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RESEARCH ARTICLE

Power Quality Improvement in Nonlinear Lighting Load Applications Using Shunt Active Power Filter Control

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ABSTRACT This paper develops an enhanced current control approach for a Three-Phase Four-Wire (3P4W) split-capacitor Shunt Active Power Filter (SAPF) to mitigate current harmonics produced by Compact Fluorescent Lamps (CFLs). A Fuzzy Hysteresis Current Controller (FHCC) and a Modulated Hysteresis Current Controller (MHCC) are proposed to provide the triggering signals for the Insulated-Gate Bipolar Transistors (IGBTs) of the SAPF to ensure improved switching performance and reduced steady-state error near the Shifted Zero-Crossing Area (S-ZCA). The Synchronous Reference Frame (SRF) power theory is adopted for reference current generation. The effectiveness of both techniques, FHCC and MHCC, is evaluated through simulations in MATLAB®/Simulink and validated in real time using the Hardware-in-the-Loop (HIL) platform, especially with the Typhoon HIL-402 device. As both techniques act exclusively for switching gate signal generation techniques and not reference-current extraction methods, the structures are general in nature and are not load-dependent. Comparative analysis with the conventional hysteresis current controller (HCC) demonstrates significant improvements in the reduction of Total Harmonic Distortion (THD) to 1.08% and the overall improvement of power quality without notches in waveforms near zero crossings. The results confirm the robustness and efficiency of the proposed MHCC strategy in the HIL implementation.

INDEX TERMS Shunt active power filter (SAPF), power quality improvement, harmonic mitigation, compact fluorescent lamps (CFLs), fuzzy hysteresis current controller (FHCC), modulated hysteresis current controller (MHCC), hardware-in-the-loop (HIL), typhoon HIL402.

A. ABBREVIATIONS

The following abbreviations are used in this manuscript:

CFL: Compact Fluorescent Lamp.
 PF: Power Factor.
 NL: Nonlinear Load.

SRF: Synchronous Reference Frame.
 PLL: Phase-Locked Loop.
 APF: Active Power Filter.
 LPF: Low Power Filter.
 SAPF: Shunt Active Power Filter.
 HAPF: Hybrid Active Power Filter.
 HB: Hysteresis Band.
 THD: Total Harmonic Distortion.
 PCC: Point of Common Coupling.

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FLC:	Fuzzy Logic Controller.
HCC:	Hysteresis Current Controller.
FHCC:	Fuzzy Hysteresis Current Controller.
MHCC:	Modulated Hysteresis Current Controller.
3P4W:	Three-Phase Four-Wire.
4W-2C:	Four-Wire Two-Capacitor.
MCB:	Miniature Circuit Breaker.
IGBT:	Insulated-Gate Bipolar Transistor.
LED:	Light-emitting diode.
PQ:	Active and Reactive Power.
HIL:	Hardware-in-the-Loop.
PWM:	Pulse-Width Modulation.
LV:	Low Voltage.
ZCA:	Zero-Crossing Area.
S-ZCA:	Shifted Zero-Crossing Area.
PFC:	Power Factor Correction.
VSI:	Voltage Source Inverter.
SCADA:	Supervisory Control and Data Acquisition.
IEEE:	Institute of Electrical and Electronics Engineers.
IEC:	International Electrotechnical Commission.

I. INTRODUCTION

Power quality has become a critical concern in modern electrical systems due to the increasing use of nonlinear loads (NLs), which generate harmonic distortions in the centralized power grid due to their non-sinusoidal current consumption [1], [2]. The increasing penetration of distributed generation units within centralized power systems introduces additional power quality challenges, including voltage fluctuations, harmonic distortions, and reverse power flows, which complicate system stability and protection schemes [3], [4], [5]. Compact Fluorescent Lamps (CFLs) and Light Emitting Diodes (LEDs) are among the primary sources of current harmonics, leading to voltage distortions, increased losses, and reduced efficiency of power distribution networks due to their reactive power consumption [6], [7]. They require an electronic ballast (EB) circuit to power up the CFL tube and the LED array as shown in FIGURE 1. Although the specific design of EB circuits varies among manufacturers depending on the desired light output characteristics, the fundamental operating principles remain largely consistent across different brands. In particular, the rectification stages within EB circuits can introduce adverse effects on the power grid, including waveform distortion [11], [12]. To mitigate these issues, filter stages are typically incorporated into EB designs to improve waveform quality, increase the power factor (PF), and reduce total harmonic distortion (THD). While there are no regulations that mandate specific power factor correction (PFC) topologies for commercial CFL and LED products, manufacturers must comply with harmonic current and EMI limits defined by standards such as IEC 61000-3-2 [13] and EN 55015/CISPR 15 [14], [15]. Within these constraints-particularly for low-power lighting products-manufacturers often favor cost-effective solutions,

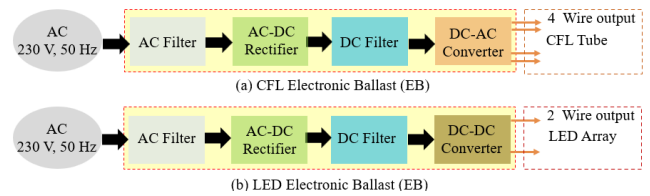


FIGURE 1. Block diagram of CFL and LED lamps circuit configuration.

leading to the widespread use of passive *RLC* networks, typically based on inductive and capacitive elements rather than active PFC circuits [16].

To mitigate these issues, Shunt Active Power Filters (SAPFs) have been extensively studied as effective solutions [17]. By accurately estimating and compensating the harmonic and reactive components of the load currents, the SAPF injects sinusoidal source currents with reduced THD. The improved waveform quality contributes to lower system losses, enhanced voltage regulation, and better compatibility with sensitive loads. They are more efficient in mitigating current harmonics compared to passive power filters. Furthermore, passive filters ensure fixed compensation and are subject to issues such as resonance effects and sizing concerns [18]. Note that Hybrid Active Power Filters (HAPFs) are preferred in high-power applications where a smaller active filter is combined with a passive filter to reduce cost and size. HAPFs are especially effective under complex loading conditions when advanced intelligent control strategies are employed. Intelligent strategies such as PSO-GWO-optimized FOPID controllers [19], type-2 fuzzy PID control [20], dual-tree complex wavelet transforms with type-2 fuzzy logic controllers [21], RECKF-based estimation [22], and adaptive fuzzy hysteresis control [23] allow a significant reduction in THD under balanced, unbalanced, steady-state, and transient conditions. This work adopts a simple SAPF approach, as it is well suited to mitigate the current harmonics generated by CFLs and is compatible with low voltage (≤ 400 V) and low power applications (≤ 10 kW). Meanwhile, the effectiveness of these SAPFs depends on their control and command techniques. Therefore, various classical and modern control techniques have been studied in the literatures [24], [25], and [26], such as PQ [27], [28], Conservative Power Theory (CPT) [29], SRF [30], Petri net theory [31], and Adaptive Frequency Proportional-Integral-Resonant Controller [32] to provide the reference current for SAPF as shown in TABLE 1. In this paper, the SRF theory is used due to its simplicity and robustness for the generation of the reference current to the current controller that provides the switching gate pulses for the IGBT switches. The current controller also goes through several advances concerning the developed techniques, such as simple techniques; the Hysteresis Current Controller (HCC) [33], [34], [35], PWM controller [36], Adaptive Frequency Fixed (AFF) [37], etc. or advanced techniques; Space Vector Pulse Width Modulation (SVPWM) [38], [39], fuzzy neural network [40], artificial intelligence (AI), etc.

TABLE 1. Comparative Table: Different lighting loads before and after SAPF.

Lighting type	Power level (W)	A_{THD} before SAPF	A_{THD} after SAPF	SAPF control technique
CFL [8]	20 (each)	102.84% (100 CFL)	17.70% (100 CFL) 4% (100 CFL and linear load)	Average modeling and carrier-based control strategies
LED [9]	78	27.83%	3.62%	Recursive Least Squares (RLS)
CFL [10]	20	90.00%	2.18%	DQ theory

Among these various current control strategies of SAPF, HCC was widely adopted for its simplicity and fast dynamic response. However, conventional HCC suffer from drawbacks, such as variable switching frequency, high ripple content, and increased switching losses [39].

To overcome these limitations, this paper proposes an advanced control technique that integrates a Fuzzy Hysteresis Current Controller (FHCC) based on Fuzzy Logic Control (FLC) which is presently at the forefront of contemporary technological innovation. This innovative method offers a new approach for solving regulatory and control problems in various applications. In this work, we focus specifically on the development and application of this technique in Hysteresis Band (HB) current control. This advanced technique will be used to avoid human interaction at the level of setting the HB value and to dynamically adjust the HB based on real-time operating conditions. In particular, the goal is to enhance the performance of SAPFs with respect to THD reduction, reactive power compensation, and improved power quality.

However, for further improvement in power source quality, a new modified current control strategy is applied for the first time in SAPFs. This decision is taken after understanding the behaviors of these NLs; while after investigation, an instant high ripple content in the constant HB HCC and FHCC in some zones is noticed. This leads to some notches in the waveforms of the current delivered by the voltage source. The new technique has been applied in [41] and [42] to improve the current waveform of a Ćuk converter that functions as a PFC circuit for LED lighting applications. The technique involves the use of a HB modulation to improve signal output waveforms near the Zero-Crossing Area (ZCA) which leads to power quality improvement. Similarly, improving the input current near the ZCA of the input voltage is regarded as the optimal solution for some applications. In this work, some modifications are applied to this original technique to minimize the adverse effects of those notches on the electrical networks near the Shifted ZCA (S-ZCA). This leads to an overall improvement of the power quality and minimizes the THD, which represents the second main objective achieved in this paper. In addition to the control of SAPFs, their design based on loads and/or SAPF topologies [43] is another important aspect. CFLs are considered as Three-Phase Four-Wire (3P4W) NL loads. Meanwhile, the 3P4W split-capacitor (also called Four-Wire Two-Capacitor or 4W-2C) SAPF topology is used due to their simplicity of control and adaptability to our CFL loads.

Therefore, the continuous pursuit to improve power quality in Low Voltage (LV) electrical networks supplying NL CFL

loads has motivated researchers to develop advanced active power filter topologies and control techniques. The main objective is to mitigate the current harmonics injected by CFLs, thus enhancing the overall power quality. To achieve this objective, this paper presents two advanced current controllers implemented in a 3P4W split-capacitor SAPF topology connected to an LV electrical network, as follows:

- First, a Fuzzy Hysteresis Current Controller (FHCC) based on Fuzzy Logic Control is proposed to overcome the limitations of conventional HCC by eliminating manual hysteresis band tuning and enabling real-time adaptive adjustment. This reduces THD, improves reactive power compensation, and overall power quality.
- Second, a modified modulated hysteresis current control strategy is introduced for SAPFs to address high ripple content and current notches observed near the zero-crossing area. By adapting hysteresis band modulation around the S-ZCA, the proposed approach significantly improves source current waveforms and minimizes THD.

The effectiveness of the proposed controllers is evaluated through MATLAB®/Simulink simulations and further validated using real-time implementation on the Hardware-in-the-Loop (HIL) platform, especially the Typhoon HIL402 device. Comparative analysis with conventional HCC shows significant improvements of the SAPF performance, such as THD reduction, optimization of switching frequency, while ensuring compliance with international standards.

The remainder of this paper is structured as follows. Section II presents the description of the system and impact of the CFLs using conventional HCC. After investigating the issue of power quality near the S-ZCA with HCC, the problem formulation is given. Section III discusses the theoretical background and application of the proposed FHCC approach. Although the power quality in terms of THD is improved compared to conventional HCC, notches near the S-ZCA still exist with FHCC. To compensate for this issue, Section IV introduces the new MHCC technique and explains its operating principle. Section V presents the result for another type of nonlinear diode-bridge rectifier with RL load. In Section VI the validation and performance investigation of the MHCC technique using numerical simulations are given along with a discussion and a comparison of the results. Finally, Section VII concludes the article with key findings and future research directions.

II. SYSTEM OVERVIEW AND PROBLEM STATEMENT

In this section, we focus on both power-stage for real CFL NLs and control-stage of the overall system. The SRF-based

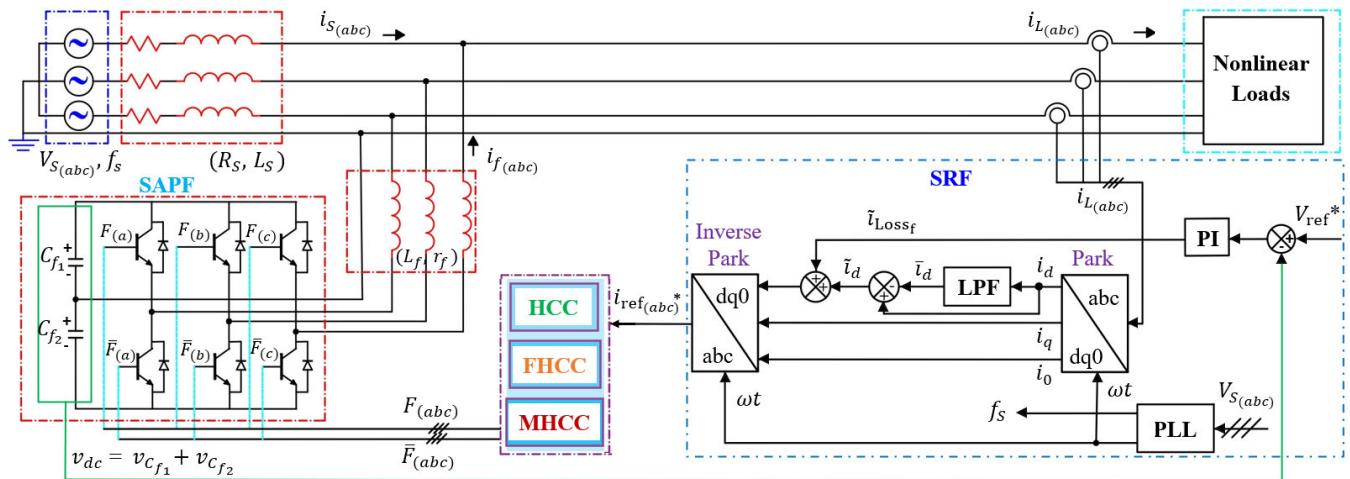


FIGURE 2. Schematic circuit diagram of a 3P4W split-capacitor SAPF with SRF and different current controllers HCC, FHCC, and MHCC for CFLs load.

TABLE 2. Power-stage system parameters.

Parameters	Value
Source voltage and frequency (V_S, f_S)	400 V, 50 Hz
Source impedance (L_S, R_S)	1 mH, 2 m Ω
Filter inductance (L_f, r_f)	0.1 mH, 1 m Ω
DC-link capacitor (C_{f1}, C_{f2})	2200 μ F, 2200 μ F
DC-link Reference voltage V_{ref}^*	600 V
Switching frequency (f_c)	10 - 12 kHz
Nonlinear load (P, Q, PF)	1.5 kW, 2.23 kVA, 0.655

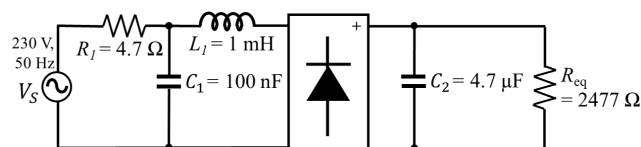


FIGURE 3. Electrical equivalent circuit model of one CFL lamp.

conventional HCC shows some issues in power quality and also provides an opportunity for improvement.

A. SYSTEM DESCRIPTION WITH IMPACT OF CFLs

As illustrated in FIGURE 2 the CFLs loads are powered with a 3P4W main source and the SAPF is connected at the point of common coupling (PCC) to inject compensating current $i_{f(abc)}$ into this point. The compensating currents are generated by extracting the harmonic components present in the NLs load current $i_{L(abc)}$, but phase-shifted by 180° . This effectively cancels out the harmonic currents within the system, ensuring that the source current $i_{S(abc)}$ remains free from harmonics. To achieve this, the NLs currents are measured to determine their harmonic levels which are then utilized to calculate the reference compensating currents $I_{\text{ref}(abc)}$ *. These currents are used to control the switching $F_{(abc)}$ and $\overline{F}_{(abc)}$ of the power devices in the SAPF. TABLE 2 summarizes the power-stage parameters of the system.

While the majority of published studies on SAPF and HAPF systems evaluate their controllers using generic

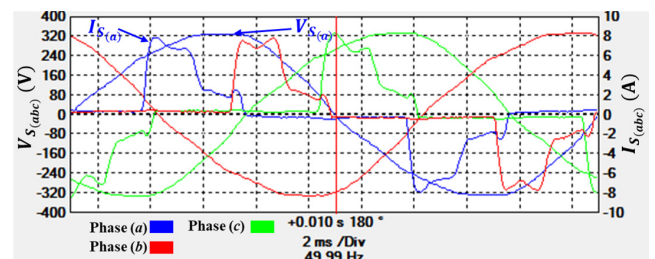


FIGURE 4. Experimental three-phase voltages and currents waveforms with 25 parallel CFLs in each phase.

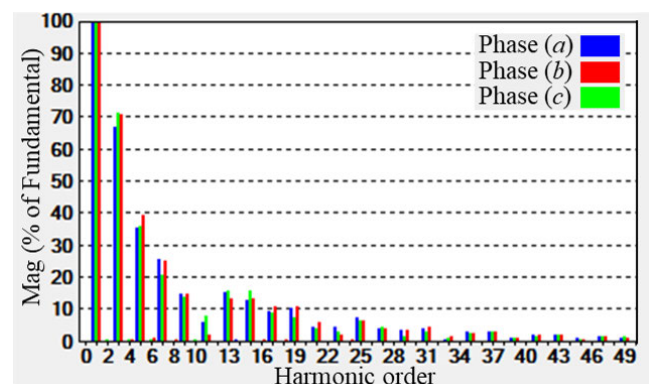


FIGURE 5. Experimental harmonic spectrum for three-phase currents.

nonlinear loads—most commonly three-phase diode or thyristor rectifiers—this configuration does not reflect the behavior of practical lighting loads. Consequently, direct comparison with such works is not always representative. In contrast, the present study focuses specifically on compact fluorescent lamps, and more precisely on the GE 20 W CFL model, whose harmonic and dynamic characteristics differ significantly from classical rectifier-based nonlinear loads.

In this work, each phase contains 25 CFLs in parallel. To evaluate the impact of the real CFL load on the grid, the equivalent circuit model of the lamp is needed.

Several previous research studies [44], [45] have employed simulation and identification techniques to validate the equivalent electrical model of real CFL lamps. As shown in FIGURE 3, the equivalent model of one 20 W CFL from the General Electric brand, operating under a 230 V power supply system, has been extensively analyzed [46]. This model consists of key electrical components such as capacitances (C_1 , C_2), resistances (R_1 , R_{eq}), inductance (L_1), and rectifier which collectively represent the behavior of the lamp under different operating conditions. With 25 parallel CFLs in each phase, the experimental measurements of the voltage, current waveforms and harmonic spectrum show 86.2%, 88.5%, and 90.4% THD, respectively, for phase (a), phase (b) and phase (c) as given in FIGURE 4 and FIGURE 5. The results, which have been documented in previous research [10], provide a reliable basis for further studies on the impact of NLs such as CFLs on power quality.

B. SRF-BASED CONVENTIONAL HCC

The SRF theory is extensively used for the extraction of fundamental (appears as a DC quantity) and harmonic (manifest as AC ripple) components from load currents as shown in FIGURE 2. In this approach, measured three-phase nonlinear load currents $i_{L(abc)}$ are transformed from the stationary abc frame into the rotating $dq0$ reference frame using Park's transformation [47]. These two current transformation blocks are synchronized with the grid voltage $V_{S(abc)}$ by a Phase-Locked Loop (PLL) system; which provides the instantaneous phase angle $\theta = \omega t$ and the source frequency f_c simultaneously. To achieve this extraction, a closed-loop Low Pass Filter (LPF) in the $dq0$ domain effectively separates the fundamental component $\tilde{i}_d$ from the harmonic content $\tilde{i}_d$, allowing precise reference current generation for compensation in the $dq0$ frame. Subsequently, these are transformed back into the stationary abc frame via the inverse Park transformation to produce the reference signals $i_{ref(abc)}$ for the current controller of SAPF.

The DC-link voltage controller acts as an energy manager, keeping the capacitor charged just enough for the inverter to work properly. Using a Proportional-Integral (PI) compensator, it automatically corrects any drop or rise in voltage by slightly adjusting the active power drawn from the grid to offset inverter switching and capacitor leakage losses $\tilde{i}_{Lossf}$. This steady and loss-compensated voltage supply allows the filter to respond quickly and accurately to harmonic and reactive power demands. In HCC, the measured filter currents $i_{f(abc)}$ are subtracted from the reference signals and passed through constant HB comparator to generate gate signals for the switches as shown in FIGURE 6. From the development and implementation of HCC, the switching frequency f_c and the duty cycle D vary depending on several parameters (such as input voltage, HB, components values, etc.). A study based on the quasi-static approach is conducted to determine the quasi-stationary values of the switching frequency of the switches.

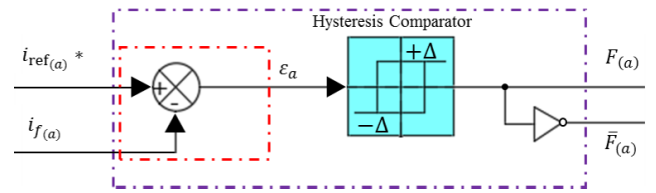


FIGURE 6. Block diagram of the conventional HCC for phase a.

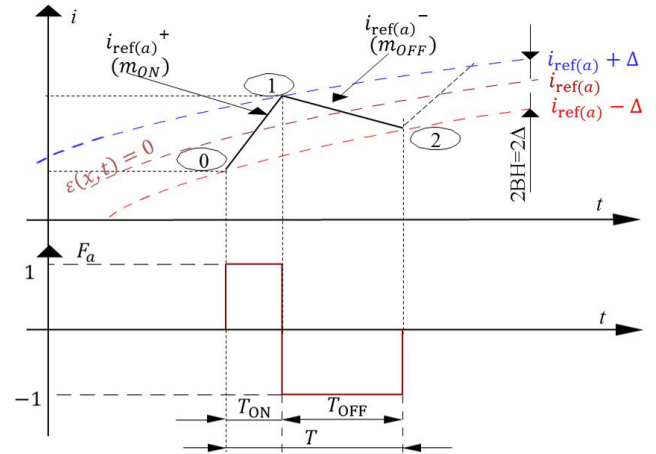


FIGURE 7. Stable operating surface of the HCC determining the switching frequency f_c .

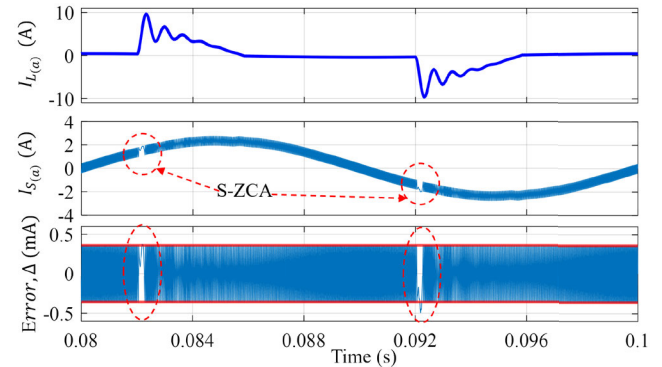


FIGURE 8. Waveforms of the load current, source current, and error signal for phase a after connecting the HCC controlled SAPF.

Assuming operation in HCC and taking 2Δ as the width of the hysteresis window, the waveforms of the switching function $\varepsilon(x, t)$ (the error) can be described as triangular signals, as shown in FIGURE 7, where f_c represents the switching frequency and can be expressed according to (1) [41], [48].

$$f_c = \frac{1}{T} = \frac{1}{T_{ON} + T_{OFF}} = \frac{1}{2\Delta} \cdot \frac{m_{ON} \cdot m_{OFF}}{m_{ON} + m_{OFF}} \quad (1)$$

where T_{ON} and T_{OFF} represent the duration of the switching intervals; given that $F = 1$ for the "ON" state and $F = 0$ for the "OFF" state, with the total duration $T = T_{ON} + T_{OFF}$. In addition, m_{ON} and m_{OFF} are the slopes of rise and fall of the error signal $\varepsilon(x, t)$, and Δ is the constant width of the HB.

C. PROBLEM FORMULATION

To further analyze and closely examine the error signals of the HCC, FIGURE 8 presents simulation results only for phase a with the generated error signal. Similarly other two phases (phases b and c), are shifted by $+120^\circ$ and -120° , respectively, with respect to phase a . The sinusoidal waveforms of the source current after connecting the SAPF are determined by the forward current of the error signal of the HCC and therefore, a constant error current regulation is mandatory to obtain a well sinusoidal waveform at the source. Variable frequency control, such as HCC, offer the advantage of a fast system response to parameter variations.

However, and as observed in FIGURE 8, when using a constant hysteresis width for HCC, harmonic distortions appear close to the Shifted Zero-Crossing Area (S-ZCA) of the input voltage (see the red notch). These distortions become more significant at lower output CFLs current and power levels. This affects power quality and destroys the sinusoidal waveforms and the desirable operation of the SAPF. It should be noted that those notches are also noticed in several previous research works, with different command and control techniques. To mitigate this problem, near this S-ZCA some modifications in a new technique that has been developed and implemented in [41], [42] are necessary. In this paper, this new technique will be modified and applied to the SAPF near the S-ZCA.

III. FUZZY HYSTERESIS CURRENT CONTROLLER (FHCC)

To generate the switching signal $F_{(abc)}$ and $\bar{F}_{(abc)}$ for the SAPF, various techniques have been explored in the literature, such as the HCC [49], the PWM controller [31], and the adaptive current controller [50]. Although the HCC method is simple and easy to implement, it has the drawback of high and uncontrollable variable switching frequencies. These high frequencies impose significant stress on power IGBT devices and result in substantial switching losses. The advantages of operating at a fixed switching frequency f_c is typically executed through software using system parameters. However, to ensure sufficient and precise control, a deep understanding of the operating conditions is required. Therefore, for our specific application, an FHCC is used to enhance the performance of these control approaches. This fuzzy technique aims to minimize deviations between reference currents $i_{ref(a)}^*$ and actual currents $i_{f(a)}$ absorbed by the SAPF while maintaining a constant frequency. The FHCC depend on the dynamic adjustment of the HB width to maintain a consistent switching frequency f_c . This strategy has been successfully employed in various applications, such as three-phase machine current control [51] and grid on/off photovoltaic (PV) system control [52], [53].

A. GENERATION OF THE SWITCHING SIGNALS

Establishing a FHCC controller involves predefining input/output parameters. In our case, the source voltage $V_{S(a)}$ and the slope of the filter current $d(i_f(a)^*)/dt$ are

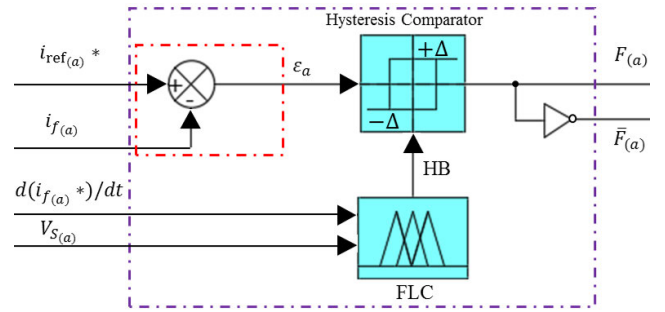


FIGURE 9. Block diagram of the fuzzy hysteresis control for phase a .

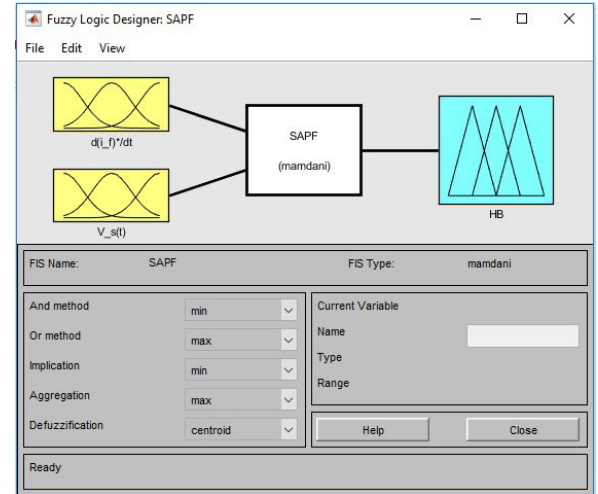


FIGURE 10. The architecture of the fuzzy input/output parameter adjustment mechanism in MATLAB®.

TABLE 3. FHCC control rules for inputs $V_{S(abc)}$, $di_{f(abc)}/dt$ and output HB.

HB	$d(i_f^*)/dt$				
	NL	NM	ZE	PM	PL
$V_s(t)$	NL	SP	SP	MP	SP
	NM	SP	MP	LP	MP
	ZE	VSP	MP	VLP	MP
	PM	SP	MP	LP	MP
	PL	SP	SP	MP	SP

selected as inputs, while the HB is chosen as the output, as illustrated in FIGURE 9, which represents the FHCC control principle. FIGURE 10 shows the architecture of the fuzzy input/output parameter adjustment mechanism in MATLAB®. The fuzzy logic controller can be designed with five fundamental membership function types: triangular, trapezoidal, sigmoid, Gaussian, and Gaussian bell. After a comparative study of harmonic compensation performance under stable and transient load conditions in the literature, it was observed that triangular membership functions provide the best results [52].

The next level of the control principle is to determine the set of linguistic values associated with each input/output variable for control purposes.

The membership functions of the input and output variables are illustrated in FIGURE 11, visually representing how each linguistic value relates to its corresponding variable.

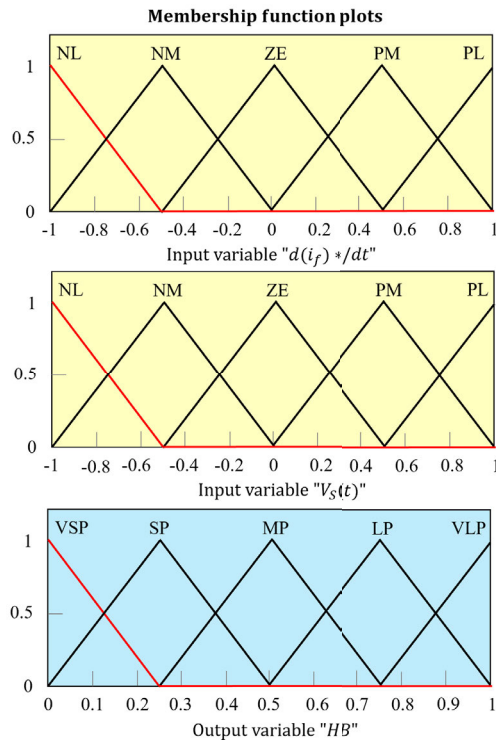


FIGURE 11. The linguistic values associated with each input and output variable for the control system. Input: NL – Negative Large, NM – Negative Medium, ZE – Zero, PM – Positive Medium, and PL – Positive Large. Output: VSP – Very Small Positive, SP – Small Positive, MP – Medium Positive, LP – Large Positive, and VLP – Very Large Positive.

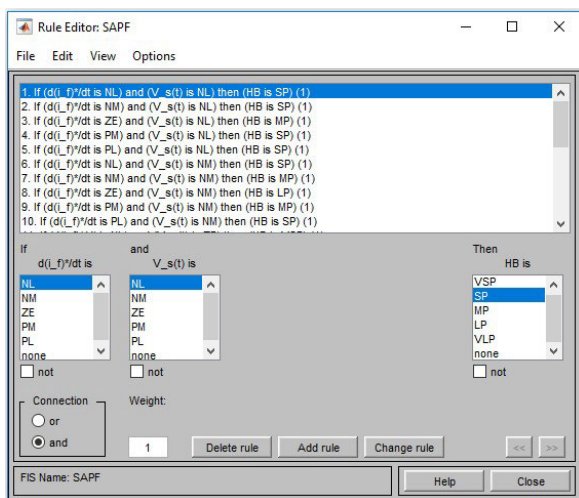


FIGURE 12. The first ten FHCC rules for the HB.

Finally, the set of resulting rules is presented in TABLE 3, where a total of twenty-five rules is written and integrated into the FLC. The first ten rules are shown in FIGURE 12, which illustrates the rule editing process of the FLC in the fuzzy rule adjustment mechanism under MATLAB®. Therefore, for our specific application, an FHCC is used to enhance and refine these control approaches. This fuzzy technique aims to minimize the deviations between the calculated (reference) currents and the practical (actual) currents absorbed by the

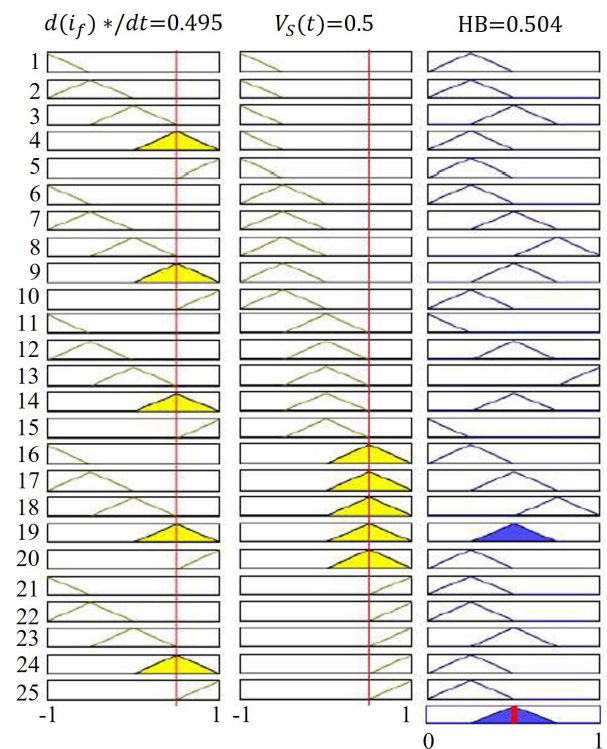


FIGURE 13. Surface of fuzzy rule sets with adjustment mechanism under the MATLAB® fuzzy rule set mechanism.

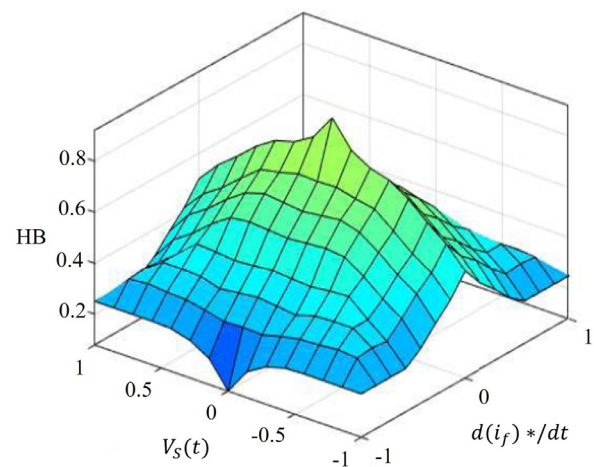


FIGURE 14. 3D surface plot of the FHCC for the HB.

SAPF while maintaining a constant frequency. The FHCC relies on the dynamic adjustment of the HB width to ensure consistent f_c . This methodology has been successfully applied in various fields, such as controlling the currents of a 3P machine and regulating a grid-connected PV system. A set of weighted fuzzy “if – Then” rules (5×5) has been designed to keep the HB constant, thereby maintaining a stable switching frequency f_c . FIGURE 13 illustrates the surface plots of the designed FHCC for the HB in one case with varying input parameters. Additionally, FIGURE 14 presents the 3D plot of this controller.

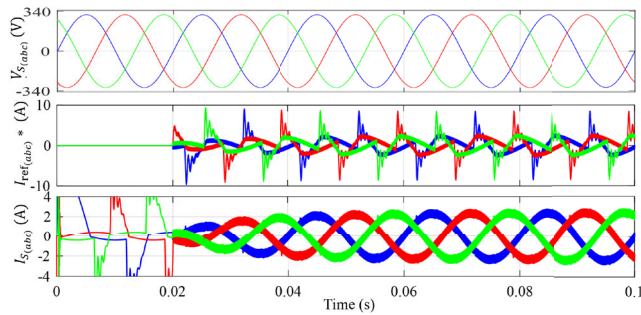


FIGURE 15. Waveforms of the source voltage, the compensating currents, and source currents after filtering using the FHCC method.

B. PERFORMANCE EVALUATION

The system is simulated and analyzed using MATLAB[®] along with the Simscape Power System Toolbox for this new configuration. The fuzzy logic library is used specifically with the pre-configured data from the previously studied FLC. The circuit diagram of the system implementing the FHCC technique is illustrated in FIGURE 2, which presents the complete block diagram of the system studied in this manuscript, including the overall main power circuit, the reference current calculation block using the SRF method, and finally, the proposed hysteresis modulation block based on fuzzy logic controller. Referring to a personal choice the instant $t = 0.02$ s is the time where the SAPF is activated.

To investigate and evaluate the proposed technique, particularly in terms of its ability to compensate for reactive power and harmonic distortions caused by CFLs in the electrical network, the results obtained are compared to those of the conventional HCC-based SAPF in our previous work [54]. For consistency, in this study the same conditions and parameter values as in the previous paper are applied.

Following this study and after connecting the SAPF to the system at $t = 0.02$ s, it is evident from FIGURE 15 and that the source current waveforms become nearly sinusoidal. This confirms that the conventional algorithm used in this work successfully compensates for harmonic disturbances by injecting harmonic currents of equal magnitude but in opposite phases into the electrical network. Furthermore, the voltages and the source currents waveforms are in phase, as shown in the same figures, leads to a Power Factor (PF) close to 1.

FIGURE 16(a), and FIGURE 16(b) illustrate the harmonic spectra of the currents before and after connecting the SAPF using the FHCC technique. FIGURE 16(b) illustrates that the A_{THD} of the current is reduced to 1.73% after compensation, instead of $A_{THD} = 2.18\%$ with the simple hysteresis controller [10], which indicate a significant improvement in power quality meeting the criteria defined in Institute of Electrical and Electronics Engineers (IEEE) and International Electrotechnical Commission (IEC) standards [55], [56]. Additionally, the fundamental amplitude values of the current for phase (a) remain almost unchanged before and after the instant $t = 0.02$ s, with $I_s = 2.466$ A and $I_s = 2.381$ A. This leads that the studied SAPF exclusively injects harmonic

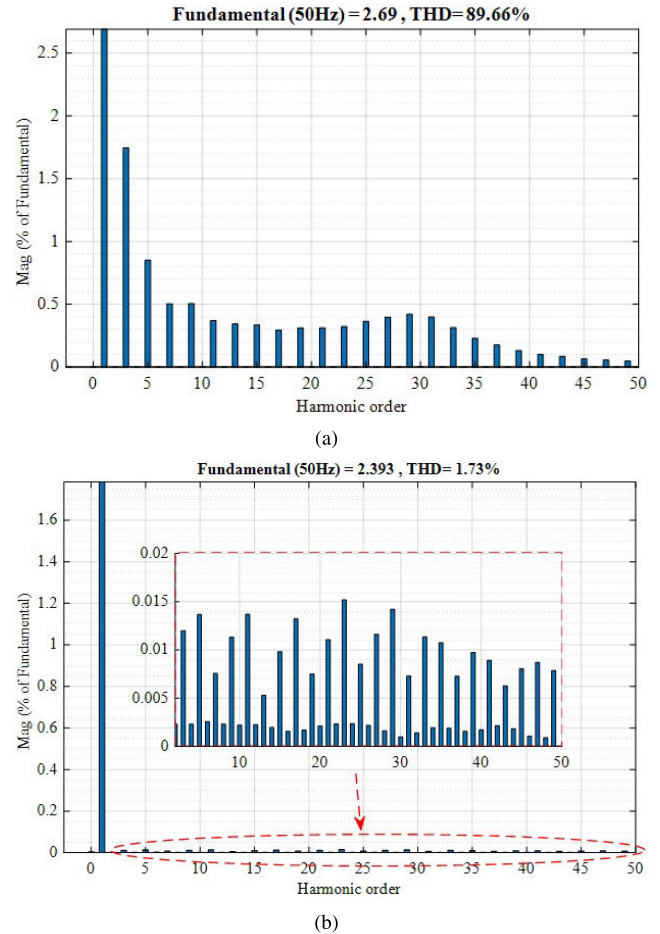


FIGURE 16. Harmonic spectrum of the source current (a) before and (b) after filtering for phase a.

currents, while the network only supplies the fundamental component of the NLs CFLs currents. TABLE 4 presents the currents and their harmonic phases at different points of the SAPF up to the 21st harmonic order.

It is noteworthy that the harmonics generated by the SAPF using the FHCC have the same amplitude but are in opposite phases to those of the CFL loads. This confirms that the compensation philosophy is well respected and is achieved successfully with this control technique. As a result, the FHCC strategy has shown better performance in terms of injected currents in the low voltage electrical network compared to the fixed HB strategy (HCC) developed and studied in [10] which represents the first goal achieved in this paper.

IV. NOVEL MODULATED HYSTERESIS CURRENT CONTROLLER (MHCC)

As it is well known and as indicated in (1), reducing the HB width Δ leads to an increase in the switching frequency f_c . This is not the preferred choice in this case. Unlike what was previously studied, in this section, the modulating hysteresis current controller (MHCC) will not be applied to the ZCA (i.e., at the instant $t = n\pi$), but instead, it will be applied

TABLE 4. Currents and their harmonic phases at different points of the SAPF before and after compensation with the FHCC technique.

Range	Frequency (Hz)	Before (THD = 89.66%)		Compensation Current		After (THD = 1.73 %)	
		Amplitude (A)	Phase (°)	Amplitude (A)	Phase (°)	Amplitude (A)	Phase (°)
1	50	2.69	37.30	1.65	-81.30	2.39	-0.10
3	150	1.74	-88.60	1.75	91.50	0.0	0.0
5	250	0.85	170.1	0.85	-9.0	0.01	142.8
7	350	0.50	111.5	0.54	-68.1	0.01	-42.0
9	450	0.50	33.20	0.53	213.4	0.0	0.0
11	550	0.37	-46.30	0.40	133.9	0.01	-32.80
13	650	0.34	247.5	0.39	66.60	0.01	129.70
15	750	0.34	167.4	0.40	-13.70	0.0	0.0
17	850	0.29	93.90	0.39	269.2	0.01	95.6
19	950	0.31	20.20	0.45	192.5	0.0	0.0
21	1050	0.31	-59.40	0.54	104.90	0.0	0.0

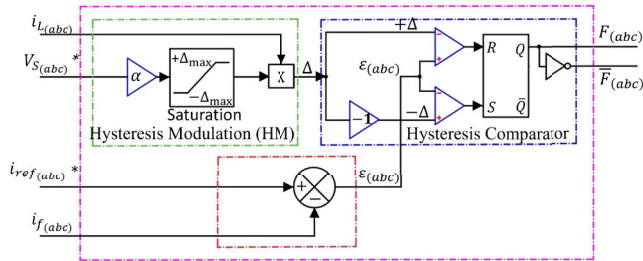


FIGURE 17. Block diagram of the new MHCC for a 3P4W SAPF.

at the instant $(t = (n.\pi) + \tau)$ (i.e., near the S-ZCA). Here, τ represents the disturbed zone where the anomaly occurs, and it is expressed in seconds (s). This technique involves adding an additional feedforward loop in the control level to adjust the hysteresis window Δ using the calculated current of NLs CFLs, as illustrated in FIGURE 17. Also, this technique utilizes an RS flip-flop, to generate the switching signals for the SAPF IGBT switches.

A. THE MODIFIED CONTROL TECHNIQUE

As shown in FIGURE 17, the hysteresis control law is given as follows:

$$F_{(abc)}(t) = \begin{cases} 0, & \text{if } \varepsilon_{(abc)}(t) > +\Delta, \\ & \text{or } \varepsilon_{(abc)}(t) < \Delta \text{ and } \varepsilon_{(abc)}(t^{-1}) = +\Delta \\ 1, & \text{if } \varepsilon_{(abc)}(t) > -\Delta, \\ & \text{or } \varepsilon_{(abc)}(t) < \Delta \text{ and } \varepsilon_{(abc)}(t^{-1}) = -\Delta \end{cases} \quad (2)$$

The input current error is defined as $\varepsilon(abc) = i_{ref(abc)} * -i_{f(abc)}$, which is also the input of the hysteresis comparator. The term t^{-1} indicates the last point in time when the control signal reached the flipping output limits defined by $\pm\Delta$. Then to avoid harmonic distortion near the S-ZCA of the NLs CFLs lamps currents $i_{L(abc)}((\pi/2) + \tau)$ and $i_{L(abc)}(\pi + \tau)$ for all current levels $i_{L(abc)}$, two modulations are applied to the hysteresis window Δ . The first modulation considers the time-varying input line voltage $V_{S(abc)} *$ (the same as $V_{S(abc)}$ but shifted by (τ)), while the second modulation depends on the reference currents of the CFLs lamps $i_{L(abc)}$. Consequently, the modified hysteresis width $\Delta(t + \tau)$ near the S-ZCA (τ) can

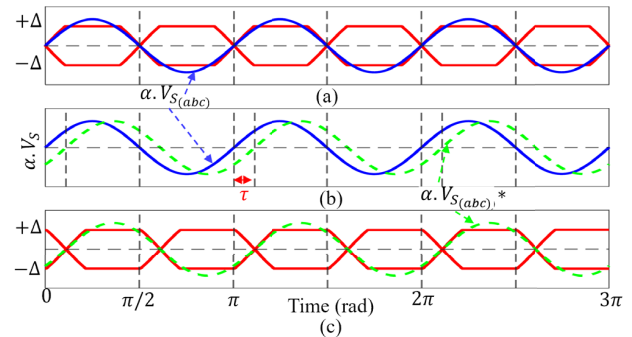


FIGURE 18. The evolution of the new constant quasi-trapezoidal modulated hysteresis window Δ , in terms of the normal and shifted source voltages, respectively $V_{S(abc)}$ and $V_{S(abc)} *$: (a) Near the ZCA, (b) The phase shift between $V_{S(abc)}$ and $V_{S(abc)} *$, (c) Near the studied S-ZCA (shifted by (τ)).

be expressed as follows:

$$\Delta(t + \tau) = \begin{cases} \alpha \cdot V_{S(abc)} \cdot i_{L(abc)}, & \text{if } \alpha \cdot V_{S(abc)}(t + \tau) \cdot i_{L(abc)} < \Delta_{max} - \varepsilon_{(abc)} \\ \Delta \cdot i_{L(abc)}, & \text{if } \alpha \cdot V_{S(abc)}(t + \tau) \cdot i_{L(abc)} > \Delta_{max} - \varepsilon_{(abc)} \end{cases} \quad (3)$$

The output waveforms of the modulated hysteresis window $\Delta(t)$ and the shifted modulated hysteresis window $\Delta(t + \tau)$ are illustrated in FIGURE 18(a) and FIGURE 18(c) respectively in terms of the normal source voltages $V_{S(abc)}$ and the shifted one $V_{S(abc)} *$ respectively, near the ZCA and the studied area of S-ZCA as shown in FIGURE 18(b).

Here, (τ) is a constant that varies between 0 and $\pi/2$. Since the error waveforms $\varepsilon(abc)$ can be approximated as triangular during a normal switching cycle, the switching frequency f_c of the SAPF can be expressed similarly to the case of a simple hysteresis band (see (1)). The values of α and Δ_{max} are chosen to ensure that f_c remains within a desired predefined range. With this modified approach, a minimum switching frequency is achieved near $t = n.\pi$, while a highest switching frequency is obtained near the S-ZCA at $t = ((n.\pi) + \tau)$, which leads to harmonic compensation in those areas. Therefore, near the S-ZCA, both the upper and lower switching boundaries adjust their direction and amplitude,

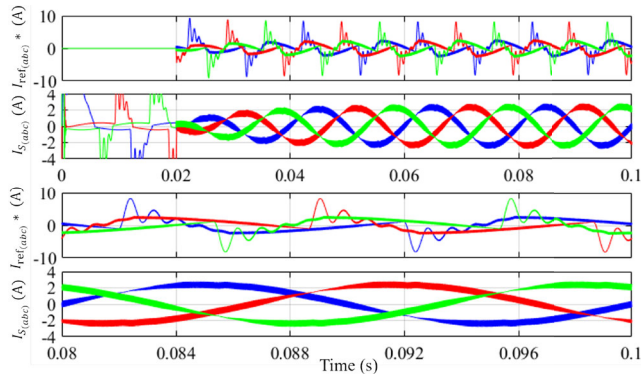


FIGURE 19. Waveforms of three-phase reference and source currents after compensation with the MHCC. Upper: 5 cycles, Lower: zoom of 1 cycle.

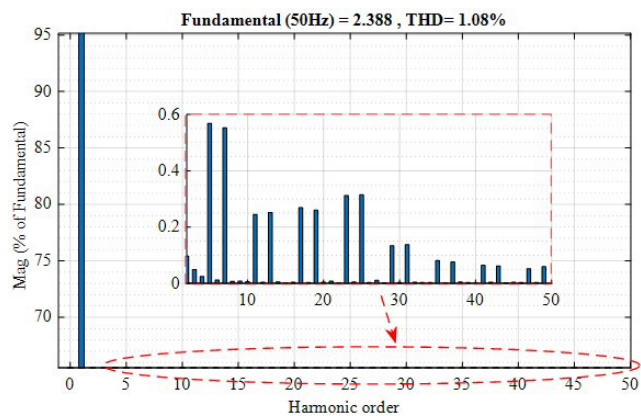


FIGURE 20. Harmonic spectrum of the source current after filtering for phase *a* with MHCC.

reaching zero when necessary. This adaptive behaviour minimizes steady-state error and effectively mitigates the notch phenomenon. By improving the power waveform near the S-ZCA region, the MHCC significantly improves the power quality of the LV network grid.

B. PERFORMANCE EVALUATION

As in the previous work, the same loads and source parameter are used in this new arrangement. An SAPF is connected between the source and the CFLs loads. This filter consists of three main parts: first, the power stage, a two-level inverter also called a Voltage Source Inverter (VSI) with a midpoint capacitor, the computation block containing the SRF control strategy, and finally the modified MHCC block to generate the VSI control pulses. The system is simulated using MATLAB®/Simulink. TABLE 2, in the previous section, summarizes all the details of the proposed parameters for the load, power system, and SAPF used in this work. The results obtained in this section will be compared with those obtained through the HCC and the FHCC.

For the rest of this paper, it is important to note that the NL is connected to the electrical grid at $t = 0$ s, while the SAPF is connected at $t = 0.02$ s. All parameters are also measured after the connection of the SAPF for this new arrangement.

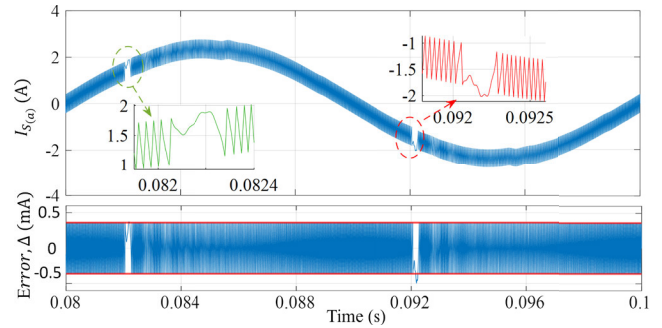


FIGURE 21. Waveforms of the source current and error signal for phase *a* after compensation with the FHCC.

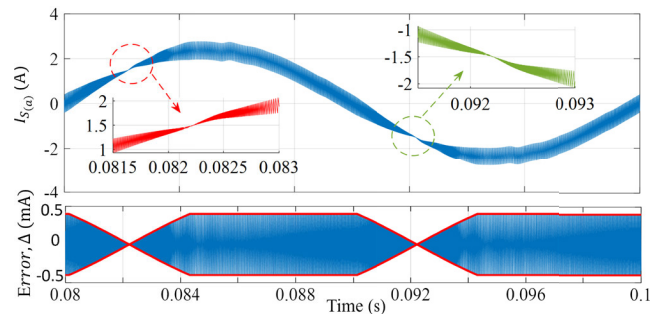


FIGURE 22. Waveforms of the source current and error signal for phase *a* after compensation with the MHCC.

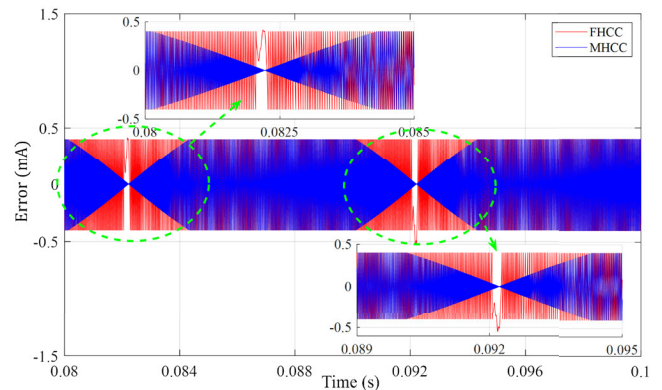


FIGURE 23. Waveforms of the error signal after compensation for phase *a* with FHCC and MHCC (Mixed error signals).

This will allow for a fair comparison of these results by MHCC with those obtained from HCC and FHCC. The results from the various simulation tests of the waveforms of the currents for the SAPF after compensation with the modified new hysteresis modulation control MHCC are presented in FIGURE 19. FIGURE 20 shows their harmonic spectra of the source currents. Additionally, FIGURE 21 and FIGURE 22 presents the same source currents after compensation for phase *a*, respectively, controlled by the HCC and MHCC techniques. To further explore the proposed new technique, the error signals are also presented for both cases: simple FHCC and MHCC near the shifted ZCA zone.

In this MHCC control, we can observe that the use of the shifted (modified) hysteresis modulation window $\Delta(t + \tau)$ in

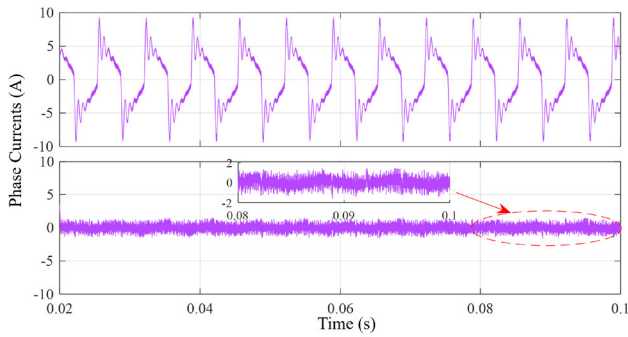


FIGURE 24. Waveforms of the source neutral currents before (upper) and after (lower) filtering using the FHCC.

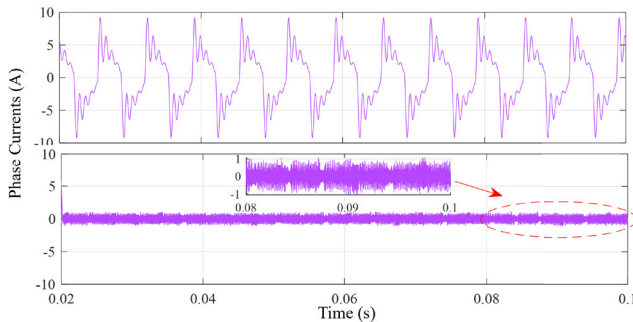


FIGURE 25. Waveforms of the source neutral currents before (upper) and after (lower) filtering using the MHCC.

the system, instead of the fixed fuzzy hysteresis band $\pm\Delta$, can improve the waveform quality of the source currents $i_{S(abc)}$ near the S-ZCA studied. It is clearly noticeable that the system absorbs a good sinusoidal waveform of the source currents $i_{S(abc)}$. This leads to an improvement in the PF and a reduction in the THD to $A_{THD} = 1.08\%$ as illustrated in FIGURE 19, compared to the THD produced by the conventional HCC and the FHCC, which are respectively, $A_{THD} = 2.18\%$ and $A_{THD} = 1.73\%$.

Moreover, to evaluate the effectiveness of the proposed control strategies, the neutral source current was analyzed before and after compensation as shown in FIGURE 24, and FIGURE 25. Prior to compensation, the nonlinear CFL loads cause the circulation of neutral current in the three-phase four-wire system. After applying the shunt active power filter, both FHCC and MHCC techniques significantly reduce the neutral source current. In both cases, the compensated neutral current is regulated within a hysteresis band of $\pm\Delta$ around the reference, leading to a negligible RMS value and a nearly suppressed instantaneous waveform. These results confirm that both the fuzzy and the modulated hysteresis control techniques are effective in mitigating neutral current in three-phase four-wire systems.

The proposed methods aim to mitigate several power quality issues commonly associated with CFL-based lighting systems, including: harmonic distortion due to nonlinear ballast behaviour, reactive power consumption, current notching near the S-ZCA, neutral current amplification in four-wire systems. This results in better filtering performance, with an

TABLE 5. Comparison of SRF-based modulation techniques of SAPF.

Method	Frequency	A_{THD} (%)	PF	Notch
PWM [10]	Fixed	1.62	≈ 1	Yes
HCC [10]	Variable	2.18	≈ 1	Yes
FHCC	Variable	1.73	≈ 1	Yes
MHCC	Variable	1.08	≈ 1	No

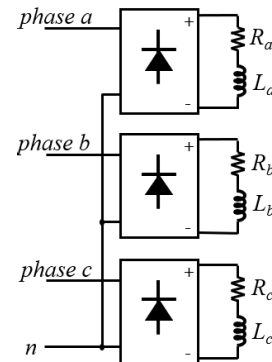


FIGURE 26. Three single-phase full-bridge rectifier RL load for 3P4W system.

improved source current sinusoidality, achieving the lowest THD value compared to other control strategies. Compared with national and international standards, the results obtained adhere well to the limits of these standards. Also, FIGURE 23 represents the mixed waveforms for both control techniques. This confirms that the MHCC technique can provide better results, characterized by small ripples in the shifted ZCA zone as shown in TABLE 5.

V. PERFORMANCE EVALUATION WITH RECTIFIER RL LOAD

In order to further validate the robustness and generalization capability of the proposed control strategies, FHCC and modified MHCC are evaluated under another real and highly nonlinear load type. The considered load consists of three single-phase diode full-bridge rectifiers, each supplying an RL load as shown in FIGURE 26. With $R_a = R_b = R_c = 50 \Omega$ and $L_a = L_b = L_c = 0.1$ mH, connected to the same 3P4W LV distribution system. This configuration is commonly encountered in industrial and commercial installations and is known to generate high current harmonics, load unbalance, and a significant neutral current [57].

When the SAPF is controlled using the FHCC technique, the compensated source currents shown in FIGURE 27 and FIGURE 29(b) become nearly sinusoidal and balanced. The neutral current is significantly reduced and maintained within a narrow band around zero (FIGURE 28 (lower)), demonstrating the effectiveness of the fuzzy-based adaptive hysteresis mechanism in mitigating harmonic and unbalanced components. However, slight current ripples can still be observed in the same figure, which are attributed to the variable switching frequency inherent to the hysteresis-based control, even with fuzzy adjustment of the hysteresis band. On the other hand, before compensation source currents

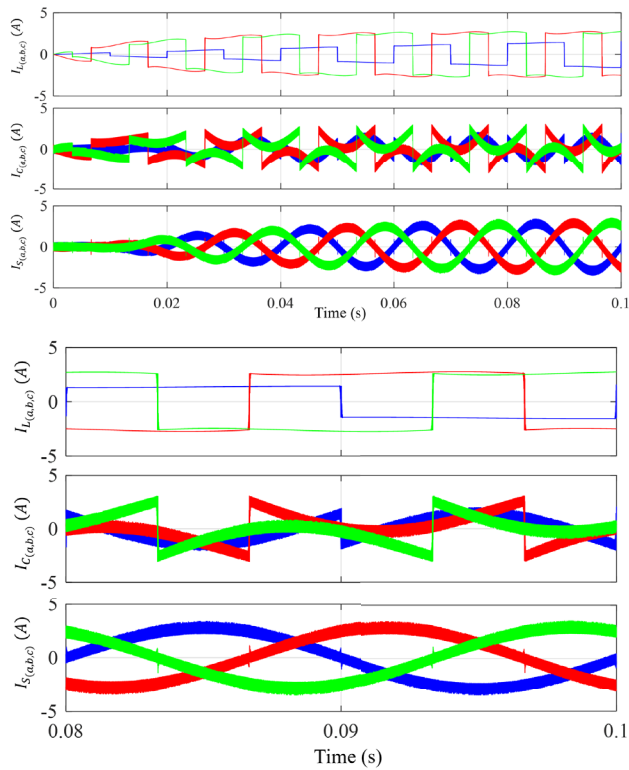


FIGURE 27. Waveforms of three-phase load, compensation and source currents after compensation with the FHCC. Upper: 5 cycles, Lower: zoom of 1 cycle.

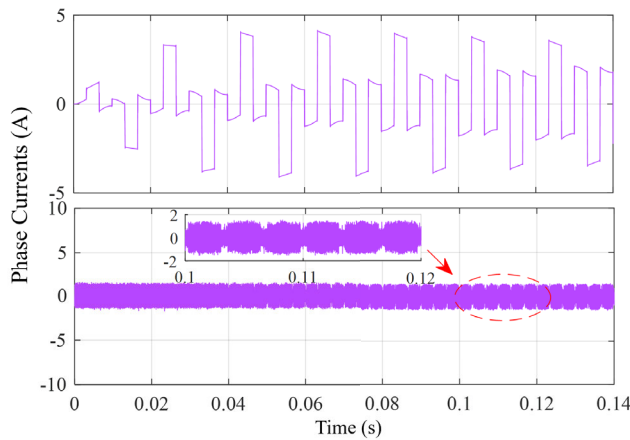
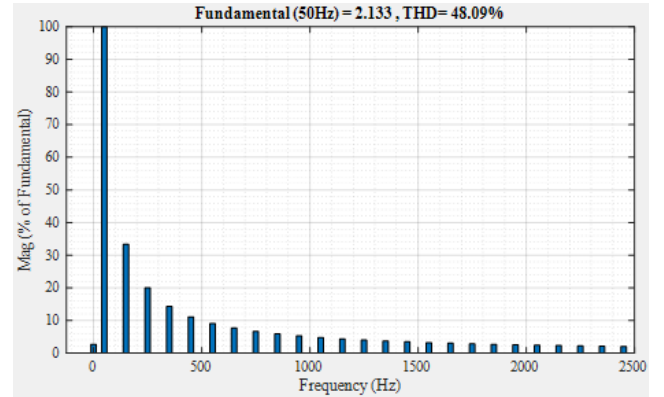


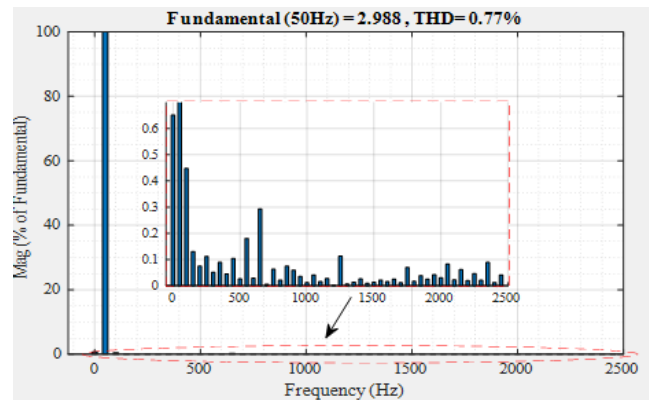
FIGURE 28. Waveforms of the source neutral current before (upper) and after (lower) filtering using the FHCC.

contain pronounced distortion (see FIGURE 29(a), harmonic-rich currents, and a substantial neutral current (in FIGURE 28 (upper)) can be observed due to the rectifier-based loads. The non-sinusoidal nature of the currents confirms the strongly nonlinear behavior of the tested load and highlights the necessity of an efficient compensation strategy.

FIGURE 30 illustrates the system performance under the new proposed MHCC strategy. Compared to FHCC, the source currents exhibit a smoother waveform with reduced ripple and improved sinusoidal shaping specially near the



(a)



(b)

FIGURE 29. Harmonic spectrum of the source current (a) before and (b) after filtering with FHCC for phase *a* with rectifier *RL* load.

S-ZCA. From FIGURE 31, the neutral current is further minimized and remains tightly confined around zero within the modulated hysteresis band $\pm\Delta$. This improvement is mainly due to the analytical modulation of the hysteresis band, which enables better regulation of the switching frequency and enhances current tracking accuracy under rapidly varying nonlinear load conditions near the S-ZCA.

The corresponding harmonic spectra of the source currents, depicted in FIGURE 29(b) and FIGURE 32, confirm that both FHCC and MHCC achieve a substantial reduction in harmonic components introduced by the rectifier loads from 48.09% to 0.77% and 0.62%, respectively with FHCC and MHCC. Nevertheless, MHCC consistently provides lower harmonic magnitude, indicating superior harmonic mitigation capability and improved power quality performance.

Overall, these results clearly demonstrate that both FHCC and the modified MHCC techniques are robust and effective when applied to different nonlinear load types. also, compared with national and international standards, the results obtained adhere well to the limits of these standards While FHCC ensures satisfactory compensation performance, the modified MHCC offers enhanced current quality near the S-ZCA, reduced neutral current, and improved stability under severe rectifier-based loading conditions. This additional validation confirms the suitability of the proposed MHCC

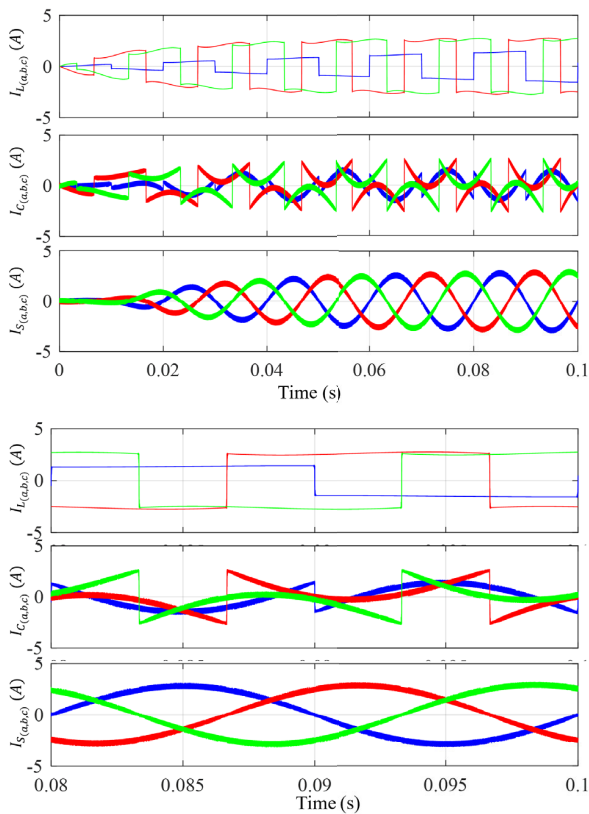


FIGURE 30. Waveforms of three-phase load, compensation and source currents after compensation with the MHCC. Upper: 5 cycles, Lower: zoom of 1 cycle.

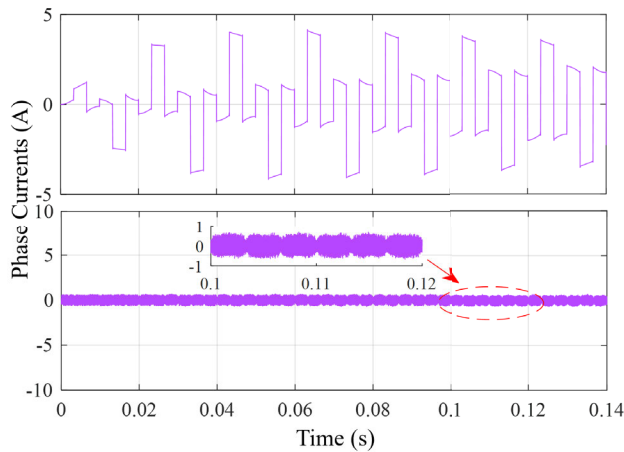


FIGURE 31. Waveforms of the source neutral current before (upper) and after (lower) filtering using the MHCC with rectifier RL load.

strategy for practical power quality improvement in real low-voltage distribution systems supplying diverse nonlinear loads.

VI. VALIDATION OF MHCC USING REAL-TIME HIL IMPLEMENTATION

In this section, we present the validation of the new modified MHCC technique studied in this paper using a HIL simulator device. The results will be compared with those presented in

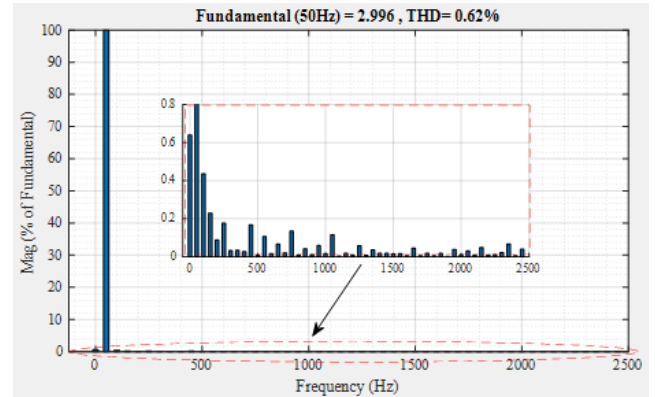


FIGURE 32. Harmonic spectrum of the source current after filtering for phase a using MHCC with rectifier RL load.

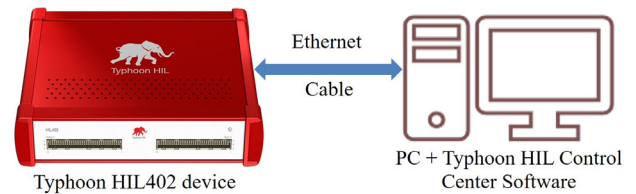


FIGURE 33. The Typhoon HIL-402 device.

the previous sections. Typhoon HIL is a simulator designed for the modeling, simulation, and testing of electrical power systems in real time. It is a cutting-edge tool widely used in power electronics, renewable energy, energy storage systems, and electric grids [58], [59]. As shown in FIGURE 33, the Typhoon HIL-402 is an ideal solution for rapid prototyping and real-time control systems testing. It allows the validation of complex control strategies without risks to physical equipment. Some of its key features include (a) real-time simulation precision, (b) fanless architecture, (c) advanced user interface, (d) support for control systems, (e) risk-free testing capability, etc.

in the context of this paper, the Typhoon HIL-402 is primarily used for modeling and testing the SAPF with the novel modified MHCC technique. The real-time validation is performed with a real-time stepsize of $0.5 \mu s$, ensuring precise replication of the system dynamics. The power circuit and the proposed control algorithm were integrated into a real-time simulation test bench using the HIL Schematic Editor. This SAPF is applied to a three-phase electrical network that powers a load consisting of a three-phase rectifier bridge connected to a RL load. This will allow for effective validation of our control strategies and ensure that power quality requirements are met before practical implementation. Comparative studies with conventional HCC demonstrate that MHCC provides lower THD, and more stable switching behaviour.

The SRF technique was used to generate the reference currents for the SAPF to compensate for the harmonic currents generated by the load on the electrical network. The topology of the inverter in this section is a three-arm

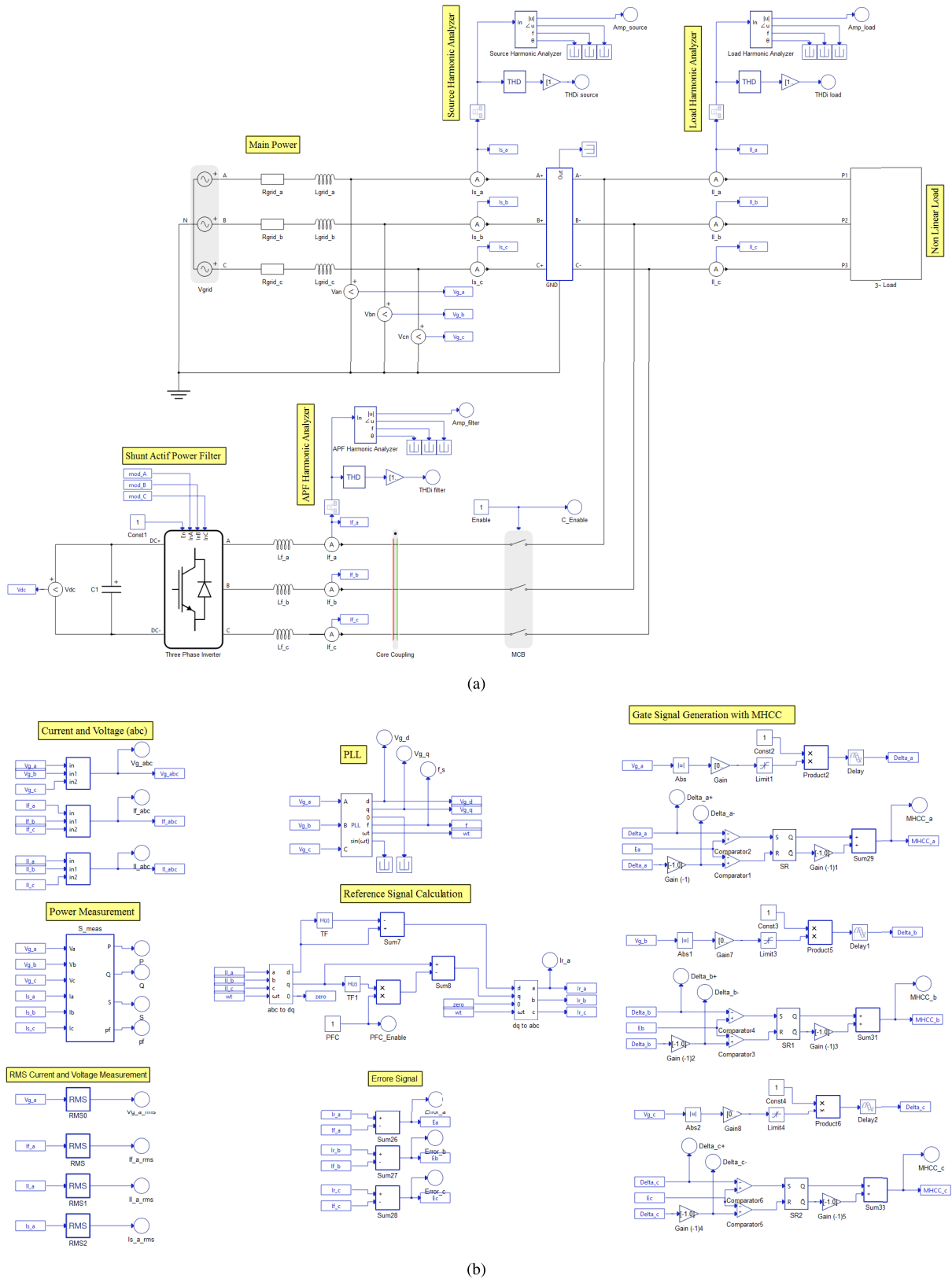


FIGURE 34. (a) The power and (b) control circuit diagram of a 3P4W SAPF with SRF and FHCC under the Typhoon HIL software.

configuration, since the load under study is a three-phase load without a neutral. The parameters used for the load

implementation are respectively $R_2 = 150 \Omega$ and $L_2 = 2 \text{ mH}$, and the parameters of the electrical network are also the same

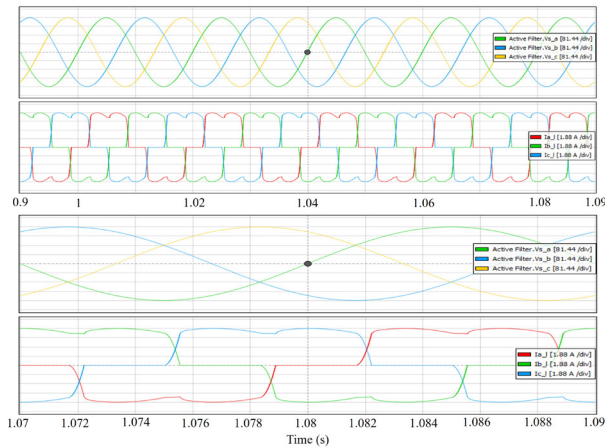


FIGURE 35. Waveforms of the voltages and currents of the grid before compensation using Typhoon HIL. Upper: 5 cycles, Lower: zoom of 1 cycle.

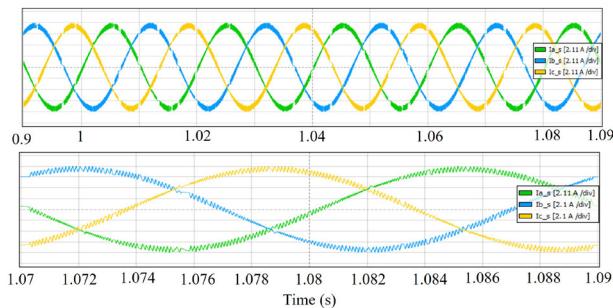
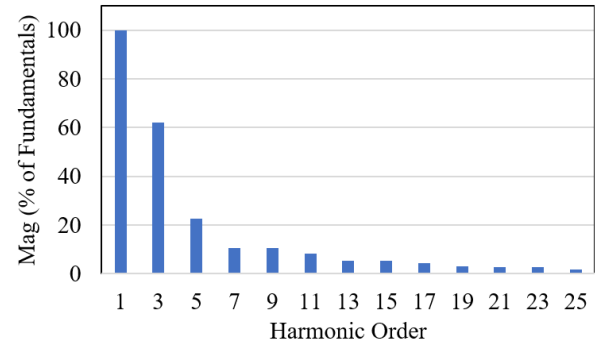


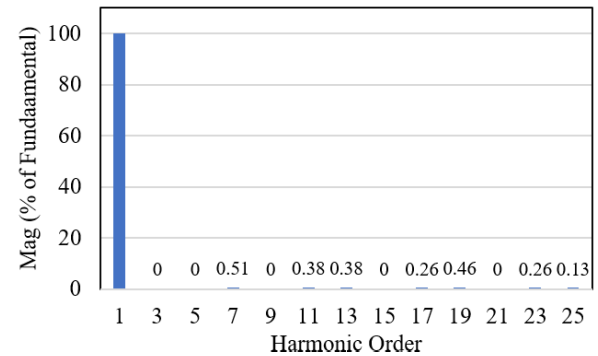
FIGURE 36. Currents waveforms of the grid after compensation under the Typhoon HIL environment. Upper: 5 cycles, Lower: zoom of 1 cycle.

as those indicated in TABLE 2. The power and control circuit diagrams under the HIL Schematic Editor environment are shown in FIGURE 34. The reference currents in this section are generated using the MHCC studied earlier to validate their real-time performance. For the rest of this work, it should be noted that the load and the SAPF are connected to the network at time $t = 0$ s. Supervision, control, and real-time data acquisition are performed through the Supervisory Control and Data Acquisition (SCADA) platform provided by HIL402. A triggering signal is generated in the real-time simulator environment to synchronize the recording of the system variable data. It is important to note that the connection time t of the SAPF can be modified using the same HIL SCADA interface by adding a triggering signal for the active filter linked to the Miniature Circuit Breaker (MCB) switch (enable button). Furthermore, all parameters are measured after the connection of the SAPF for these control techniques and the operation of the SAPF.

FIGURE 35 presents the source currents and voltages before the SAPF connection. Practically, the waveforms of the source currents and voltages, before filtering, have the same shape and amplitude as those found in the MATLAB[®]/Simulink simulation. Therefore, the total harmonic distortion (THD) of the source current signals before filtering is also the same, $\text{THD} = 89\%$. FIGURE 36 shows the



(a)



(b)

FIGURE 37. Harmonic spectrum of the source current in the Typhoon HIL environment (a) before and (b) after filtering for phase a .

source currents after the SAPF connection. After connecting the SAPF, we can see that the source current signals become sinusoidal, indicating that only the fundamental currents circulate in the LV electrical network. Finally, FIGURE 37(a) and FIGURE 37(b) present the harmonic spectra up to rank 25 of the phase current a before and after the SAPF connection respectively. This results in a good PF very close to 1 and a significant reduction in THD (close to 1%).

The numerical simulation and the HIL results demonstrate that the proposed technique offers a faster dynamic response compared to the conventional method, with a reduced THD, when the same conditions are applied to the load and the electrical grid meeting the limits set by IEEE and IEC standards.

This paper focuses on two types of nonlinear loads. In particular, the CFL loads due to their pronounced high-order harmonics higher than 50% and notching behaviour, both MHCC and FHCC techniques offer modulated bandwidth control, lower switching losses, and improved accuracy near zero crossing operating zones or near the critical zone as per for our case. These techniques can be extended to other nonlinear loads (the control strategies are not load-dependent) such as variable-speed drives, electric vehicle chargers, all types of rectifiers with PFC system, grid-connected inverters, and power electronic converters. They may also be integrated into hybrid active filters and multi-level inverter topologies. However, such extensions must consider the fact that the S-ZCA must be well studied and defined, or it is also possible to add a new block to estimate the exact notch time.

Note that both controllers are primarily designed to compensate for classical harmonic and reactive components generated by nonlinear lighting loads. In the present study, the CFL load did not generate significant interharmonics; therefore, interharmonic-oriented testing was not included. Creating a synthetic interharmonic-rich signal and validating the controller is an important extension that will be undertaken in future work. It is also important to note that both the MHCC and FHCC used in this work act exclusively as switching gate signal generation techniques and not as reference-current extraction methods. Therefore, the presence of interharmonics does not directly affect the operation of these controllers as long as the upstream reference-current extraction stage is able to identify and process the interharmonic components.

On the other hand and compared to advanced techniques like Model Predictive Control (MPC) and Sliding Mode Control (SMC), the MHCC method is simpler, requires less computation, and is easier to apply in real time. MPC and SMC are very effective, but they need a complex model, a high sampling frequency, and high computational power. MHCC provides similar performance with much fewer constraints. In addition, unlike MPC and SMC, these techniques cannot reduce the notch in the current behaviour. Our method reduces this notch for the first time in an SAPF, which represents an important improvement in control performance.

VII. CONCLUSION

In this paper, a new modified control technique based on the MHCC is proposed for a 3P4W SAPF with a mid-point capacitor topology. Simulation and practical tests were conducted under HIL equipment to validate the new MHCC strategy, together with the conventional SRF algorithm to determine the reference currents for the SAPF. The results of various simulations and HIL environments performed in this paper clearly demonstrate the good performance of this SAPF with the new control technique implemented. This leads the system to absorb a purely sinusoidal waveform, thus producing the lowest THD value of 1.08% for the source currents, compared to the results of the classical HCC and Fuzzy HCC. Furthermore, this technique also shows good stability and performance under different load conditions such as full-bridge diode rectifier with RL . The harmonics and reactive power are fully compensated for and the neutral current is nearly zero. The results show that the new MHCC technique can replace controllers suffering from complex modeling or slow real-time implementation, either in the ZCA region or in the S-ZCA region. Therefore, the MHCC approach can be considered a general solution for all such types of problem, not only those related to CFLs or LEDs. Future research will explore predictive enhancements to MHCC to estimate the exact time of the S-ZCA, its integration into HAPF, and its application to emerging nonlinear loads of modern lighting (such as LED) in smart-city environments.

ACKNOWLEDGMENT

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