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PERFORMANCE ANALYSIS AND COMPARATIVE STUDY OF DIFFERENT HYBRID POWER FILTER TOPOLOGIES USING IRPT

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Abstract

As more modern devices with nonlinear power demands come online, they're causing current harmonics — little distortions in the electrical flow that mess with power quality and can hurt how well the whole system performs. To tackle this problem, the study looks into a mixed-filtering solution that combines a passive shunt filter with an active power filter in series. The active filter uses a voltage-source inverter that sits between the power supply and the tricky, non-linear load — all connected through a series transformer to help smooth things out. To reduce harmonic distortion, the system injects a smart corrective voltage. This helps keep the current flowing from the source smooth and mostly sinusoidal—while still making sure the main, desired current stays strong and on target. To make the active filter work properly, we use a current control method based on hysteresis—which helps generate the precise switching signals needed. To figure out the reference compensating current, we use the synchronous reference frame (SRF) method — it's a smart way to simplify things in real-time. Then, we add a proportional-integral (PI) controller to help the system react faster and stay more. Also, the Instantaneous Reactive Power Theory (IRPT) is used to calculate the exact reference current needed to cancel out unwanted harmonics — basically, it helps the system stay clean and efficient by neutral. We tested how well the new hybrid filter performs under various load conditions using MATLAB simulations—to see how reliable and responsive it really is. The results show a clear drop in unwanted current harmonics—and overall, the power quality has gotten much better.

Keywords: *Shunt Active Power Filter (SAPF), Proportional controller (PI), Power quality (PQ), Synchronous Reference Frame Theory (SRF), Total Harmonics Distortion (THD), Hybrid filter (HF).*

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1. Introduction

The general implementation of power electronic converters has greatly streamlined the transformation of electrical energy between AC and DC systems. In today's industrial and digital systems, nonlinear loadsincluding data processing devices, variable-speed drives, and electronic power suppliesare becoming more widespread. These loads pull distorted current from the utility grid, causing harmonic pollution at the point of common coupling (PCC) and reducing overall power quality [1], [2]. Harmonics lead to waveform distortion, raise system losses, and negatively impact the performance of electrical equipment tied to the grid [3], [4].

To mitigate the adverse impacts of harmonics and other power quality issues, standards like IEEE 519-2014 and IEC 61000-2 -2 set recommended thresholds for voltage and current distortion [1]. Passive power filters (PPFs) have long been favored for their affordability and straightforward design. Nevertheless, their performance can be affected by changes in system impedance, and resonance may arise in specific operating conditions, potentially causing harmonic currents to increase. Despite their superior compensation performance, active power filters are frequently limited in adoption due to elevated investment and maintenance expenses [4], [5]. Moreover, passive filtering systems typically need more installation space compared to active filtering options. [5]. Hybrid power filters (HPFs), combining passive and active filtering methods, offer a balanced solution that reconciles performance, cost, and reliability [5], [6]. In these setups, passive filters are typically used to dampen major harmonic elements, whereas active filters address leftover distortions and enhance the system's dynamic performance. This synchronized operation reduces resonance problems and boosts the effectiveness of harmonic mitigation.

Harmonic distortion in power systems can lead to equipment overheating, excessive vibration, low power factor, capacitor failures, higher energy losses, diminished efficiency, and unstable voltage levels. Because harmonics travel through the electrical system, they can adversely affect the operation of equipment used by utilities and consumers alike. Therefore, reliable harmonic compensation methods are crucial for ensuring good power quality. As a result, active power filters have garnered significant attention, prompting the creation of many control and compensation algorithms. This work utilizes the synchronous reference frame (SRF) method to produce the reference compensating current for the active filter. The proposed method relies solely on load-current measurements and is implemented in MATLAB to assess its effectiveness in reactive power compensation, power factor enhancement, voltage balancing, and THD reduction.

1.1 State of the Art on Hybrid Power Filters

Advancements in power quality technology have enabled the development of filtering solutions capable of mitigating harmonics generated by a wide variety of nonlinear loads. Modern filtering techniques address several power quality issues, including harmonic distortion, voltage fluctuations, current imbalance, transient disturbances, and reactive power compensation. Depending on load characteristics, filters can be applied to voltage-source loads, current-source loads, or systems that exhibit a combination of both operating modes. Several hybrid filter topologies have been reported in the literature, including series, shunt, and combined configurations. These systems may be implemented in single-phase or three-phase networks, with or without neutral conductors. Various converter technologies based on voltage-source converters (VSCs) and current-source converters (CSCs) have also been investigated to improve filtering performance. Owing to their balanced combination of cost-effectiveness and compensation capability, hybrid filters are increasingly recognized as a suitable solution for maintaining high-quality AC power under nonlinear loading conditions.

1.2 Classification of Hybrid Power Filters

Hybrid power filters can be classified according to their structural configuration, supply-system arrangement, and converter type employed within the active filtering stage. Depending on application requirements, HPFs may be used in single-phase systems, three-phase three-wire systems, or three-phase four-wire systems. The active filtering section may utilize either a voltage-source converter (VSC) or a current-source converter (CSC), provided that an appropriate control strategy is implemented.

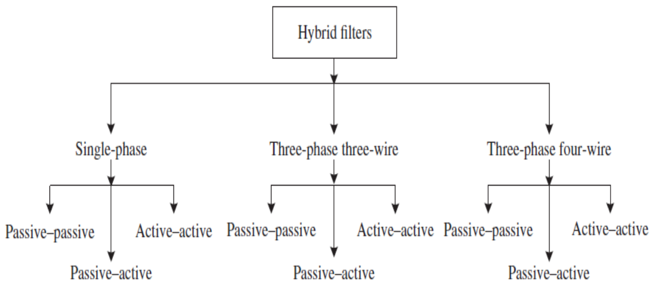

Figure 1: Classification of hybrid filters power filter

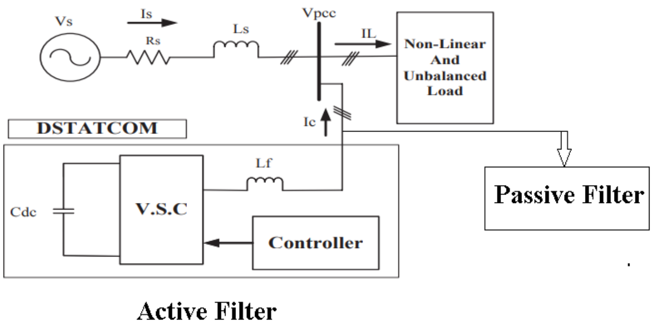

Figure 2. Diagram showing the configuration of a hybrid filter combining shunt active and shunt passive components

1.3 Operating Principle of Hybrid Power Filters

The primary objective of a hybrid power filter is to improve power quality by compensating for disturbances introduced by nonlinear loads. Through the coordinated action of passive and active filtering components, the HPF effectively suppresses harmonic currents, reduces reactive power demand, mitigates voltage distortions, and improves load balancing. As a result, electrical equipment can operate more reliably even when connected to networks affected by power quality disturbances.

Hybrid filters are capable of addressing both voltage-related and current-related issues. Voltage harmonics, voltage imbalance, and voltage fluctuations can be reduced, while current harmonics, reactive currents, and unbalanced currents are simultaneously compensated. Furthermore, appropriate control of the DC-link voltage ensures stable operation of the active filter and supports continuous compensation performance [7].

1.4 Control of Hybrid Power Filters Based on Instantaneous Reactive Power Theory

The control strategy adopted in this work is based on Instantaneous Reactive Power Theory (IRPT). In the proposed scheme, three-phase source voltages and currents are measured and transformed into α–β stationary reference-frame components. Using these transformed variables, instantaneous active power and instantaneous reactive power are calculated.

The resulting power signals contain both DC and AC components. The DC portions represent the fundamental active and reactive power components, whereas the AC portions correspond to harmonic and unbalanced components. Appropriate filtering techniques are employed to separate these components and identify the distortion-related quantities that require compensation.

To maintain the DC-link voltage at its desired value, the measured DC voltage is compared with a reference value. The resulting error is processed through a proportional–integral (PI) controller, whose output contributes to the generation of the reference compensation signal. A low-pass filter is incorporated into the control loop to reduce high-frequency fluctuations and improve voltage regulation performance.

Based on the calculated reference powers, the corresponding harmonic reference currents are generated. These reference currents are subsequently processed through a pulse-width modulation (PWM) controller to produce the switching signals required for the active filter converter. The injected compensating voltage enhances the performance of the passive filtering stage and enables effective suppression of harmonic distortion across a wide range of operating conditions.

In these expressions, the fundamental load power is converted into DC components ps and qs, while distortion or negative sequence components are transformed into AC components ~ps and ~qs. The DC components of active and reactive power are isolated using two high-pass filters. Moreover, the active filter regulates its DC capacitor voltage autonomously, requiring no external power source. When the active filter produces a fundamental voltage that is in phase with the fundamental leading current of the passive filter, the active power generated by that current and voltage is delivered to the DC capacitor. Thus, the electrical quantity that needs to be regulated in the DC voltage of the AF feedback loop is incorporated into the reactive power (~qs). To build up the DC bus voltage of the AF, the difference between the measured DC bus voltage and the reference DC bus voltage is fed into a PI controller. The PI controller's output is combined with the AC portion of the instantaneous reactive power. Therefore, the reference powers for the harmonic currents are calculated as:

$$p^* = \tilde{p}_L,$$
$$q^* = \tilde{q}_L + x_{pi},$$

Where xpi represents the output signal from the PI controller. In this setup, a low-pass filter is incorporated into the DC bus voltage feedback loop to suppress high-frequency ripples in the DC bus voltage.
The reference three-phase harmonic currents (isha; ishb; i*shc) are calculated as:

$$\begin{pmatrix} i^*_{sha} \\ i^*_{shb} \\ i^*_{shc} \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} v_{s\alpha} & v_{s\beta} \\ -v_{s\beta} & v_{s\alpha} \end{pmatrix}^{-1} \begin{pmatrix} p^* \\ q^* \end{pmatrix}$$

The estimated harmonic current per phase is multiplied by a gain K and fed into a PWM controller as a reference voltage V*. Kish. The gating signals are produced by comparing the reference voltage V*c against a triangle wave carrier frequency. This generates a voltage in series with the three-phase passive filter, thereby enhancing the passive filter's performance on its own, as described by the compensation principle of a hybrid filter.

2. Gravitational Search Optimization

GSA was recently developed by Rashedi et al. based on Newton's laws of gravity and motion. In this algorithm, the agent's individuals are treated as masses. The competence in exploitation and exploration can be enhanced due to its flexible yet stable structure [1]. Today, numerous researchers have applied this algorithm to tackle a wide range of problems. All entities in the search space are drawn toward one another based on Newtonian gravitational principles, and those masses exerting gravitational force converge on optimal solutions through movement within the search space. This mass movement occurs in accordance with Newton's second law of motion. Throughout the algorithm, this heaviest mass moves more slowly than the others and draws them in. Once the stop criterion is met, the problem's optimal solution will have the greatest mass.

3. PI Controller

In control systems, securing controller parameters that ensure system stability is crucial. One approach for obtaining these parameters is the SBL method. The SBL method is a graphical technique for identifying controller parameters that ensure system stability. Selecting the right type of controller is essential for meeting the desired design specifications. In most cases, simpler, structured controllers are favored. PID controllers are frequently favored in the industry due to their straightforward structure and reliable performance traits. The optimization process involves choosing the most suitable option from the existing scenarios. Optimization models using Simulink have been created according to integral performance metrics. The optimization process starts by inputting initial values for the controller parameters. Once the smallest error value is achieved, the optimization halts, yielding the most appropriate controller parameters. For tuning the PI controller parameters, the IAE, ISE, and ITAE criteria are employed.

1. $IAE = \int |e(t)|\, dt$
2. $ISE = \int e^2(t) dt$
3. $ITAE = \int t\, |e^2(t)|\, dt$

4. Block Diagram of Hybrid filter as a combination of Active shunt And Passive shunt Filter

Figure 4 illustrates the fundamental circuit layout of the compensated line. The active filter is linked in parallel alongside a passive filter that is also configured in parallel. The MATLAB/ SIMULINK simulation is implemented using the instantaneous reactive power theory control strategy, identical to that employed in a series active and passive shunt hybrid filter setup. The gating pulses for the VSI are generated by comparing the source current and reference current against a rectangular pulse generator. Hybrid filters are generally seen as an economical solution for enhancing power quality, mitigating adverse effects caused by nonlinear loads, or delivering a clean sinusoidal AC supply to sensitive equipment.

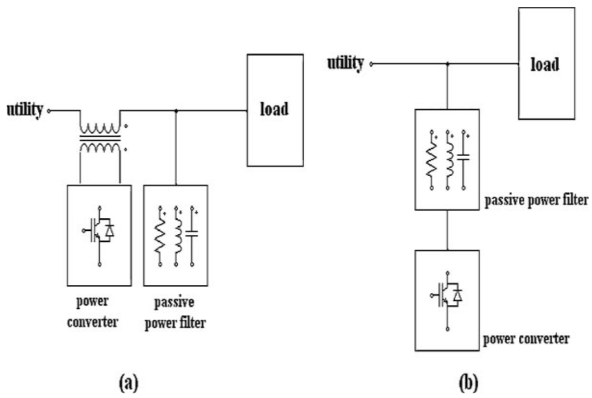

Figure 4: Line Diagram of the system with Shunt Active and Shunt Passive Filter compensation

5. Simulation and Results

The system's behavior and performance are evaluated by simulating the result in the MATLAB/ Simulink toolbox. The system is simulated under a nonlinear load condition using a Gravitational Search Algorithmbased controller for a hybrid shunt active and passive filter. The primary goal is to reduce odd harmonic components through the Gravitational Search Algorithm.

Figure 5 shows the source current without compensation. Without any compensation, the load current waveform matches the source current waveform precisely. It is evident that the source current includes harmonic components, making it non-sinusoidal.

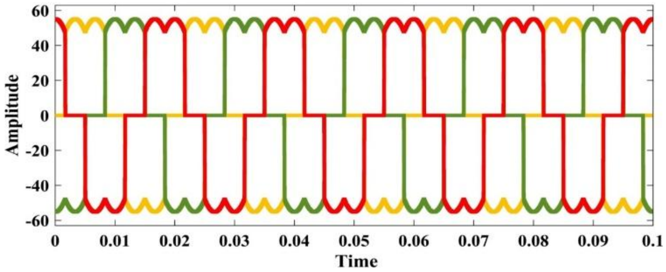

Figure 5: source current and load current waveform before compensation

Figure 5 illustrates the waveform of the source current and load current when the Hybrid Filter is absent from the system, as harmonic current componentspotentially generated by nonlinear loadsare not being filtered. As shown in the above figure, the harmonic in the current is caused by the connected nonlinear loads. It is clear that the source current in the above figure is non-sinusoidal, which will lower the power factor and increase power loss in the system. It also impacts the stability of the system's source side. Without compensation, the source current exhibits 12.34% total harmonic distortion (THD), exceeding the IEEE 519-1992 standard, while its fundamental component measures 23.29A. The FFT analysis is illustrated in Figure 6.

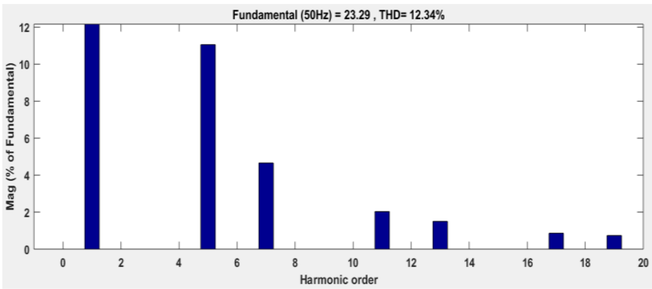

Figure 6: FFT analysis of source current without compensation

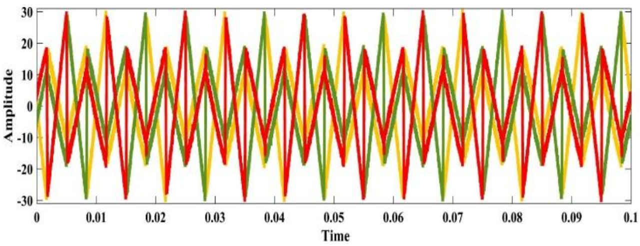

Figure 7: Waveform of generated filter current when hybrid filter is connected

Figure 7 illustrates the waveform of the filter current generated to counteract harmonic current that nonlinear loads may produce. This filter current is injected at the Point of Common Coupling (PCC) to reduce the system's Total Harmonic Distortion (THD). This filter current matches the harmonic current produced by the nonlinear load in magnitude but acts in the opposite direction.

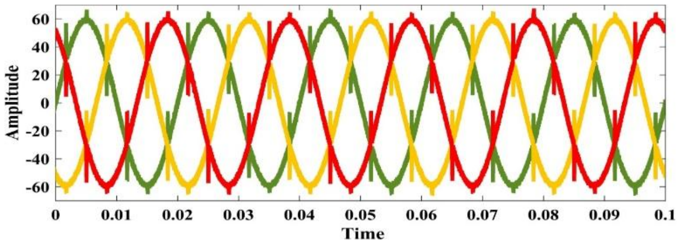

Figure 8: Simulation result of source current when hybrid filter is connected

Figure 8 displays the waveform of the compensated current, as shown above. 5.8 It is evident that when a hybrid filter is connected to the system, it injects a compensating current equal in magnitude but opposite in phase to the harmonic components generated by nonlinear loads within the system. When the hybrid filter is activated, the waveform improves, and the source current waveform becomes closer to sinusoidal compared to before compensation. Figure 9 illustrates the capacitor charging voltage (Vdc), which produces the necessary current containing harmonics to compensate for reactive power. The capacitor starts charging at 150 volts..

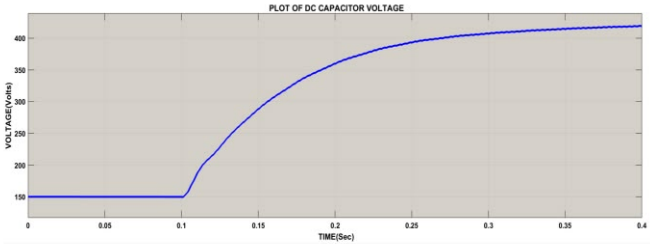

Figure 9: Simulation result DC capacitor voltage

Figure 10-12 displays the FFT waveform of the generated source current. The simulation results using controller parameters tuned for ITAE, IAE, and ISE performance metrics are presented:

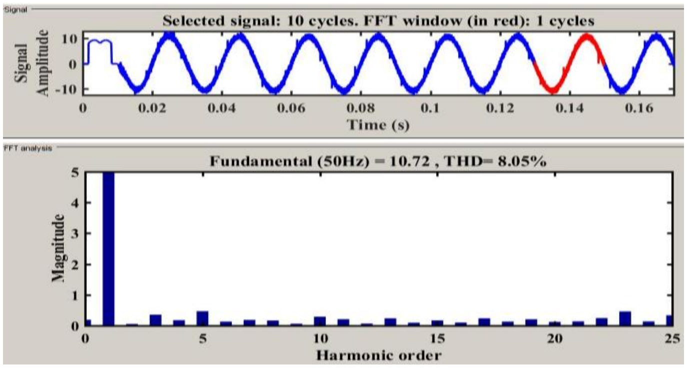

Figure 10: FFT analysis of Source current using Gravitational Search (IAE Criteria)

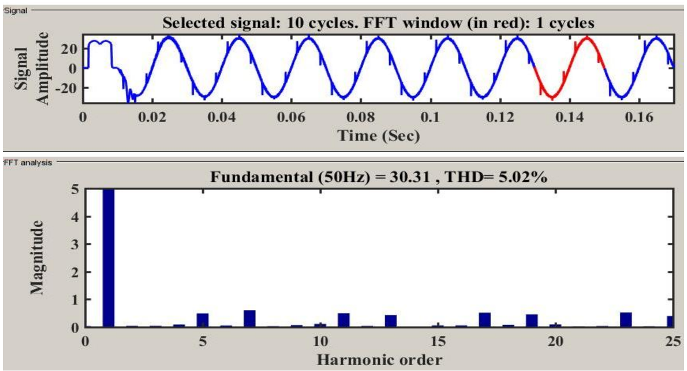

Figure 11: FFT analysis of Source current using Gravitational Search (ITAE Criteria)

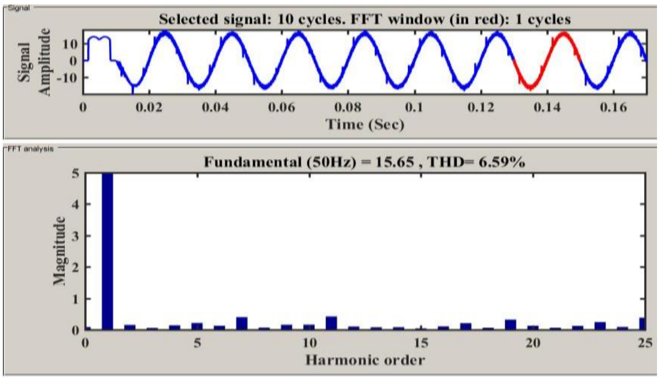

Fig 12:- FFT analysis of Source current using Gravitational Search (ISE Criteria)

This section outlines the results achieved through the use of the Gravitational Search Algorithm (GSA). The Gravitational Search Algorithm is employed to optimize the PI controller, aiming to minimize Total Harmonic Distortion in the source current. Figure 11 illustrates the FFT analysis of the source current employing the Gravitational Search algorithm, evaluated under the ITAE criterion. The THD value of 5.02% is observed to be lower than the THD values obtained under the Gravitational Search algorithm using both IAE and ITAE criteria Figures 10 and 12 illustrate the FFT analysis of the source current when employing Gravitational Search with IAE and ITAE criteria. The THD value of 6.59% is lower than that obtained under the Gravitational Search algorithm using the IAE criterion, yet higher than the THD value achieved with the ISE criterion for the same algorithm.

Table 1

CSA Parameter	IAE	ISE	ITAE
P	601.54	416.13	369.56
I	331.12	351.89	415.71
Kp	415.2	248.12	221.23
Ki	175. 42	112. 31	104.43
CURRENT THD (%)	8.05	5.02	6.39

Tuned values of GSA parameters such as P, I, Kp, and Ki, obtained through Gravitational Search Algorithm optimization, are shown in the table. As shown in Table. It is evident that, under the ISE criterion, the current THD is minimized compared to the IAE and ITAE criteria. The parameters P, I, Kp, and Ki represent the simulation settings for the PI controller, which can be fine-tuned using the Gravitational Search Algorithm optimization method.

6. Conclusions

The use of electronic switches has significantly raised the level of non-linear loads in the system. The rise in non-linear loads significantly increases the percentage of Total Harmonic Distortion (THD). As the percentage of THD rises, so do the issues related to equipment failure. Power filter technology has expanded significantly, offering solutions for managing various non-linear loads via current-based compensation and mitigating voltage harmonics, sags, swells, and improving voltage regulation through voltage-based compensation methods. Hybrid filters demonstrate a cost-effective approach to eliminating harmonics and enhancing system performance when compared to using active or passive filters on their own. Passive filters suffer from fixed compensation and resonance issues, which active filters can address.

The simulation mentioned above is conducted based on three criteria: Integral time absolute error (ITAE), Integral square error (ISE), and Integral time square error (ITSE), as shown in Table 1. It is evident that ISE provides a lower THD compared to both ISE and ITAE. The Gravitational Search optimization method is utilized to address reactive power and power quality challenges.

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