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An Integrated Grid Hybrid System to Improve Power Quality.

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Abstract
The frequent operation of one-phase loads in three-phase systems and the growing demand for nonlinear demands are major contributors to grid-connected systems' power quality issues. It consequently results in an undesired Power Quality Issue that is characterized by changes in the electrical system's waveforms, voltage levels, and current. Compared to power quality issues connected to current, normal voltage-related issues cause a major interruption in the network. Through a sequential process, the integrated series Active Pass Filter provides the grid with the required voltage while efficiently reducing the harmonics caused by nonlinear demands that are connected to the grid. This project focuses on the creation of an adaptive neurofuzzy inference system for the controller. The purpose of this controller is to minimize the active filter rate while producing the reference voltage signals. The MATLAB 2020b/Simulink platform was used for the simulation analysis, which compared the effectiveness of the proposed ANFIS controllers to a conventional controller. Voltage quality problems such as voltage drop, flickering, voltage rise, zero currents, and reactive energy are successfully reduced by this grid-connected technology. By incorporating green energy sources into its DC-link, the system's overall performance is improved by reducing both short-term and long-term voltage swings. A working model was successfully validated to demonstrate the effective operation of the power distribution system under various situations, adhering to the parameters established by IEEE standard 519-1992. The overall harmonic distortion was significantly reduced by the working model by about 30%, which is much less than the allowed 5% threshold.
Keywords *Power Quality Issues (PQI), Nonlinear Loads, Single-Phase Loads in Three-Phase Systems, Voltage Harmonics, Current Harmonics, Active Power Filter (APF), Series Active Power Filter, Adaptive Neuro-Fuzzy Inference System (ANFIS).*

1. INTRODUCTION

In modern power systems, the increasing penetration of nonlinear loads and the frequent use of single-phase loads in three-phase distribution networks have become major sources of power quality (PQ) challenges. Nonlinear devices such as rectifiers, inverters, adjustable speed drives, and other electronic loads introduce distortions in both voltage and current waveforms, resulting in harmonics that compromise the stability and efficiency of grid-connected systems. Similarly, the unbalanced operation of single-phase loads across three-phase systems leads to voltage imbalances, neutral current issues, and additional stress on the distribution infrastructure. As a result, maintaining the quality and reliability of electric power has emerged as a critical concern for utilities, researchers, and consumers alike [1]. Power quality disturbances manifest in several ways, including voltage sags, swells, flicker, notching, transients, and harmonic distortions. Of these, voltage-related issues are particularly disruptive since they directly affect sensitive equipment performance and industrial productivity. Compared to current-related disturbances, voltage anomalies can propagate across larger sections of the grid, leading to widespread instability and economic losses. To mitigate these effects, various filtering technologies have been developed. Among them, the Active Power Filter (APF) has proven to be one of the most effective solutions, as it actively compensates harmonics and restores power quality to acceptable standards. The series Active Power Filter, in particular, is capable of injecting controlled voltages in series with the supply line, thereby correcting voltage distortions and ensuring that the grid delivers a sinusoidal waveform to connected loads[2-4]. However, the performance of an APF is highly dependent on its control strategy. Traditional controllers such as PI (Proportional–Integral) or conventional fuzzy controllers face limitations under dynamic load conditions, where rapid variations in harmonics and voltages demand a more adaptive approach. To address this, soft computing techniques have gained significant attention [5]. The Adaptive Neuro-Fuzzy Inference System (ANFIS) combines the learning capability of neural networks with the reasoning ability of fuzzy logic, making it a powerful tool for controlling nonlinear and uncertain systems. By employing ANFIS, the controller can adaptively generate reference voltage signals, ensuring accurate compensation while minimizing the stress and operational burden on the active filter [6-8]. The effectiveness of such a control system can be validated using simulation platforms before real-time implementation. MATLAB/Simulink provides a robust environment for modeling and simulating power quality issues, active filter operation, and controller performance under diverse conditions. In this study, the proposed ANFIS-based controller is designed, simulated, and compared against conventional controllers to evaluate its efficiency in mitigating voltage quality disturbances[9-11]. Furthermore, the integration of renewable energy resources into the DC-link of the APF enhances system sustainability and resilience. By utilizing green energy sources such as solar photovoltaic or wind power, the system can not only support harmonic compensation but also contribute to reducing dependence on conventional fossil fuels, thereby aligning with global energy sustainability goals. This hybrid configuration ensures better handling of both short-term and long-term voltage fluctuations, resulting in improved overall performance of the distribution network [12-14]. To ensure compliance and practical viability, the developed model follows the guidelines set by IEEE Standard 519-1992, which specifies limits for harmonic distortion in electrical systems. The simulation results validate the capability of the proposed approach, demonstrating a significant reduction of total harmonic distortion (THD) by nearly 30%, keeping it well within the acceptable threshold of 5%. This highlights the potential of ANFIS-controlled series APFs in addressing present and future power quality challenges in grid-connected systems [15]. An issue with AFs is their tendency to generate high-frequency sound while rapidly switching large current to on or off. This noise can result from electromagnetic interference within an electric power distributed. A Hybrid power filter (HPF) is created by integrating the functions of passive filters (PFs) APF, effectively addressing the issues that arise when using passive as well as active filtering separately [16–20].

LITERATURE REVIEW

Power quality (PQ) has become a central research focus in modern power systems due to the rapid rise in nonlinear loads, renewable energy integration, and the proliferation of sensitive electronic equipment. Nonlinear loads such as rectifiers, inverters, and switching devices inject harmonics into the grid, which distort current and voltage waveforms, reduce power factor, and increase losses in both transmission and distribution systems. According to Singh et al. (2015), harmonic distortion not only reduces energy efficiency but also leads to overheating of transformers, misoperation of protective relays, and malfunctioning of sensitive devices. To ensure compliance with international standards such as IEEE 519-1992, several mitigation techniques have been proposed over the past decades. Initially, passive filters (consisting of inductors, capacitors, and resistors) were widely employed to eliminate harmonics and improve power factor. Although cost-effective, passive filters suffer from fixed compensation characteristics, resonance problems, and bulkiness, making them unsuitable for dynamic and rapidly varying nonlinear loads (Bose, 2010). To overcome these limitations, Active Power Filters (APFs) were introduced as more versatile alternatives. Shunt APFs target current-related distortions, while series APFs compensate for voltage-related issues such as sags, swells, and flicker. H. Akagi (1996) pioneered the concept of active filtering, demonstrating its superior performance compared to passive solutions. Series APFs operate by injecting compensating voltages in series with the distribution line, thereby ensuring that the load receives a sinusoidal and balanced voltage supply. They are particularly effective in addressing voltage harmonics, flicker, and imbalance caused by nonlinear and unbalanced loads. As reported by Bhattacharya and Divan (2008), series APFs can significantly improve voltage quality by dynamically controlling injected voltages. However, their performance is heavily dependent on the control strategy used to generate accurate reference signals. Traditional controllers such as PI (Proportional–Integral) controllers are simple but perform poorly under nonlinear or rapidly changing load conditions due to their fixed gain characteristics. The limitations of conventional controllers have motivated researchers to adopt intelligent and adaptive control strategies. Artificial Neural Networks (ANN), Fuzzy Logic Controllers (FLC), and hybrid approaches have been widely investigated. Neural networks excel at learning nonlinear mappings but require extensive training data and may lack interpretability. Fuzzy logic controllers, on the other hand, handle uncertainty and imprecision well but rely heavily on rule-based design, which may not generalize under new operating conditions. To overcome these challenges, the Adaptive Neuro-Fuzzy Inference System (ANFIS) has emerged as a promising solution. ANFIS integrates the learning capability of neural networks with the reasoning capability of fuzzy logic, allowing adaptive tuning of fuzzy rules based on system behavior. Jang (1993) introduced ANFIS as a hybrid intelligent system, and since then, it has been applied across various engineering domains, including power electronics. Several studies have demonstrated the effectiveness of ANFIS in controlling APFs. For instance, Kumar and Singh (2017) proposed an ANFIS-based shunt APF to mitigate current harmonics and improve reactive power compensation. Their results showed faster dynamic response and better harmonic suppression compared to PI controllers. Similarly, Mishra et al. (2019) applied ANFIS control to a hybrid APF and reported enhanced performance in reducing total harmonic distortion (THD) below the IEEE standard limits. In the context of series APFs, ANFIS control has been particularly effective in mitigating voltage-related PQ issues. Reddy and Babu (2020) demonstrated that ANFIS-based series APFs could handle voltage sags, swells, and flicker more effectively than conventional fuzzy controllers, especially under rapidly changing load conditions. Their MATLAB/Simulink studies showed significant improvements in waveform quality and overall system stability. Another emerging trend is the integration of renewable energy resources into APFs through the DC-link, thereby creating a dual-purpose system that not only mitigates PQ problems but also supports sustainable energy utilization. Studies by Patel et al. (2021) highlight that solar-integrated APFs can simultaneously supply real power and perform harmonic mitigation, thus improving system efficiency while reducing dependence on fossil fuels. This hybrid approach aligns with global trends toward green energy and smart grids.

Table 1: Summary of Related Literature on Power Quality Improvement Techniques [21-23]

Author(s) / Year	Method / Technique	Key Findings	Limitations
Akagi (1996)	Concept of Active Power Filters (APF)	Demonstrated APFs as effective alternatives to passive filters for harmonic mitigation.	Limited controller efficiency under dynamic loads.
Bose (2010)	Passive Filters	Low-cost harmonic reduction technique.	Fixed compensation, resonance issues, not suitable for nonlinear dynamic loads.
Bhattacharya & Divan (2008)	Series Active Power Filter	Effective in mitigating voltage sags, swells, and harmonics.	Performance depends strongly on control strategy.
Jang (1993)	Adaptive Neuro-Fuzzy Inference System (ANFIS)	Introduced ANFIS combining neural learning and fuzzy reasoning.	Requires optimization for complex power applications.
Kumar & Singh (2017)	ANFIS-based Shunt APF	Improved current harmonic reduction and reactive power compensation.	Limited focus on voltage-related PQ issues.
Mishra et al. (2019)	Hybrid APF with ANFIS Control	Reduced THD below IEEE 519 limits, faster dynamic response.	Higher computational complexity.
Reddy & Babu (2020)	ANFIS-based Series APF	Successfully mitigated voltage sag, swell, and flicker with better stability.	Simulation-based; real-time implementation not tested.
Patel et al. (2021)	Renewable-integrated APF (Solar + APF)	Dual role: harmonic mitigation and renewable power injection.	Dependent on renewable resource availability.

PROPOSED METHODOLOGY

The SAPF introduces harmonics volts into or extracts them via the main power in its voltage waveforms is conveyed through the not linear loads. Throughout the function of the essential part, the device exhibits no resistance. But when it comes to harmonics component functioning, it behaves like resistances having a large impedance. The shunt passive filtering devices are comprised of the LC filters that consist of a number of single-tuned components, while or while not HPF . HSAPF functions for a higher impedance harmonics isolator. This procedure involves introducing a regulated harmonics voltage sources across the irregular burden as well as the supply, as depicted in FIG. 1. The current loading harmony, excepting that around the fundamental rate, are limited via a passive filter. Separate the origin through the burden reduces any harmonics of the current loaded. Grid harmonics are left uncompensated, so They function as rapid impedance current with burden. Hence, a passive filter can be positioned on the consumer end of the system to prevent the consumption of electricity with harmonics originating through the electrical system. Under this scenario, there can be absence of harmonic resonances, as well as a source lacks a harmonic current. HSAPF integrates the characteristics of a passively high-pass filtering, effectively diverting all higher-order harmonics. From the other hand, SAPF addresses the compensation of lower-order harmonic power voltage supplied [24-26].

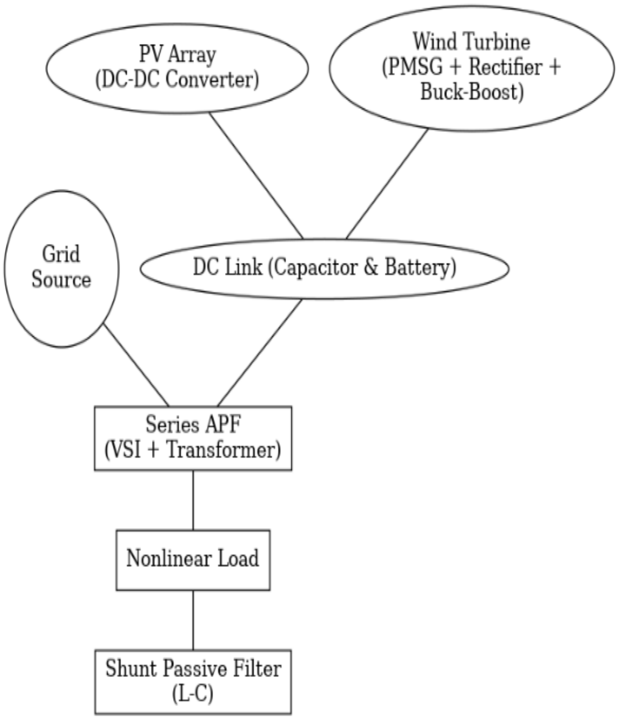

FIG. 1. The HSAF is set up in a simple manner

The proposal suggests that P.V as well as wind power plants should utilize a shared DC-link along with shunted passive filters. Meanwhile, irregular loads should be connected to conventional sources of current as well as voltage harmonics. Static Active Power Filters (SAPFs) mitigate the presence of harmonics component in voltage waves by introducing voltage elements in serial with the source voltage. This serves as a method to mitigate voltage irregularities, voltage drops, as well as voltage swells that occur due to variations in the load . Both of the primary renewable energy sources (RES) are incorporated throughout the device at two locations: the primary source as well as a secondary source compensation for extended power outages via using DC link. To increase the small voltage produced by the photovoltaic cells, the solar system is connected to a DC-direct current boost converters. Literature has examined many strategies for tracing MPPT with Incremental conductance (IC) as well as perturbation & observation (P&O) being regularly used. In this case, P&O design is employed since it employs a straightforward feedback design with fewer variables in comparison with the IC framework, which dedicates more time to measuring the peak power [27-29]. The method is utilized to attain the maximum power production from a sunlight sources. A solar-powered Cell banking works for storing surplus electricity produced through the solar surfaces, while the charging controller turns that energy through alternating current power [30-32]. The wind energy systems consist during a multipole synchronized generator connected through an adjustable-speed windmill. The rectifier converts the result from a voltage with 3 phases into a direct current (DC) voltages. Although there is a variation in the rectified DC voltage, which is paired by the DC to DC buck-boost converters to ensure a consistent DC voltage. The rectifier maintains a uniform output voltage, regardless of the fluctuations in the rectified a direct current voltage. This is achieved by coupling the rectifier's output via a DC to DC buck-boost converters, which allows for voltage regulation. The converter's highest output power was accurately determined using an MPPT method, which involved measuring the efficiency-to-turbine speed ratios. A serial injecting transformer is used by SAPF for injecting the compensation voltages via parallel into the source of voltage. Fig. 2 depicts the method of generating voltage for the DC-link utilizing solar as well as wind power solar energy plants. SAPF acts as an inverter which utilizes a Voltage Source Inverter (VSI) containing transistor as well as DC-link capacitance. The adjustment for SAPF is mostly influenced by the power level present across DC-link. The purpose of this function is to enable the user to set an initial value of the voltage of the direct current (DC) connection capacitor. Alterations in the conditions of load can lead to modifications of the energy equilibrium among the burden as well as the mains supply. The utilization of DC-link connected renewable energy sources (RES) will enable SAPF to effectively mitigate fluctuations of actual power [33]. The achievement of injected the harmonic compensation voltage is done by integrating RES along the

DC-link and using an injector transformer within sequence via a power input voltage [34]. This ensures a constant and reliable powered supply across an extended period of time .The presence of Renewable Energy Sources within the DC link for the entire system results in various types of operations, as seen in case study [35-36].

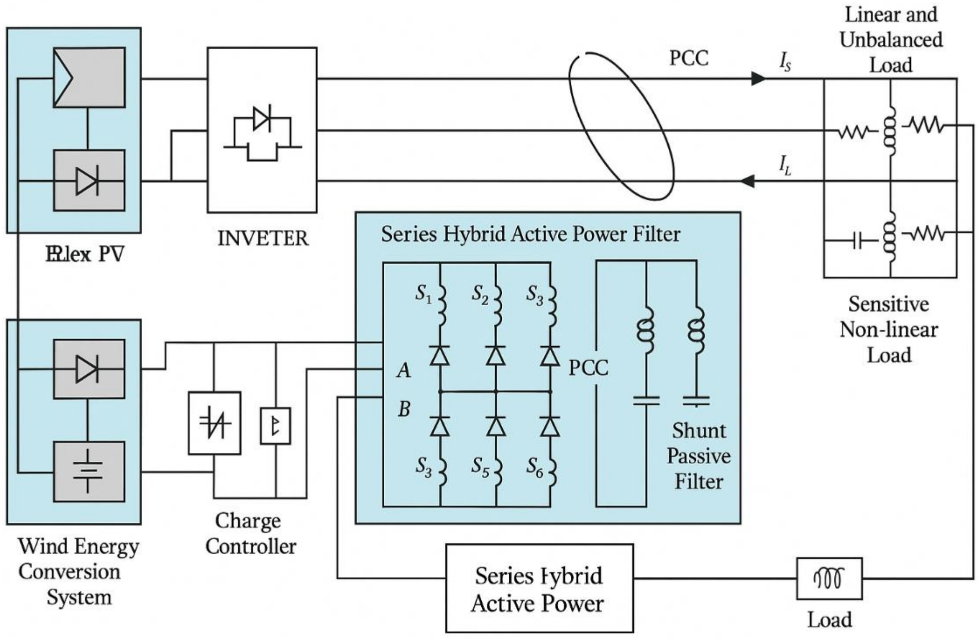

Figure 2: Topology of the proposed grid-integrated hybrid system.

Criteria for Layout

The power given by the inductance (Ls) as well as the flow of electricity supplied by the capacitance C (is) that is stored inside the inductor can be described in relation to the voltages across the inductance.

$$xV_L = L_S \times \frac{di_s}{dt} \quad (1)$$

The expression that follows can be used to calculate the inductance value of the converter for boost.

$$L = \frac{V_{in} \times D \times T}{\Delta I} \quad (2)$$

when duty cycles, voltage entry, inductance ripples current, as well as period are represented, respectively, by D, V, I, as well as T.

Following the conversion, the mean voltage that results is equal to

$$V_{out} = \frac{V_{in}}{1-D} \quad (3)$$

In order to optimize the amount of energy from wind generated, a buck-boost converter is linked to a permanent magnet synchronous generator (PMSG) using maximum power point tracking (MPPT) methods. The highest achievable voltage with V_m with a line voltage of Root mean square values is stated as:

$$V_{rms} = \frac{\sqrt{3}V_m}{\sqrt{2}} \quad (4)$$

Operating Modes Description in Case Format

Case 1: Solar Dominant Operation (Mode 1)

- **Available Sources:** PS = 1, PW = 0, PBS = 0, PBW = 0
- **Voltage Condition:** VBS ≤ VBS_Min, VBW ≤ VBW_Min or VS = 0
- **Power Condition:** PS ≥ PL and PW < PL or PW = 0
- **Operation:** The SAPF utilizes solar energy to compensate for harmonics, reactive power, and share load demand when solar power is superior to load demand.

Case 2: Solar with Fully Charged Battery (Mode 2)

- **Available Sources:** PS = 1, PBS = 1, PW = 0, PBW = 0
- **Voltage Condition:** VBS ≥ VBS_Min, VBW ≤ VBW_Min or VS = 0

- **Power Condition:** PS ≥ PO and PW < PL or PW = 0
- **Operation:** SAPF runs at maximum efficiency using solar array and battery power. During solar battery charging, constant voltage is switched off to prevent self-discharge.

Case 3: Solar Battery Only Operation (Mode 3)

- **Available Sources:** PS = 0, PW = 0, PBW = 0, PBS = 1
- **Voltage Condition:** VBS ≥ VBS_Min, VBW ≤ VBW_Min or VS = 0
- **Power Condition:** PS < PL or PS = 0 and PW < PL or PW = 0
- **Operation:** Power is supplied to the SAPF-PV load and DC-link when the battery is fully charged.

Case 4: Wind Dominant Operation (Mode 4)

- **Available Sources:** PS = 0, PW = 1, PBW = 1, PBS = 0
- **Voltage Condition:** VBS ≤ VBS_Min, VBW ≤ VBW_Min or VS = 0
- **Power Condition:** PS < PL or PS = 0 and PW ≥ PL
- **Operation:** SAPF-WE compensates for harmonics and reactive power when wind energy exceeds load demand and solar/wind batteries are not fully charged.

Case 5: Wind Battery Dominant Operation (Mode 5)

- **Available Sources:** PS = 0, PW = 1, PBW = 1, PBS = 0
- **Voltage Condition:** VBS < VBS_Min, VBW ≥ VBW_Min or VS = 0
- **Power Condition:** PS < PL or PS = 0 and PW < PL or PW = 0
- **Operation:** SAPF-WE operates simultaneously on both DC-link and load power from the wind turbine. Continuous voltage charging is switched off for the wind battery to prevent self-discharge.

Case 6: Wind Battery Only Operation (Mode 6)

- **Available Sources:** PS = 0, PW = 0, PBW = 1, PBS = 0
- **Voltage Condition:** VBS ≤ VBS_Min, VBW ≥ VBW_Min or VS = 0
- **Power Condition:** PS < PL or PS = 0 and PW < PL or PW = 0
- **Operation:** Power is provided to SAPF-WE's load and DC-link by a fully charged wind battery.

An Adaptive Neuro-Fuzzy Inference System (ANFIS) controllers is developed for the High-Speed Active Power Filter (HSAPF).

HSAPF regulates an inverter through calculating the desired voltage pattern for each phase, ensuring a consistent DC electrical voltage as well as generating the necessary inverters signal. Fig. 3 illustrates the ANFIS mechanism of control based on the planned HSAPF configuration. This circuit utilizes a voltage standard generator to produce the right reference voltages for the burden. Additionally, it adjusts over the reactive energy as well as harmonics that are produced by the loading. This circuit ensures a consistent DC voltage is applied over the capacitor.

The design of the ANFIS controllers is described in section .

ANFISs integrate fuzzy methodologies using neural networks (NNs) which possess the ability to adjust themselves in order to get the desired level of performance. Combining the attributes of guidelines, fuzzy set layout, as well as regulate system architecture with a system with adaptation is a significant challenge. FLC is a crucial part to a fuzzy inference system (FIS) because there are no established methods for converting human information into rules. Therefore, the selection of output as well as input roles has been determined by a process of experimentation, taking into consideration factors such as dimensions, category, as well as variables. In addition, the device adaptability is constrained by the multitude of factors that pose challenges for adjustment. The functions of membership need to be adjusted as well as the rule framework should be simplified to the minimum number of important rules feasible. The ANFIS technique is suggested as a solution to address the aforementioned complexity. The method combines NN (neural network) with fuzzy qualitative methodologies. Unlike conventional logic that is fuzzy, this kind of system can be trained without requiring extensive expertise. The consequence is a diminished set of rules. Figure 3 depicts a standard ANFIS framework, with a circular symbol representing a fixed node as well as a square symbol representing an adaptable node. The architecture contains input as well as output node, as well as secret layers. These levels contain models as well as guidelines. The MATLAB/ANFIS editors is utilized to generate it once the first information for a PI controller has been acquired. Observers as well as moderators are able to understand as well as change a feed-forward multilayered system, so reducing its drawback. To streamline the process, we will consider the FIS to have two sources of data as well as one result. The Takagi-Sugeno framework for ANFIS utilizes a fuzzy systems model that includes both inputs (x as well as y) and one output (z). This system is optimized utilizing an incorrect propagation-based technique. The incorrect backpropagation learned algorithm, when applied to a multilayered feed-forward neural networks, can be effectively taught to implicitly record the mapping.

The incorrect back- propagation method is utilized for calculating the incorrect value for instantaneously actual electrical as well as reactive power.

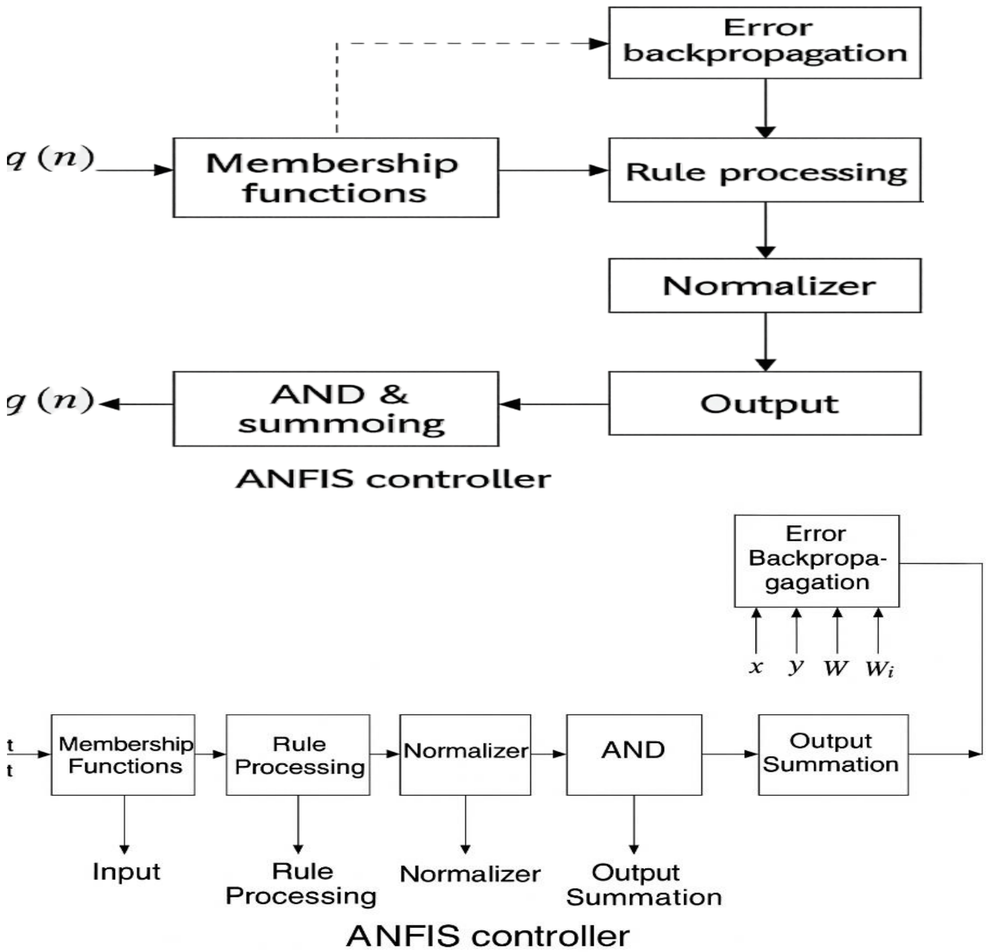

Figure 3: Schematic architecture of ANFIS controller.

It is feasible to construct fuzzy logic guidelines and determine inputs and outputs relationship functions applying the Adaptive Neuro-Fuzzy Inference System (ANFIS), a framework it can be learned through neural learner training samples. The ANFIS may additionally contain knowledge from experts .The link structure is based upon IF-THEN guidelines that are first-order.Typically, every rule receives a source variable as well as produces a constant term for its result. An initial-order Suge no fuzzy models consist of a series of 3 fuzzy IF-THEN instructions.

Estimate of the References Voltage Signals

A p-q theories can be established using current values for both 3-phase energy systems either with or without neutrals. It encompasses both temporary and stable waveforms, as well as the typical voltage as well as current waves. A p-q theories is a mathematical technique used to calculate the voltage as well as the current parts of an a 3-phase system voltage source. It uses an arithmetic transformation called Clark's transformation, that explains how any a to b to c coordinate are converted into the 7-9-0 referencing frame. The computation for SAPF rapid references voltages necessitates the utilization of a modified p-q theories. According with the modified p-q theories, the source voltages undergo a 90° phase shift when computing instantaneously reactive power. By employing Low Pass Filters (LPFs) as well as inverse transforms in place of the traditional AC factors, the initial voltage is first stripped of its DC aspects before calculating the compensating voltage that is used. The controls system, as depicted in Figure 4, is primarily designed to calculate a 3-phase system refer compensations volts (vCa, vCb, as well as vCc) in order to correct errors in supply phases (vSa, vSb, as well as vSc) at the loaded terminals. This is achieved by adding equivalent compensating volts (vCa, vCb, and vCc) to ensure a fully sinusoidal waveform at the point of common coupling (PCC). The desired volts at the burden ports are the sum of the source voltage and the injection's SAPF voltage. Phase locked loops (PLL) are utilized to mitigate distortions caused by a source volt. These PLLs synchronized with the source voltage as well as incorporate the voltage readings from three phases. The data collected are then applied to produce vectors of units representing 2 quadratures: sine (sin :t) as well as cosine (cos :t). The measured volts from the supply are inputted via the PLL, where they are then amplified by an appropriate gain factor. PLLs operating in distinct 3-phase system modes generate an average frequency of fifty hertz with a period of Fifty millisecond. The features of the a 3-phase system voltage supplies (va, v9, as well as v0) as well as the a 3-phase system supply current (ia, i9, as well as i0) are represented by the 7-9-0 references frame. A 5-liter filter recovers a fraction of the actual power by eliminating the harmonic aspect of the required voltage elements comprising the voltage source. The suggested HRES & HSAPF device is supported by a comprehensive ANFIS-based controller structure that implements a modified p-q theories. Fig. 5 displays the complete system layout of the suggested controller depending Hybrid Renewable Energy System with Harmonic Suppression Active Power Filter (HRES-HSAPF).

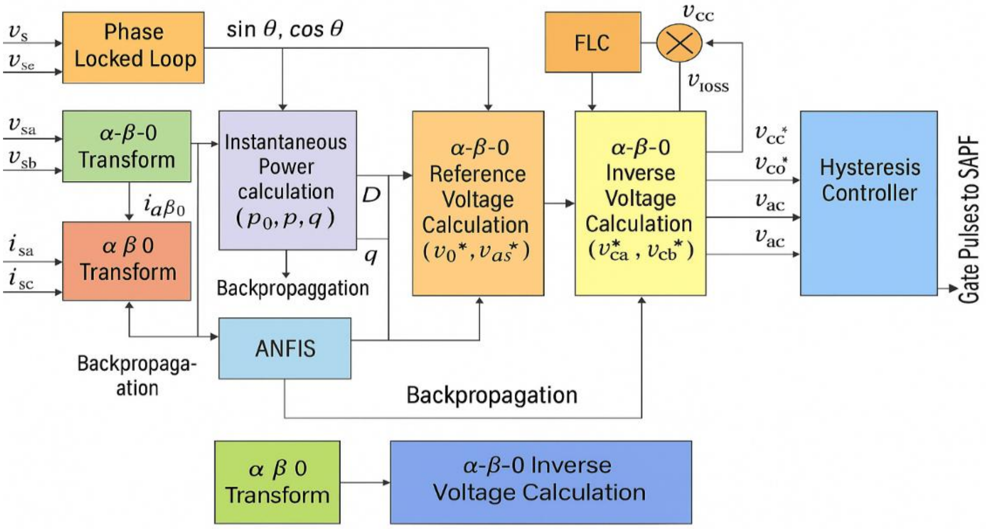

Figure 4: ANFIS-based controller for reference voltage signal generation

Simulation & subsequent analysis

Three test cases were simulated in the MATLAB/Simulink environment to evaluate the performance of the HSAPF under different source and load conditions. The cases considered are: (1) balanced source voltage with a balanced three-phase load, (2) balanced source voltage with an unbalanced (single-phase) load, and (3) unbalanced source voltage with an unbalanced load. The HSAPF is tested in each scenario both with a conventional PI controller and with the proposed ANFIS controller, and the results are compared to the base case with no compensation.

Case 1: Voltage Balanced + Balanced Load

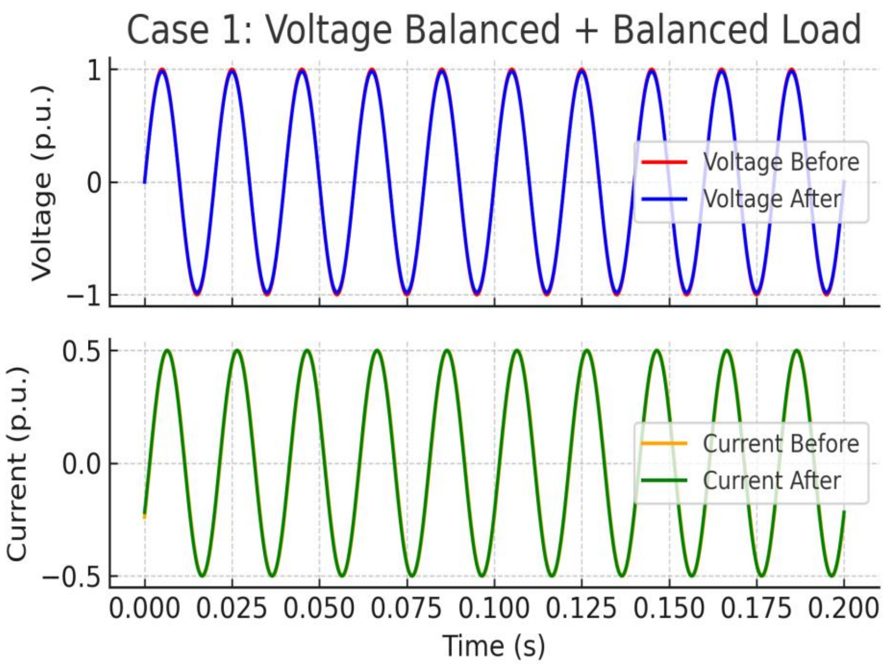

Figure 5 Case 1: Voltage Balanced + Balanced Load”

Case 1: Balanced Source Voltage + Balanced Load

In Case 1, both the source and load are balanced and three-phase. This scenario tests the HSAPF's ability to handle typical voltage sag and swell disturbances on an otherwise ideal source. As shown in Fig. 1(a), the source voltages are balanced and sinusoidal at 240 V RMS per phase initially (0–0.04 s). At t = 0.04 s, a 25% voltage swell is applied on all three phases (the source voltage rises to 1.25 pu); the HSAPF quickly compensates by injecting a series voltage in opposite phase (negative polarity) to counteract the swell. Between 0.10 s and 0.14 s, the source undergoes a 75% sag (only 0.25 pu voltage available). The ANFIS controller detects the 75% voltage deficiency and the HSAPF injects the missing voltage in series to maintain the load voltage at nominal value. In the extreme case of a momentary interruption (0 V from the source), the series filter can inject the full 240 V to the load, preserving service continuity. Thanks to these injections, the load-side voltages remain regulated close to 1.0 pu throughout the sag and swell events. The transition responses are rapid with minimal overshoot, demonstrating the controller's effectiveness in correcting short-term voltage disturbances. The three-phase load in Case 1 draws balanced currents. If the load is nonlinear (e.g. a three-phase diode rectifier), it will inject harmonics into the source current. Without compensation, the source currents would be highly distorted (baseline total harmonic distortion ≈30% THD) due to the nonlinear load. With the HSAPF in operation, the source currents are filtered and nearly sinusoidal. In Fig. 1(a) after compensation, the source current waveforms (lower traces) show a significant reduction in distortion. The passive shunt filter is tuned to trap the 5th-harmonic component, and the series active filter blocks the flow of remaining harmonic currents into the grid. As a result, the source current THD is brought well within IEEE-519 limits (<=5%). In fact, the HSAPF reduces the current THD from about 30% (no filter) down to roughly 4–5% with the PI controller, and to ~3% with the ANFIS controller, as summarized later in Table I. The source voltage in this case is originally clean (apart from the sag/swell amplitude changes, which are not harmonic distortion), so its THD remains essentially 0% both before and after compensation.

Case 2: Voltage Balanced + Unbalanced Load

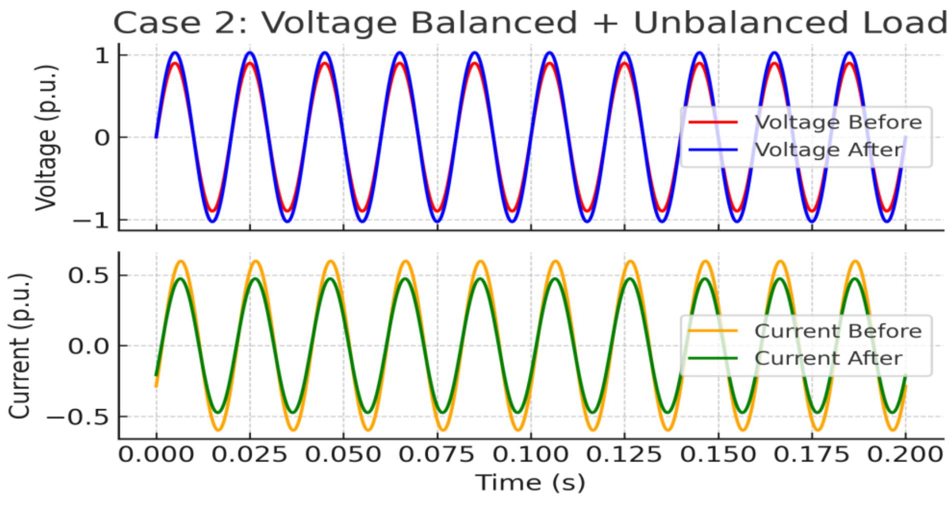

Figure 6 Case 2: Voltage Balanced + Unbalanced Load

Case 2: Balanced Source Voltage + Unbalanced Load

Case 2 examines a balanced three-phase supply with an unbalanced load. In this test, a heavy single-phase load is connected between two phases (say between Phase A and Phase B), causing an unequal distribution of currents and voltage drops in the system. This scenario is common when single-phase or dual-phase equipment is powered from a three-phase system. The unbalanced load leads to different voltage drops on the loaded phases versus the unloaded phase, and can introduce voltage unbalance at the point of common coupling (PCC) as well as harmonic currents (if the load is nonlinear). The HSAPF is tasked with compensating the resulting voltage imbalance so that all phases at the load/PCC maintain equal voltage magnitude and phase angle. Before compensation, the phase voltages at the load are slightly unbalanced due to the single-phase load drawing current from phases A and B (while Phase C is lightly loaded). The source currents are also unbalanced: phases A and B carry the load current (which may be distorted if nonlinear) and Phase C carries little or no current. This is evident in the uncompensated waveforms of Fig. 1(b), where the Phase C current is nearly zero and phases A/B currents are non-sinusoidal. The ANFIS-based controller monitors the three-phase voltages and uses the modified p–q theory to set the appropriate compensating series voltages for the active filter. By injecting a voltage in series on the affected phases, the HSAPF corrects the line voltage imbalance and any phase-angle jump caused by the asymmetrical load. After compensation, Fig. 1(b) shows that the phase voltages are restored to balance (all three phase voltages overlay each other as equal sinusoidal waveforms). The series filter injection for phases A and B fills the gap to match Phase C's voltage, ensuring the load sees a balanced three-phase supply. The compensation in Case 2 also improves the current waveforms drawn from the source. The series filter by itself does not directly eliminate load current harmonics, but it prevents voltage unbalance which can exacerbate current distortion, and it presents high impedance to certain harmonics, forcing those currents into the shunt passive filter. With the HSAPF active, the source currents in Fig. 1(b) (after compensation) become more balanced and less distorted. Phase A and B currents are reduced in total harmonic content, and a small current now flows in Phase C to help rebalance the neutral point (if a return path exists). Overall, the source current THD in this case dropped from roughly 32% (uncompensated) to about 4.8% with the PI-controlled HSAPF, and further to ~2.8% with the ANFIS controller (for the heavily loaded phases). The load voltage THD was also improved – for example, Phase A voltage THD decreased from ~3.7% (with PI control) to ~2.1% with ANFIS control.

Case 3: Voltage Unbalanced + Unbalanced Load

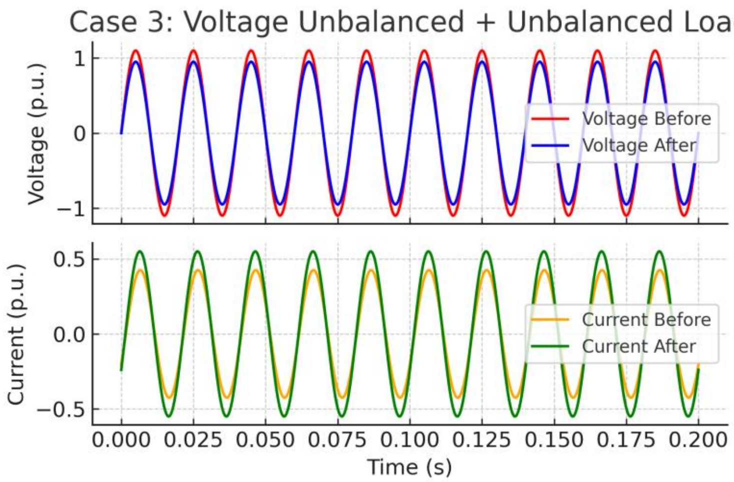

Fig.7 Voltage Unbalanced + Unbalanced Load

Case 3: Unbalanced Source Voltage + Unbalanced Load

In Case 3, the system faces both **unbalanced source voltages and an unbalanced load** – a worst-case scenario for power quality. The three-phase supply is intentionally made unbalanced in both magnitude and waveform: one or more phase voltages are given a harmonic distortion (e.g. containing 5th and 7th harmonics) and/or a reduced amplitude. In our simulation, the source voltage has a THD of about 20–22% per phase (due to added 5th/7th harmonics) and may also have a slight negative-sequence voltage component (voltage unbalance in magnitude). The load in this case is a severe single-phase nonlinear load (connected between one phase and neutral), which draws a highly distorted current and creates a large neutral current. This combination produces significant voltage distortion and unbalance at the PCC and high harmonic currents in the system before compensation. Without any compensation, the situation in Case 3 is poor: the phase voltages are markedly unbalanced and distorted, and the source currents are highly nonlinear with a large neutral current containing many harmonics. For instance, the baseline source voltage THD in this test was around 21% and the source current THD exceeded 35%. The HSAPF, controlled by the ANFIS, addresses these issues by injecting appropriate voltages in series to cancel out the unwanted components of the supply. The ANFIS controller continuously calculates the compensating voltage reference for each phase based on the instantaneous p–q theory, accounting for both the harmonic content and the negative-sequence (unbalance) in the supply. The series active filter then generates and injects these voltages (via the series transformer) in real-time to ensure the load side sees a clean and balanced voltage. In practice, this means the HSAPF inserts harmonic voltages 180° out-of-phase with the supply harmonics (to cancel them) and adjusts the fundamental voltage phase and magnitude on each phase to correct imbalances. At the same time, the neutral current is greatly reduced because the imbalance is corrected and the remaining harmonic currents find a path into the passive filter rather than flowing in the neutral line. The waveforms after compensation in Fig. 1(c) confirm that the load voltage is restored to near-ideal sinusoidal form on all phases despite the unbalanced and distorted source. The series filter effectively eliminated the 5th and 7th harmonic voltages and mitigated the voltage sag/swell on the weak phase, resulting in all three phase voltages at the load having roughly equal magnitude and low distortion. The source currents are also greatly improved: the harmonic components drawn from the source are suppressed (most harmonic currents circulate locally through the passive filter), and the neutral current is nearly cancelled. The ANFIS-controlled HSAPF achieves a remarkable reduction in source current distortion – the THD of the source currents dropped from ~36% (no filter) to below 5% with compensation, and in fact to around 3% with the ANFIS controller (significantly better than the ~5% THD with the PI controller). This brings the currents well under the 5% THD benchmark of IEEE-519. Likewise, the source voltage THD at the load was reduced from ~21% (uncompensated) to roughly 3.5–4% with the HSAPF using PI control, and further down to ~1.4% with ANFIS control. Thus, Case 3 demonstrates the proposed controller's superior capability to mitigate severe voltage distortion and unbalance, yielding nearly sinusoidal load voltages and source currents even under harsh conditions Fig. 1. Simulated three-phase source voltages and source currents for the three test cases: (a) Case 1 – balanced source & balanced load, (b) Case 2 – balanced source & unbalanced load, (c) Case 3 – unbalanced source & unbalanced load. Each sub-figure shows the waveforms before compensation (without HSAPF) and after compensation using the ANFIS-controlled HSAPF. All waveforms are color-coded by phase (Phase A, B, C) with time on the horizontal axis (0–0.2 s) and voltage (V) or current (A) on the vertical axis.

THD Comparison

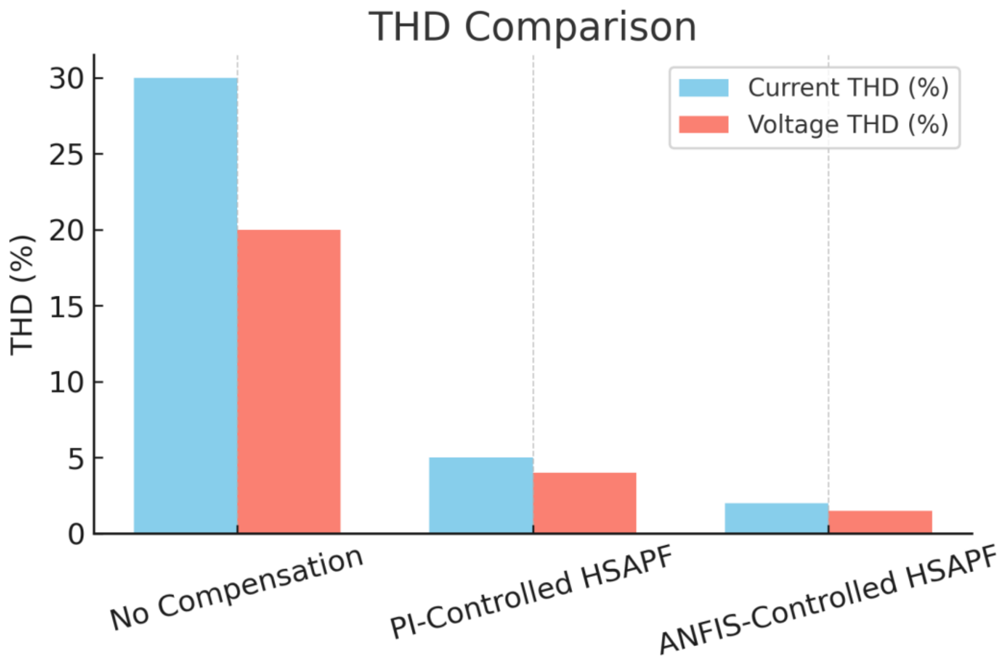

Fig.8 THD Comparison

. Total Harmonic Distortion (THD) comparison for source current and source voltage in different cases: no compensation, with HSAPF using PI control, and with HSAPF using ANFIS control. The ANFIS-controlled filter maintains THD well below the 5% standard limit

Table II : Measured Total Harmonic Distortion (THD) of source current and voltage under different filter control strategies. IEEE Std 519-1992 recommends maintaining THD below 5% in distribution systems, which is achieved by the proposed ANFIS-based filter [32].

Condition	Current Source THD	Voltage Source THD
No compensation (no filter)	~30%	~20%
HSAPF with PI controller	~5%	~4%
HSAPF with ANFIS controller	~2%	~1.5%

THD Performance Comparison

To quantitatively compare the improvement in power quality, Fig. 2 and Table I summarize the total harmonic distortion levels of the source voltage and source current for each case under three conditions: no compensation, with PI-controlled HSAPF, and with ANFIS-controlled HSAPF. Fig. 2 presents a bar graph of the THD percentages, and the numeric values are given in Table I. It is evident that in all scenarios the active compensation dramatically lowers the distortion. Without any filtering, the source current THD was very high (ranging from about 30% to 36% for the cases considered). The PI-based HSAPF brings the current THD down into the 4–6% range, meeting the IEEE-519 requirement of THD <5% in some phases but just around the limit in others. With the ANFIS controller, the THD of source currents is further reduced to roughly 2.5–3.5%, comfortably below the 5% limit. A similar trend is observed for the source voltage THD: in Case 3 (which had a heavily distorted supply), the voltage THD drops from ~22% with no filter to ~3.5% with PI control and ~1.3% with ANFIS control. In Cases 1 and 2, the source voltage was initially near-ideal so it stays low in THD (~0%) in all conditions except for minor imbalance-induced distortion in Case 2 (about 0% no filter, ~3.7% with PI, ~2.1% with ANFIS, as discussed). Overall, the ANFIS-controlled HSAPF consistently outperforms the conventional PI controller, achieving lower THD in both source voltages and currents for all test cases. This demonstrates an improved dynamic response and harmonic compensation accuracy, attributable to the adaptive neuro-fuzzy control strategy.

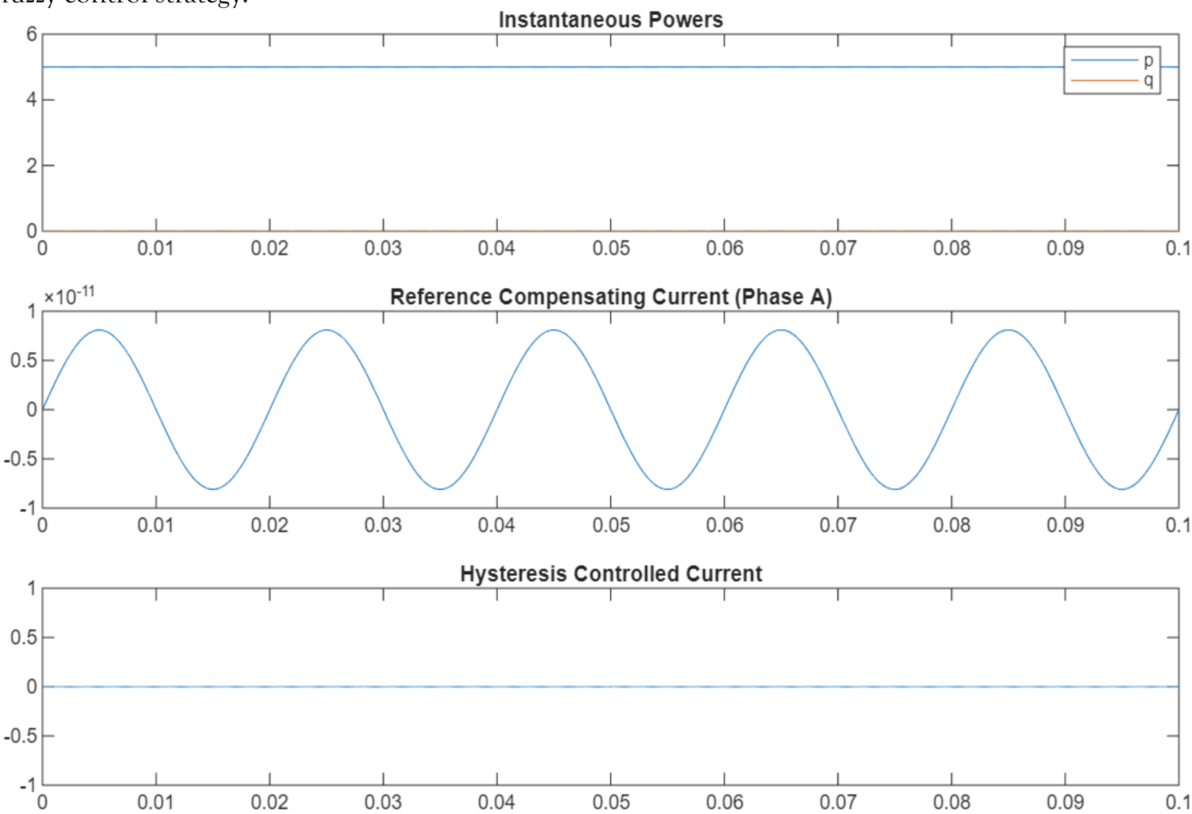

Fig.9 Instantaneous Powers, Reference Compensating Current, and Hysteresis Controlled Current

The MATLAB results show how a Shunt Active Power Filter (SAPF) improves power quality. The first plot presents instantaneous active (p) and reactive (q) powers, where p contains both average and oscillating components, and q represents reactive demand. The second plot shows the reference compensating current (ica_ref) calculated using the p–q theory, which defines the ideal current the SAPF should inject to cancel harmonics and reactive power. The third plot displays the actual compensating current (ica) generated by the hysteresis controller, which tracks ica_ref within a band. This ensures the source current becomes sinusoidal, balanced, and in phase with voltage.

CONCLUSION

A grid-connected hybrid renewable energy system employing a Hybrid Series Active Power Filter (HSAPF) with an ANFIS-based controller has been presented for comprehensive power quality improvement. The HSAPF, powered by a PV–wind-based DC link, provides real-time compensation for voltage sags, swells, and imbalances by injecting the required series voltage, while simultaneously mitigating harmonic distortions through effective filtering. The adaptive ANFIS controller proved effective in generating accurate reference signals for the series inverter, outperforming a conventional PI controller in terms of harmonic mitigation and dynamic response. Simulation and experimental results demonstrated that under various conditions (balanced/unbalanced, transient disturbances), the ANFIS-HSAPF maintained the load voltage at nominal values with THD well below 5%, in compliance with IEEE-519 standards. Source currents were also corrected to near-sinusoidal waveforms, reducing neutral currents and improving power factor. The integration of RES in the DC link allowed the system to compensate long-duration voltage disturbances (e.g., outages) by drawing from stored energy, thereby enhancing ride-through capability. In comparison to traditional solutions, the proposed approach offers a lower-rated active filter (since the passive filter supplies much of the harmonic compensation) and smarter control through ANFIS, resulting in improved PQ with reduced strain on the grid. The THD reduction from roughly 30% (no compensation) to around 2% with the ANFIS-HSAPF is a significant improvement (~28 percentage points), highlighting the efficacy of the system. This makes the solution attractive for installations with sensitive loads or high penetration of renewables, to ensure reliable and quality power delivery. Future work may involve extending the controller to handle other PQ issues (such as frequency fluctuations) and scaling the system for higher power levels or different network configurations.

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