Performance Analysis of a Hybrid Filter Enhanced with Improved HUA Optimization in Conjunction with PI-SRF Control for Power Quality Improvement and Reactive Power Management

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Abstract- In this paper, a unique strategy for managing a hybrid active filter (HAF) that uses the Improved Human Urbanization Algorithm (IHUA) in conjunction with a tuned Proportional-Integral (PI) control scheme within the Synchronous Reference Frame (SRF) is presented. The HAF is a particularly built power device that addresses power quality concerns caused by harmonics and imbalances while also facilitating reactive power compensation. This is accomplished without placing any extra limits on the design requirements of active filter components like as inverters and their accompanying switches. The HAF system's efficacy is inextricably related to its control design, which is in turn dependent on important controller design characteristics, with the PI controller bearing special importance. The SRF control technique is a critical component of the active filter's control strategy, and the PI controller has a significant impact on its performance. When compared to other existing approaches, our suggested IHUA-based optimization for the PI controller offers significant improvements in terms of control accuracy and responsiveness. Furthermore, the SRF control strategy for managing the active filter component inside the HAF system is versatile, allowing it to provide reactive power assistance based on its rating. The HAF system consists of a four-leg shunt active filter and a shunt passive filter that work together to handle harmonic difficulties, neutral current compensation, and reactive power correction. A complete simulation study is performed using MATLAB/SIMULINK to assess the performance of our proposed HUA-tuned PI-SRF-based HAF. In addition, we do a comparison study to evaluate the efficacy of several tuning strategies for the PI controller.

Keywords Hybrid active filter (HAF), Improved Human urbanization algorithm (IHUA), Synchronous reference frame (SRF), Proportional-integral (PI), Current harmonic mitigation, Load unbalancing, VAR mitigation.

1. Introduction

Custom power devices represent a significant innovation with the potential to transform the way we approach power quality issues as well as reactive power compensation [1]–[8]. Extensive research efforts have been devoted over the last two decades to investigating various devices classified as bespoke power devices. Passive filters, shunt active filters, series active filters, hybrid filters, UPQC (Unified Power Quality Conditioner), and other iterations thereof are generally included in this category [9]-[11].

The Shunt Active Power Filter (SAPF) [12]-[18] is a cutting-edge breakthrough in power electronics and control systems. Through the use of advanced control algorithms and high-speed semiconductor devices, this cutting-edge technology actively rectifies difficulties such as harmonic currents, reactive power, and other disturbances in real-time. However, the SAPF has a design rating constraint that limits its capacity to deliver the necessary reactive power correction [18]. As a result, the hybrid active filter (HAF), which blends active and passive filter components, emerges as a viable option. In this design, the passive filter not only supplements the active filter in terms of reactive power compensation, but it also plays an important role in reducing harmonic distortions [19], [20]. Basic architecture of HAF and their classification has been discussed in [21]. Different control mechanisms have been developed for the same over the years [22]-[24], but can be categorized basically in three categories [25]. One is the PQ theory which was devised very early, since its inception. Second is the Id-Iq method which is also termed as SRF (synchronous reference frame) method. And third is the Unit Vector Template (UVT) method. Various other extended and different versions of the same methods have been investigated upon by the researchers [26], [27]. Among the three, SRF method is found to be better in performance and control as compared to other two [26].

To manage the converter, the control architecture of bespoke power devices, such as the Synchronous Reference Frame (SRF) technique, relies heavily on the exact tuning and successful functioning of its error processing controller [28]-[30]. Extensive experience has shown that the Proportional-Integral (PI) controller is the most durable and practically feasible option for applications such as active filter or HAF control design [31]. As a result, when improving the system's control structure to achieve higher flexibility and dynamic responsiveness is a main design goal, accurate tuning of these PI controller settings to enable quick responses becomes critical.

Metaheuristic optimization is important in the PI-SRF control approach for power quality and reactive power management, owing to its ability to solve complex, high-dimensional, and non-convex optimization problems [32] [33]. This study presents a PI-SRF-based control system for a HAF that is modified using the Improved Human Urbanization Algorithm (IHUA). We investigate the performance of our suggested HAF and compare it to standard approaches. This type of system has its practical applicability for basically rectifier and inverter motor drive system or similar type of loads where harmonic presence exist due to switching devices and also reactive power demand due to heavy inductive loads.

A four-leg shunt active filter and a three-phase tuned passive filter are used in tandem in the HAF construction. They collaborate to solve problems caused by imbalanced loads such as reactive power demand, current harmonics, and neutral currents. The HAF’s control mechanism is based on the Synchronous Reference Frame (SRF) technology. An error processing PI controller is used in this framework, and its tuning is optimized using the IHUA-based technique.

The primary goals of implementing this proposed system are:

- To mitigate and manage mitigation of current harmonics and keeping the source current THD limit within 5 %.
- To compensate and manage reactive power demand by load.
- To reduce the design rating requirements of active filter components by precisely controlling the allocation of reactive power compensation between active and passive filter.
- To improve its dynamic performance, both under initial conditions and during load fluctuations with proposed IHUA optimization of PI controller.

The paper is organized as follows: Firstly, HAF proposed configuration is discussed for unbalanced load system that includes three-phase and single-phase non-linear and linear loads. Then the IHUA based PI-SRF control structure is discussed. Thereafter, IHUA optimization method is discussed in detail. This follows with discussion on simulation analysis of the proposed configuration under different scenarios and conditions like different load condition and also includes a comparative analysis of proposed optimization method with other optimization methods.

2. HAF Configuration for Three-phase and Single-Phase Load System

The focus of this study article is on the analysis of a three-phase four-wire distribution system, as shown in Figure 1. This system is coupled to an imbalanced load structure, which includes a three-phase nonlinear load represented by an unregulated rectifier connected to an RL load. A three-phase linear load is also included to cater for reactive power requirements. In addition, we create two single-phase nonlinear loads, coupled to phases A and B, to indicate the presence of system imbalances. The major goal of this research is to thoroughly analyse the consequences and complexity generated by this particular system configuration inside the distribution network. A significant component is the HAF system, which consists of a three-phase four-leg shunt APF system joined by coupling inductors and a three-phase passive filter. The passive filter's phases are made up of a series combination of a filter inductor and a filter capacitor. We use the suggested Improved Human Urbanization Algorithm (IHUA) adjusted PI-SRF approach, which is the focus of our study, to efficiently manage the APF inside the HAF system.

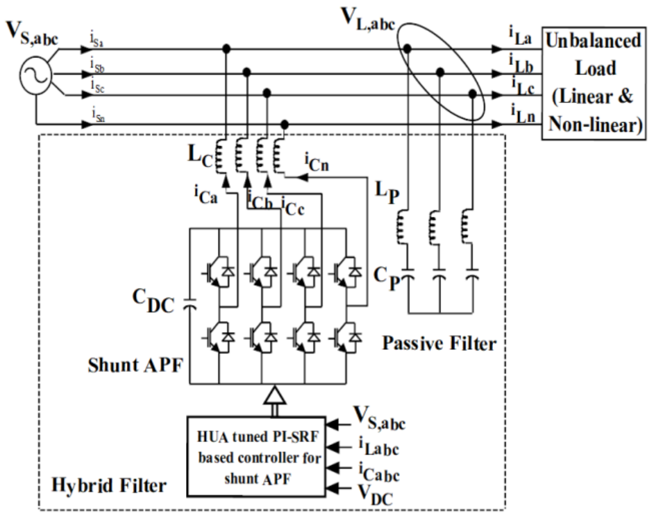

Fig 1. 3-phase 4-wire system: HAF configuration

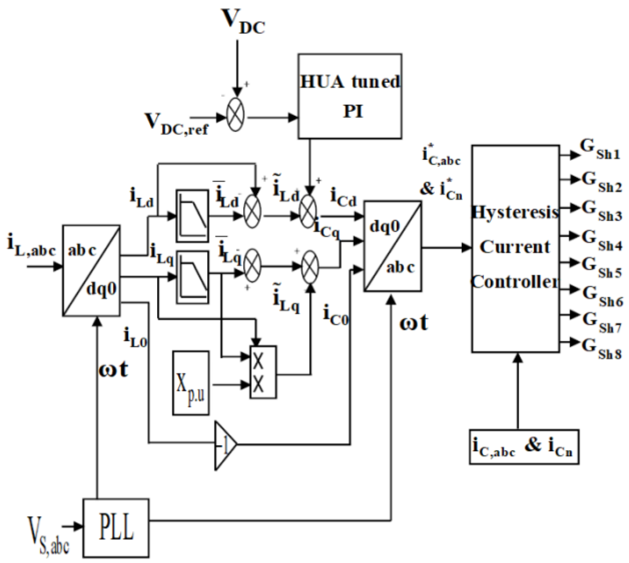

Fig 2. IHUA based PI tuned shunt APF of HAF: Control block diagram

2.1 IHUA based PI-SRF Control for HAF

Fig 2 depicts the control block diagram for the APF part of the HAF, which employs the IHUA-tuned PI-SRF control technique. This component is critical in resolving a variety of challenges, including minimizing current harmonics caused by non-linear loads, neutral current caused by load imbalances, and considerable compensation of reactive power needs caused by linear loads.

In this paper, investigating the use of a reference source current signal and a reference compensating current signal as the principal reference signals for a shunt active filter coupled with an SRF-based controller is within the scope of this research article. Our primary focus is on investigating the viability of using more manageable compensating current reference signals, and we conduct a comparison with the real compensating current signals. It's also worth noting that the shunt APF successfully controls a considerable percentage of the basic reactive current needs coming from the load side.

Three phase load current signal are converted to active current (d) and reactive current (q) components using abc-dq0 transformations

$$\begin{bmatrix} i_{l0} \\ i_{ld} \\ i_{lq} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \sin\omega t & \sin\left(\omega t - \frac{2\pi}{3}\right) & \sin\left(\omega t + \frac{2\pi}{3}\right) \\ \cos\omega t & \cos\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} \quad (1)$$

A unique low-pass filter is used to separate the average components of the active current, which include both oscillating and average elements indicated by the d-axis component. The loss component of this filter is efficiently integrated with the oscillating active current, as defined by the processed error produced from the DC-link capacitor voltage using a IHUA-tuned PI controller. The q-axis component, which represents reactive current, is similarly low-pass filtered to recover the oscillating reactive current component. An input value labelled as x p.u is used to control the amount of reactive power supplied by the HAF's active filter portion. This number is determined by factors such as the rating of the passive filter (i.e., its capacity to manage load reactive power) and the total demand for reactive power from the load.
The dq0-abc transformation converts dq0 compensating current components back to abc three-phase compensating currents:

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = \begin{bmatrix} \cos\omega t & -\sin\omega t & 1 \\ \cos\left(\omega t - \frac{2\pi}{3}\right) & -\sin\left(\omega t - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\omega t + \frac{2\pi}{3}\right) & -\sin\left(\omega t + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} i_{ld} \\ i_{lq} \\ i_{l0} \end{bmatrix} \quad (2)$$

Furthermore, in order to regulate the fourth leg of the active filter inverter, the reference three-phase compensating currents (denoted as $i_{ca}^*, i_{cb}^*, i_{cc}^*$) are utilized to calculate the neutral compensating reference current, as shown by the equation:

$$i_n^* = i_{ca}^* + i_{cb}^* + i_{cc}^* \quad (3)$$

As a result, we use a hysteresis current controller to create switching pulses for the active filter (G_{sh1} to G_{sh8}) by comparing these compensating reference currents to the actual compensating currents.
The next part goes into the suggested optimization approach for the PI controller, specifically the HUA method.

3. Improved Human Urbanization Algorithm (HUA)

3.1 HUA Introduction

The Human Urbanization Algorithm, one of the metaheuristic algorithms, is inspired by the dynamics of human urbanization with the goal of maximizing life situations. This method is driven by individual movement patterns, particularly in reaction to changing circumstances and city expansion [34]. The HUA strategy is based on the idea of pursuing better living circumstances in urban areas. This technique is influenced by a variety of urbanization characteristics, including travel, immigration, depopulation, and exposure. Journeying is the process of discovering new locations based on prior experiences and random movements, whereas migrations are shifts in livelihoods from one town to another, which are typically driven by the facilities available. Populations are steered by multiple roads that bring them to different towns, and the HUA's mission takes into account every possible consequence during the search process.

3.2 IHUA Implementation

In the paper, this method can be utilized for optimizing the adjustment of k_p and k_i parameters for the Proportional-Integral (PI) controller employed in a Shunt Active Power Filter (SAPF). The optimization objective is to minimize the Integral of Time multiplied by Absolute Error (ITAE). The subsequent steps detail the application of the HUA for this specific optimization task

Step 1: Initialization

During this phase, the input parameters, including load current, dc link voltage, source voltage, and the proportional and integral gain constants within the PI controller, are already identified and defined.

Step 2: Random Generation

In this step, the initially established parameters undergo random generation.

$$D = \begin{bmatrix} K_{pt}{}^{11}K_{it}{}^{11} & K_{pt}{}^{12}K_{it}{}^{12} & \cdots & K_{pt}{}^{1n}K_{it}{}^{1n} \\ K_{pt}{}^{21}K_{it}{}^{21} & K_{pt}{}^{22}K_{it}{}^{22} & \cdots & K_{pt}{}^{2n}K_{it}{}^{2n} \\ \vdots & \vdots & \vdots & \vdots \\ K_{pt}{}^{m1}K_{it}{}^{m1} & K_{pt}{}^{m2}K_{it}{}^{m2} & \cdots & K_{pt}{}^{mn}K_{it}{}^{mn} \end{bmatrix} \quad (4)$$

Step 3: Fitness function Evaluation

The objective of the proposed method's fitness function (FF) is to minimize costs by effectively adjusting the k_p and k_i parameters of the PI controller utilized in SAPF. This function is formally defined in equation (5).

$$FF = f(k_p, k_i) \quad (5)$$

Here, FF denotes the cost associated with the fitness function. Our design employs the integral absolute error (ITAE) as the selected cost function.

Step 4: Updating position

By employing the equation below, the city's population, similar to the HUA method, has been restructured into a fitness metric

$$P_i(t+1) = P_i(t) + Indx_j \quad (6)$$

Where, $Indx_j$ represents index of city

Step 5: Determine the Radius of the City

The city radius is established in below equation,

$$R_i = \frac{k * D * R}{P_i} \quad (7)$$

In this context, the notation R_i represents the radius of city i, P_i denotes the population of city i, and k signifies the iteration number. The variable D measured is contingent on the quality of the city center relative to the city's capital. Specifically, D is measured as follows

$$D = arc\ tan\left(\left|\frac{(F(capi) - F(discent))}{F(capi)}\right|\right) + 0.5 \quad (8)$$

Here, *F(discent)* represents the measurement of the distance from the city center.

Step 6: obtaining the Optimal Location

In Step 6, parameters that have been previously defined based on their proximity to the city center are stored and segmented. These values are then utilized to identify the optimal active power, which is subsequently assigned to the city's capital. Consequently, Steps 3 and 4 are repeated for each iteration.

Step 7: Stopping Criteria

Sequences are evaluated to reach their maximum potential, and if the optimal solution is not yet achieved, the process is reiterated until the desired solution is attained

4. Outcomes and discussions

Figure 1 depicts the results of an examination of the HAF using the suggested IHUA-based PI-SRF approach under various load circumstances. Furthermore, we conducted a comparative analysis to establish its efficacy in contrast to other optimization strategies. We employed MATLAB/SIMULINK (version R2022A) to create the aforementioned system for this assessment. The load section is divided into three categories: three-phase non-linear loads, three-phase linear loads, and single-phase non-linear loads. A non-linear load adds harmonic content to the system, whereas a linear load places large demands on active and reactive power. Finally, single-phase non-linear loads cause system imbalance. Our simulation analysis serves two functions. First, it intends to test the effectiveness of the SRF-based APF system in terms of its diverse contributions to improving power quality. Second, it tries to conduct a comparative study of various tuning methods that operate under similar load situations. Table I lists the simulation parameters that were used.

Table 1. Simulation parameters for case study

Source	Per phase steady state voltage	228 V (RMS)
	Frequency	50 Hz
Shunt APF	Coupling Inductor	3.2mH
	PI controller optimized with IHUA	K_P = 0.24 & K_I = 7.1
Passive filter	Filter Inductor	8.5 mH
	Filter Capacitor	28 µF
DC Link	Capacitor	2800 µF

	Reference Voltage	720 V
Load	3 Ø Linear Load	2.1 kW, 5.1 kVAR
	3 Ø Non-Linear Load (Rectifier with RL load)	R = 25 Ω, L = 9.5 mH
	1Ø Non-Linear Load (Rectifier with RL load) - Phase A	R = 14 Ω, L = 10 mH
	1Ø Non-Linear Load (Rectifier with RL load) - Phase B	R = 34 Ω, L = 9 mH

4.1 Three-phase Non-linear Load

In this scenario, the electrical load system is entirely made up of non-linear loads, such as hefty rectifiers or other converter-based loads. Such loads are infamous for causing severe harmonic distortion in the source current, considerably fouling the power supply system. In this context, we examined the HAF's accuracy using the suggested HUA-based PI-SRF approach. This evaluation is supplemented by a performance comparison incorporating both the new method and established procedures. In addition, we give a simulated study of the HAF using the suggested technique to demonstrate its usefulness in harmonic mitigation.

To understand the harmonic mitigation capability of the HAF, a simulation study of the system represented in Fig. 3 is performed using just three-phase non-linear load. This is because, when compared to both linear and non-linear loads, only non-linear loads have larger harmonic content in the source current. The three-phase source voltage accessible from the grid source is shown in Fig. 3(a), which is believed to be balanced and ideal. Figure 3(b) depicts the three-phase source current without harmonic correction. In addition, its harmonic content is depicted in Fig. 3(c) in terms of THD (Total harmonic Distortion). THD is estimated to be approximately 28.73%. Figure 3(d) depicts the three-phase source current after HAF correction. In comparison to the source current before correction, the source current is practically sinusoidal. Its THD content is also indicated in Fig. 3(e), which was determined to be 2.27%, which is less than the IEEE requirement of 5%. Fig 3(f) and 3(g) illustrate the APF current and PF current, which together contribute to source current compensation. Also shown in Fig. 3(h) is an FFT analysis of PF current to demonstrate how the passive filter is set to compensate for the 7th order harmonic component in the source current. The role of the passive filter in harmonic compensation is examined here. However, as indicated in the next analysis section, the passive filter not only helps to harmonic compensation, but it also plays a significant role in reactive power compensation.

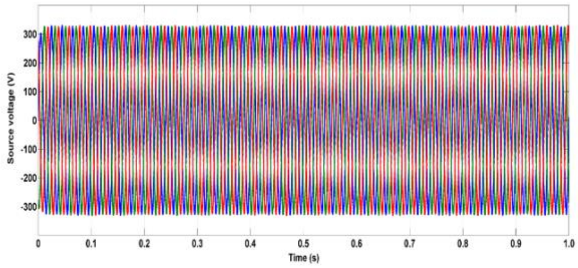

Fig 3(a). Initial three phase source voltage

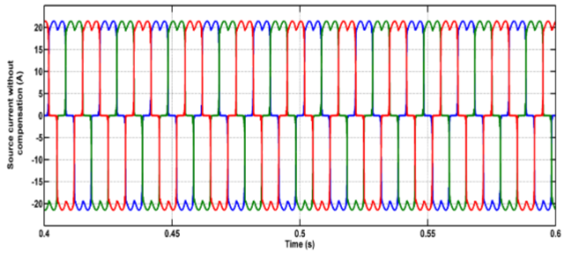

Fig 3(b). Pre compensation source current

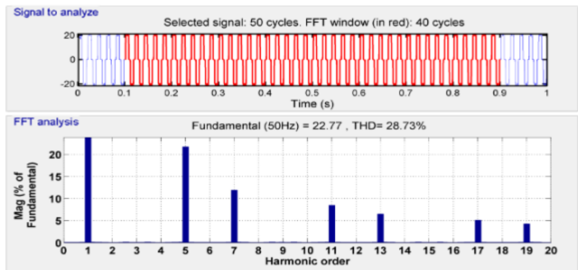

Fig 3(c). FFT analysis for pre compensation source current

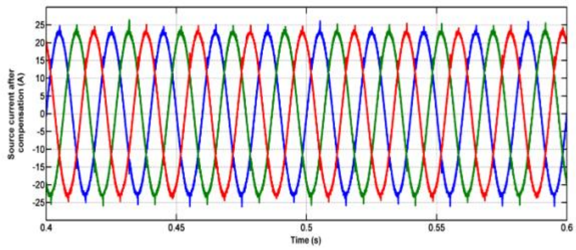

Fig 3(d). Source current: post compensation

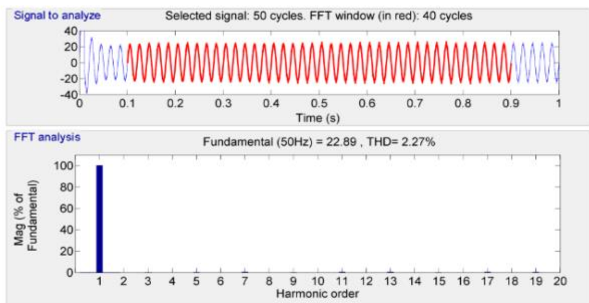

Fig 3(e). FFT analysis of post compensation source current

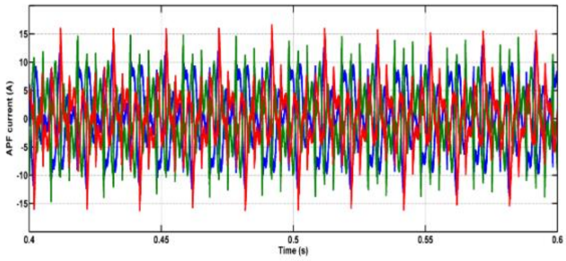

Fig 3(f). Compensating Current from active power filter

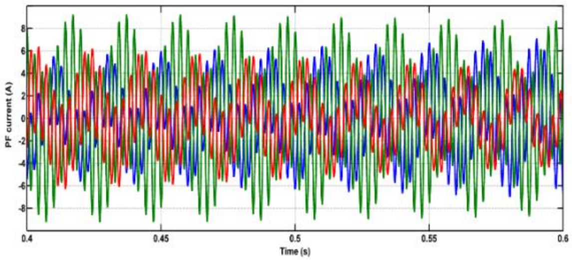

Fig 3(g). Compensating Current from passive filter

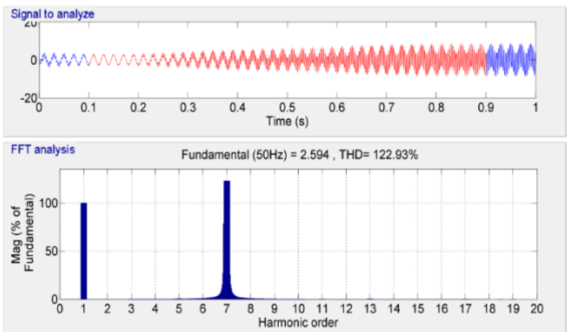

Fig 3(h). FFT analysis of Compensating Current from passive filter

4.2 Linear and Non-linear Load

The addition of linear and non-linear loads necessitates the use of reactive power as well as harmonic adjustment. However, harmonic correction is not required in the non-linear load case. The simulation study of the system represented in Fig. 1 is described first in this section, with load as a combination of linear and non-linear load. A comparison study is also given to understand the efficacy of HAF over solely passive and active filters. The source voltage is the same as in Fig. 3(a).

Figure 4(a) depicts the source current without correction, demonstrating its non-sinusoidal character. In addition, its THD content is indicated in Fig. 4(b), which is 21.14%. After HAF adjustment, the source current becomes sinusoidal, as shown in Fig. 4(c), and its THD is decreased to 1.87%, as shown in Fig. 4(d). A reactive load of 5 kVAR is posed by the linear load. The HAF, which has both active and passive components, compensates for this reactive load. The reactive power demand, compensation, and sharing are depicted pretty effectively in Fig. 4(e). Active filters account for around 3.7 kVAR of total demand, whereas passive filters account for approximately 1.3 kVAR. This sharing of VAR demand will now have a considerable influence on APF rating decrease. TABLE 2 shows a comparison of the effects of HAF vs active and passive filters alone. By integrating a single passive filter calibrated to compensate for the 7th harmonic, the active filter rating is reduced by 16%.

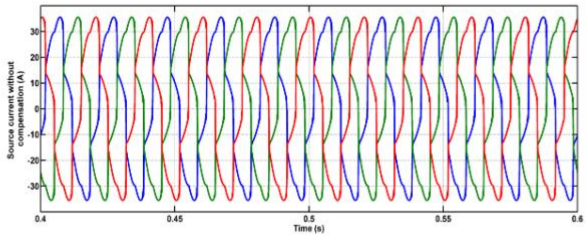

Fig 4(a). Pre-compensation Source current

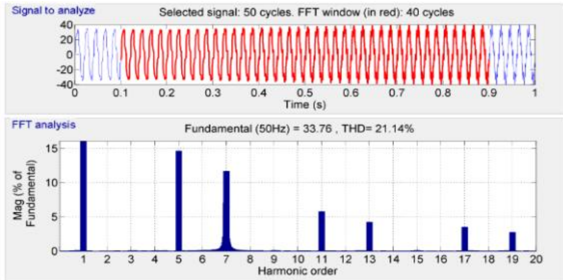

Fig 4(b). FFT analysis of Pre-Compensation Source Current

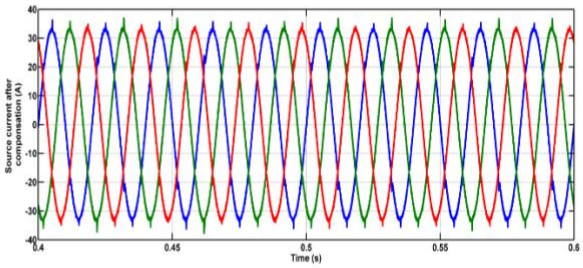

Fig 4(c). Post compensation source current

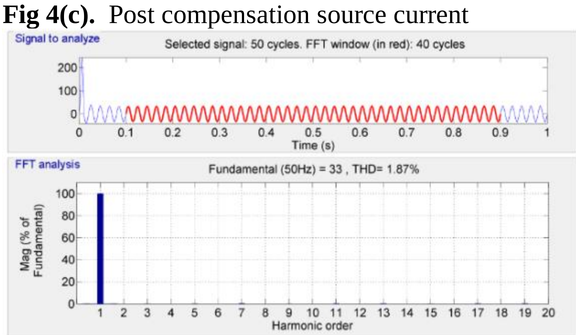

Fig 4(d). FFT analysis of Post-Compensated Source Current

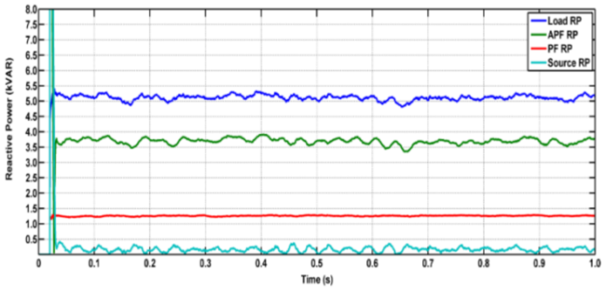

Fig 4(e). Reactive Power Comparison: Load, Active & Passive Filters, Source

Table 2. Performance Comparison: No Filter vs. Passive, Active, and Hybrid Filters

Conditions	Source			Reactive power (kVAR)		
	THD (%)	Current (A)	AP (kW)	Source	APF	PF
No Filter	28.6	20.6	11.2	5.1	---	----
Only Passive Filter	21.5	19.5	10.8	4.3	----	0.75
Only APF	2.7	16.3	11.4	0.16	4.7	---
HAF	2.3	16.4	11.3	0.15	3.9	1.2

*AP: active power, RP: reactive power. APF: active power filter, PF: passive filter

4.3 Comparative Performance Analysis of Various PI Tuning Methods

The performance and reactivity to transient events such as initial condition or load shift are closely related to the DC-link capacitor voltage profile in any HAF or APF based power conditioning system. In this case, too, the analytic outcome is the DC-link voltage profile, which is used to understand the efficacy of the suggested HUA adjusted PI-SRF approach over a few alternative optimizations. Grey wolf optimization (GWO), chimp optimization algorithm (ChOA), whale optimization algorithm (WOA), and genetic algorithm (GA) are the other optimization approaches utilized for PI controller tuning.

Figure 5 depicts the DC-link voltage pattern for several approaches during a time of 5 seconds and a voltage range of 800 V. At 1.0 s, the linear load is linked with the non-linear load to examine the transient response. The first condition to be examined is the initial reaction time, the second is the transient response time, and the third is the fluctuation recorded during the fleeting moment. Table 3 shows the comparison parameters from the results. The results and data given show that the suggested technique provides greater control and reaction than existing methods. The HAF's performance parameter is determined by the DC-link voltage profile pattern. When compared to GWO optimization, HUA results in about 82% and 92% less reaction time during initial (at the start) and transient conditions (during load change), respectively, and even better than others. Furthermore, the compensation performance increases with source current THD at 1.87% when compared to others with greater THD for the same load scenario. Following that, the success of the suggested strategy is affectively depicted in terms of harmonic mitigation and response time in the data supplied.

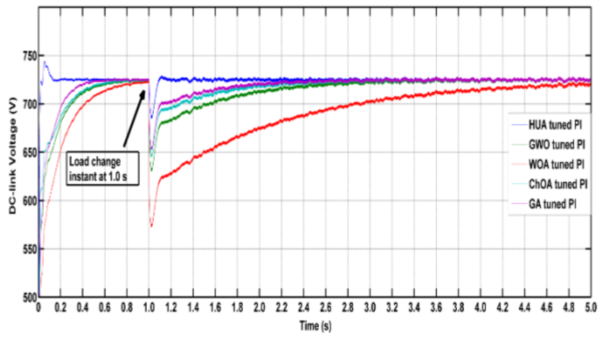

Fig 5. DC-Link voltage variation with various Metaheuristic Algorithms

Table 3. Comparative Analysis of PI Controller tuned values via various optimization techniques

PI tuning method	kp, ki values	Initial settling time (s)	Voltage under shoot (%)	Transient settling-time (s)	THD_Is (%)
IHUA	0.24, 7.1	0.12	4.7	0.15	1.85
GWO [35]	1.3, 10.2	0.54	9.7	1.22	3.84
WOA [36]	3.3, 13.4	0.76	10.2	1.63	4.25
ChOA [37]	4.2, 16.9	0.87	13.2	1.82	4.47
GA [38]	6.2, 14.6	0.97	21.4	4.93	4.78

4.4 Unbalanced Load Condition

To analyze the proposed HUA tuned PI-SRF method under unbalanced load conditions, two different types of non-linear loads are considered here, one is a three-phase rectifier based load and the other is a set of two single-phase rectifier based load (unequal) for phases A and B. Single-phase load causes system unbalance and the generation of neutral current, which must be addressed.

The unbalanced three-phase source current without compensation is shown in Fig. 6(a), and the three phases are different in size due to the non-sinusoidal character of the wave form. Unbalance is also detected in the presence of source neutral current, as illustrated in Fig. 6(b). Figure 6(c) exhibits the same three-phase source current after HAF compensation, demonstrating that the three phases are entirely balanced in amplitude and sinusoidal in type. As a result, the source neutral current decreases to a negligible amount after correction, as illustrated in Fig. 6(d).

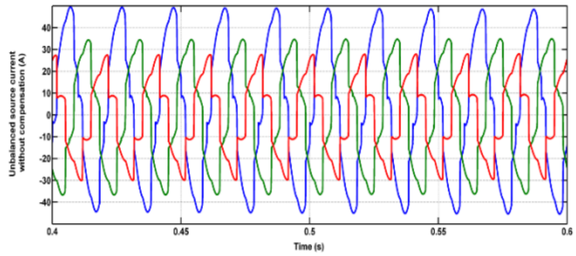

Fig.6(a). Pre-Compensation unbalanced source current

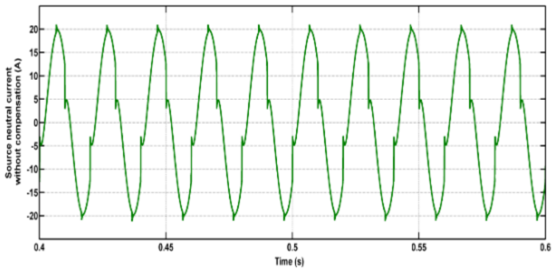

Fig.6(b). Pre-Compensation Source-Neutral Current

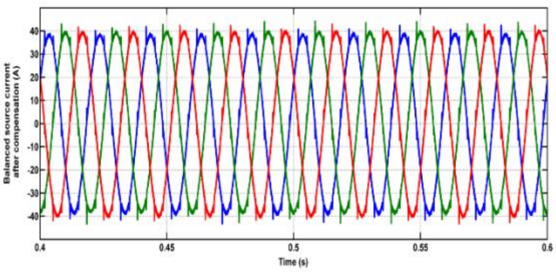

Fig.6(c). Post compensation balanced source current

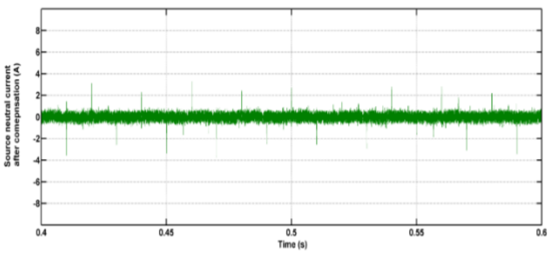

Fig. 6(d). Post-Compensation Source-Neutral Current

5. Conclusions

A thorough simulation analysis was carried out to evaluate the functionality and efficacy of a HAF employing the IHUA-tuned PI-SRF approach. This analysis covers a wide range of operating conditions and scenarios, including scenarios with high harmonic contamination due to non-linear loads only, scenarios with both non-linear and linear loads to evaluate its ability to compensate reactive power, and unbalanced load conditions to evaluate its ability to compensate for neutral currents. The SRF control method has shown to be a simple solution to reactive power compensation by the active filter while keeping the load within the design limitations. Furthermore, the IHUA optimization approach has been compared to other optimization strategies to demonstrate its superior performance. When compared to the GWO optimization technique, the suggested optimization methodology achieves an approximate reduction of 82% in reaction time during the initial startup phase and a reduction of 92% during transient situations, exceeding other approaches as well. Furthermore, the compensation performance has been improved, with the source current total harmonic distortion (THD) lowered to 1.87%, much lower than other approaches under the same load circumstances.

5.1 Limitation and Future Scope

While the suggested method has several potential uses and benefits, it is necessary to recognize key limitations. When subjected to considerable fluctuations in system frequency, the SRF control depends on a standard PLL (phase-locked loop), which may exhibit performance difficulties. Implementing a four-leg inverter can enhance the complexity and expense of switching devices.

The proposed setup and research efforts may be expanded to include a variety of supply voltage circumstances, such as voltage sag/swell and voltage imbalance. A customized PLL architecture might also be used to account for both voltage and frequency changes. Furthermore, within the UCS framework, various inverter designs such as split capacitor and H-bridge are worth investigating and comparing to the four-leg inverter, particularly in the context of three-phase and four-wire systems.

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