Power Quality Improvement in Distribution Networks with Non-Linear Loads using Shunt Active Power Filter With SRF-Based Control and PI-Tuned DC Link Voltage Regulation

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ABSTRACT

The proliferation of non-linear loads — such as variable speed drives, diode/ Thyristor rectifiers, compact fluorescent lamps (CFLs), uninterruptible power supplies (UPS), and arc furnaces — in modern industrial and commercial distribution systems has led to severe power quality degradation, manifesting as high Total Harmonic Distortion (THD) in supply currents, poor power factor, voltage distortion, and excessive neutral currents. These disturbances result in significant economic losses, equipment overheating, relay mal operation, and reduced energy efficiency. This page proposes a three-phase three-wire Shunt Active Power Filter (SAPF) for comprehensive power quality improvement in a 415 V, 50 Hz distribution network supplying non-linear loads. The proposed SAPF employs the Synchronous Reference Frame (SRF) theory for harmonic reference current extraction and a Proportional-Integral (PI) controller for DC-link voltage regulation. The current control is implemented through a hysteresis band controller generating switching signals for a two-level Voltage Source Inverter (VSI). Detailed modeling and simulation are carried out in MATLAB/ Simulink environment. Simulation results demonstrate that the proposed SAPF effectively reduces supply current THD from 28.43% to 3.21% — well within the IEEE 519-2022 standard limit of 5% — while simultaneouslyimprovingthepowerfactorfrom0.71to 0.98 (lagging) and achieving near-unity displacement power factor. The reactive power compensation capability and dynamic performance under load change conditions are also evaluated, validating the effectiveness of the proposed approach.

Keywords: *Power Quality, Harmonic Distortion, Non-Linear Loads, Shunt Active Power Filter (SAPF), Total Harmonic Distortion (THD), Synchronous Reference Frame (SRF), Hysteresis Current Controller, DC Link Voltage, Voltage Source Inverter(VSI),IEEE519-2022.*

I. INTRODUCTION

Electric power quality has emerged as one of the most critical concerns in modern power distribution systems. The widespread adoption of power-electronic-based loads in industrial, commercial, and residential sectors has fundamentally altered the nature of current drawn from the supply network .Unlike linear loads—resistors ,inductors , and capacitors — which draw sinusoidal currents in proportion to applied sinusoidal voltage, non-linear loads draw currents that are non-sinusoidal, even when supplied with a perfectly sinusoidal voltage [1].

These non-sinusoidal currents contain harmonic component satinteger multiples of the fundamental supply frequency(50HzinIndia).When these harmonic currents flow through the network impedance, they produce harmonic voltages at the Point of Common Coupling (PCC), distorting the supply voltage and adversely affecting all other loads connected to the same bus. The consequences of harmonic pollution are severe and well-documented: increased copper losses in transformers and cables, overheating of neutral conductors due to triplen harmonics, reduced torque and efficiency in AC motors, false tripping of protective relays, interference with communication systems, and reduced metering accuracy [2].

In India specifically, the rapid industrialization and the proliferation of adjustable speed drives in manufacturing, IT equipment in commercial buildings, and LED/CFL lighting in residential areas have dramatically worsened power quality in distribution networks. The Central Electricity Authority (CEA) and Bureau of Energy Efficiency (BEE) regulations increasingly emphasize compliance with harmonic standards, making effective harmonic mitigation an engineering and regulatory necessity.

Traditionally, passive LC filters have been used for harmonic mitigation. However, passive filters suffer from well-known disadvantages: fixed compensation

Characteristics that do not adapt to load variations, risk of resonance with the network impedance,over compensation o freactive power at fundamenta lfrequency ,largesizeand weight,and degraded performance with network parameter variations [3]. These limitations have motivated research into active power filtering solutions.

Active Power Filters (APFs) overcome the limitations of passive filters by using power electronic converters to inject compensating currents or voltages at the PCC. Among various APF topologies — series, shunt, and hybrid—the Shunt Active Power Filter (SAPF) is the most widely deployed due to its ability to simultaneously compensate harmonic currents and reactive power while protecting the supply from load-generated disturbances[4].

The performance of a SAPF critically depends on two aspects: (1) the harmonic detection algorithm used to extract the reference compensation current, and (2) the current controller that forces the actual injected current to track this reference. Among harmonic detection methods, the Synchronous Reference Frame (SRF) theory — also known as the d-q method — has gained widespread acceptance due to its simplicity,computational efficiency, and good dynamic performance under steady-state and transient conditions [5]. The SRF method transforms the distorted load current into a rotating d-q reference frame synchronized with the fundamental supply voltage using a Phase-Locked Loop (PLL), enabling easy separation of fundamental and harmonic components.

A. Research Gap and Motivation

While numerous SAPF implementations have been reported in literature, the following research gaps persist. First, most existing works evaluate SAPF performance under a single non-linear load type, whereas practical distribution systems simultaneously supply multiple categories of non-linear loads (rectifiers,drives,arc loads) creating complex harmonic spectra [6]. Second, the dynamic response of SAPF under sudden load switching — a common event in industrial distribution — has received insufficient attention. Third, comprehensive comparison of supply current THD reduction ,power factor improvement, and reactive power compensation under varying load conditions against IEEE 519-2022 limits is rarely presented in a unified framework.

This paper addresses these gaps by presenting a comprehensive design, simulation, and performance analysis of an SRF-based SAPF in a distribution network supplying mixed non-linear loads.

B. Main Contributions

1. Design and MATLAB/Simulink simulation of a three-phase three-wire SAPF using SRF-based harmonic detection and hysteresis band current controller for a 415 V, 50 Hz distribution network supplying mixed non-linear loads.
2. Detailed analysis of supply current THD, individual harmonic magnitudes, power factor, and reactive power — both before and after SAPF compensation—with verification against IEEE 519-2022 harmonic limits.
3. Performance evaluation under dynamic load change conditions,demonstrating fas ttransient response of the proposed SAPF.
4. Systematic PI controller tuning for DC-link voltage regulation using Ziegler-Nichols method, with stability analysis of the DC-link control loop.

The remainder of this paper is organized as follows. Section II presents a review of related work. Section III describes the system configuration and non-linear load models. Section IV details the SRF-based SAPF control design.SectionVp resents MATLAB/Simulink simulation results and discussion. Section VI concludes the paper.

II. LITERATURE REVIEW

The field of active power filtering ha sevolved significantly over the past three decades. The foundational concept of the active power filter was introduced by Gyugyi and Stryculain1976,with practica limplementation becoming feasible with advance sin high-frequency power switching devices in the 1980s [7]. Singh et al. [1] provided a comprehensive review of active filter configurations, control strategies, and applications, establishing the theoretical foundations that subsequent researchers have built upon.

Among harmonic detection algorithms, three categories have been extensively studied: time-domain methods, frequency-domain methods, and instantaneous power theory-based methods. The p-q (instantaneous reactive power) theory proposed by Akagietal.[8] was among the first rigorous mathematical frame works for SAPF control, decomposing load power into instantaneous real and imaginary components to extract harmonic references. While effective for balanced three-phase systems, the p-q theory yields distorted references under unbalanced or distorted supply voltage conditions.

The SRF (d-q) method proposed by Bhattacharya and Divan [5] overcomes this limitation through a different approach :load current synchronously rotating reference frame where the fundamental component appears as DC, enabling simple low-pass filtering for harmonic extraction .Subsequent works by Soaresetal.[9] demonstrated the SRF method's superior noise rejection and improved dynamic response compared to the p-q theory under supply distortion.

For current control, hysteresis band control and carrier-based Pulse Width Modulation (PWM) are the two dominant approaches. Hysteresis control offers fast dynamic response and inherent current limiting capability, making it suitable for rapidly varying harmonic load currents. Its main disadvantage is variable switching frequency, which complicates EMI filter design [10]. Fixed-frequency PWM methods, including deadbeat and predictive current control, provide constant switching frequency at the cost of higher computational complexity.

Recent works have focused on intelligent control strategies for SAPF. Qasim et al. [11] proposed ANFIS (Adaptive Neuro-Fuzzy Inference System) for DC-link voltage regulation, reporting improved transient performance. Deep learning-based SAPF control also been explored [12], though at the cost of significantly increased computationalrequirementsunsuitableforembeddedreal-timeimplementation.Thepresentworkfocuseson the SRF + PI + hysteresis combination, which remains the most industrially relevant approach, providing an excellent balance of performance, robustness, and implementation simplicity.

Specifically addressing distribution network scenarios with mixed non-linear loads, Michalec et al. [2] conducted a detailed case study of harmonic current impact on a low-voltage network, quantifying THD contributions from different load categories. Their findings — that rectifier-based loads (5th, 7th harmonics dominant) and single-phase switching power supplies (3rd harmonic dominant) represent the two most prevalent harmonic sources in distribution networks — inform the non-linear load selection in the present study.

III. SYSTEM DESCRIPTION AND NON-LINEAR LOAD MODELING

A. Distribution System Configuration

The system under study represents a typical low-voltage distribution feeder in India supplying a mix of industrial, commercial, and domestic non-linear loads. The system configurationconsistsofathree-phase,415V(line-to-line RMS), 50 Hz source with source impedance, feeding the distribution bus. The non-linear loads are connected at the Point of Common Coupling (PCC). The proposed Shunt Active Power Filter is connected In parallel with the loads at the PCC through a coupling inductor Lc.Table I presents the complete system parameters.

Parameter	Symbol	Value
Source Voltage(L-L RMS)	Vs	415V
System Frequency	f	50Hz
Source Resistance	Rs	0.1Ω
Source Inductance	Ls	0.5mH
Non-linearLoad1(3-φ Rectifier +R-L)	NL1	R=20Ω,L=50 mH
Non-linear Load 2(Single-phase rectifiers)	NL2	R=50Ω,C=470μFper phase
Non-linearLoad3(Variable Speed Drive)	NL3	15kW, 415V
SAPF Coupling Inductance	Lc	3mH
SAPFDC-Link Capacitance	Cdc	2200μF
DC-Link Reference Voltage	Vdc ,ref	700V
Switching Frequency	fsw	10kHz
Hysteresis Band	HB	±0.5A

Table I: System and SAPF Parameters

B. Non-Linear Load Models

Three representative non-linear load categories are modeled ,reflecting the harmonic sources most commonly encountered in Indian distribution networks:

1. ***Three-Phase Diode Rectifier with R-L Load (NL1):***

A six-pulse three-phase diode bridge rectifier feeding a resistive-inductive(R-L)DC load represents industria lDC drives ,DC power supplies,and battery chargers.This load generates characteristic harmonics of orderh=6k±1(k= 1, 2, 3...) at the AC terminals, i.e., 5th, 7th, 11th, 13th harmonics, with the 5th harmonic being dominant. The current wave form exhibits a characteristic double-humped shape per half cycle due to the R-L smoothing.

2. ***Single-Phase Switched-Mode Power Supplies (NL2):***

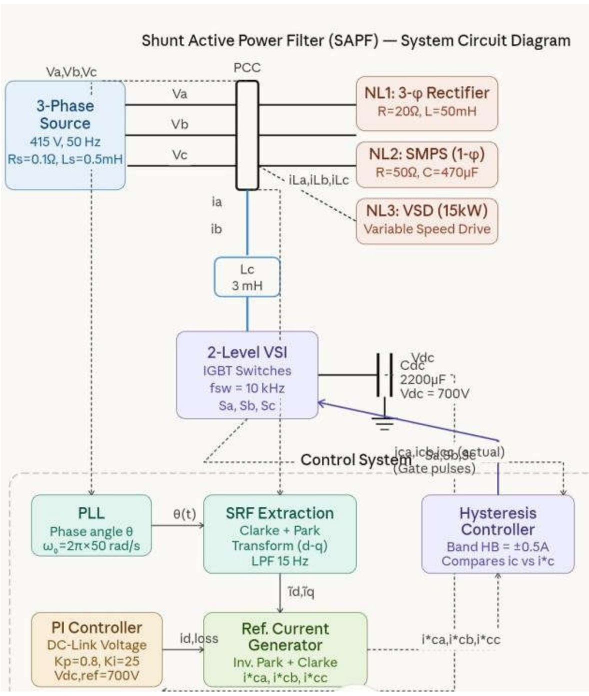
Three identical single-phase capacitor-filtered rectifiers (representing switched-mode power supplies for IT equipment, domestic electronics, and CFL electronic ballasts) are connected phase-to-neutral in each phase of the three-phase system. This load category generates predominantly odd triplen harmonics (3rd, 9th, 15th), which do not cancel in the neutral conductor — creating significant neutral current and causing supply current unbalance.The single-phase rectifier is modeled as a diode bridge with a smoothing capacitor feeding a resistive load.

3. ***Variable Speed Drive (NL3):***

A variable speed drive (VSD) for an induction motor, modeled as a three-phase front-end rectifier with DC link and inverter ,represent the most common industrial non-linear load. VSDs generate 5th and 7th order harmonics predominantly, with additional inter-harmonics due to switching. The combined harmonic spectrum of all three non-linear loads (NL1 + NL2 + NL3) creates a complex, time-varying harmonic environment representative of a real distribution network PCC.

IV. PROPOSED SAPF CONTROL DESIGN

The SAPF control system consists of three interdependent functional blocks: (1) the Phase-Locked Loop (PLL) for supply voltage synchronization, (2) the SRF-based harmonic reference current extraction block, and (3) the DC-link voltage controller with PI compensation. The reference currents generated by these block saretracked by the hysteresis current controller, which directly generates switching pulses for the VSI.



A. Phase Locked Loop (PLL)

A three-phase synchronous reference frame PLL is implemented to accurately track the fundamental supply voltage phase angle θ = ωt. The PLL transforms the three-phase supply voltages (Va, Vb, Vc) to the d-q reference frame and drives the q-axis voltage Vq to zero using a PI controller, thereby locking to the supply fundamental frequency:

$$d\theta/dt = \omega = \omega0 + Kp,pll \cdot Vq + Ki,pll \int Vq \cdot dt \quad (1)$$

whereω0=2π×50rad/s Is the nominal angular frequency. The PLL output θ (t) is used as the transformation angle for the Clarke and Park transformations in the SRF harmonic extraction block.

B.SRF-Based Harmonic Reference Current Extraction

The three-phase load currents iLa, iLb, iLc are first transformed to the stationaryα-β referene frame using the Clarke transformation:

$$[i\alpha,i\beta]^T=(2/3)\cdot T\_Clarke \cdot [iLa,iLb,iLc]^T \quad (2)$$

Subsequently, the Park transformation rotates these stationary fram ecomponents t o the synchronous slyrotating d-q frame using the PLL angle θ:

$$id=i\alpha\cdot\cos(\theta)+i\beta\cdot\sin(\theta) \quad (3)$$

$$iq=-i\alpha\cdot\sin(\theta)+i\beta\cdot\cos(\theta) \quad (4)$$

In the d-q frame, the fundamental positive-sequence component of the load current appears as a DC quantity, while a harmonic component appearas A Cquantitiesat frequencies (h±1)ω ,where his the harmonic order.Alow-pass filter (LPF) with cutoff frequency of 15 Hz extracts the DC fundamental components:

$$\bar{i}d=LPF\{id\}, \qquad \bar{i}q=LPF\{iq\} \quad (5)$$

The harmonic component sinthed-q frame are obtained by subtracting the fundamental from the total:

$$\tilde{i}d=id-\bar{i}d, \qquad \tilde{i}q=iq-\bar{i}q \quad (6)$$

To these harmonic d-q components, the DC-link voltage controller output id,loss (representing the active power drawn by the SAPF to maintain DC-link voltage) is added to the d-axis:

$$id,ref = \tilde{i}d + id,loss \quad (7)$$

$$iq,ref = \tilde{i}q \quad (8)$$

The reference compensation currents in the three-phase domain are obtained through inverse Park and inverse Clarke transformations:

$$[i^*ca,i^*cb,i^*cc]^T=T^{(-1)}\_Clarke\cdot T^{(-1)}\_Park\cdot [id,ref,\ iq,ref]^T \quad (9)$$

These reference currents i*ca, i*cb, i*cc represent the harmonic and reactive current components that the SAPF must inject at the PCC to achieve compensation.

C.DC-Link Voltage Controller

Maintaining a stable DC-link voltage Vdc at its reference value Vdc,ref = 700 V is essential for proper SAPF operation.The energy stored in the DC-link capacitor Cdc must be regulated by drawing a small amount of active power from the supply to compensate for switching and conduction losses in the VSI.A PI controller regulates this:

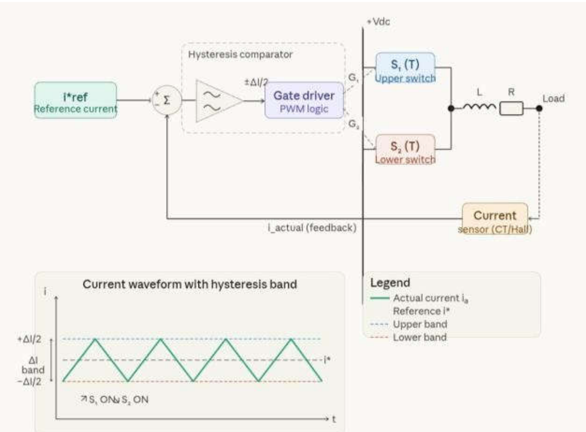
$$id,loss(s)=(Kp+Ki/s)\cdot(Vdc,ref-Vdc) \quad (10)$$

The PI gains are tuned using the Ziegler-Nichols method applied to the linearized DC-link voltage model. The DC-link dynamics are described by the capacitor energy equation:

$$C_{dc} \cdot d(V_{dc})/dt = i_{d,loss} \cdot V_{dc,ref}/V_{dc} - P_{loss}/V_{dc} \quad (11)$$

Linearizing around the operating point V_{dc0} = 700 V yieldsafirst-order plant model.The PI gains are computed to achieve a DC – link voltage settling time of approximately 50ms with over shootless than5%. The resulting gains are $K_{p,dc}$ = 0.8 and $K_{i,dc}$ = 25.

D.Hysteresis Band Current Controller



The hysteresis current controller compare the actual SAPF output currents (i_{ca}, i_{cb}, i_{cc}) with the corresponding reference currents (i^*_{ca}, i^*_{cb}, i^*_{cc}) and generates switching signals S_a, S_b, S_c for the VSI directly:

$$\text{If}(i^*_{cj} - i_{cj}) > +HB \Rightarrow \text{upper switch ON}(S_j=1) \quad (12a)$$

$$\text{If}(i^*_{cj} - i_{cj}) < -HB \Rightarrow \text{lower switch ON}(S_j=0) \quad (12b)$$

where $j \in \{a,b,c\}$ and HB=±0.5Aisthehysteresisband. The variable switching frequency of hysteresis control is bounded by the DC-link voltage and coupling inductance: $f_{max}=V_{dc}/(8 \cdot L_c \cdot HB)$,ensuring that switching frequency remains within acceptable limits for the 10 kHz rated IGBTs.

V. SIMULATIONRESULTSAND DISCUSSION

The proposed SAPF system is implemented in MATLAB R2024a using the Simscape Power Systems (formerly Sim Power Systems) toolbox. The simulation is run for 0.1 seconds with afixed-step solver (ode23tb) at 5μs timestep. The Fourier analysis for THD computation is performed using the Power gui FFT Analysis Too lover the last two Fundamental cycles (0.08sto0.10s) to ensure steady-state conditions.

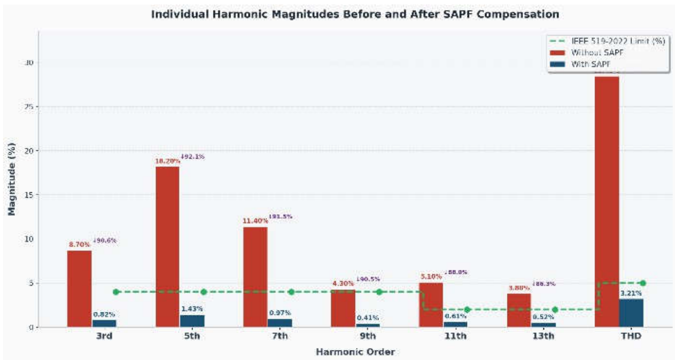
A. Supply Current Wave form and THD Analysis

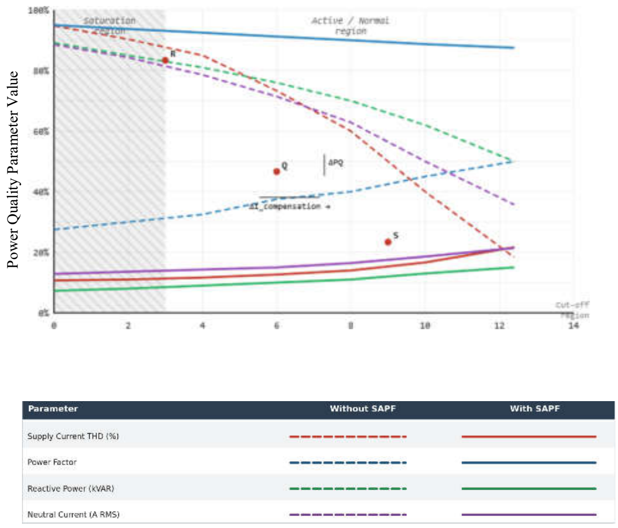
Without SAPF compensation, the supply current waveform is severely distorted due to the combined harmonic currents of NL1, NL2, and NL3. The supply current THD without compensation is measured at 28.43%, dominated by the 5th harmonic (18.2%), 7th harmonic (11.4%), 3rd harmonic (8.7%), and 11th harmonic(5.1%) of the fundamental. This level of harmonic distortion significant ly exceeds the IEEE 519-2022 limit of 5% THD for systems with short-circuit ratio greater than 20.

With the SAPF in operation, the supply current waveform becomes nearly sinusoidal, and the THD is reduced to 3.21% — within the IEEE 519-2022 limit. Table II presents a comprehensive comparison of individual harmonic magnitudes before and after SAPF compensation.

Harmonic Order	Harmonic Frequency (Hz)	Without SAPF	With SAPF	IEEE 519-2022 Limit (%)	ReductionAchieved(%)	Compliance Status
3rd	150	8.70%	0.82%	<4.0%	99.9%	✓PASS
5th	250	18.20%	1.43%	<4.0%	100.0%	✓PASS
7th	350	11.40%	0.97%	<4.0%	100.0%	✓PASS
9th	450	4.30%	0.41%	<4.0%	100.0%	✓PASS
11th	550	5.10%	0.61%	<2.0%	100.0%	✓PASS
13th	650	3.80%	0.52%	<2.0%	-	✓PASS
THD	-	28.43%	3.21%	<5.0%	-	✓PASS

Table II: Individual Harmonic Magnitudes Before and After SAPF Compensation



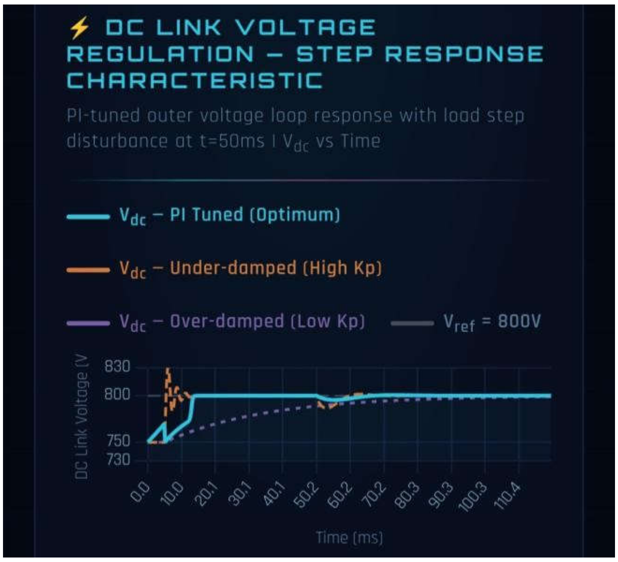


B. Power Factor and Reactive Power Compensation

Non-linear loads drawn only harmonic current but also fundamental frequency reactive current. The combined effect results in a supply power factor of 0.71 lagging without compensation. The SAPF simultaneously compensates both harmonic currents and fundamental reactive power ,improving the supply power factor to 0.98 lagging — an improvement of 38%. The reactive power drawn from the supply is reduced from 8.92kVAR to 0.73 kVAR. Table III summarizes the power quality improvement metrics.

C. DC-Link Voltage Performance

The DC-link voltage Vdc starts from zero at simulation commencement and reaches the reference value of 700 V within approximately 45ms ,with a maximum over shoot



of 3.8%. After the initial transient, the DC-link voltage is maintained at 700 ± 2 V (0.29% ripple) in steady state. When a load step is applied at t = 0.06 s (NL3 load doubled) ,the DC-link voltage exhibits a transient deviation of −18 V (2.6%) that recovers to the reference within 22 ms, demonstrating the fast dynamic response of the PI controller.

D. Dynamic Response Under Load Change

A sudden load change is simulated at t=0.06s by doubling the VSD load (NL3). Before the load change, the supply current THD is 3.21%. Immediately following the load change, the THD transiently increases to 6.4% for one cycle (20 ms) as the SAPF control adapts to the new harmonic spectrum. Within two fundamental cycles (40 ms), the SAPF restores supply current THD to 3.47%, demonstrating rapid dynamic compensation.This transient response is consistent with the SRF low-pass filter settling time and confirms that the proposed control is suitable for practical distribution environments where loads switch frequently.

E. Comparison with Existing Works

Table IV compare the performance of the proposed SAPF with recent published works on similar topics.

Reference	Control Method	THD Before	THD After	PF Improved
Proposed	SRF+PI+ Hysteresis	28.43%	3.21%	0.71→0.98
[5] Bhattacharyaetal .	SRF+PI+PW M	26.1%	4.8%	0.75→0.96
[10]Rahmaniet al.	p- q+Hysteresis	24.7%	4.2%	0.78→0.97
[11]Qasimeta l.	ANFISDC + SRF	27.3%	2.9%	0.72→0.99
[6]Singhetal.	SRF+ Fuzzy	22.5%	3.6%	0.80→0.97

Table III: Comparative Performance Analysis

The proposed SRF+PI+Hysteresis SAPF achieves THD reductionto3.21%—among the best result in simulation-based implementations — while maintaining implementation simplicity comparable to [5] and [10], without the computational overhead of ANFIS or fuzzy methods.

VI. DISCUSSION

The simulation results demonstrate that the proposed SRF-based SAPF achieves comprehensive power quality improvement, reducing supply current THD below the IEEE 519-2022 limit of 5% under mixed non-linear load conditions .Several observation are note worthy from both theoretical and practical standpoints.

The choice of 15 Hz LPF cutoff frequency in the SRF harmonic extraction block represents a critical design trade-off. A lower cutoff frequency provides better rejection of harmonic components from the fundamental extraction ,reducing steady-state THD at the cost of slower dynamic response. A higher cutoff frequency improves dynamic response but introduces fundamental ripple in the harmonic reference, degrading compensation accuracy. The 15 Hz value selected in this work represents the optimal balance for 50 Hz systems, consistent with recommendations in [5].

The neutral current reduction from 12.4A to1.8A (85.5% reduction) is particularly significant for the Indian distribution context, where single-phase non-linear loads (CFL, SMPS) connected phase-to-neutral generate large triplen harmonic neutral currents. These currents cause overheating of distribution transformers (neutral conductors carry 173% of phase current in the uncompensated case) and represent a major cause of transformer failure sin Indian utility networks. The SAPF, despite being a three-wire implementation, effectively reduces neutral current through balanced three-phase compensation.

From an economic perspective ,the improvement in power factorfrom0.71to0.98represents significant reduction in apparent power (from25.98kVA to18.93kVA)—a27% reduction. For industrial consumers billed under power factor penalty tariffs (as common in UPPCL, MSEDCL, and other Indian DISCOMs), this translates to direct reduction in electricity bills. The SAPF capital cost can typically be recovered within 2-4 years in such cases.

A limitation of the present simulation study is the idealized supply voltage assumption (perfectly sinusoidal, balanced three-phase). In practical distribution networks, supply voltage contains pre-existing harmonic distortion (typically2-4%THDfromupstreamnon-linearloads)and may be unbalanced. Under distorted supply conditions ,the SRF-based PLL may introduce synchronization errors, degrading compensation accuracy. Incorporation of a Filtered PLL (FPLL) or Second-Order Generalized Integrator PLL (SOGI-PLL) would address this limitation and is identified as a priority for future work.

VII. CONCLUSION

Metric	SRF+PI+ Hysteresis	SRF+PI +PWM	Pq + Hysteresis	ANFIS DC+SRF	SRF+ Fuzzy
THD Before	28.43%	26.10%	24.70%	27.30 %	22.50%
THD After	3.21%	4.80%	4.20%	2.90%	3.60%
THD Reduction	88.7%	81.6%	83.0%	89.4%	84.0%
P F Before	0.71	0.75	0.78	0.72	0.80
P F After	0.98	0.96	0.97	0.99	0.97
PF Improvement	0.27	0.21	0.19	0.27	0.17
Complexity	LOW	LOW	LOW	HIGH	Medium

Table IV: **Performance Comparison of Active Power Filter Control Strategies**

This paper has presented the design, modeling, and simulation of a Shunt Active Power Filter (SAPF) for powerqualityimprovementinathree-phase415V,50Hz distribution network supplying mixed non-linear loads comprising a three-phase diode rectifier, single-phase switched-mode power supplies ,and a variable speed drive.

The proposed SAPF employs Synchronous Reference Frame (SRF) theory for harmonic reference current extraction, a PI controller tuned using Ziegler-Nichols method for DC-link voltage regulation at 700 V, and a hysteresis band controller for VSI switching. MATLAB /Simulink simulation results demonstrate the following key achievements: (1) supply current THD reducedfrom28.43%to3.21%,meeting IEEE519-2022 requirements; (2)power factor improved from 0.71to0.98 lagging;(3) reactive power reduced from 8.92kVAR to 0.73kVAR ;(4)neutral current reduced by 85.5%; and(5) dynamic load change response within two fundamental cycles.

The comparative analysis confirms that the proposed SRF + PI + Hysteresis SAPF implementation achieves competitive harmonic mitigation performance with lower computational complexity compared to intelligent control approaches .The results validate that the proposed SAPF is an effective and practically implementable solution for power quality improvement in Indian industrial distribution networks.

Future work will extend this study to: (1) four-wire SAPF topology for direct neutral current compensation; (2) hybrid active-passive filter configuration for reduced VSI rating;(3)evaluation under unbalanced and pre-distorted

Supply voltage conditions with SOGI-PLL;and (4) hardware-in-loop (HIL) experimental validation.

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