MULTIVARIABLE APPLICATION OF SHUNT APF USING THREE-PHASE FOUR-LEG VSI WITH PI AND AI CONTROLLERS

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Abstract:
An intelligent controller technique is used to analyze the performance of a three-phase, four-leg voltage-source inverter (VSI). Reduced current harmonic components and mitigated unbalanced and negative sequence currents, usually caused by single-phase nonlinear loads, are achieved through the integration of a four-leg VSI. Simulation results show that the proposed shunt active power filter (APF) and its accompanying control mechanism can compensate in both steady-state and transient situations. Due to the fact that an APF is basically a VSI that is controlled by current, intelligent logic controllers and PI controllers have recently found their way into APF control applications. This work proposes a PI-and intelligent controller-based shunt APF that uses the effective time notion to reduce computational cost by doing away with trigonometric calculations. To improve power quality, a regulated three-phase four-leg inverter is used, and the simulation results show that the shunt APF with intelligent controllers and PI works. To find out how effective each control approach is, we compare the results.

Keywords: Shunt APF, LEG VSI, power quality, PI and AI Controllers

1.Introduction

Nowadays, non-linear loads are becoming more and more important in electrical systems. These loads can cause harmonic distortions, voltage imbalances, and other power supply disturbances, making power quality a significant concern. These disruptions have the potential to reduce system efficiency, raise operational costs, shorten the lifespan of electrical equipment, and worsen their performance. Therefore, for commercial, industrial, and residential electrical networks to run smoothly, reliable and high-quality power must be maintained. Recently, Active Power Filters (APF) have gained popularity as a reliable way to address power quality concerns, particularly in systems that deal with non-linear loads.

1.1 Overview of Active Power Filters

Active Power Filters (APFs) are power electronic devices designed to improve the quality of electrical power in systems disturbed by harmonic distortions, voltage imbalances, and other power quality issues. Unlike traditional passive filters, which are designed to filter out specific frequencies, APFs actively compensate for undesirable power quality issues in real-time by injecting compensating currents into the system. They are essential for modern electrical grids, particularly in industrial, commercial, and residential applications where non-linear loads (e.g., rectifiers, computers, variable speed drives) are commonly used.

1.2 Types of Active Power Filters

- **Shunt Active Power Filter (ShAPF)**: In harmonic compensation, this setup is preferred. As a result, non-linear loads' harmonic currents are immediately mitigated. To work, the ShAPF measures the current flowing through the load, separates out the harmonic components, and then injects a compensatory current to eliminate them. It contributes to a more stable system and better-quality current waveforms.

- **Series Active Power Filter (SAPF)**: Voltage distortions can be corrected using a series APF. When the load causes voltage harmonics or imbalance, it compensates by injecting a voltage into the system. Applications where voltage purity is of utmost importance often employ SAPFs.
- **Hybrid Active Power Filter (HAPF)**: To create a hybrid filter, experts blend active and passive filtration methods. Efficient and cost-effective harmonic correction is usually achieved by combining a smaller active filter with a bigger passive filter.

1.3 Applications of Active Power Filters

APFs are used in a wide range of applications, particularly where high-quality power is critical:

- **Industrial Applications**: APFs are used to mitigate harmonic currents generated by industrial equipment like arc furnaces, motors, and large drives. They help ensure that the machinery operates within specified voltage and current limits.
- **Power Distribution Systems**: In power distribution systems, APFs are used to improve the power quality delivered to consumers, reducing the adverse effects of harmonics and unbalance on transformers and other equipment.
- **Renewable Energy Systems**: In systems with renewable energy sources such as wind or solar, APFs can help mitigate power quality issues like harmonic distortion, which may arise due to inverters used for power conversion.
- **Residential and Commercial Applications**: In environments with sensitive equipment, such as data centers and healthcare facilities, APFs are used to reduce harmonic distortion and ensure that voltage fluctuations do not interfere with the proper operation of sensitive electronic equipment.

1.4 Scope of the Research

This research develops and evaluates a shunt APF based on a three-phase four-leg VSI to tackle harmonic currents, voltage imbalance, and negative-sequence components from nonlinear loads. It implements and compares PI and intelligent controllers (e.g., fuzzy logic, neural networks), assessing dynamic response, stability, and computational efficiency—including innovations like an effective-time concept to lower complexity. Through comprehensive simulations across steady-state and transient conditions, the study quantifies improvements in THD, voltage balancing, and overall power quality. Findings target practical deployment in industrial settings with sensitive equipment, delivering a more adaptive, robust, and efficient power-quality solution

1.5 Objectives of the Study

The primary objectives of this study are:

1. To design and simulate a shunt APF topology using a three-phase four-leg PWM VSI.
2. To implement both PI and intelligent controllers for the control of the VSI.
3. To compare the performance of the two control strategies (PI and intelligent controllers) in terms of power quality improvement, harmonic reduction, and dynamic response.
4. To demonstrate the efficiency of the proposed system through simulation results in various operating conditions.

2. LITERATURE REVIEW

This review of existing studies related to the mechanical performance, material selection, and modal characteristics of camshafts, particularly under the influence of alternative materials.Recent advancements in four-leg SAPF (Shunt Active Power Filters) for three-phase four-wire systems highlight their effectiveness in reducing Total Harmonic Distortion (THD) and neutral current, especially in campus and industrial environments (Hajjej et al., 2024; Popescu et al., 2024). The integration of intelligent control systems, including adaptive neural networks and hybrid neuro-fuzzy approaches (ANFIS/TS-ANFIS), has shown significant improvements in THD reduction and faster DC-link recovery during load transients (Taghzaoui et al., 2022; Siddique et al., 2024). Modern designs increasingly combine classical PI controllers for DC-link regulation with intelligent current control techniques to optimize both current quality and voltage balance under dynamic loads. These control strategies, including model predictive control (MPC) and 3D/three-level space-vector modulation, offer enhanced performance in handling inverter states and neutral-leg dynamics, particularly during deep unbalances (Zhang et al., 2022; Amrani et al., 2024). Additionally, renewable-integrated APFs, such as PV-powered shunt APFs, have gained prominence, offered energy capture while stabilized power quality (Benazza et al., 2024). Practical deployments confirm the real-world benefits of these advanced control schemes, demonstrating compliance with IEEE-519 limits and superior disturbance rejection, with intelligent supervision handling fast inner loops while PI manages the DC link (Chakraborty et al., 2025; Popescu et al., 2024). This combination of PI and intelligent controllers in a hybrid control stack has emerged as best practice, delivering lower THD, improved voltage balancing, and robust neutral-current suppression across diverse load profiles.

3. ACTIVE POWER FILTERS

Modern power systems rely on disturbance correction algorithms to deal with increasing loads and nonlinear equipment. These non-linear loads may exhibit a poor power factor along with numerous harmonics. An active power filter (APF) may simultaneously handle problems with reactive and harmonic power. Scientists and engineers have developed APFs—which have voltage source inverters and a dc capacitor—to improve transmission networks' power factor and dependability. To get leading or lagging reactive power from the supply, APF can alter the inverters' synthesized ac voltage amplitude by adjusting the dc-link voltage or pulse width modulation. Today, APFs are the go-to solution for power quality issues. In place of more traditional methods like capacitors and passive filters, the shunt active power factor filter (APF) can fix issues with power factor, balance, and harmonics in the current. Utilizing passive LC filters is the quickest and most straightforward method for eliminating line current harmonics and increasing the system power factor. Resonance between series and parallel, large numbers of passive components, and a constant compensation characteristic are the three primary issues with passive LC filters.

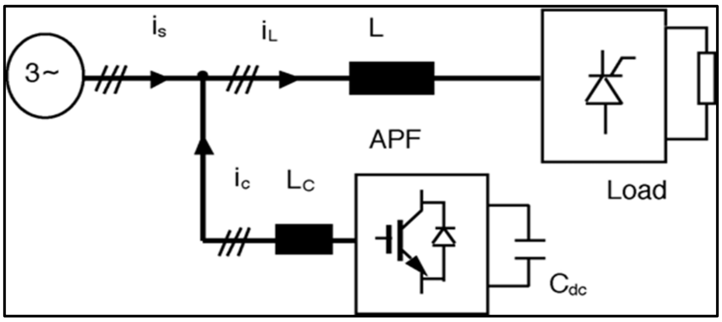

Figure 1: Block diagram of APF

A provides a sufficient reference for balancing currents even in systems with less than perfect voltages. The primary focus is on improving APF performance in less-than-ideal or distorted mains voltage environments. In a number of less-than-ideal mains test cases, the suggested system outperformed the instantaneous reactive power algorithms.

3.1 Active power filter

The fundamental APF block design, depicted in Fig. 1, incorporates non-linear demand on three-phase supply conditions. This work models a non-linear load on three-phase ac mains as an ohmic-inductively loaded three-phase controlled thyristor bridge rectifier. The load may be controlled by adjusting the firing angle; it draws non-sinusoidal currents from the AC mains. Alternative power filters (APFs) circumvent passive filter issues by eliminating harmonic current using a switching mode power converter. An active power filter known as a shunt was created to lower reactive power and produce harmonic currents all at once

3.2 Power quality

In an ideal power system, the power supply would have a perfect sinusoidal waveform, meaning it would deliver electric energy at a constant frequency at a given voltage with minimal disruptions. Concerns about power quality are rising in importance among electricity users across the board. Nowadays, non-linear loads and sensitive equipment are more prevalent in both commercial and industrial settings as well as in homes. This is leading to a growing concern about power quality among those who use energy.

3.3 Harmonics

When non-linear loads distort the supply voltage or load current periodically in a sinusoidal pattern, this phenomenon is known as harmonic distortion. Harmonics can only be measured in terms of integer multiples of the fundamental source frequency. This distorted waveform can be described using Fourier series analysis in terms of the harmonic order, amplitude, and phase of each frequency component. The generation and distribution of electrical electricity in India takes place at 50 Hz, which is the fundamental frequency. Harmonics are components of signals whose frequencies are integer multiples of the fundamental frequency of the system.

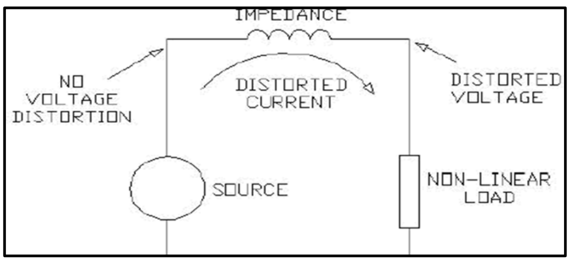

Figure 2: Deterioration of voltage caused by distorted current

3.4 Total harmonic Distortion (Distortion factor)

The THD is a percentage that represents the relationship between the RMS values of the harmonic components and the fundamental component. A periodic waveform with harmonics can have their divergence from a pure sine wave measured using this index. THD is zero for a perfectly sinusoidal signal operating at its fundamental frequency.

Divide Active Power Filters into Different Categories

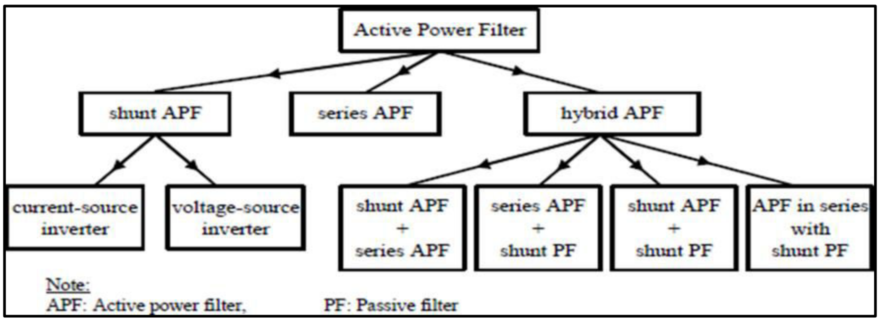

Figure 3: classification of active power filters

3.5 SHUNT ACTIVE POWER FILTER

A shunt active power filter is an effective tool for removing harmonic components from non-linear loads. Figure 4 illustrates the APF coupled in parallel to the power system at the point of common coupling (PCC) between the power users and the metropolitan electrical authority (MEA), emphasizing the fundamental idea of SAPF.

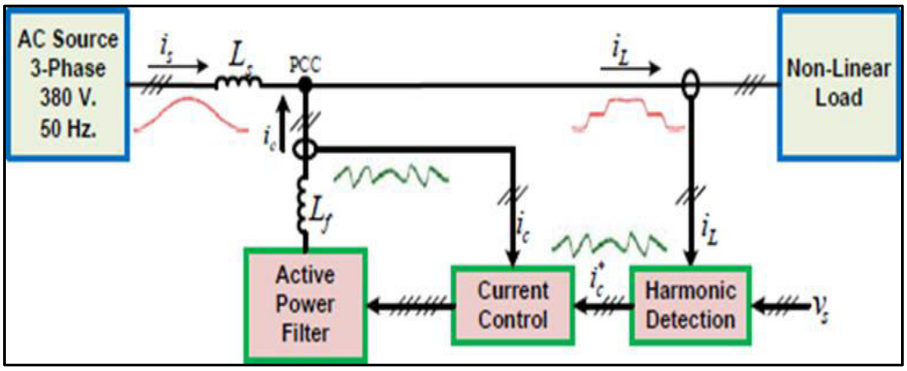

Figure 4: The system using shunt active power filter

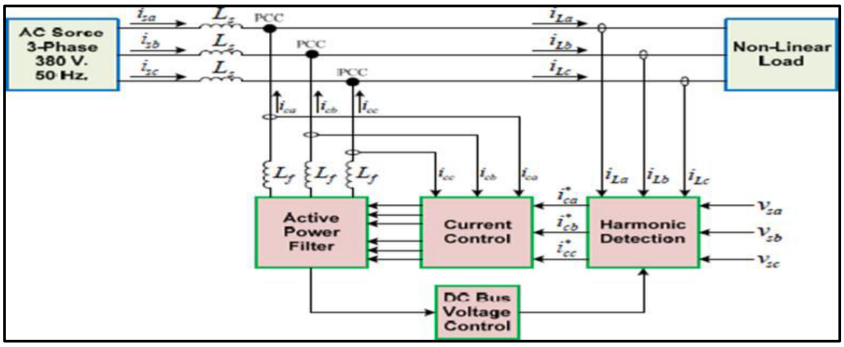

Figure 5: Three – phase shunt active power filter

3.6 Series Combination of Series-APF And Shunt Passive Filter

Power systems can have their voltage and current quality improved using a hybrid solution that combines a Series Active Power Filter (Series-APF) with a Shunt Passive Filter. To maintain clean and steady voltage delivered to the load, this design connects the Series-APF in series with the power supply. This configuration filters out voltage harmonics, transients, and sags induced by nonlinear loads. By establishing a parallel connection with the load, the Shunt Passive Filter is able to mitigate current harmonics, particularly those with lower frequencies.

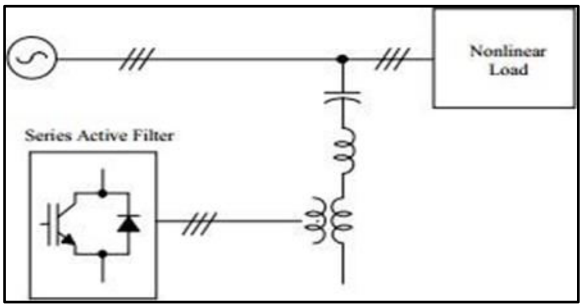

Figure 6: a simple schematic of a series-active passive filter (SPF) and a shunt passive filter combined

Figure 6 shows a schematic of a Series-APF and a Shunt Passive Filter working together. This setup uses a Series-APF connected in series with the power source to eliminate transients and harmonics from the voltage supplied to the nonlinear load, keeping it clean and stable. The Shunt Passive Filter can control current harmonics, especially low-frequency ones, when connected in parallel with the load.

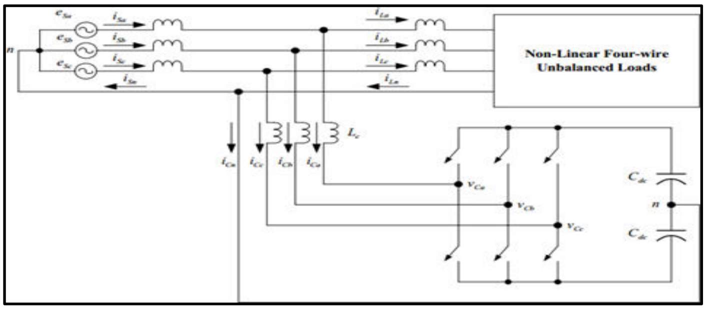

Figure 7: Capacitor midpoint four-wire shunt APF

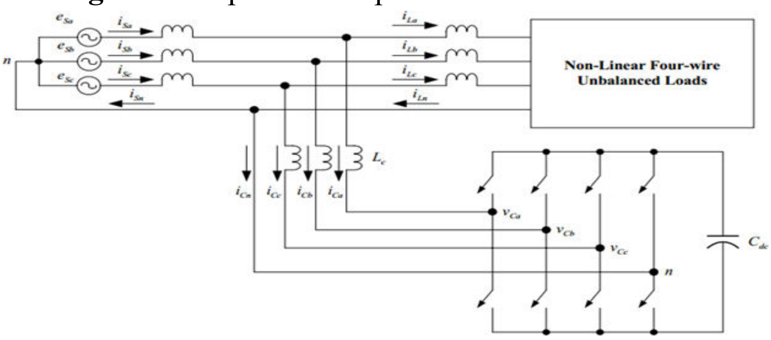

Figure 8: Four-pole four-wire shunt APF.

4. RESULT AND DISCUSSIONS

The nonlinear nature of renewable energy has an effect on power quality due to the fact that high-power static PWM converters are required to link wind and solar power facilities to the grid. Because power generation is not uniform in shape, voltage distortion and its consequences on voltage regulation are direct results of this. To deal with this novel scenario in power distribution systems, sophisticated compensatory techniques will be required. Active power filters used with three-phase four-leg voltage-source inverters (4L-VSI) have been the subject of previous technical literature; nevertheless, the primary contribution of this study is the predictive control approach that was created and used to this application. Traditionally, the current and dc-voltage loops of active power filters have been controlled with pre-tuned controllers, such as PI-type or adaptive.

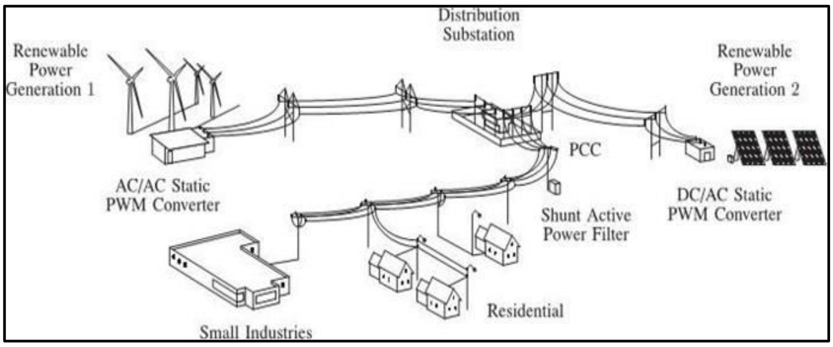

Figure 9: hybrid power generating system that operates independently, utilising a shunt active power filter.

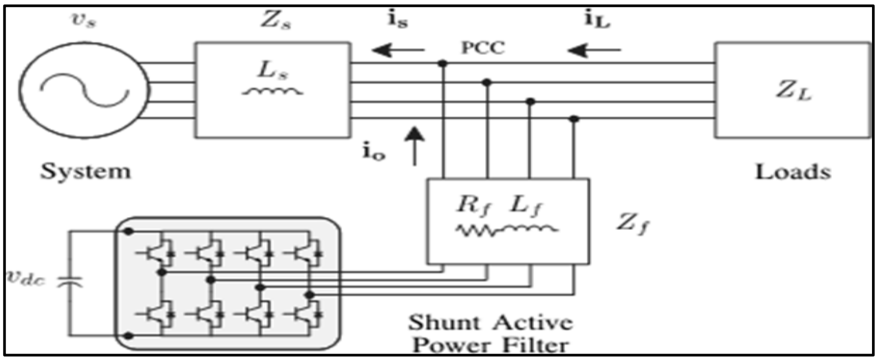

Figure 10: Active power filter shunt design with three-phase equivalent circuit.

Results from experiments conducted on a 2 kVA laboratory prototype corroborate the simulation-based demonstration of control scheme compensation.

4.1 Four-Leg converter model

Renewable power generation is depicted in Fig which displays the usual layout of a power distribution system. It includes a wide range of loads and power generating equipment. Home and small business power generation often makes use of renewable resources like wind and sunshine. Both forms of power generation rely on static pulse width modulators (PWM) to convert voltages and store energy for later usage in battery banks. In order to collect as much energy as possible, these converters keep an eye on the strongest spots of the sun and the wind. Due to the unpredictable and unpredictable nature of electrical energy consumption, its behaviour can be balanced, unbalanced, linear, nonlinear, or tri-phase.

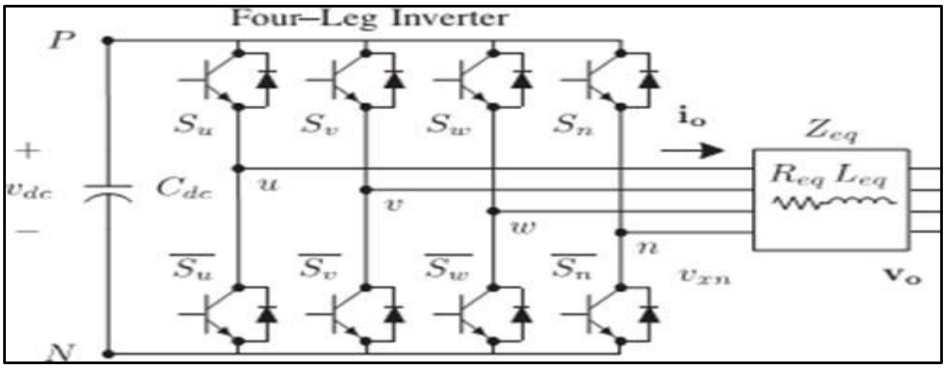

Figure 11: Two-level four-leg PWM-VSI topology

From the neutral point (n), the voltage in any leg x of the converter can be represented in terms of switching states in the following way:

$$v_{xn} = S_x - S_n\, v_{dc}, \quad x = u,\ v,\ w,\ n. \qquad \text{(1)}$$

Filter mathematical model based on Fig. 4.2's corresponding circuit is

$$\mathbf{v_o} = v_{xn} - R_{eq}\,\mathbf{i_o} - L_{eq}\frac{d\,\mathbf{i_o}}{dt} \qquad \text{(2)}$$

Thevenin impedances measured at the converter's output terminals Zeq are the 4-L-VSI output parameters, Req and Leq. Accordingly, the Thevenin equivalent impedance can be determined by making a series connection between the ripple filter impedance Zf, the system equivalent impedance Zs, and the load impedance ZL.

$$Z_{eq} = \frac{Z_s Z_L}{Z_s + Z_L} + Z_f \approx Z_s + Z_f \qquad \text{(3)}$$

By maintaining the series reactance within the range of 3-7% p.u., ignoring the resistive half of the system's equivalent impedance, and assuming that ZL>>Zs, this model makes a decent approximation of the real system. With Req=Rf and Leq=Ls+Lf, we can derive from equations (2).

4.2 Digital predictive current control

This digital predictive current control technique is illustrated in Fig. 12, which is a block diagram. A microprocessor is required to execute this control system because it is essentially an optimisation algorithm. Time delays and approximations are additional constraints that necessitate the use of discrete mathematics in the analysis's development.

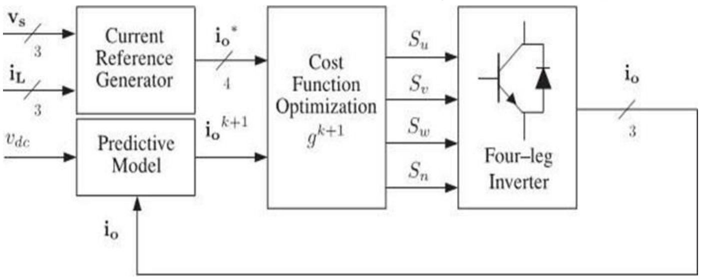

Figure 12: Proposed predictive digital current control block diagram.

Using the system model to foretell how the controlled variables will behave in the future is the defining feature of predictive control. With this data, the controller can apply the power converter's optimal switching state based on previously established optimisation criteria. As illustrated in Figure 4.4, the predictive control algorithm consists of three primary building elements that are both simple and straightforward to apply.

- **Current Reference Generator:** This device is designed to generate the current reference that is required to compensate for the undesirable components of the load current. This is where we take the signals (IV) from the dc-voltage converter, load currents, and system voltages and use them to generate the neutral load current and neutral output current.
- **Prediction Model:** The current output of the converter can be predicted using the converter model. Since the controller operates in discrete time, it is essential to represent the system model and controller in a discrete time domain [22]. A recursive matrix equation represents this system of predictions in the discrete time model. Knowing the states of the converter and the control variables at Instant kTs allows us to predict the following states at any instant [k+1] Ts for any given sampling time Ts. A first-order estimate is sufficient because the model in (1)-(2) is described by first-order state equations.

$$\frac{dx}{dt} \approx \frac{x[k+1]-x[k]}{T_s} \quad \text{……………………………….. (4.4)}$$

The 16 possible output current predicted values can be obtained from (2) and (4) as

$$\mathbf{i}_o[k+1] = \frac{T_s}{L_{eq}}(v_{xn}[k] - \mathbf{v}_o[k]) + \left(1 - \frac{R_{eq}T_s}{L_{eq}}\right)\mathbf{i}_o[k] \quad \text{……………………… (4.5).}$$

According to (4.5), we need the input voltage vo and the converter output voltage vx N to forecast the output current io at the time (k+1). Each of the 16 possible combinations of the state variables has its corresponding value computed by the algorithm. The following is an optimisation procedure for the cost function that must be applied to the 16 expected values of io[k+1] in order to choose the best switching state for the power converter:

4.3 MATLAB/SIMULINK RESULTS

The proposed model of a Renewable Energy Source (RES)-fed four-leg Active Power Filter (APF) system, implemented using MATLAB/Simulink, incorporates both formal Proportional-Integral (PI) and intelligent controllers to optimize power quality in a multi-variable context. The system is designed to mitigate harmonic distortion, correct voltage imbalances, and suppress neutral currents caused by non-linear loads. The four-leg voltage source inverter (VSI) is employed to manage the compensation for harmonic currents and reactive power across all three phases while utilizing the fourth leg to handle zero-sequence components.

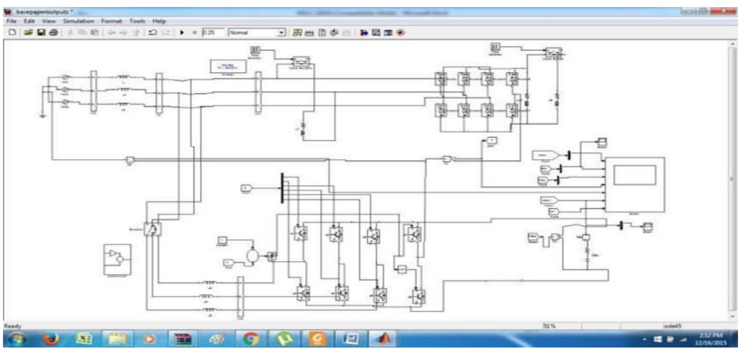

Figure 13: An RES-Fed 4-Leg APF System Model in Matlab/Simulink with Specified PI and Intelligence Controllers

Case 1: Proposed RES Fed APF with Conventional PI Controller

In order to improve power quality, the suggested Active Power Filter (APF) uses a traditional Proportional-Integral (PI) controller to reduce harmonic distortion and voltage imbalances. The APF is fed by Renewable Energy Sources (RES). The DC-link voltage is supplied by the RES (solar or wind power), and the system makes use of a four-leg voltage source inverter (VSI).

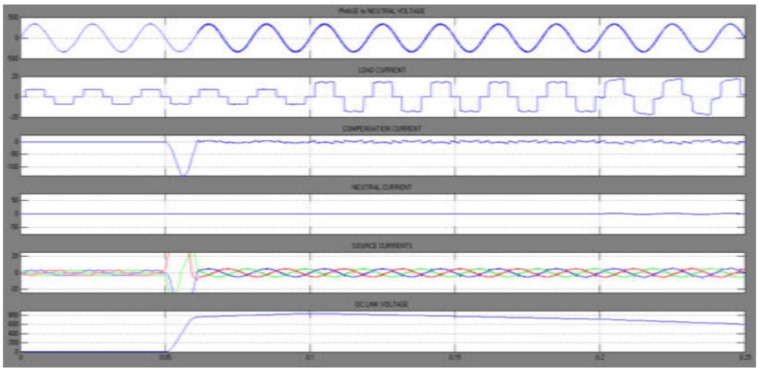

Figure 14: Simulation results for APF with Formal PI Controller

(a) Source Voltage. (b) Load current. (c) Compensator Current (d) Neutral Current, (e) Source Current (f) DC Link Voltage

At 0.05 seconds, the compensator is turned on, just before we detect harmonics from the non-linear load. When the compensator is turned on, it distorts our parameters and causes them to become sinusoidal.

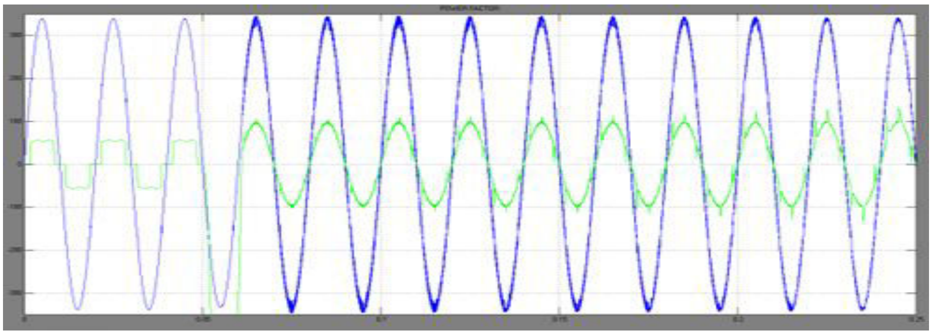

Figure 15: Power Factor for APF with Conventional PI Controller.

The figure shows the power factor waveform for the Active Power Filter (APF) system with a conventional PI controller. The blue and green curves represent the voltage and current waveforms, respectively. A significant feature of this system is the improvement in the power factor after compensation. The system compensates for harmonic currents and reactive power, leading to a near-unity power factor. This demonstrates the effectiveness of the PI control in maintaining voltage regulation and reducing distortion in the system, ultimately improving overall power quality and efficiency.

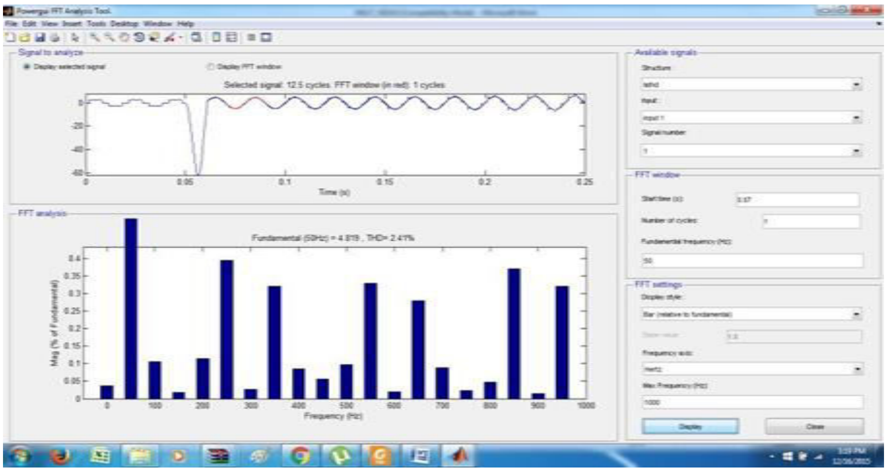

Figure 16: FFT Analysis of Phase-A Source Current with PI Controlled APF

In Figure 16, we can see the results of an FFT analysis of the Phase-A source current in a system where the Active Power Filter (APF) is controlled by PI. By displaying the source current's frequency spectrum, the analysis draws attention to the harmonics. With a Total Harmonic Distortion (THD) of 2.41% and a fundamental frequency of 50 Hz, the PI controller has successfully reduced harmonics and improved the system's power quality. That the PI-controlled APF is able to reduce harmonic currents and make the system run more efficiently is supported by this data.

Case 2: Proposed APF with Intelligence based Fuzzy Controller

The proposed Active Power Filter (APF) with an intelligence-based fuzzy controller aims to enhance power quality by addressing harmonic distortion, voltage imbalances, and neutral currents in real-time. Unlike conventional PI controllers, the fuzzy logic controller adapts based on the system's operating conditions, making it highly effective in dynamic environments with varying loads. By using fuzzy rules and membership functions, the controller generates optimal compensation signals to reduce Total Harmonic Distortion (THD) and improve overall power factor. This adaptive approach ensures better performance, especially in systems where load conditions fluctuate rapidly or where nonlinearity is prominent, providing enhanced stability and efficiency compared to traditional methods.

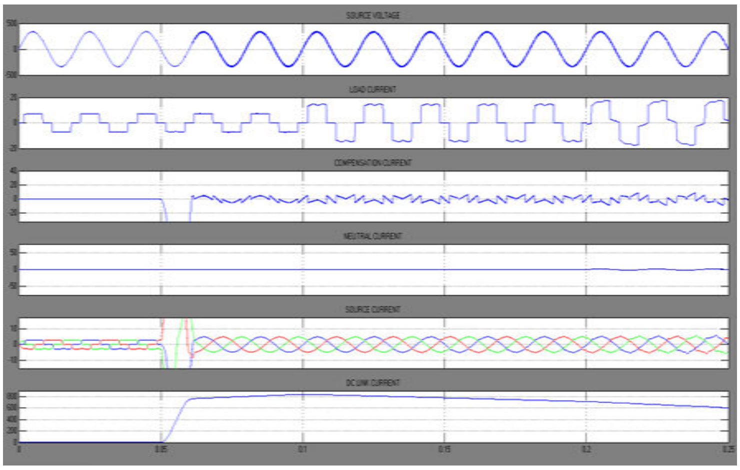

Figure 17: Simulation results for APF with Fuzzy Controller (a) Source Voltage. (b) Load current. (c) Compensator Current. (d) Neutral Current, (e) Source Current (f) DC Link Voltage

Figure 17 shows the simulation results for the APF with a fuzzy controller. Before the compensator is activated at 0.05 seconds, harmonics from the nonlinear load distort the system's parameters. Once the fuzzy controller is engaged, it compensates for the distortions, restoring the system to a sinusoidal waveform and improving overall power quality.

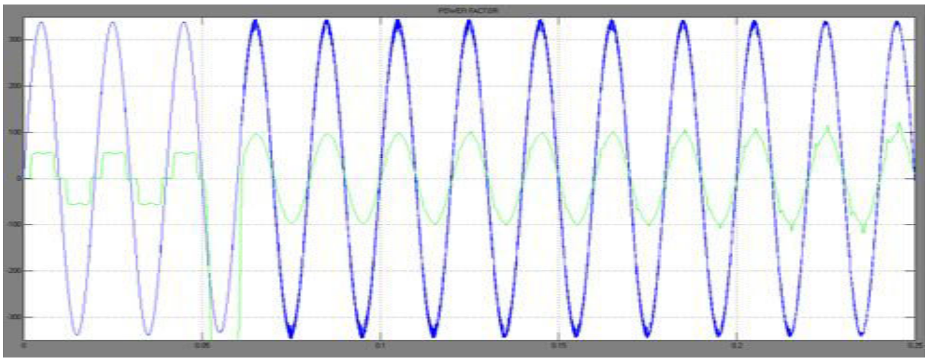

Figure 18: Power Factor for APF with intelligence Controller

Figure 18 shows the power factor waveform for the APF with an intelligent controller. The blue and green curves represent the voltage and current waveforms, respectively. After the intelligent controller compensates for the harmonics and reactive power, the power factor reaches unity, indicating efficient power quality restoration and optimal system performance. The figure highlights the controller's ability to maintain a stable and balanced system even under dynamic conditions.

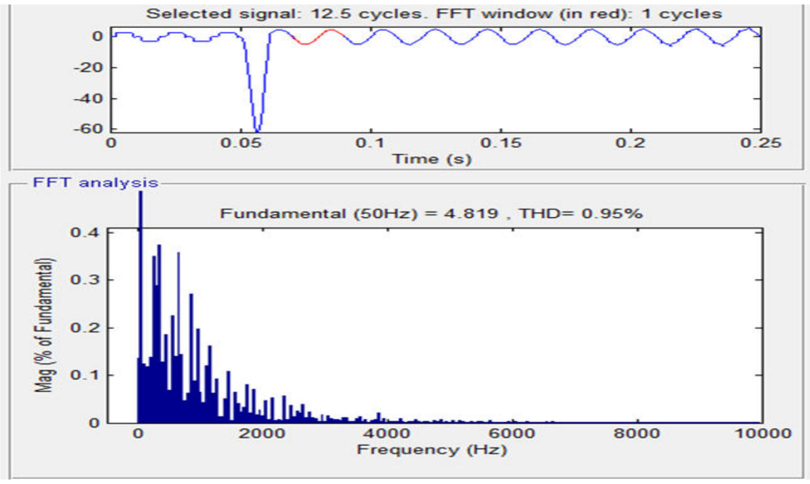

Figure 19: FFT Analysis of Phase-A Source Current with Fuzzy Controlled APF.

In Figure 19, we can observe the results of the Fourier transform (FFT) examination of the Phase-A source current in an APF-controlled system. There is a fundamental frequency of 50 Hz and a Total Harmonic Distortion (THD) of 0.95% in the frequency spectrum of the source current, according to the research. This shows that the fuzzy controller was successful in lowering harmonic distortion, which improved power quality by reducing harmonic content in the system.

CONCLUSIONS

Power systems experience higher losses and a low power factor as a result of harmonics caused by nonlinear loads. Active power filters (APFs) with shunts are frequently used to reduce the impact of this problem. The inclusion of an intelligent logic controller dramatically enhances current tracking and transient response, as demonstrated in this study's introduction of an intelligent controller-based shunt APF. According to the simulation results, the intelligent control method that was suggested is a better option than the old linear control methods. The results also demonstrate how effective the active power filter's compensation is; compared to traditional controllers, the intelligent logic controller reduced Total Harmonic Distortion (THD) from 2.41% to 0.95%. To further improve power quality, we also provide a strategy to compensate reactive power and harmonic current in power distribution systems that use renewable energy sources. Among the many advantages of the approach are its clarity, simplicity, and ease of modelling and implementation. By including a predictive control method into the converter's current loop, the tracking of current and transient responsiveness were both significantly enhanced. The predictive control algorithm provides a solid substitute for traditional linear control methods, as shown by both experimental and simulation findings. By effectively addressing power quality challenges, the suggested method proves its practicality.

Future scope

Future research can explore the integration of advanced intelligent control techniques, such as machine learning and deep learning, to further enhance the adaptability and robustness of active power filters under highly dynamic load conditions. Additionally, combining the proposed predictive control algorithm with real-time data analytics could optimize the system's performance in power distribution networks, especially in the presence of renewable energy sources. Future studies could also focus on scaling up the implementation to larger, more complex power systems, while evaluating its long-term stability and cost-effectiveness.

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