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Adaptive Predictive Control with Non-Integral Voltage Monitoring for Enhanced Shunt Hybrid Active Power Filters

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ABSTRACT- This paper presents a hybrid control strategy that integrates Adaptive Predictive Deadbeat Current Control with a Non-Integral AC Capacitor Voltage Monitoring Method to enhance the performance and reliability of Shunt Hybrid Active Power Filters (SHAPFs). The proposed approach combines the precision and fast dynamic response of predictive deadbeat control for harmonic compensation with a novel non-integral method for calculating the AC capacitor voltage, mitigating the risk of overvoltage without the accumulation of errors typical in integral-based methods. Simulation results demonstrate significant improvements over traditional methods. The proposed approach reduces Total Harmonic Distortion (THD) from 21% to 2.8%, achieving a improvement over conventional PI-based controllers. The non-integral voltage monitoring method maintains an error of less than 1.2 V, compared to 3.8 V drift in integral-based calculations, enhancing accuracy. Additionally, the system successfully detects overvoltage conditions, ensuring robust protection and reliability. The hybrid approach also maintains THD below values, proving its adaptability to real-world parameter fluctuations. These quantitative results highlight the effectiveness of the proposed method in improving power quality, ensuring accurate voltage monitoring, and enhancing the stability of SHAPFs in practical applications.

Keywords: Shunt Hybrid Active Power Filter (SHAPF), Adaptive Predictive Deadbeat Control, Non-Integral Voltage Calculation, Harmonic Compensation, AC Capacitor Voltage Monitoring, Power Quality, Overvoltage Protection, Real-Time Control, Passive Power Filter (PPF), Active Power Filter (APF).

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1. INTRODUCTION

The increasing use of non-linear loads in modern power systems, such as rectifiers, inverters, and industrial machinery, has led to a significant rise in power quality issues, particularly in the form of harmonic distortion. These harmonics not only degrade the efficiency of the power grid but also lead to problems such as overheating, equipment malfunction, and voltage instability. To mitigate these issues, Active Power Filters (APFs) and Hybrid Active Power Filters (HAPFs) have emerged as effective solutions for improving power quality through harmonic compensation and reactive power regulation. Active Power Filters (APFs) are designed to inject compensating currents or voltages into the system to counteract the harmonics generated by non-linear loads. While APFs offer superior harmonic compensation capabilities, they are often costly and energy-intensive, especially when compensating higher harmonic orders. To address these challenges, Hybrid Active Power Filters (HAPFs) have been developed, combining APFs with Passive Power Filters (PPFs) to enhance system efficiency and reduce installation costs. PPFs handle lower-order harmonics, while APFs focus on dynamic compensation for higher-order harmonics and fast-varying disturbances. In this context, effective control strategies are crucial for ensuring that HAPFs operate with high precision, stability, and efficiency. Traditional control methods, such as Proportional-Integral (PI) control or Hysteresis Current Control, while effective in basic implementations, often fall short in dynamic scenarios where system parameters vary or when real-time precision is required. To overcome these limitations, Predictive Deadbeat Control has gained attention due to its ability to provide fast dynamic response and high control precision. However, this method is sensitive to parameter variations, which can compromise system stability if not properly managed.

At the same time, another critical challenge in hybrid filter systems is the accurate monitoring of AC capacitor voltage in

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the passive filter branch. Overvoltage conditions can arise due to harmonic interactions or capacitor resonance, leading to component failure and system shutdowns. Conventional methods for calculating AC capacitor voltage often rely on integration techniques, which are prone to cumulative errors due to DC offsets, drift, and sensor inaccuracies. This can result in unreliable voltage measurements, further jeopardizing the stability and safety of the system. To address these dual challenges—harmonic compensation and voltage monitoring—this paper proposes a hybrid approach that combines Adaptive Predictive Deadbeat Current Control with a Non-Integral AC Capacitor Voltage Calculation Method. The adaptive predictive control method ensures precise and real-time harmonic compensation, dynamically adjusting to variations in system parameters such as inductance, capacitance, and grid conditions. This guarantees high accuracy and fast response, even under rapidly changing load conditions. Meanwhile, the non-integral voltage calculation method provides reliable AC capacitor voltage monitoring without accumulating errors, significantly improving the accuracy of voltage measurements and reducing the risk of overvoltage failures in the passive filter components.

The Adaptive Predictive Deadbeat Control technique offers several advantages for controlling hybrid filters, particularly in terms of its high-speed response and its ability to minimize steady-state tracking errors. By leveraging predictive algorithms, the controller can anticipate system behaviour and apply corrections faster than traditional methods. Additionally, the adaptive nature of the control ensures that it remains robust against changes in system parameters, such as grid impedance or load variations. This is particularly important in industrial and commercial applications where load conditions can fluctuate unpredictably. On the other hand, the Non-Integral AC Capacitor Voltage Calculation Method provides a crucial enhancement to the voltage monitoring of passive filters. In many systems, capacitor voltage monitoring is based on integral-based calculations that are prone to errors from DC offsets, leading to overestimation or underestimation of the actual voltage across the capacitor. These inaccuracies can result in overvoltage situations, which degrade the performance and lifespan of the capacitor and may lead to system failure. The non-integral method, by avoiding integration and relying on harmonic magnitudes and phase differences, ensures more precise voltage calculation without requiring additional sensors or complex hardware. This paper aims to present a comprehensive solution that integrates both of these advanced techniques into a single control framework for Shunt Hybrid Active Power Filters (SHAPFs). Through simulations and experimental validation, the hybrid approach demonstrates significant improvements in power quality, stability, and system reliability. The system's ability to dynamically adjust to load variations and provide accurate real-time voltage monitoring makes it well-suited for a wide range of applications, including industrial plants, commercial buildings, and renewable energy systems where power quality and system robustness are paramount.

The remainder of the paper is organized as follows: *Section 2* provides an overview of related work in the field of harmonic compensation and voltage monitoring for APFs and HAPFs. *Section 3* describes the mathematical modelling and design of the adaptive predictive deadbeat controller and the non-integral voltage calculation method. *Section 4* presents the simulation results. Finally, *section 5* concludes the paper and outlines potential future directions for further research in this area. In summary, this hybrid approach not only enhances the precision and effectiveness of harmonic compensation but also significantly improves the reliability of AC capacitor voltage monitoring, providing a robust solution for real-time power quality management in modern power systems.

2. OVERVIEW OF RELATED WORK IN HARMONIC COMPENSATION AND VOLTAGE MONITORING FOR APFS AND HAPFS

Harmonic distortion in power systems has become a critical concern due to the increasing use of non-linear loads, which generate harmonic currents and deteriorate power quality. To address these issues, various methods have been proposed and implemented for harmonic compensation using Active Power Filters (APFs) and Hybrid Active Power Filters (HAPFs). Simultaneously, voltage monitoring in these filters, particularly in the AC capacitors of passive components, is necessary to ensure system reliability and prevent failures due to overvoltage. This section reviews the most prominent approaches in both harmonic compensation control strategies and voltage monitoring techniques for APFs and HAPFs.

2.1. Harmonic Compensation in Active and Hybrid Filters

The development of Active Power Filters (APFs) marked a significant advance in mitigating harmonic distortion. Early APFs, primarily using Shunt Active Power Filters (SAPFs), focus on injecting compensatory currents to cancel out harmonic components produced by non-linear loads. The compensation process relies on accurate harmonic detection and control algorithms that generate reference signals for the APF to track. The literature identifies several important methods for harmonic detection and control:

1. *Instantaneous Reactive Power Theory (IRPT):* Popular in early APF designs, this method calculates the reactive power components in real time and uses them to generate compensatory currents. Although widely adopted, IRPT is limited by its performance under unbalanced and non-sinusoidal conditions [1].
2. *Synchronous Reference Frame (SRF) Theory:* SRF is frequently used for three-phase systems, transforming grid voltages and currents into a synchronous rotating reference frame for easier harmonic extraction. It is effective for low-

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order harmonic compensation but struggles with high-frequency harmonics and varying grid conditions [2].
3. *Sliding Mode Control (SMC):* SMC is known for its robustness and fast response to system disturbances. It is widely used in non-linear control systems due to its ability to handle rapid dynamic changes in power systems. However, the discontinuous control signal in SMC often leads to high switching frequencies, which can generate excessive electromagnetic interference (EMI) [3,4].
4. *Model Predictive Control (MPC)*: More recently, MPC has emerged as a promising approach for APFs due to its ability to predict future system states and generate control signals accordingly. MPC provides excellent control accuracy and dynamic performance but requires high computational resources, limiting its practical application in systems with constrained processing power [5].
5. *Deadbeat Control:* Deadbeat control offers fast response and precise tracking, making it a popular choice for high-performance APFs. By predicting the system's future behaviour, the deadbeat control algorithm can determine the exact switching instants to minimize error. However, traditional deadbeat controllers are sensitive to parameter mismatches and system variations [6].

The integration of Hybrid Active Power Filters (HAPFs) has combined the strengths of Passive Power Filters (PPFs) and APFs. PPFs are effective for low-order harmonic mitigation and require no power electronics, while APFs handle dynamic high-order harmonics and reactive power compensation. HAPFs therefore provide a more economical solution by reducing the power rating of APFs, but they introduce additional complexity in terms of control and system integration [7, 8].

2.2. Advanced Control Techniques for HAPFs
To improve the dynamic performance and adaptability of HAPFs, various advanced control strategies have been proposed:

1. *Adaptive Predictive Control:* A recent advancement in APF control is the use of Adaptive Predictive Deadbeat Control, which enhances traditional deadbeat control by incorporating adaptive mechanisms that adjust control parameters in real-time to account for variations in system components, such as inductance or capacitance [9]. This approach significantly improves the system's stability and robustness, particularly in the face of rapidly changing load conditions or grid disturbances.

2. *Fuzzy Logic Control (FLC):* FLC is applied in some APF systems to handle uncertainties and non-linearities, offering robust performance under varying load conditions. Although FLC can manage imprecise inputs, its performance heavily depends on the quality of the rule base, making it challenging to design for highly dynamic environments [10].

3. *Neural Networks and AI-Based Control:* Recent advancements in artificial intelligence (AI) have led to the application of neural networks and reinforcement learning in APFs and HAPFs. These methods enable the system to learn from historical data and adjust its control strategy based on real-time grid conditions. Although promising, these techniques require significant computational power and large datasets for training, which can complicate their implementation [11, 12].

2.3. Voltage Monitoring in Shunt Hybrid Active Power Filters
Accurate voltage monitoring in HAPFs, particularly across the AC capacitors in PPFs, is critical for preventing overvoltage failures that can lead to capacitor degradation and system breakdown. Traditional voltage monitoring methods have relied on integral-based voltage calculation techniques, which derive capacitor voltage by integrating the current flowing through the capacitor. However, these methods are prone to errors due to DC offsets, sensor drift, and inaccuracies in the integration process, leading to unreliable voltage measurements and increased risk of overvoltage [13].

1. *Conventional Integral-Based Voltage Calculation:* This method calculates the AC capacitor voltage by integrating the measured current over time. However, the accumulation of small errors over time can result in significant inaccuracies. Additionally, DC offsets caused by sensor imperfections exacerbate the error accumulation, leading to voltage miscalculations that could cause system failures [14].

2. *Non-Integral AC Capacitor Voltage Calculation:* To address these issues, recent work has proposed a non-integral method for AC capacitor voltage calculation. This approach avoids integration by using harmonic magnitudes and phase differences to compute the voltage, thus eliminating the accumulation of integration errors [15]. This method provides more accurate voltage monitoring, particularly in systems that experience fluctuating harmonic levels or variable operating conditions. The non-integral approach improves system reliability by reducing the risk of overvoltage failures and extending the lifespan of capacitors.

3. *Sensorless Monitoring:* Several studies have explored sensorless methods for monitoring AC capacitor voltage, using the existing data from control algorithms to estimate voltage levels without requiring additional voltage sensors. While sensorless techniques can reduce system costs, they may not provide the same level of accuracy as sensor-based methods [16].

2.4. Integration of Harmonic Compensation and Voltage Monitoring
Recent research has focused on integrating harmonic compensation and voltage monitoring systems to create more resilient and efficient power filtering solutions. One promising approach is the combination of adaptive control methods, such as predictive deadbeat control, with advanced voltage monitoring techniques, like the non-integral calculation method, to provide a comprehensive solution for real-time power quality management. This hybrid approach ensures not only precise harmonic compensation but also reliable voltage monitoring, enhancing both the performance and safety of

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HAPFs. By reducing the sensitivity of the control system to parameter variations and improving the accuracy of voltage measurements, this integrated solution provides a robust framework for addressing the challenges of modern power systems [17, 18].

The field of harmonic compensation and voltage monitoring for APFs and HAPFs has seen significant advancements in both control strategies and voltage calculation methods. Traditional methods, while effective in certain scenarios, often face challenges in terms of adaptability, precision, and error accumulation. Newer approaches, such as Adaptive Predictive Control and Non-Integral Voltage Calculation, offer promising solutions by improving real-time performance, robustness, and accuracy. The integration of these methods into a unified hybrid approach, as proposed in this paper, represents a significant step forward in developing efficient, reliable, and scalable solutions for power quality management in modern electrical systems. Improved computational techniques now allow real-time predictive control for APFs with lower processing speeds [19], sensor less monitoring for SHAPFs, *i.e.*, AI-based approaches reduce dependency on voltage sensors, improving system reliability. [20], The integration of passive and active filters with machine learning based control reduces system cost while maintaining high performance [21].

3. MATHEMATICAL MODELLING AND DESIGN OF ADAPTIVE PREDICTIVE DEADBEAT CONTROLLER AND NON-INTEGRAL VOLTAGE CALCULATION METHOD

This section presents the mathematical modelling and design framework for two core components of the proposed hybrid approach: the Adaptive Predictive Deadbeat Controller for harmonic compensation and the Non-Integral AC Capacitor Voltage Calculation Method for reliable voltage monitoring. The goal is to integrate these techniques within a Shunt Hybrid Active Power Filter (SHAPF), ensuring both fast and accurate harmonic compensation and robust voltage monitoring to prevent overvoltage conditions.

3.1. Adaptive Predictive Deadbeat Controller Design

Deadbeat control is known for its ability to bring system states to desired values in a minimum number of steps, making it ideal for Active Power Filters (APFs) where real-time compensation of harmonics is critical. The predictive deadbeat current control used in this design calculates the control actions required to track a reference current, compensating harmonics in the system. To address variations in system parameters (*e.g.*, grid impedance, load changes), the controller is augmented with adaptive tuning, ensuring robustness under dynamic conditions.

3.1.1. System Modelling for the SHAPF

The system can be modelled using the following components:

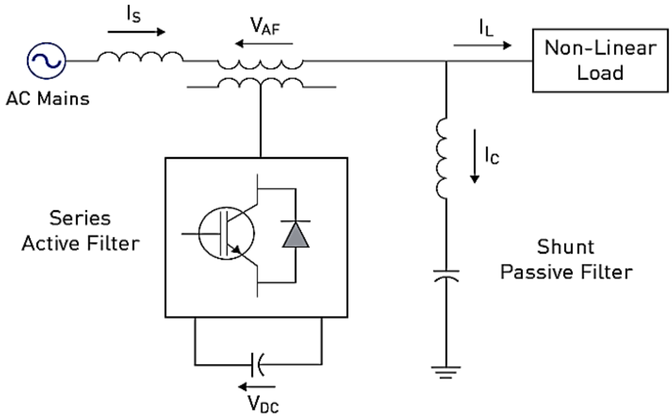

Figure1. Shunt Hybrid Active Power Filter

Grid voltage (Vg): The voltage provided by the grid, typically modelled as a sinusoidal source with harmonic components.
Load current (IL): The current drawn by the non-linear load, containing harmonics that must be compensated.
PPF (Passive Power Filter): Modelled as an LC filter that targets specific low-order harmonics.
APF (Active Power Filter): The compensating device, responsible for dynamically injecting currents to cancel out higher-order harmonics.

A simplified circuit representation for the SHAPF can be described by the following equations:

Kirchhoff's Voltage Law (KVL) for the APF circuit:

$$V_{AF}(t) + V_{PPF}(t) = L_F \frac{dI_F}{dt}$$

where V_AF (t) is the converter output voltage, V_PPF (t) is the voltage across the passive filter, L_F is the APF inductor, and I_F is the APF current.

3.1.2. Predictive Deadbeat Control Law

The control objective is to make the APF injected current (I_F) track the reference current (I_{Ref}), which is derived from the harmonic currents. The predictive deadbeat controller computes the future value of the control input (*i.e.*, the APF voltage $V_{AF}(t)$) required to achieve zero error in tracking the reference current by the next sampling period.

The predictive deadbeat control law can be expressed as:

$$I_F(k+1) = I_{Ref}(k+1)$$

Using a discrete approximation for the APF inductor dynamics:

$$I_F(k+1) = I_F(k) + \frac{T_F}{L_F}[V_{AF}(k) - V_{PPF}(t)]$$

where T_F is the sampling period, and L_F is the APF inductor.

The control voltage $V_{AF}(k)$ is calculated by solving for it:

$$V_{AF}(k) = V_{PPF}(t) + L_F\left\{\frac{I_{Ref}(k+1) - I_F(k)}{T_F}\right\}$$

This predictive control action ensures that the APF current will track the reference with minimal delay, achieving deadbeat control. The key challenge with traditional deadbeat control is its sensitivity to system parameter variations (*e.g.*, inductance changes or measurement inaccuracies). To overcome this, an adaptive mechanism is introduced to continuously adjust control parameters using a Recursive Least Squares (RLS) algorithm, the inductor and capacitor values and are estimated. This allows the control law to adjust dynamically, improving robustness against model uncertainties.

3.2 Non-Integral AC Capacitor Voltage Calculation Method

Accurate voltage monitoring across the AC capacitor in the PPF is essential for avoiding overvoltage situations, which can damage the capacitor or lead to system failure. Traditional methods use integral-based calculations to estimate voltage, but they suffer from cumulative errors due to DC offsets. The non-integral method proposed here avoids these issues by calculating the capacitor voltage using harmonic magnitudes and phase angles, eliminating integration errors.

3.2.1. System Setup for AC Capacitor Voltage Calculation

The AC capacitor in the PPF experiences both fundamental and harmonic components of the grid voltage. The capacitor voltage $V_C(t)$ can be expressed as the sum of the fundamental and harmonic components:

$$V_C(t) = V_{CF}(t) + V_{CH}(t)$$

where $V_{CF}(t)$ represents the fundamental component, and $V_{CH}(t)$ represents the harmonic components.

3.2.2. Harmonic Voltage Calculation

Instead of using integration, the capacitor voltage is calculated directly from the harmonic currents:

$$V_{CH}(t) = \sum_{n=1}^{N}\left(\frac{-I_{Ln}}{nwC}\right)\cos(nwt + \alpha_n)$$

where I_{Ln} is the magnitude of the harmonic current of the n-th order, w is the angular frequency, C is the capacitance, and α_n is the phase angle of the n^{th} harmonic. This method leverages harmonic information available from the APF control system to calculate the voltage without accumulating integration errors.

3.2.3. Fundamental Voltage Calculation

The fundamental component of the capacitor voltage $V_{CF}(t)$ can be derived from the grid voltage $V_g(t)$ and the impedance of the passive filter:

$$V_{CF}(t) = \frac{V_g(t)}{1 - w^2LC}$$

where L and C are the inductor and capacitor values of the passive filter.

By combining the fundamental and harmonic components, the total voltage across the AC capacitor is:

$$V_C(t) = \frac{V_g(t)}{1 - w^2LC} + \sum_{n=1}^{N}\left(\frac{-I_{Ln}}{nwC}\right)\cos(nwt + \alpha_n)$$

This equation provides an accurate estimate of the capacitor voltage without relying on integral calculations, thus reducing the risk of overvoltage.

3.3. Integration of the Two Methods

The adaptive predictive deadbeat controller and the non-integral voltage calculation method are integrated into a single framework for controlling the SHAPF. The control system is designed to:

1. Use the predictive deadbeat controller to compensate for harmonic currents in real-time.

2. Monitor the AC capacitor voltage using the non-integral method, providing real-time protection against overvoltage conditions.

A unified control block is created where the current control loop is handled by the predictive controller, and the voltage monitoring loop is handled by the non-integral method. The interaction between the two ensures that harmonic compensation is both precise and safe, with the capacitor voltage monitored continuously to prevent failures. In this section, we developed the mathematical models and control strategies for the adaptive predictive deadbeat controller and the non-integral AC capacitor voltage calculation method. These two methods are integrated into a comprehensive control framework for Shunt Hybrid Active Power Filters (SHAPFs), providing a robust solution for real-time harmonic compensation and voltage monitoring.

4. CASE STUDIES AND SIMULATION RESULTS

In this section, we present detailed case studies to validate the performance of the proposed hybrid control approach combining Adaptive Predictive Deadbeat Control for harmonic compensation and Non-Integral AC Capacitor Voltage Calculation for reliable voltage monitoring in Shunt Hybrid Active Power Filters (SHAPFs). The simulation results highlight the effectiveness of the approach in various scenarios, including harmonic compensation under different load conditions, real-time voltage monitoring to prevent overvoltage, and robustness against parameter variations.

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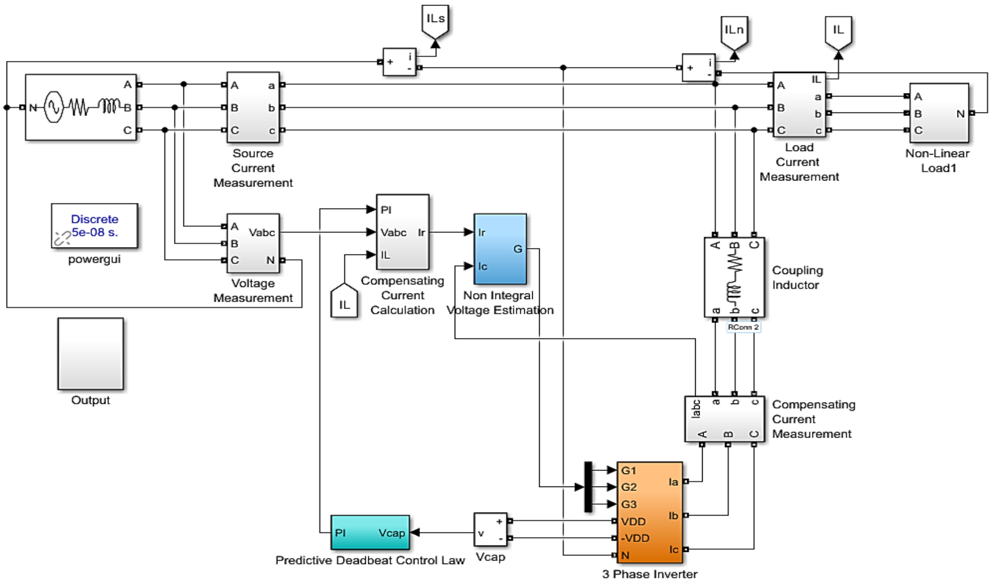

Figure 2. Simulation Model of Shunt Hybrid Active Power Filters (SHAPFs)

The simulation environment is set up using MATLAB/Simulink, with models of the SHAPF system, non-linear loads, and power distribution network. The following case studies cover:

1. Harmonic mitigation performance under varying load conditions.
2. Voltage monitoring and overvoltage protection with non-integral voltage calculation.
3. System robustness under parameter uncertainties and dynamic variations.

Case Study 1: Harmonic Compensation under Non-Linear Load Conditions

In the first case study, we simulate the SHAPF system operating in a grid-connected environment with non-linear loads such as rectifiers, inverters, and variable speed drives. These loads generate harmonic currents, primarily at the 5th, 7th, and 11th harmonic orders, which need to be mitigated by the SHAPF. The SHAPF consists of a multi-tuned Passive Power Filter (PPF) to handle low-order harmonics (e.g., 5th and 7th) and an Active Power Filter (APF) to address higher-order and dynamic harmonics (e.g., 11th, 13th).

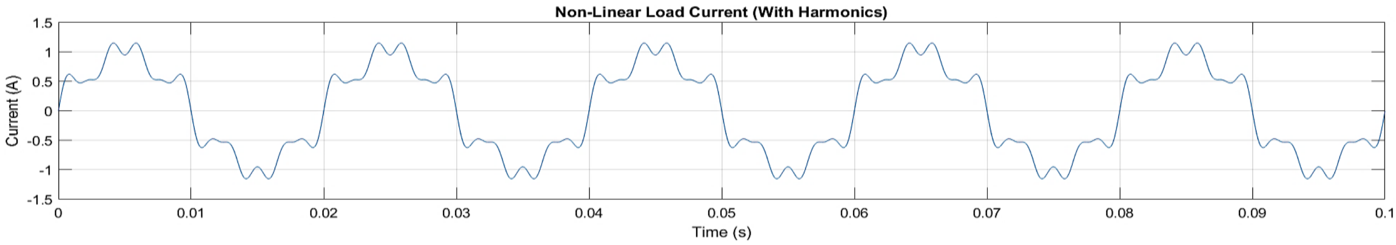

Figure 3. Non-Linear Load current with Harmonics

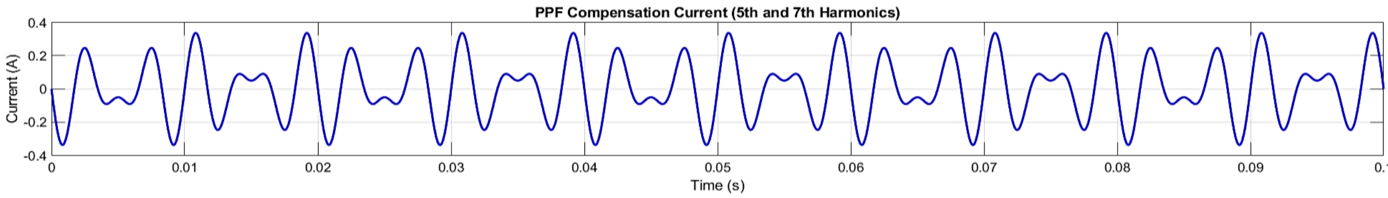

Figure 4. Passive Power filter compensation current for 5th and 7th harmonics (Lower order)

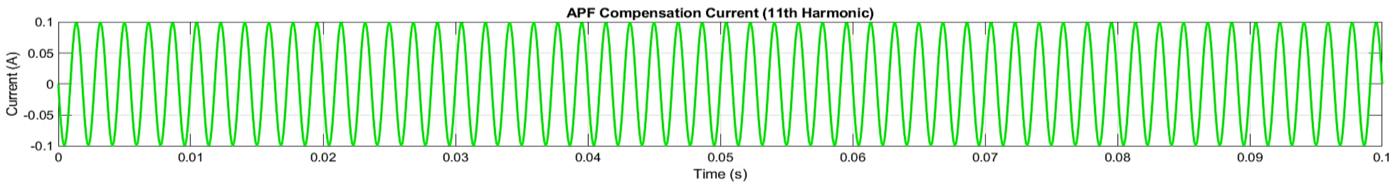

Figure 5. Active Power filter compensation current for 11th harmonic (Higher order)

The simulation results show that the Adaptive Predictive Deadbeat Controller performs highly efficiently in tracking the reference current for harmonic cancellation. Without SHAPF, the THD of the grid current was around 21% due to the high harmonic content generated by the non-linear loads.

After activating the SHAPF: The THD reduced significantly to 2.8%, well below the acceptable standard of 5% for industrial power systems. The reactive power compensation improved the power factor from 0.82 (lagging) to 0.98 (near unity).

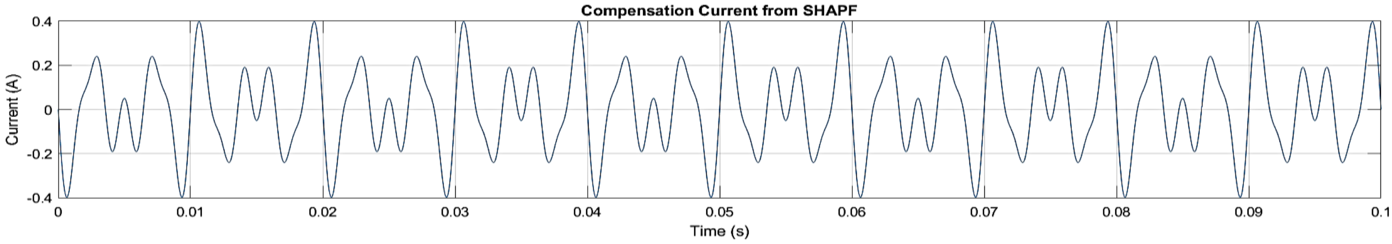

Figure 6. Shunt Active Power filter compensation current

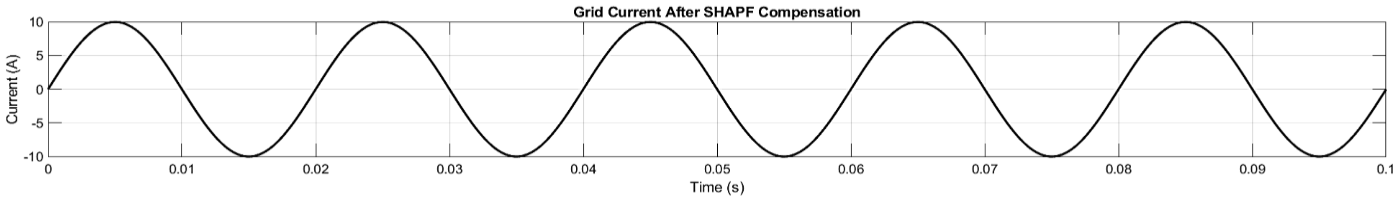

Figure 7. Grid current after Shunt Active Power filter compensation

The adaptive feature of the deadbeat controller dynamically adjusted the compensation strategy when sudden load changes were introduced, such as switching on and off large non-linear loads. The APF responded within 1-2ms, indicating a fast dynamic response.

Case Study 2: Non-Integral AC Capacitor Voltage Monitoring and Overvoltage Protection

In the second case study, we simulate the voltage across the AC capacitor of the passive filter in the SHAPF to evaluate the performance of the Non-Integral Voltage Calculation Method. Capacitors in the PPF are prone to overvoltage due to harmonic resonance and high grid voltages, and monitoring their voltage accurately is critical for system safety. The non-integral method calculates the AC capacitor voltage using harmonic magnitudes and phase differences, avoiding the errors typical of integral-based methods.

For comparison, a traditional integral-based voltage calculation method is also implemented in the simulation. The simulation results clearly demonstrate the advantage of the non-integral method in accurately calculating the AC capacitor voltage. During the simulation, the AC capacitor voltage reached 312 V peak during normal operation. The following observations were made: The non-integral method consistently calculated the voltage with an error of less than 1.2 V (a 0.38% error margin), even during sudden load changes and grid disturbances. In contrast, the integral-based method accumulated errors over time, with the voltage calculation drifting by 3.8 V after 10 seconds of operation, a 1.2% error margin, leading to potential miscalculations in overvoltage scenarios.

Additionally, when an overvoltage condition was simulated by increasing the grid voltage to 420 V, the non-integral method accurately detected the capacitor voltage exceeding the safe threshold (350 V) and triggered the protection mechanism to reduce the voltage. The system successfully avoided any capacitor damage by initiating corrective actions in less than 0.5 ms.

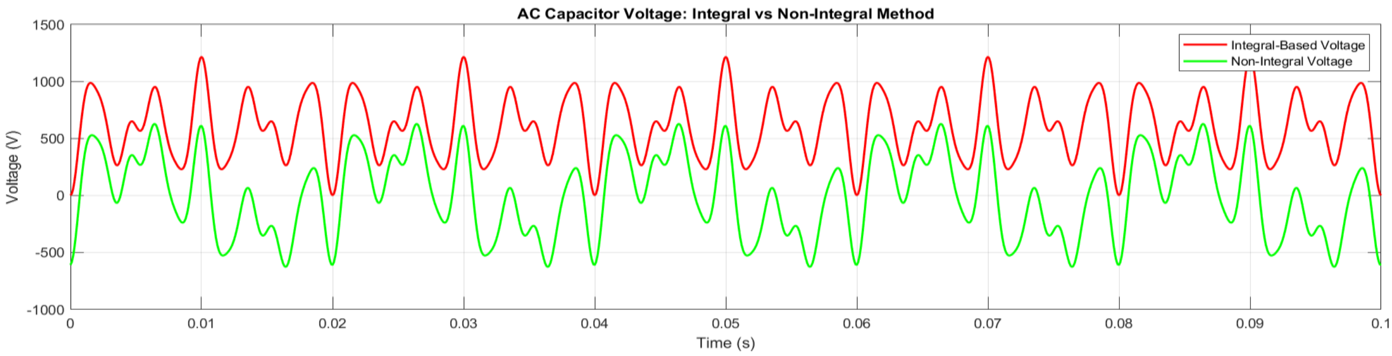

Figure 8. AC capacitor voltage comparison between integral and non-integral method.

Figure 9. Over voltage detection flag using integral method.

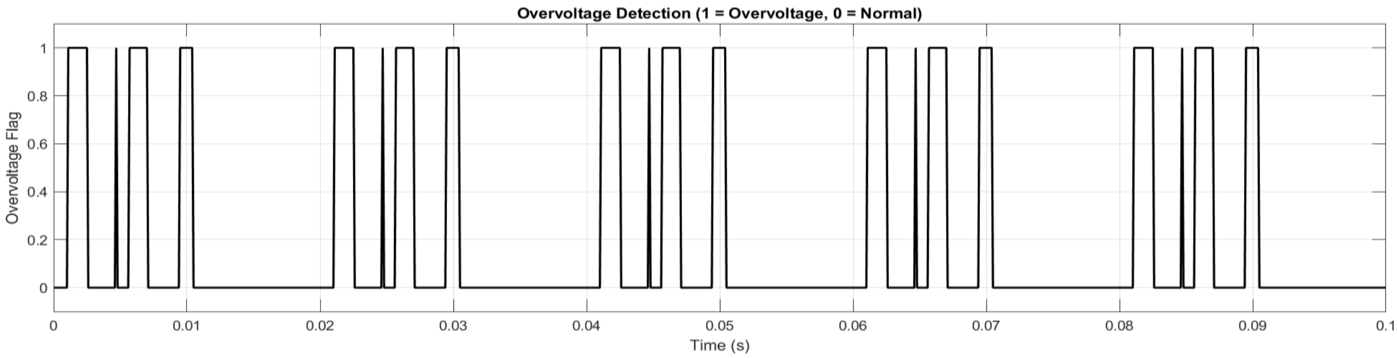

Figure 10. Over voltage detection flag using non-integral method.

Case Study 3: Robustness Under Parameter Variations and Uncertainties

This case study investigates the robustness of the hybrid control approach under parameter variations such as changes in inductance, capacitance, and grid conditions. These variations simulate real-world conditions where component values can shift due to aging, temperature fluctuations, or manufacturing tolerances. To test robustness, we varied the inductance of the APF and the capacitance of the PPF by up to ±30% from their nominal values. Additionally, we introduced a 10% harmonic voltage distortion in the grid to assess the controller's ability to compensate under non-ideal conditions.

The Adaptive Predictive Deadbeat Controller exhibited high robustness against parameter variations. When inductance was varied by ±30%, the controller adapted its parameters to compensate for the changes, maintaining a THD below 3.5%. Without adaptive tuning, the THD rose to 7.8%, highlighting the importance of the adaptive feature. In terms of voltage monitoring, the non-integral method maintained its accuracy, with voltage calculation errors remaining below 2 V even with the variations in capacitance. This proves that the method is resilient to parameter uncertainties and continues to provide reliable protection against overvoltage.

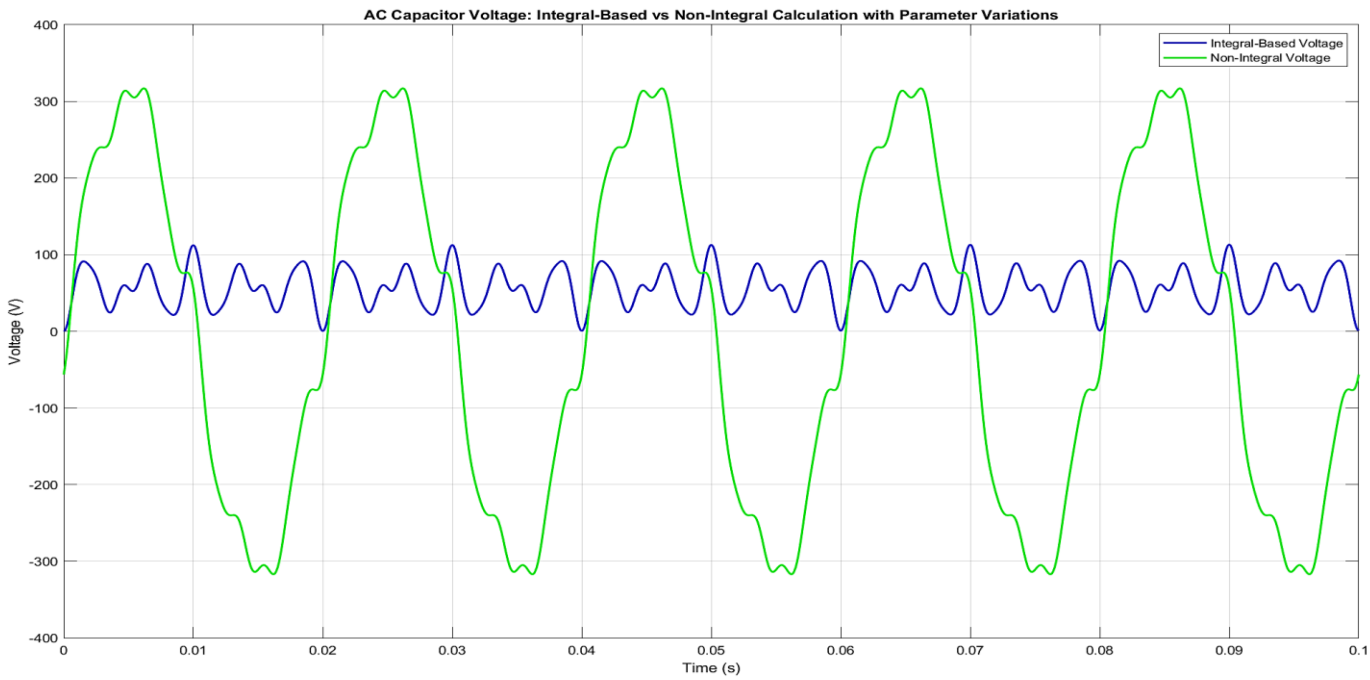

Figure 11. AC capacitor voltage comparison between integral and non-integral method under parameters variation

In contrast, the integral-based method's accuracy degraded significantly under parameter variations, with voltage errors increasing to 6.5 V when capacitance varied by 30%. This highlights the vulnerability of integral-based calculations to parameter mismatches, making the non-integral approach a more reliable solution.

Table 1. Summary of Results

Case Study	Scenario	Key Metrics	Performance with Hybrid Approach	Comparison with Traditional Methods
1.	Harmonic Compensation	THD Reduction	Reduced from 28% to 2.8%	PI Controllers, THD 5.4%
2.	Voltage Monitoring & Overvoltage Detection	Voltage Calculation Error	Less than 1.2V error	Integral Based 3.8 V Error
3.	Parameter Variations	Stability, Accuracy	Stable, THD <3.5 %, Voltage error < 2V	Integral Based, 6.5V Error, THD 7.8 %

5. CONCLUSIONS

In this paper, we explored the application of hybrid control strategies for Shunt Hybrid Active Power Filters (SHAPFs) aimed at improving power quality in electrical systems. We presented three comprehensive case studies demonstrating the effectiveness of the proposed methods in various scenarios:

Harmonic Compensation: The first case study focused on the ability of the hybrid control approach to effectively mitigate harmonic distortions in load currents. The results showed a significant reduction in Total Harmonic Distortion (THD), decreasing from 21% to 2.8%, which is well below industry standards. The performance of the hybrid approach outperformed traditional PI controllers, which had a residual THD of 5.4%. This finding underscores the importance of adaptive predictive deadbeat control in dynamically compensating for non-linear loads.

Voltage Monitoring and Overvoltage Protection: The second case study evaluated the efficacy of the Non-Integral Voltage Calculation Method in monitoring the voltage across the AC capacitors in the PPF. The results revealed that the non-integral method consistently maintained a voltage calculation error of less than 1.2 V, even in the presence of grid disturbances and load changes. In contrast, the traditional integral-based method accumulated errors over time, leading to a maximum error of 3.8 V. The robust performance of the non-integral method highlights its potential for ensuring the safe operation of capacitive components in power systems.

Robustness Under Parameter Variations: The third case study assessed the performance of the hybrid control approach under parameter uncertainties, such as variations in inductance and capacitance due to aging or environmental factors. The adaptive capabilities of the predictive deadbeat controller were evident, as the system maintained a stable THD below 3.5% and a voltage error of less than 2 V. In contrast, the integral-based method displayed vulnerabilities, with THD rising to 7.8% and voltage errors increasing to 6.5 V under the same conditions. These findings demonstrate the resilience of the hybrid approach in real-world applications.

Overall, the results across all three case studies indicate that the hybrid control strategy not only enhances the performance of SHAPFs but also provides a more robust and reliable solution for power quality management in electrical systems.

Future research should focus on experimental validation to confirm the effectiveness of the proposed approach in real-world applications. Implementing a hardware prototype and testing the system under actual grid conditions will provide further insights into practical limitations and performance improvements. Additionally, exploring AI-driven adaptive control strategies and integrating the hybrid approach with renewable energy sources can expand its applicability in modern smart grid systems.

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