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Harmonic Mitigation using Hybrid Active Harmonic Filter with Reduced Switch Multilevel Inverter for Power Quality Enhancement

Pranita Chavan [a, *], **B.R. Patil** [b]

[a] Department of Electrical Engineering Sardar Patel College of Engineering, Andheri-400058, India
[b] Vishwaniketan's Institute of Management Entrepreneurship and Engineering Technology, Khalapur, 410202, India
* Corresponding Author Email: pranitashelukar44@gmail.com

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Abstract: Power electronics-based loads significantly degrade power quality due to their nonlinear characteristics. These loads introduce harmonics in the system and lower the power factor, leading to increased reactive power demand and energy billing. Harmonic power filters are employed to mitigate the power quality issues in the supply system. Hybrid power filters, which combines the advantages of both active and passive approaches, offer enhanced performance. The voltage source inverter is the core component of the active filter. In this work, a modified five level inverter topology with fewer switches is implemented for the active part of the filter, while the passive filter is tuned to third order harmonic to reduce the active filter rating and to take benefits of multilevel inverters. Active filter control is the critical part of the APF operation. Here to take advantage of artificial intelligence techniques, a fuzzy controller is implemented for DC voltage regulation. The reactive power (p-q) theory is applied for harmonic extraction, and the PWM technique is adopted for pulse generation with multicarrier signals. The proposed system is developed using the MATLAB / Simulink platform. The results are satisfactory and meet the IEEE std for harmonic limits.

Keywords: Power Quality, Harmonics, Multilevel Inverter, Total Harmonic Distortion, Harmonic Filter.

1. Introduction

Power quality is deteriorating due to the increasing power electronics based nonlinear loads and renewable energy conversion systems. The current harmonics created by these nonlinear nature loads and conversion systems result in a non-sinusoidal supply current. These harmonics affect the efficiency and performance of power system equipment. This results in both technical and financial losses for the utility and the consumer [1, 2]. Therefore, it is necessary to compensate for these harmonics. The passive filters using R, L, and C components are a simple and economical method preferred by the industries. However, they have shortcomings like large size, resonance problems, and fixed tuning [3-5]. Active harmonic filters, which use power electronics technology, have become a popular solution over passive filters over a time. However, the cost of active filters increases in high power systems due to increase in converter ratings [6]. Hybrid filter technology, which combines the benefits of both passive and active filters, offer economical solution. The passive filter eliminates the low order high amplitude dominant harmonics, and the rest are reduced using an active filter, thereby reducing the active filter rating [7-9].

The voltage source inverter (VSI) is a crucial component of active filters. While traditional inverters (VSI) became popular in the power industry, they face problems in high-power systems, such as significant switching losses and device ratings constraints. A multilevel inverter based active filter is an effective solution in high-power systems, as it uses low rating switches to achieve desired voltage with low switching frequency and stress [10].

Most existing studies focus on two-level inverters and conventional multilevel inverters which have many components that increase their cost and complexity. It is necessary to explore modified inverter topologies with reduced switches and components for hybrid filter application [11, 12]. Also, compared to conventional controllers, artificial intelligence controllers are gaining attention for control of active filter topologies [13, 14]. Hence, in this work, a reduced switch multilevel inverter based intelligent hybrid filter is proposed to take merits of both passive and active filter techniques. This work advances the current state of the art of hybrid filter technologies.

The control of the APF plays a critical role in the optimized operation. Many control methods are cited in the literature. These include the reference signal generation for harmonic elimination, DC bus voltage control to compensate switching losses, and the creation of pulse signals for switching devices to mitigate harmonics in the nonlinear systems. Due to development in the field of artificial intelligence, AI-based methods are now used for the control of APF [15, 16]. In this regard, the PI controller for DC link regulation is substituted by the knowledge-based fuzzy controller. The fuzzy controller handles the uncertainties; therefore, it is suitable for nonlinear systems that are difficult to model [17].

In this work, a hybrid filter method is implemented for the elimination of the current harmonics. Section 2 describes the proposed system, including the hybrid filter structure and its compensation control method. The design of the hybrid filter is presented in section 3, while the control method of an active filter is described in section 4. Section 5 discusses the simulations of the proposed system. The results are discussed in section 6. Hardware implementation is detailed in section 7, and the conclusion is presented in section 8.

2. Shunt Hybrid Active Power Filter

Figure 1 illustrates the hybrid filter used to lowers harmonics in the distribution system with nonlinear loads. The hybrid filter, which combines passive and active filters, is in shunt at the PCC. The primary purpose of a passive filter is to eliminate lower order dominant harmonics to reduce stress on the active filter. The passive filter eliminates the third harmonic component. The active filter is deployed using a reduced switch five-level voltage source inverter to take advantage of multilevel inverters. The current injected by the APF to decrease the harmonic level mainly depends on the control strategies.

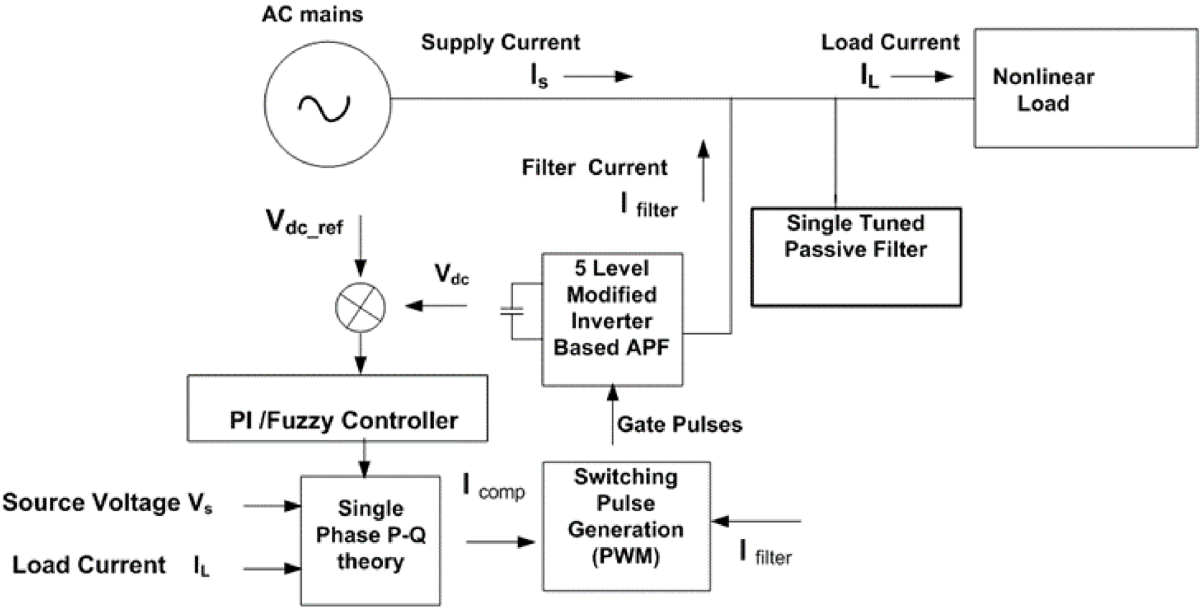

Figure 1. Block diagram of hybrid active power filter

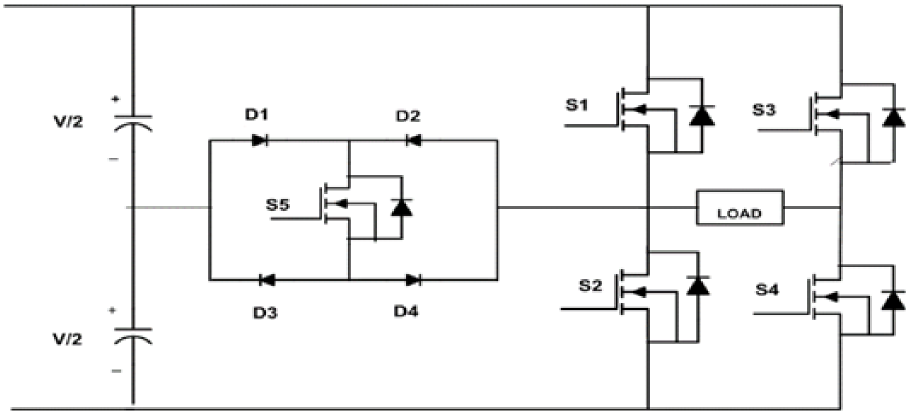

Figure 2. Voltage source Inverter configuration for active part of harmonic filter

The reference signal is generated based on the single-phase reactive power (p-q) theory, while switching pulses are generated through a multicarrier PWM technique. A fuzzy and PI controller is used for DC bus voltage control. The source current total harmonic distortions (THDi) are observed using different compensation techniques, and the system is developed using MATLAB Simulink. The modified inverter topology with reduced switch count is presented in Figure 2. The structure can be independently added and controlled for a three-phase system. As compared to conventional multilevel inverter, the proposed topology has fewer components and less complexity.

3. Hybrid Filter Design

The design of a passive-tuned harmonic filter, which consists of an inductor and a capacitor, begins with the selection of components configured to reduce a specific harmonic frequency. These filters are usually installed in parallel with the power system. The design process initiates with the estimation of the required reactive power compensation (kVAr), which depends on the desired power factor correction and the standard ratings of commercially available capacitors. It is also observed that decreasing the capacitor kVAr causes an increase in the size of the inductor. Therefore, an optimal balance between the inductor and capacitor values is essential during the design process of shunt passive filters [18, 19].

The first steps involved in the design of a single tuned passive filter are to determine the capacitor size Qc (KVAr) for the reactive power demand of the load. With knowledge of the KVAr of the capacitor, the capacitive reactance is calculated using equation (1).

$$X_c = \frac{kv^2}{Q_c} \tag{1}$$

Once capacitive reactance is determined, the capacitance is calculated using equation (2).

$$C = \frac{Q_c}{2\pi f k v^2} \tag{2}$$

The inductive reactance required for eliminating the harmonic of order h_n is determined using equation (3).

$$X_L = \frac{X_c}{h_n^2} \tag{3}$$

The value of the filter reactor is obtained using equation (4)

$$L = \frac{1}{2\pi f X_L} \tag{4}$$

For the active filter design, the procedure outlined below is followed [20, 21]. For the proper functioning of the APF, the DC link voltage must be higher than the peak value of the system voltage and it is determined using equation (5). This is based on the theoretical requirement for the appropriate operation of the inverter to compensate for all harmonic components.

$$V_{DC} = 2\sqrt{2}V_{rms} \tag{5}$$

For practical purposes, it can be more conveniently approximated as shown in equation (6) to avoid the oversizing of the DC link capacitor and to simplify the design process with a safety margin

$$V_{DC} = 1.5V_{peak} \tag{6}$$

The DC-link capacitor is determined based on the second harmonic ripples voltage approach caused by load imbalances. It is given as:

$$C_{dc} = \frac{I_{DC}}{2\omega V_{DC\,ripple}} \tag{7}$$

Where, $I_{DC} = I_{rms}$ and $V_{DC\,ripple}$ is the ripple in DC voltage, typically limited to 1-3 % of V_{DC}

Table 1. Specification Table

Source	Voltage 230V (RMS)
Load	Full wave diode bridge rectifier driven R = 5 Ω, L = 10mH
Active Filter	DC link Voltage = 440 V Switching frequency = 5KHz Configuration: Modified CHB Capacitors = C_1 = C_2 = 3000μF Control scheme: PQ theory with fuzzy controller
Passive Filter	Single Tuned 3rd order R = 0.0325Ω L = 3.45mH C = 326.21μF
Coupling Inductor	1.5 mH

The value of the AC side coupling inductor L_f, used to limit current ripple, is given by the following equation (8)

$$L_f = \frac{V_{dc}-V_{peak}}{4 f_S I_{crpp}} \qquad (8)$$

Here, I_{Crpp} is current ripple, with limit of 5-10% of rated current, and f_s is the switching frequency. The system specifications are provided in Table 1.

4. Control Method Applied to Active Filter

The mitigation current of the APF depends on three major factors: the reference current generation for the current control loop, DC-link control, and firing pulse generation. Harmonics are identified using the widely adopted single phase p-q theory. Here, for DC voltage control, the PI and Fuzzy control approach is applied [22, 23]. Finally, switching pulses are created using PWM techniques.

4.1. P-Q Theory for Reference Current Generation in Single Phase System

To generate reference signal for the active filter, the p-q theory derived from three phase theory is applied. The supply voltage V_S and load current I_L are transformed to α-β space using equations (9) and (10)

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} V_S(\omega t) \\ V_S(\omega t + \frac{\pi}{2}) \end{bmatrix} \qquad (9)$$

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \begin{bmatrix} I_L(\omega t) \\ I_L(\omega t + \frac{\pi}{2}) \end{bmatrix} \qquad (10)$$

The real and reactive power in α – β axis are given by equation (11)

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \qquad (11)$$

These powers contains both fundamental and harmonic components and decomposed as follows

$$p = \bar{p} + \tilde{p} \qquad (12)$$

$$q = \bar{q} + \tilde{q} \qquad (13)$$

Where,

$\bar{q}, \bar{p}$ = Fundamental components

$\tilde{q}, \tilde{p}$ = Oscillating components related to harmonics

To get reference current, only the harmonic component of active power $\tilde{p}$ and the entire reactive power q are considered. The reference current is given by equation (14)

$$\begin{bmatrix} i^*_{c\alpha} \\ i^*_{c\beta} \end{bmatrix} = \frac{1}{V_\alpha^2+V_\beta^2} \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} \\ -q \end{bmatrix} \qquad (14)$$

Add the P_{Loss} term to maintain DC bus voltage constant, accounting for switching losses

$$\begin{bmatrix} i^*_{c\alpha} \\ i^*_{c\beta} \end{bmatrix} = \frac{1}{V_\alpha^2+V_\beta^2} \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} + p_{Loss} \\ -q \end{bmatrix} \qquad (15)$$

The α-axis component $i^*_{c\alpha}$ provides the required reference current signal, as given by equation (16)

$$i^*_{c\alpha} = \frac{1}{V_\alpha^2+V_\beta^2} [V_\alpha(\tilde{p} + p_{Loss}) - V_\beta\, q] \qquad (16)$$

4.2 DC link control

Maintaining the DC link voltage is essential to meet switching and conduction losses in the APF. Conventionally a PI controller is used for governing the DC bus voltage. In the proposed work, PI and Fuzzy logic controllers are employed, and their performance are observed. To control the DC link voltage error and change in error between Vdc and reference value Vdc_ref, are given as input to the fuzzy controller. The output is determined based on a rule-based system of the fuzzy controller. The output is determined based on a rule-based system of the fuzzy controller. A total of 7 fuzzy sets with linguistic values are defined for each input and output, resulting in comprehensive control laws expressed in IF-THEN rules. A total of 49 rule base inference systems is formed as shown in Table 2 based on expert knowledge. The Mamdani fuzzy model is adopted in this work. The fuzzy controller follows the steps of fuzzification, implementation of fuzzy rules, and last defuzzification to get the desired output [24-26].

Table 2. Fuzzy control rule base

Δe (change in error)	**e (Error)**						
	NB	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NM	NM	NS	ZE	PS
NS	NB	NM	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PM	PB
PM	NS	ZE	PS	PM	PM	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

4.3 Switching Pulse Generation

The mitigation current of the active filter at the coupling point (PCC) is achieved by properly controlling the switching devices. In this work, the phase opposition disposition pulse width modulation (POD-PWM) strategy is employed to generate the required gate signals [27]. In this modulation scheme, the reference signal (I_{ref}) is compared with four carrier signals to determine the appropriate switching state as illustrated in Figure 3. These carriers are symmetrically paced: two are placed above the zero axis and two below, ensuring the generation of five distinct voltage levels.

- Signals 1 and 2 above zero generate $+V_{dc}$ and $+V_{dc}/2$, respectively.
- Carriers 3 and 4 below zero generate the levels $-V_{dc}/2$ and $-V_{dc}$ respectively.
- When the reference signal is between carrier 2 and carrier 3, the output level is $0\ V$.

The switching control laws corresponding to the five voltage levels with five conditions are summarized below:

- $I_{ref} \geq$ *Carrier 1*, $SW_1 = 1$, $SW_2 = 0$, $SW_3 = 0$, $SW_4 = 1$, $SW_5 = 0$, $V_{out} = + V_{dc}$
- $I_{ref} \geq$ *Carrier 2*, $SW_1 = 0$, $SW_2 = 0$, $SW_3 = 0$, $SW_4 = 1$, $SW_5 = 1$, $V_{out} = +V_{dc}/2$
- *Carrier 3* $< I_{ref} <$ *Carrier 2*, $SW_1 = 0$, $SW_2 = 0$, $SW_3 = 0$, $SW_4 = 0$, $SW_5 = 0$, $V_{out} = 0$
- $I_{ref} \leq$ *Carrier 3*, $SW_1 = 0$, $SW_2 = 0$, $SW_3 = 1$, $SW_4 = 0$, $SW_5 = 1$, $V_{out} = - V_{dc}/2$
- $I_{ref} \leq$ *Carrier 4*, $SW_1 = 0$, $SW_2 = 1$, $SW3 = 1$, $SW_4 = 0$, $SW_5 = 0$, $V_{out} = -V_{dc}$

5. Simulation of Proposed System

In this work, a shunt hybrid filter combining the benefits of both passive and active filters is designed for mitigating harmonics in a nonlinear system. The proposed system is developed in MATLAB/Simulink. The simulation model of the single-phase hybrid filter incorporating five- level modified inverter topology is shown in Figure 4. The passive filter part is designed to mitigate third-order harmonics. A nonlinear load, consisting of a diode bridge rectifier with RL load having R = 5 Ω and L = 10 mH, is used. The effective reactive power (KVAr) of the load is 17.652 KVAr.

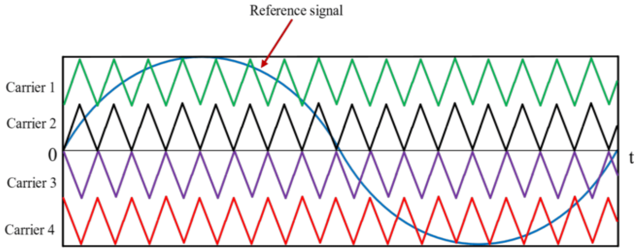

Figure 3. Phase opposition disposition PWM method

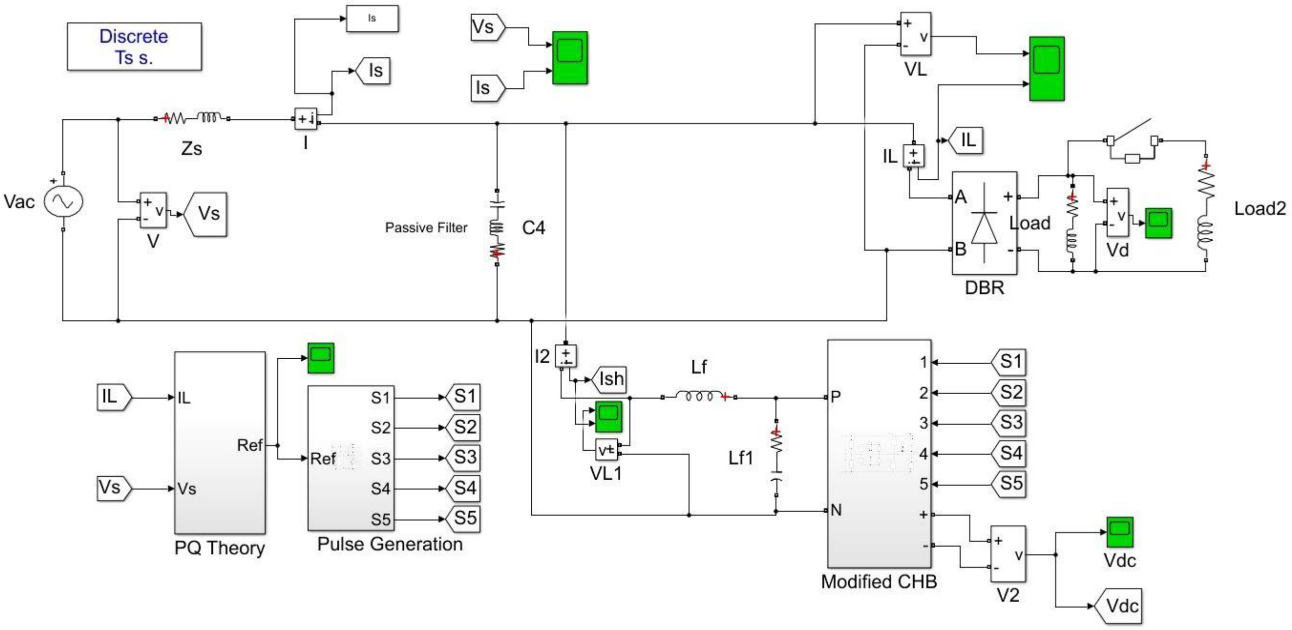

Figure 4. MATLAB simulation model of single-phase hybrid active power filter

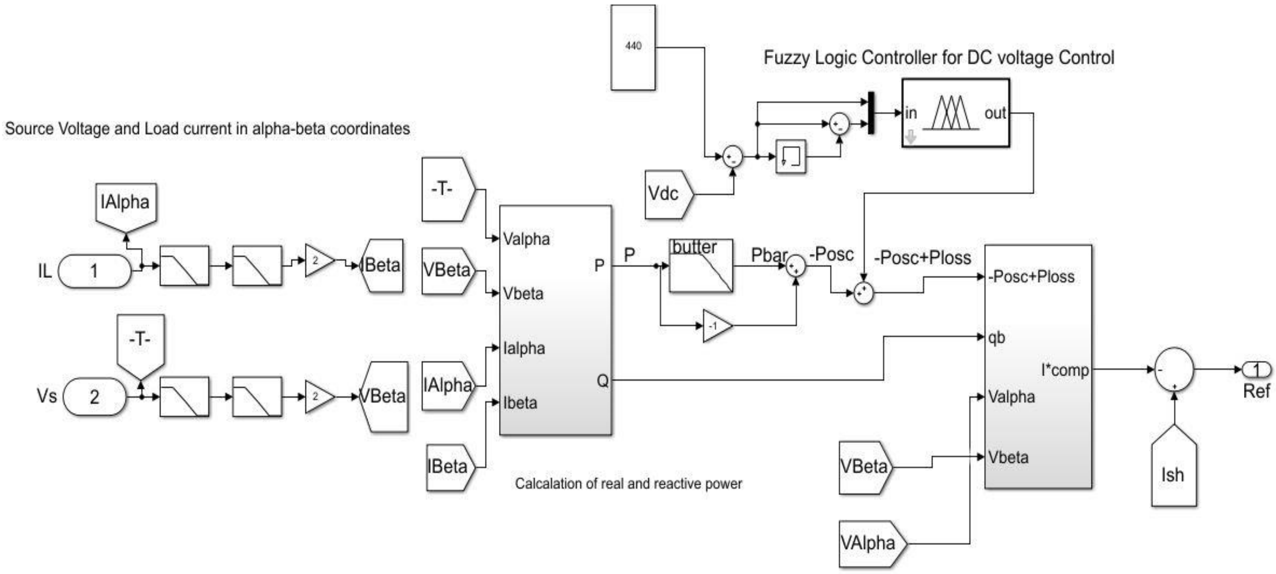

Figure 5. Control scheme with p-q theory and fuzzy logic controller

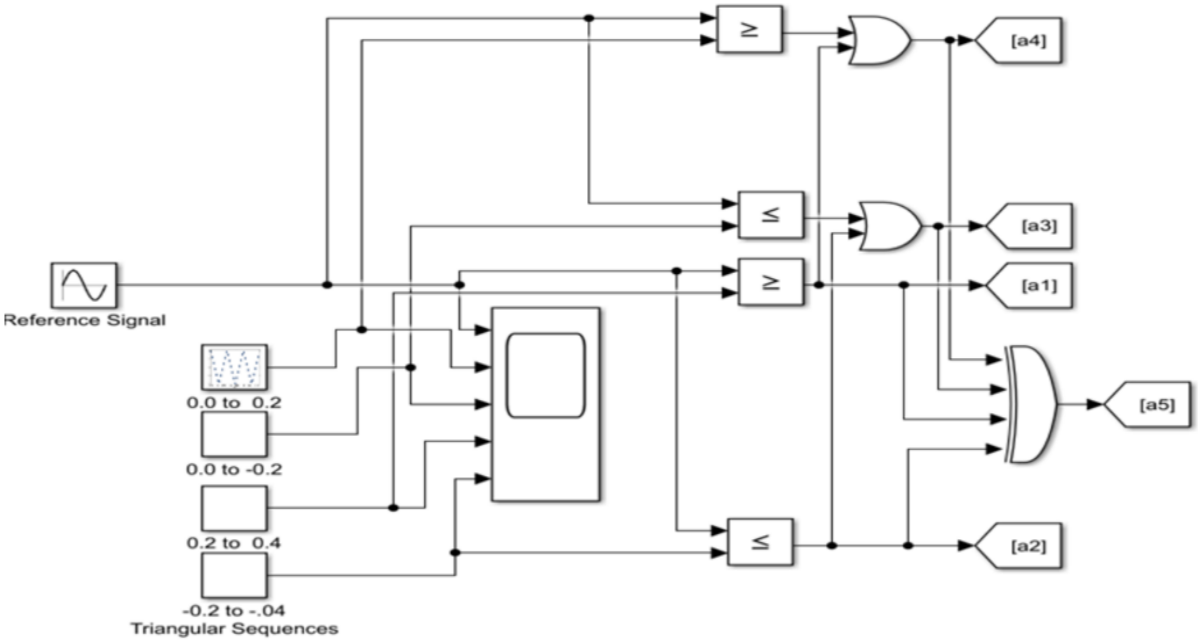

Figure 6. Switching scheme for five level modified CHB inverter

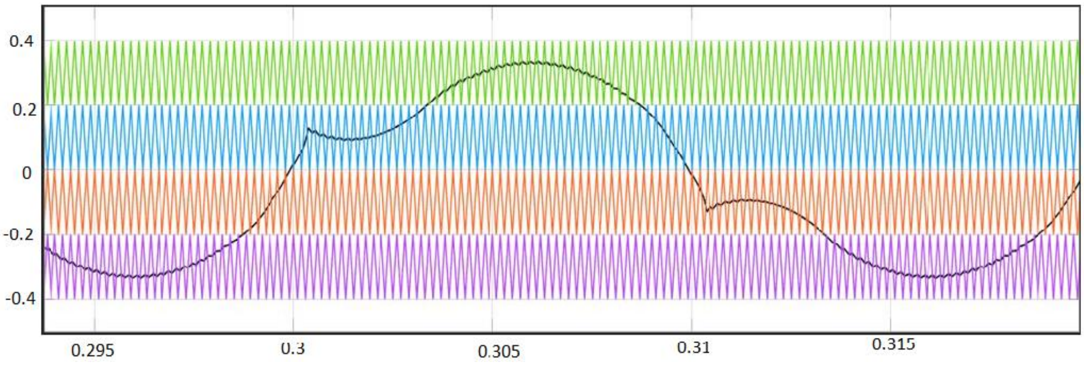

Figure 7. Gate pulse generation by comparing reference current with carrier signals

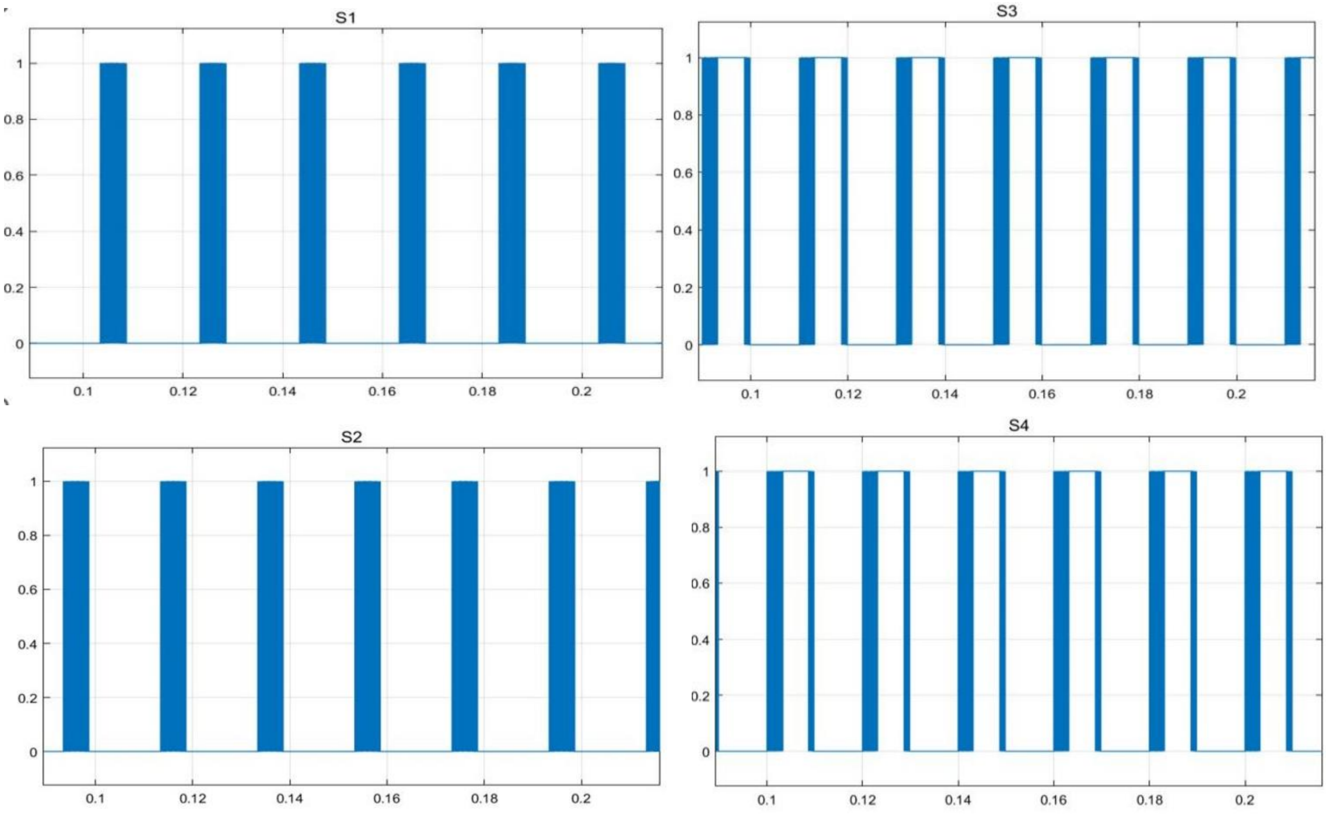

Figure 8. Switching pulses of the switching devices

The single-phase p-q theory, described in section 4.1, is implemented in MATLAB/Simulink as represented in Figure 5. The active filter is controlled through the DC link voltage regulation, employing both conventional PI and Fuzzy logic controllers. The output of the fuzzy controller is added as a loss component to generate the final reference current, which is then compared with the actual current of the active filter. The resulting error signal is processed by comparing it with four carrier signals with logic circuit, as shown in Figure 6, to generate required pulses for the inverter switches. Figure 7 presents the comparison of the error signal with four carrier signals, while Figure 8 shows the corresponding switching pulses for the modified inverter.

6. Results Analysis

To evaluate the effect of the harmonic filter in the distribution system with a nonlinear load, the Simulink model is executed for 1 sec, with a change in load at 0.5s to observe the dynamic response of the system. This study examines the effect of a hybrid filter using a fuzzy and PI controllers. Initially, the simulation results are observed without the filter. Later, the impact of passive filter, the active filter, and finally the hybrid filter is analyzed in terms of THD of the source current.

Figure 9 indicates the source voltage and current waveforms without a filter. It is observed the load current waveform is distorted. Figure 10 illustrate the source voltage and source current waveform with a hybrid filter using fuzzy controller. An increase in current is observed at time instance 0.5 second on account of increase in load.

The source current THD for different cases of without a filter, with a passive filter, with an active filter, and with a hybrid filter under increase in load condition are depicted in Figure 11(a), (b), (c), and (d) respectively. For both the initial and increased load conditions, the corresponding current THD results are presented in Table 3. With the application of a passive filter, the source current THD is decreases from 22.73% to 19.40%, representing relative reduction of 14.64%.

The harmonic mitigation ability of the hybrid filter, comprising both active and passive filters, is evaluated in this study. The reference current is generated through DC link voltage regulation achieved using PI and fuzzy control approaches. The performance of hybrid filter with conventional PI and fuzzy controllers is summarized in Table 4. It is observed that the source current THD is reduced from 19.40% to 2.93 % with PI controller and from 19.40 % to 2.69 % with fuzzy controller-based hybrid filter.

The DC Link voltage response of the filter using a fuzzy controller is shown in Figure 12. It is observed that, with an increase in load, the capacitor voltage initially drops but recovers with an eventual increase in source current, indicating that filter is effectively tracks the load variations.

Table 5 presents the time domain performance analysis of the conventional PI and fuzzy logic controllers. The results demonstrates that the proposed fuzzy controller regulate the DC link voltage with reduced rise time and lower percentage overshoot compared to the PI-based hybrid active filter. A reduced overshoot indicates better damping and stability, while lower rise time reflects faster system response.

To evaluate the performance of proposed hybrid filter,its THD performance is compared with results reported in similar studies from the literature. As seen from Table 6, praposed method achieve better harmonic mitigation performance compared to other reported studies.

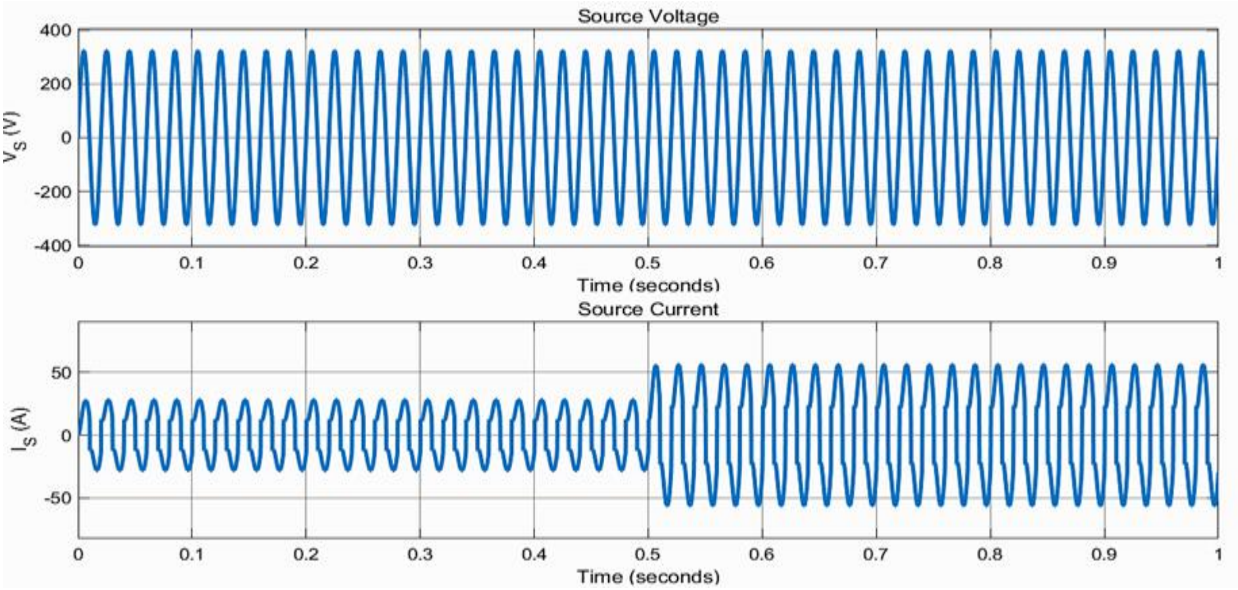

Figure 9. Source voltage and current wave shape without filter

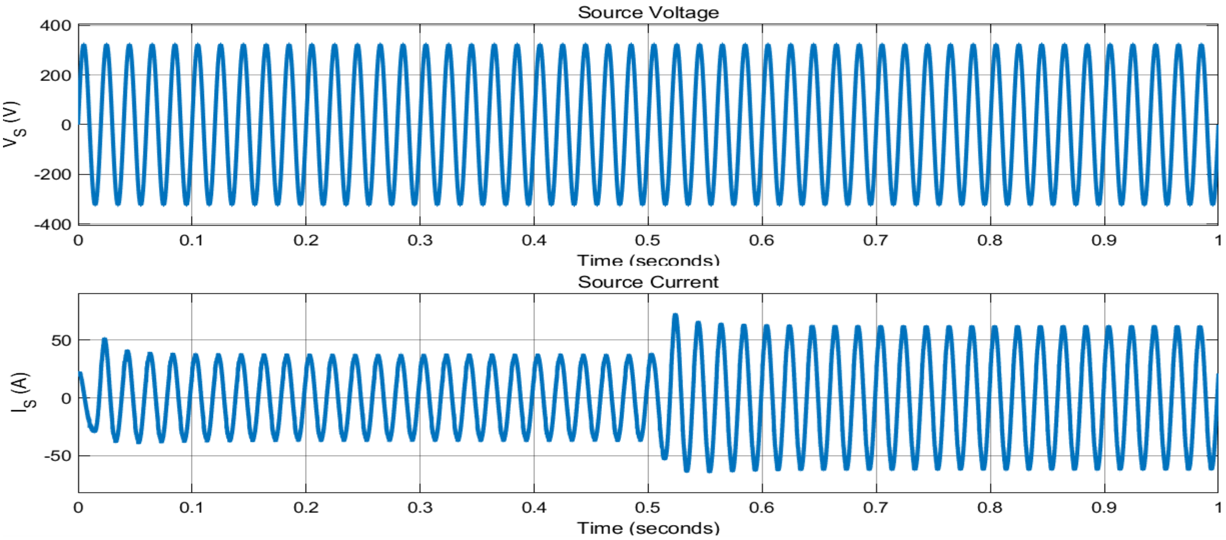

Figure 10. Source Voltage and Source Current with hybrid filter

Table 3. THD of current at various operating conditions

Particulars	I_{THD} at Initial load	I_{THD} at increase in load
THD without any compensation	24.42 %	22.73 %
THD with passive filter only	20.52 %	19.40 %
THD with active filter only	5.50 %	2.87 %
THD with Hybrid active filter	4.78 %	2.69 %

Table 4. Performance of PI Controller and fuzzy logic controller for harmonics mitigation

Particulars	PI Controller	Fuzzy Logic controller
THD without any compensation	22.73 %	22.73 %
THD with passive filter only	19.40 %	19.40 %
THD with active filter only	3.10 %	2.87 %
THD with Hybrid active filter	2.93 %	2.69 %

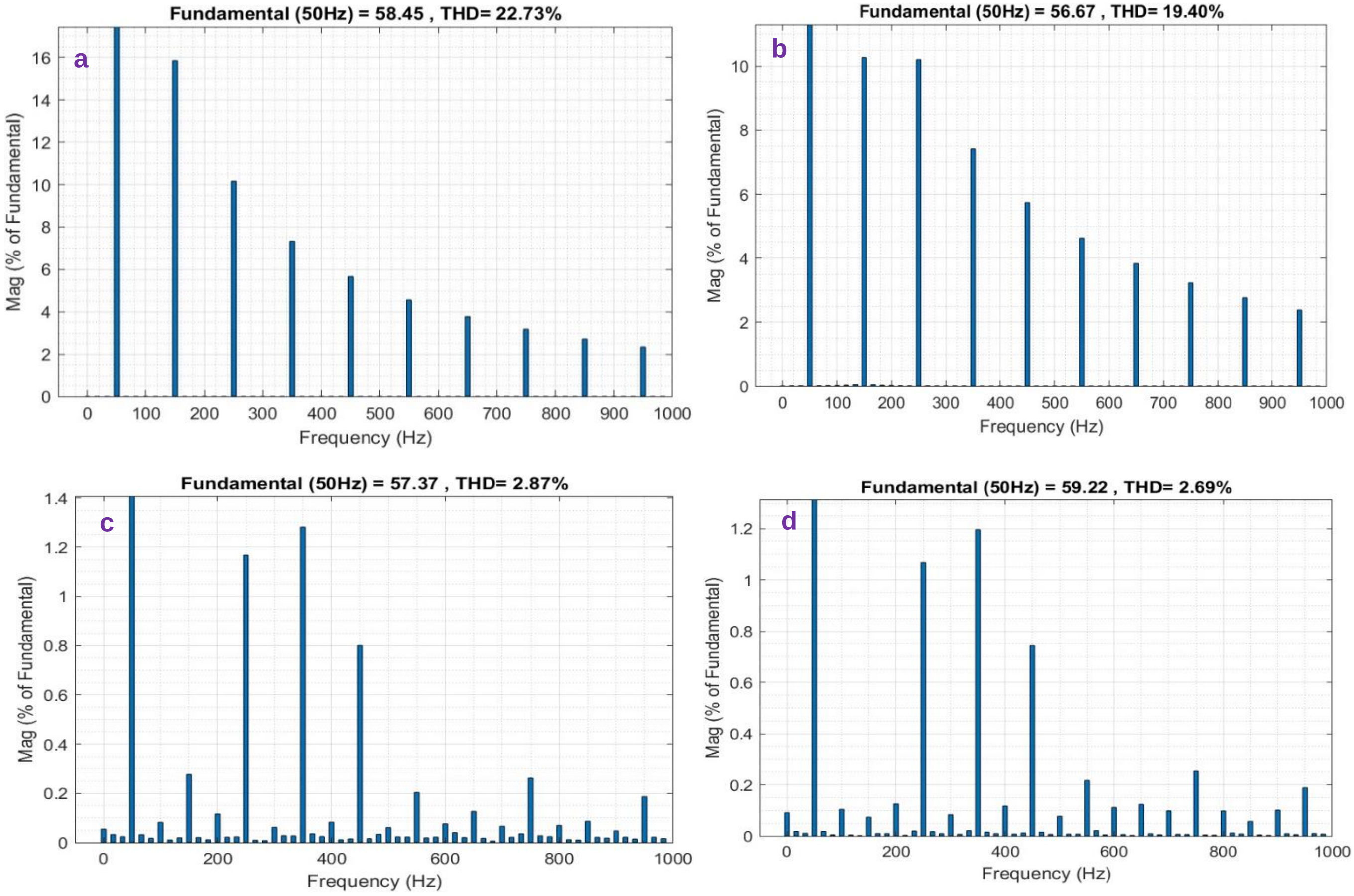

Figure 11. Harmonic analysis **(a)** without filter **(b)** with passive filter **(c)** with active filter **(d)** with hybrid filter

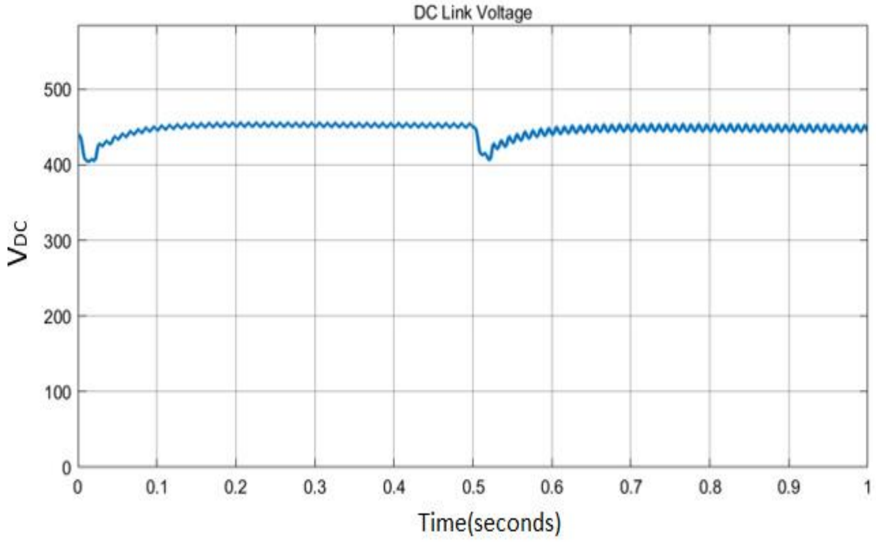

Figure 12. DC bus voltage response

Table 5. DC Link Control using PI controller and Fuzzy logic Controller

Metric	**PI Controller**	**Fuzzy Logic controller**
Overshoot	0.285 %	0.210 %
Rise time	2.653 ms	2.628 ms
Undershoot	1.957 %	1.961 %

Table 6. Comparison of proposed HAPF with state-of-the-art approaches

Reference	**Methodology**	**%THD**
M. Iqbal *et al.* [15]	ANN based HAPF	3.17 %
M. Jalil and A. Amiri [17]	HAPF using PI controller HAPF	4.17 %
Ranjbar *et al*. [21]	HAPF using PI controller	5.54 %
Mishra *et al*.2020 [26]	HAPF using optimized PID controller	3.75 %
This study	MLI based HAPF using fuzzy controller	2.69%

Table 7. Specifications of Hardware Prototype

Source	230/ 48V, 10A transformer
Load	Full wave diode bridge rectifier driven DC Motor of 50 VAR
Active Filter	DC link Voltage = 70V Switching frequency = 1KHz Configuration: Modified CHB Capacitors = $C_1 = C_2 = 2200\mu F$
Passive Filter	Single Tuned 3rd order $R = 0.0325\Omega$ L = 31 mH $C = 30\ \mu F$
Coupling Inductor	0.66mH

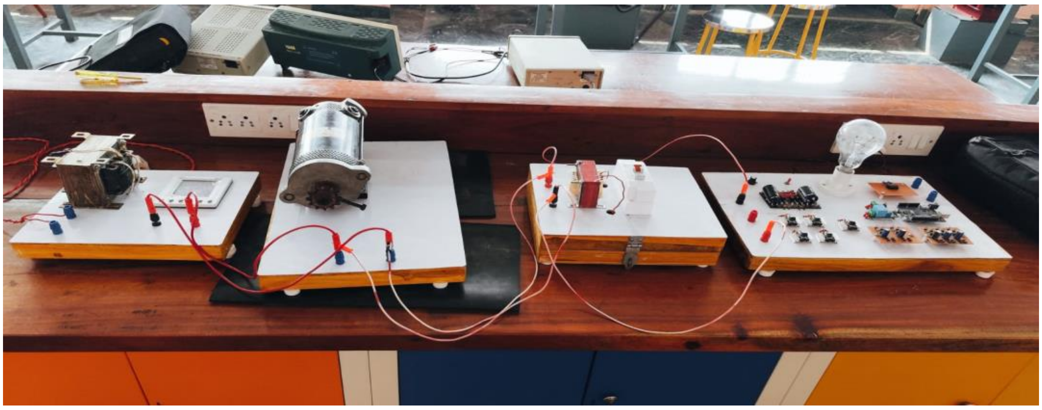

Figure 13. Experimental setup

7. Hardware Implementation

The hardware prototype model is built at 48V level with a 230/48V transformer, as shown in Figure 13. The specifications of the hardware prototype model are mentioned in Table 7. A permanent magnet DC motor is used as a load, driven through a diode bridge rectifier. The free run harmonics analysis with Selec MFM384 multifunction meter shows that the PMDC motor contributed for reactive power of 52 VAr and introduces current THD of 82% and the power factor is noted to be 0.35.

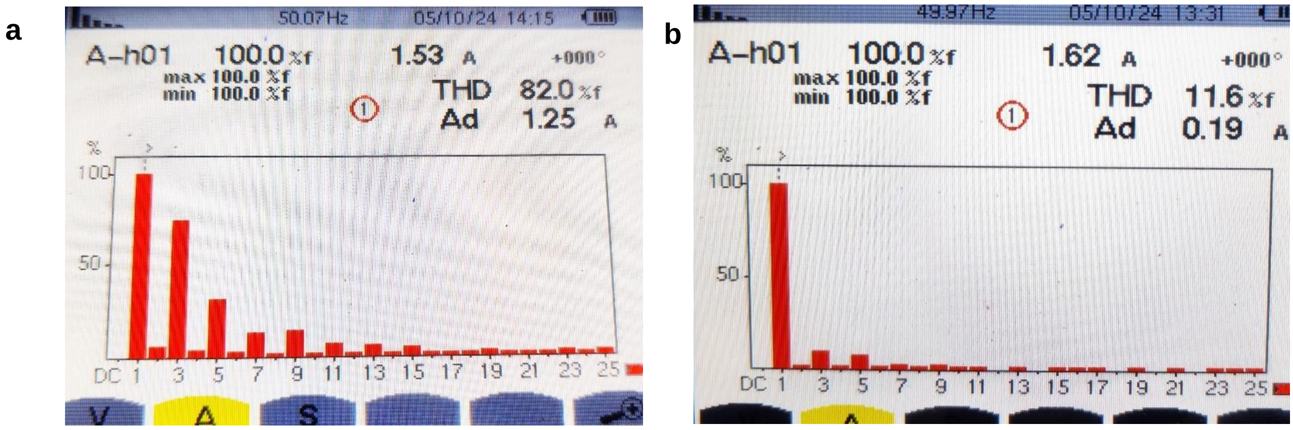

Figure 14. Harmonic analysis (a) without filter (b) with passive filter

For harmonic mitigation and power factor correction, a hybrid active power filter is designed. The passive (LC) filter, tuned to the third harmonic frequency, is designed to compensate 30 VAr reactive power with an inductor of 31mH and a capacitor of 30 μF. Experimental measurements are observed without a filter and with the passive filter. The observation shows that the passive filter reduces the THDi from 82% to 11%. The working of active filter implementation is currently in process. Figure 14 (a) presents the THD without a filter, while Figure 14 (b) shows the THD with a passive filter, indicating a significant reduction in third order component as measured using a harmonic analyzer.

In addition to the passive filter prototype, efforts were made to implement the proposed active filter part. However, due to challenges in real time coding, and component constraint and availability during the timeline, the obtained results did not meet the expected results.

Nevertheless, the active filter part was validated in the simulation, and the passive filter part was successfully implemented and tested. The active filter hardware development is therefore ongoing, based on refined code and improved design, and the present work reports simulation-based validation.

8. Conclusion

In this study, a hybrid harmonic filter is developed to combine the benefits of both passive and active filters. A reduced switch count multilevel inverter topology is employed for the active part of the filter, to take advantage of multilevel inverters in high power systems, as compared to two-level inverters, for implementing the active part of the filter. An artificial intelligence based fuzzy control approach is adapted for DC link voltage regulation of the active filter, due to its ability to express control laws in simple human language. The reactive power theory (p-q theory) is applied for harmonic extraction, and multicarrier PWM techniques are used to generate switching pulses. The harmonic spectrum of the source current waveform is observed under different compensation methods. Before compensation, the source current THD is 22.73% which is reduced to 19.40% with a passive filter. From the result, it is observed that the proposed fuzzy controller-based hybrid filter further reduces THD from 19.40 % to 2.69 %. Time domain performance analysis also confirmed that the fuzzy controller outperforms the PI controller under dynamic conditions.

While the passive filter prototype was successfully implemented, the active filter hardware is still under development. Future work will focus on completing and testing the active filter prototype to complete the hybrid filter system.

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Authors Contribution Statement

Pranita Chavan: Conceptualization, Methodology, Investigation, Validation, Writing-Original Draft, Writing-Reviewing and Editing. B.R. Patil: Conceptualization, Writing- Reviewing and Editing, Supervision. Both the authors read and approved the final version of the manuscript.

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Data Availability

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

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