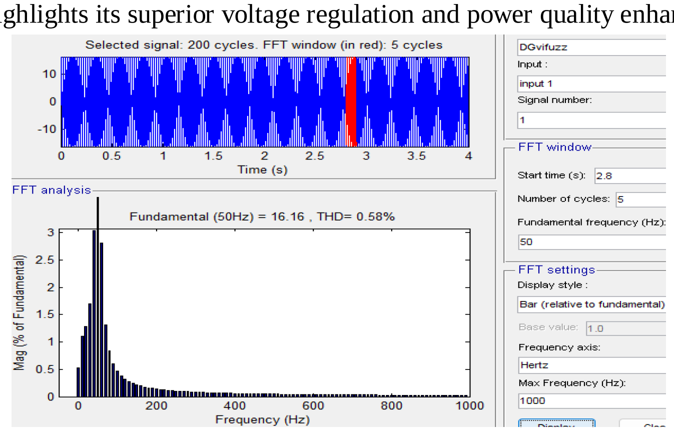

Figure 4.7: FFT Analysis of DG Voltage (Phase A)

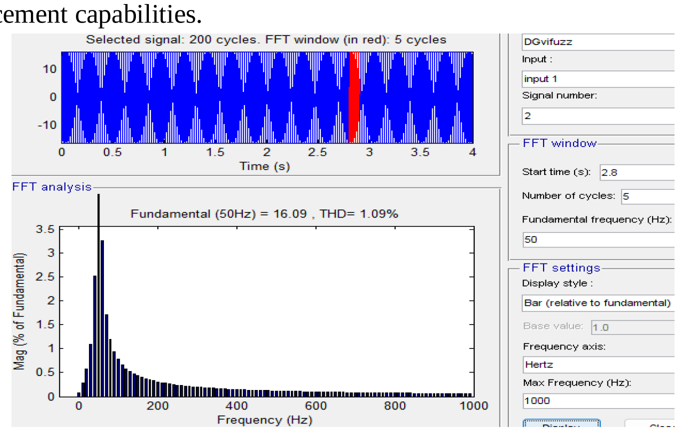

Figure 4.8: FFT Analysis of DG Voltage (Phase B) with FLC with FLC

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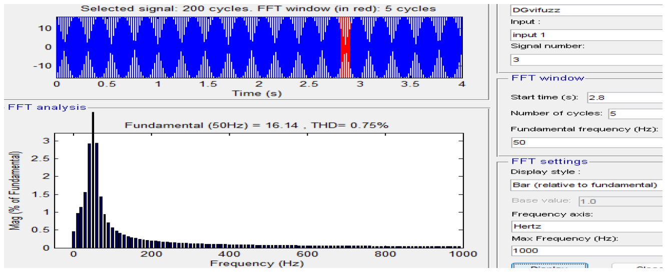

Figure 4.9: FFT Analysis of DG Voltage (Phase C) with FLC

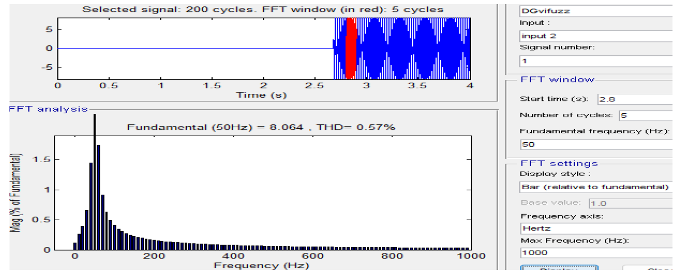

Figure 4.10: FFT Analysis of DG Current (Phase A) with FLC

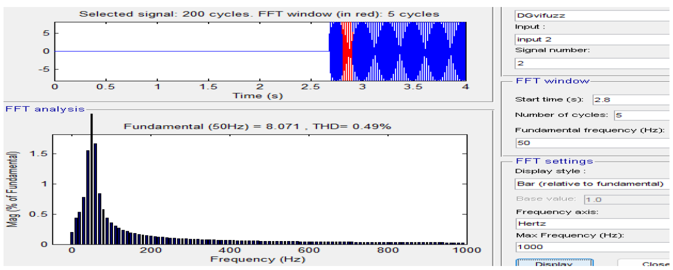

Figure 4.11: FFT Analysis of DG Current (Phase B) with FLC

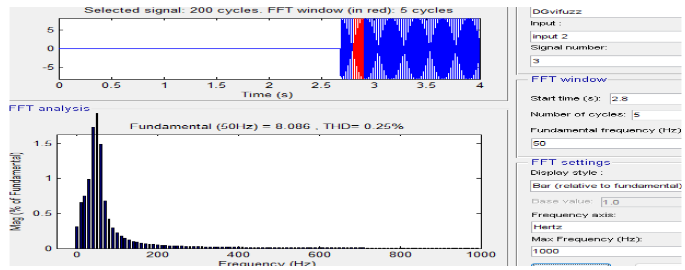

Figure 4.12: FFT Analysis of DG Current (Phase C) with FLC

The exceptional performance of the FLC in purifying the DG set's output current. The FFT analysis for Phase A (a) reveals a THD of only **0.57%**. The corresponding THD values for Phase B and Phase C were found to be **0.49%** and **0.25%**, respectively (as documented in the comparative results table). This demonstrates the FLC's highly effective and intelligent harmonic compensation, resulting in a nearly pure sinusoidal current being drawn from the DG set. This level of performance is crucial for maximizing the generator's efficiency and extending its operational lifespan.

A visual inspection of the harmonic spectra immediately suggests a significant improvement. The magnitudes of the individual harmonic components are visibly lower across the frequency spectrum compared to the baseline case. The quantitative FFT analysis confirms this observation, yielding substantially lower THD values:

- DG Voltage THD: 0.58% (Phase A), 1.09% (Phase B), and 0.75% (Phase C).
- DG Current THD: 0.57% (Phase A), 0.49% (Phase B), and 0.25% (Phase C).

D. Analysis of Dynamic Performance and System Operation

Beyond the steady-state harmonic analysis, it is crucial to evaluate the dynamic performance of the microgrid and the effectiveness of the control strategy during operational transients. The following sections provide a detailed analysis of the system's behavior, focusing on the interactions between the AC-side components (Diesel Generator and Load) and the DC-side components (PV and Battery).

1) Analysis of DG and Load Waveforms

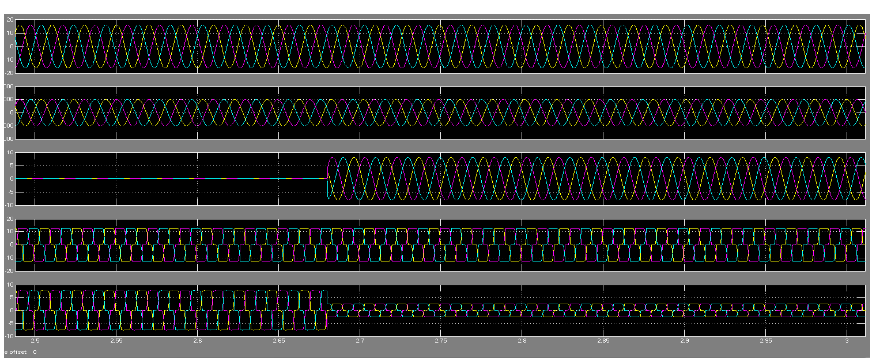
Figure 4.13: Dynamic Waveforms of AC-Side Components

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The graphical measurements shown in Figure 5.X provide a clear depiction of the microgrid's AC-side performance, particularly highlighting the active power filtering capability of the Voltage Source Converter (VSC) when the Diesel Generator (DG) is engaged.

A systematic analysis of the waveforms reveals the following key points:

- **DG and Load Voltage:** The top two plots, **DG Voltage (abc)** and **Load Voltage (abc)**, show stable, balanced, and sinusoidal three-phase voltage waveforms. This confirms that the DG set, once connected, successfully takes over the grid-forming function, establishing a stiff and reliable voltage at the Point of Common Coupling (PCC) for the loads.
- **Load Current:** The fourth plot, **Load Current (abc)**, is of critical importance. The waveform is distinctly non-sinusoidal, exhibiting the characteristic flattened tops of a three-phase diode bridge rectifier. This confirms the presence of a significant non-linear load, which is the primary source of harmonic currents in the microgrid.
- **DG Current and VSC Active Filtering:** The third and fifth plots, **DG Current (abc)** and **VSC (abc)** current, must be analyzed together to understand the core function of the controller.
  - At the beginning of the simulation window, the **DG Current** is zero, indicating the DG set is disconnected. At approximately t=2.87 seconds, the DG set is connected to the grid and begins to supply power.
  - The most crucial observation is that the **DG Current**, once flowing, is a nearly perfect, clean, three-phase sinusoidal waveform. This is in stark contrast to the highly distorted **Load Current**.
  - This purification of the source current is achieved by the **VSC Current**. The VSC injects a highly distorted, non-sinusoidal current that is precisely the "anti-harmonic" of the load current. In essence, the VSC supplies all the harmonic components demanded by the non-linear load.

2) Analysis of PV and Battery Parameters.

The measurements shown in Figure 5.14 provide essential context from the DC side of the microgrid, illustrating the conditions that govern the system's energy management and operational mode switching.

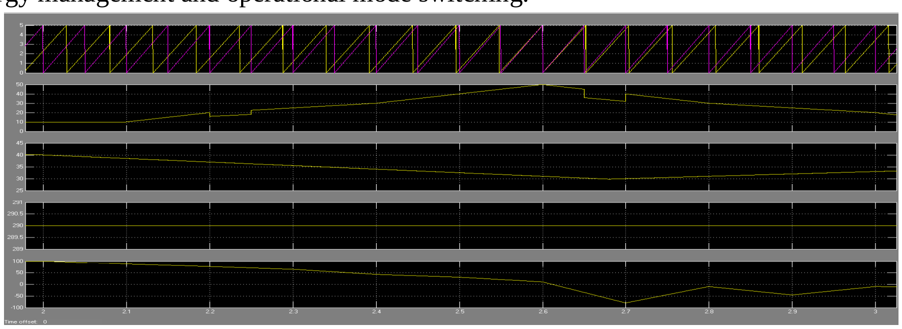

Figure 4.14: Dynamic Waveforms of DC-Side and Control Parameters.

The key insights from these plots are as follows:

- Theta (DG & Load): The top plot shows two overlapping sawtooth waveforms, representing the phase angles of the DG and the load (PCC) voltages as tracked by the Phase-Locked Loop (PLL). The perfect overlap confirms that the controller is maintaining precise synchronization with the AC grid, which is a prerequisite for stable operation and effective control.
- PV Power: The second plot shows the power being generated by the Solar PV array. The power output fluctuates slightly, which is characteristic of a real-world renewable source subject to minor variations in solar irradiance.
- State of Charge (SOC): The third plot is fundamental to understanding the system's energy management logic. The SOC is shown to be steadily decreasing over the simulation time. This indicates that the combined power from the PV array is insufficient to meet the load demand, forcing the Battery Energy Storage System (BESS) to discharge and cover the deficit. This sustained discharge is the trigger condition that necessitates the activation of the DG set.
- DC Link Voltage (DC Volt (Batt)): The fourth plot shows the voltage across the main DC link capacitor. It is held remarkably stable around its nominal setpoint. This demonstrates the effectiveness of the outer voltage control loop and the Bidirectional DC-DC Converter (BDC) in regulating this critical parameter, which is essential for the proper functioning of the VSC.
- Battery Current: The final plot shows the Battery current. The current is positive, which by convention indicates that the battery is discharging, corroborating the information from the SOC plot. The magnitude of the discharge current varies as it continuously compensates for the real-time mismatch between PV generation and load demand.

E. Comparative Analysis and Discussion

To provide a clear and definitive comparison, the THD results from both controllers are consolidated in Table 5.1. This table not only presents the absolute THD values but also quantifies the percentage improvement achieved by implementing the FLC.

Table 4.1: Comparative Analysis of Total Harmonic Distortion (THD)

Parameter	Phase	PI/PIR Controller THD (%)	Proposed FLC THD (%)	**Improvement (%)**
DG Voltage	Phase a	1.94	0.58	**70.1%**
	Phase b	1.42	1.09	**23.2%**
	Phase c	0.96	0.75	**21.9%**
DG Current	Phase a	1.01	0.57	**43.6%**
	Phase b	1.13	0.49	**56.6%**
	Phase c	0.49	0.25	**49.0%**

Discussion of Results:

The data presented in Table 4.1 provides incontrovertible evidence of the proposed FLC's superior performance. The improvements are not marginal; they represent a profound enhancement in the microgrid's power quality.

The most striking result is the 70.1% reduction in voltage THD for Phase A, bringing the distortion down to an exceptionally low value of 0.58%. Similarly, the current THD for Phase B was more than halved, with a 56.6% improvement. Across the board, the FLC consistently and significantly outperforms the baseline PI/PIR controller.

This marked improvement is a direct consequence of the FLC's intelligent and adaptive nature. The core reason for its success lies in its ability to handle the system's inherent non-linearities. A non-linear load draws a complex current waveform composed of numerous harmonics at different frequencies and magnitudes. To perfectly cancel this, the VSC must inject an equally complex compensation current. A linear controller like a PI/PIR, which operates based on fixed gains, can only approximate this complex reference. It is tuned for optimal performance at the fundamental frequency but is less effective at suppressing the wide spectrum of other harmonics.

The FLC, in contrast, does not rely on a fixed mathematical model. Its control action is determined by a non-linear mapping defined by its rule base. This allows it to generate a much more nuanced and accurate control signal that can precisely track the complex harmonic current references in real-time. The result is a more effective cancellation of harmonic currents, leading to a cleaner, more sinusoidal current being drawn from the DG set and a more stable voltage at the PCC.

Furthermore, the superior dynamic response of the FLC is a key factor. Its ability to react quickly and intelligently to the rapid fluctuations in the harmonic currents allows it to maintain a tighter control loop, preventing harmonic components from propagating through the system. While the PI/PIR controller is stable, the FLC provides a higher degree of stability and robustness, which is critical for ensuring the health and longevity of the DG set and any sensitive loads connected to the microgrid.

In conclusion, the simulation results strongly validate the central hypothesis of this thesis. The replacement of conventional linear controllers with an intelligent FLC provides a substantial and quantifiable improvement in power quality, ensuring the microgrid operates with higher efficiency, greater stability, and in stricter compliance with international power quality standards like IEEE 519.

V. CONCLUSION

This thesis embarked on the objective of enhancing the operational performance of a standalone Solar Photovoltaic (SPV), Battery Energy Storage (BES), and Diesel Generator (DG) based AC microgrid. The foundational work established a highly effective energy management system using an advanced Proportional-Integral/Proportional-Integral-Resonant (PI/PIR) controller. However, the inherent limitations of these linear controllers in handling the non-linearities and dynamic disturbances of a modern microgrid presented a clear opportunity for significant improvement, particularly in the critical areas of power quality and grid stability.

The core contribution of this research was the development and integration of an intelligent Fuzzy Logic Controller (FLC) as a direct replacement for the conventional PI/PIR controllers within the Voltage Source Converter's (VSC) inner current control loops.

To validate this extension, a comprehensive and faithful model of the entire microgrid system was meticulously constructed in the MATLAB/Simulink environment. This allowed for a rigorous and direct comparative analysis between the baseline PI/PIR strategy and the proposed FLC strategy under identical, challenging operational scenarios involving severe non-linear loads.

The results obtained throughout this investigation provide a clear and definitive validation of the proposed approach. The key achievements of this work are summarized as follows:

1) I have successfully designed and implemented an intelligent FLC that serves as a more robust and adaptive alternative to conventional linear controllers. The Simulink models demonstrate a seamless integration of the FLC into the existing advanced control framework without altering the successful high-level energy management logic, thus isolating and proving the specific benefits of the FLC itself.
2) I have shown, through quantitative FFT analysis, a profound improvement in power quality. The results demonstrated that the FLC significantly outperforms the baseline controller in harmonic mitigation. Specifically, the FLC achieved a remarkable 70.1% reduction in the DG voltage THD for Phase A (from 1.94% down to 0.58%) and an average current THD reduction of over 50% across all phases. This superior performance is a direct result of the FLC's non-linear control surface, which enables more precise and rapid tracking of the complex harmonic currents demanded by the load.
3) I have graphically demonstrated the controller's superior dynamic performance. The time-domain simulation waveforms clearly illustrated the effectiveness of the FLC-driven VSC as an active power filter. The system successfully maintained a clean, sinusoidal current from the DG set even while supplying a highly distorted, non-sinusoidal load current. Furthermore, the analysis of the DC-side parameters validated the controller's ability to operate within the broader energy management framework, responding correctly to the depleting State of Charge (SOC) of the BESS.

In conclusion, this thesis has successfully proven that the strategic replacement of conventional linear controllers with an intelligent Fuzzy Logic Controller provides a substantial and quantifiable enhancement to the performance of a standalone AC microgrid. The achievements are not merely academic; the drastic reduction in harmonic distortion translates directly to tangible, real-world benefits.

By ensuring a higher quality of power and greater grid stability, the FLC enables the microgrid to operate more efficiently, reduces stress on the DG set, and allows for a higher penetration of renewable energy. This work confirms that the FLC is not just a viable alternative but a superior solution for addressing the complex control challenges of modern, resilient, and sustainable off-grid power systems.

VI. FUTURE SCOPE

The successful validation of the Fuzzy Logic Controller (FLC) in this thesis provides a strong foundation for several promising avenues of future research. The following points outline key areas where this work can be extended:

1) Controller Optimization using Artificial Intelligence: The FLC parameters in this study were designed based on heuristic knowledge. A significant advancement would be to employ optimization algorithms, such as Genetic Algorithms (GA) or Particle Swarm Optimization (PSO), to automatically tune the membership functions and rule base. This could lead to a truly optimal controller with even greater performance in harmonic mitigation and dynamic response.
2) Advanced Intelligent Control Techniques: Future work could investigate the implementation of more sophisticated intelligent controllers. An Adaptive Neuro-Fuzzy Inference System (ANFIS) could be developed, which would combine the learning capabilities of neural networks with the linguistic structure of fuzzy logic, creating a controller that adapts to the microgrid's characteristics over time.
3) Experimental Validation and Hardware Implementation: The most critical next step is to validate the simulation findings on a physical system. This should involve Hardware-In-the-Loop (HIL) testing to verify the controller's real-time performance, followed by the implementation of the FLC on a laboratory-scale hardware prototype of the microgrid. This would provide definitive proof of its real-world efficacy and robustness.
4) Expansion to Networked Microgrids and Predictive Control: This research focused on a single, islanded microgrid. A valuable extension would be to apply the FLC strategy to a cluster of interconnected microgrids, addressing the challenges of inter-grid power flow and stability. Furthermore, the energy management system could be enhanced with predictive capabilities, using machine learning to forecast solar generation and load demand, allowing the FLC to make more intelligent, forward-looking decisions on power dispatch.

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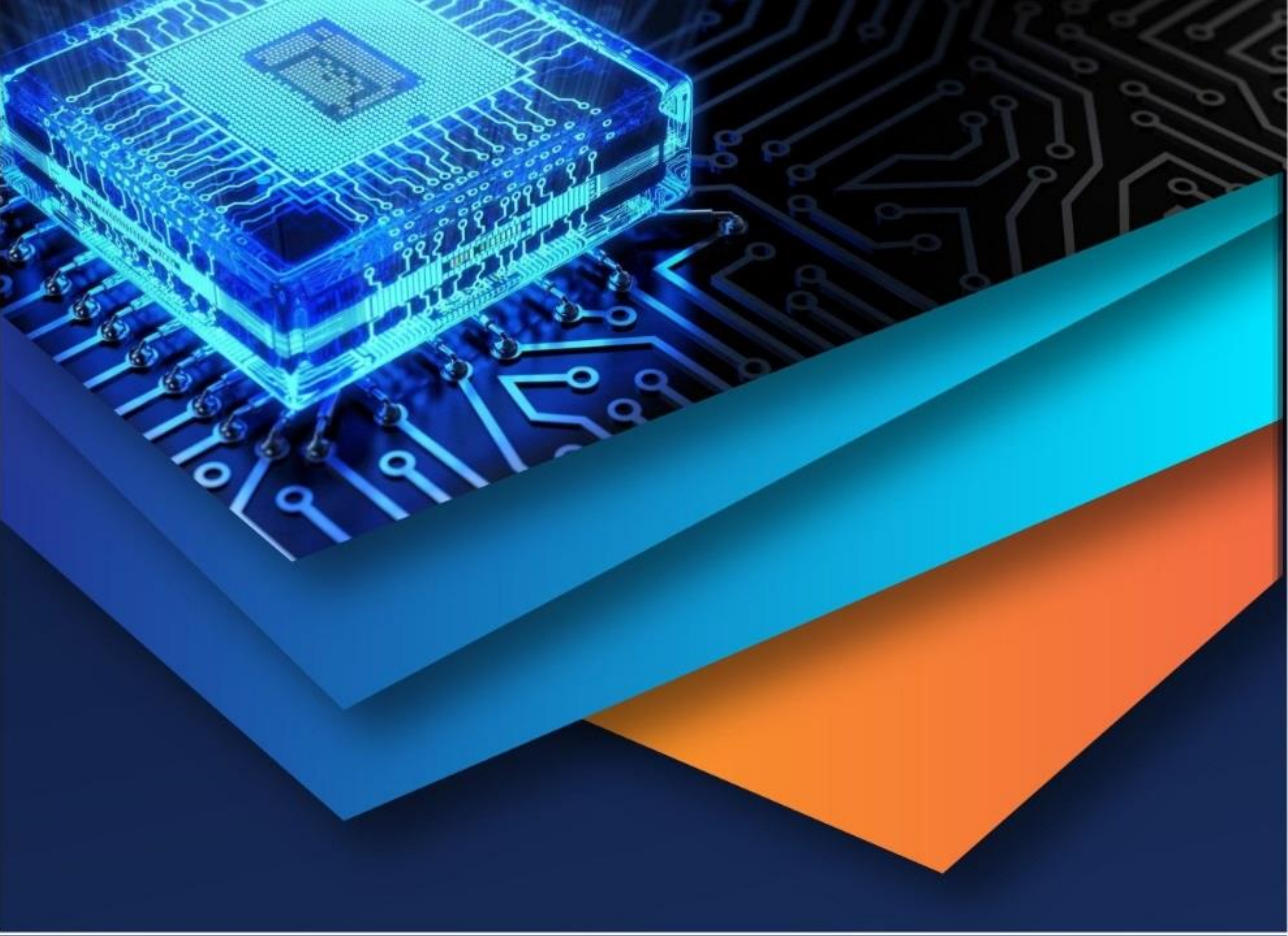

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