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Modified multilevel inverter based an active power filter using fuzzy controller for power quality enhancement

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ABSTRACT

Power electronics-based nonlinear loads generate significant current harmonics, adversely affecting the efficiency and reliability of distribution networks. Active power filters (APFs), leveraging power electronics technology, provide an alternative to passive filters in mitigating harmonics. Multilevel inverter-based (MLI) APFs, particularly for high-power applications, offer numerous advantages but often suffer from increased component count and control complexity. In this article, a novel five-level MLI topology is proposed, featuring a reduced number of switches compared to the traditional cascaded H-bridge topology with eight switches. This research reduces system cost and simplifies controller design. To further enhance system performance, a fuzzy logic controller (FLC) is implemented for DC-link voltage control. Harmonics are identified using the instantaneous p-q theory, and switching signals are generated through multicarrier pulse width modulation (PWM) techniques. Study conducted in MATLAB for a single-phase balanced system demonstrate the effectiveness of the proposed topology. Results reveal a reduction in total harmonic distortion (THD) of the source current from 34.15% to 2.31%, meeting the IEEE-519 standard. The findings validate the proposed APF's capability to enhance power quality by mitigating harmonics. By integrating advanced MLI technology with artificial intelligence-based control, this work offers a cost-effective, efficient solution to improve the performance of polluted distribution networks.

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1. INTRODUCTION

In modern distribution networks, harmonics are a major cause of poor power quality issues. This is due to rapid development in the domain of power electronics and its application in various industrial, commercial and residential purposes. These power electronics-based equipment are nonlinear in nature causing distorted current in the network. These current harmonics interact with system impedance and caused distortion in supply voltage affecting consumers connected at a common point of connection (PCC) [1].

The current harmonics severely damage the power system network. It promotes increases in losses in major equipment like transformers, and motors which result in temperature rise. Current harmonics reduce the power factor, cause maloperation of relays, failure of sensitive electronics components, damage to capacitor bank, and substation component lightning arrestor (LA). Briefly, harmonics cause technical as well as financial losses to the consumer and utilities. Therefore, it is essential to eliminate the harmonics with a well-developed solution to increase system reliability and efficiency [2], [3].

In the literature, various techniques are listed for the reduction of harmonics. Traditionally passive filters made up of R, L, and C component are affordable and simple solution adopted by consumers. But it suffers from resonance problem resulting in overloading of components, large size, fixed compensation, slow response under dynamic situations, and its characteristic changes with the aging effect [4]-[6]. This increasing harmonic problem attracted researchers to find attractive solutions. With advancements in power electronics with new switching devices like insulated gate bipolar transistor (IGBT) and metal-oxide-semiconductor field-effect transistor (MOSFET), the active power filter (APF) using inverter is well developed technology for mitigating harmonics. APFs are connected in series or shunt with the system [7]-[9].

Conventional two-level inverters used in APFs have a smaller number of switches. But to get a sinusoidal waveform it requires switching at a high frequency which causes high switching losses. Also, the high inverse voltage applied across switches affects its characteristics. APF with two levels when used in the medium or high-power applications the system becomes costly and bulky due to high rating of a switch, snubber circuit, inverse voltage constraint and the need of high rating transformer. The multilevel inverter (MLI) based APF is a viable solution in medium and high-power applications as it eliminates the need for transformer and the required voltage level is obtained using low rating switches. Also, MLI generates high output voltage which is very close to sinusoidal using low rating switches with low switching frequency and stress. The most popular MLI topologies available are diode clamped, cascade H bridge and neutral point clamped. But these topologies have some limitations a greater number of diodes, capacitors and separate DC sources are required [10]-[14].

The controller for ensuring the effective operation of the APF is a core part of it. The function of the control scheme of APF involves sensing essential signals, signal conditioning, gating reference compensating current, supervising and controlling voltage of the DC bus and providing switching pulses to the inverter switches. Diverse control techniques are mentioned in the literature and still research is beneath. For reference compensation current time domain and frequency domain methods are available to detect harmonic components [15]-[17]. Recently due to advancements in the artificial intelligence domain, the application of AI controllers has become popular in the control of APF. AI controllers like artificial neural network (ANN) controllers, fuzzy controllers, and ANN-fuzzy controllers are widely adopted for reference current generation, for DC voltage supervision and also for switching techniques [18]-[21].

In this study to overcome the limitation of popular MLI topologies modified five level inverter topology is suggested for APF application. The new modified topology reduces the number of diodes and capacitors and also reduces switch ratings. This is a recommended alternative for APFs for high power applications with less cost and reduction in complex control algorithms. This study focuses on the application of artificial intelligence techniques using the fuzzy logic controller (FLC) for DC voltage supervision. Proportional integral (PI) controller is common controller adapted to control the DC link voltage. The PI controller has limitations under variable load conditions as it requires tuning of PI gains. The fuzzy controller is suitable for the system having random information and the system is difficult to analyze mathematically. It is rule based system where control laws can be easily implemented in a human linguistic language in rule-based system. Therefore, FLC is suitable for control of DC link voltage in APFs to handle imprecise and uncertain conditions. The FLC based shunt APF is useful under nonlinear and time varying situation without mathematical modeling. It provides adaptive and flexible approach to control APF for the reduction of harmonics. The pulse width modulation (PWM) multicarrier technique with four carrier waves is used for generating switching pulses for the switches of the filter [22]-[25].

In section 2 describes the complete control block diagram of the proposed APF. The modified MLI topology is described in section 3 with the operation mode and switching control scheme. Control and operation of APF using fuzzy controller is discussed in section 4. Section 5 represents the simulation result of the system under study. Finally, in section 6 conclusion is represented with and without filter action followed by the references.

2. SYSTEM DESCRIPTION

The shunt APF is current controlled device realized by a voltage source inverter connected at the point of coupling. Figure 1 demonstrates the working view of the multilevel modified inverter topology applied for a shunt active filter. The system is composed of the AC source connected to the nonlinear load. The diode bridge rectifier is used as a nonlinear load. To reduce the harmonics drawn by the nonlinear load, the shunt APF is connected in shunt between the source and load at the PCC. The objective of an APF is to inject harmonic components in the system in phase opposition to cancel out system harmonics and keep supply purely sinusoidal.

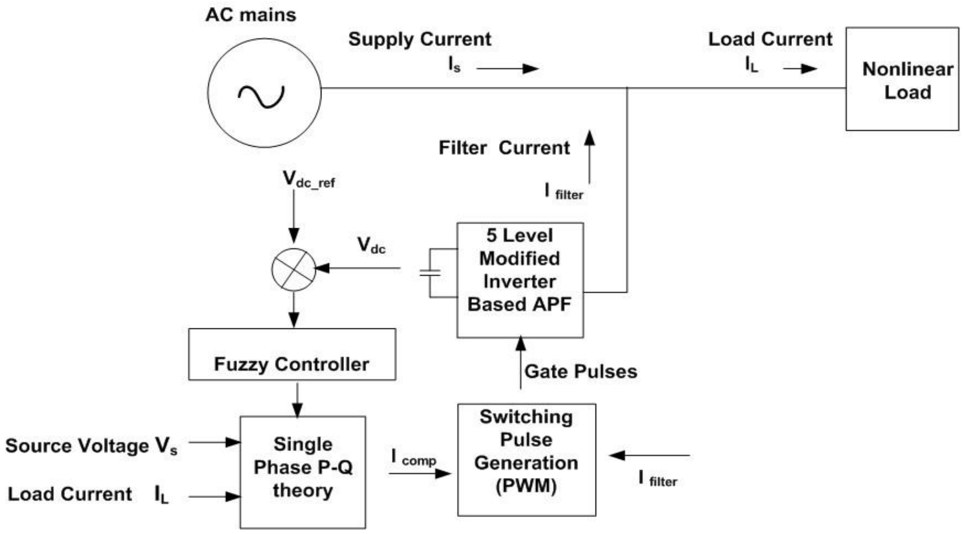

Figure 1. Control block diagram of APF

The block diagram illustrates that the operation of the APF consists of three primary components. The generation of the compensation current (I_{comp}) is accomplished through the application of the p-q theory as proposed by Akagi [26]. The implementation of DC link voltage control is achieved via a FLC, which ensures that the DC voltage remains at its reference value to offset switching losses [27]. The process of switching signal generation for the PWM inverter is executed to regulate the active filter current injected into the system, thereby effectively controlling the harmonics [28], [29]. Section 4 provides a comprehensive explanation of the control scheme for the APF.

3. MODIFIED MULTILEVEL INVERTER

Figure 2 shows the modified topology of five level inverter as substitute to cascade H bridge multilevel topology where more switching devices are required for generating five level. This structure becomes compact and can be independently connected in each phase of three phase system. The structure for each single phase has five bipolar switches with two DC sources. The required five level output voltage level *(+V, +V/2, 0, -V/2, -V)* are generated by using switching state described in Table 1.

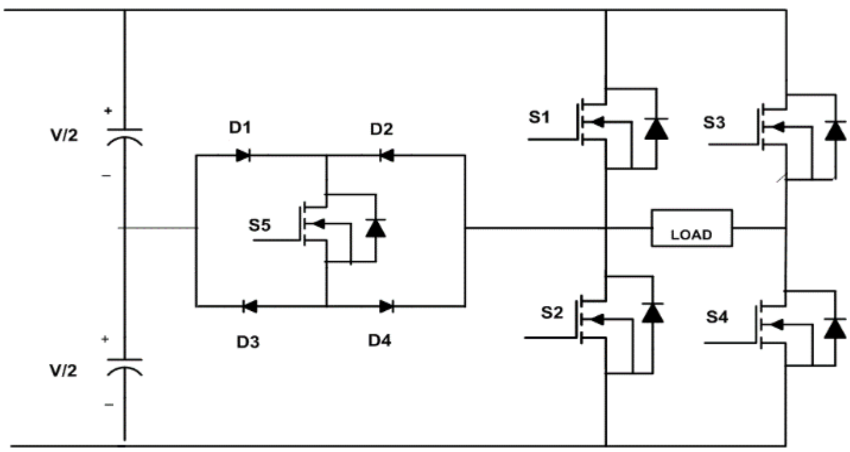

Figure 2. Modified five-level MLI configuration

Table 1. Switching control states for suggested inverter topology

Voltage output	SW_1	SW_2	SW_3	SW_4	SW_5
+V	1	0	0	1	0
+V/2	0	0	0	1	1
0	0	0	0	0	0
-V/2	0	0	1	0	1
-V	0	1	1	0	0

The modified new topology of the inverter has five modes of operation corresponding to five voltage levels. The equivalent circuits for modes $+V$ and $+V/2$ are shown in Figures 3 and 4 respectively. The same equivalent circuit can be constructed for other remaining levels by referring to the switching Table 1.

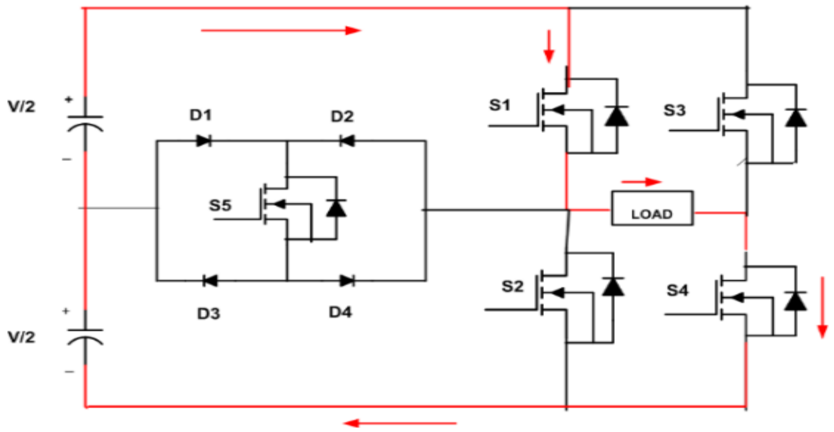

Figure 3. Operation modes for +V voltage output

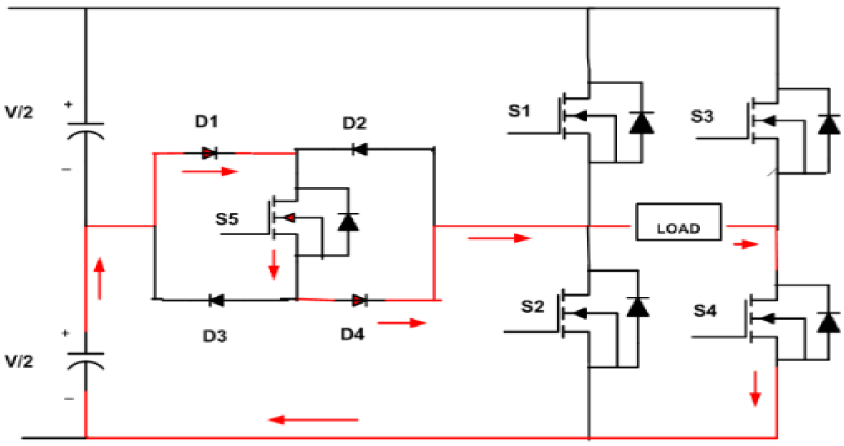

Figure 4. Operation modes for +V/2 voltage output

Table 1 describes the switching states for each switch (SW_1, SW_2, SW_3, SW_4, and SW_5) in the suggested inverter topology to achieve specific output voltage levels ($+V$, $+V/2$, 0, $-V/2$, and $-V$). The table uses binary values, where 1 represents a switch in the ON state and 0 represents a switch in the OFF state.

As illustrated in Figure 3, to achieve the maximum positive voltage $+V$, switch S_1 is turned ON, connecting the load to the positive terminal of the DC link voltage. Simultaneously, switch S_4 is turned ON, connecting the load to the negative terminal of the voltage, while all other switches remain OFF, as dictated by the switching Table 1. The current path corresponding to the +V voltage level is depicted with arrows in the figure.

Figure 4 demonstrates that to attain the half-positive voltage level +V/2, switch S_5 is activated, thereby linking the load to the positive terminal of the DC link voltage V/2 via diodes D1 and D4. At the same time, switch S_4 is activated, establishing a connection between the load and the negative terminal of the voltage V/2, while all other switches are in the OFF position, as specified in the switching table. The arrows in the figure denote the current path associated with the +V/2 voltage level.

4. ACTIVE POWER FILTER CONTROL AND OPERATION

The working steps of an APF comprise the generation of reference signal, DC capacitor voltage control, and creating of switching signal for switches. By assuming a balance system, the system is simulated for a single phase which can be independently controlled.

4.1. Creating harmonic compensation current using instantaneous p-q theory

The reactive power theory proposed by Akagi [30] is one of the most studied in active filter systems. It was introduced for three phase system initially and later presented the single-phase system to take benefits of three phase p-q theory by representing the quantity in α-β coordinates. For a single-phase system supply voltage and load current transformed to α-β coordinates by providing a π/2 lead is given by (1) and (2).

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} V_S(\omega t) \\ V_S(\omega t + \frac{\pi}{2}) \end{bmatrix} \quad (1)$$

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

The instantaneous active and reactive powers by following three phase theory given by (3).

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \quad (3)$$

The real and reactive power with fundamental and harmonic component is expressed as (4) and (5).

$$p = \bar{p} + \tilde{p} \quad (4)$$

$$q = \bar{q} + \tilde{q} \quad (5)$$

where $\bar{q}, \bar{p}$ represented fundamental components and $\tilde{q}, \tilde{p}$ represented oscillating components related to harmonics.

To get reference current for filter operation given by (6) the inverse of (3) is taken.

$$\begin{bmatrix} i^*_{c\alpha} \\ i^*_{c\beta} \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} \\ -q \end{bmatrix} \quad (6)$$

Additional P_{Loss} is needed to maintain DC bus voltage to its reference value due to switching loss and can be compensated by adding with harmonic component of active power as given by (7).

$$\begin{bmatrix} i^*_{c\alpha} \\ i^*_{c\beta} \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} + p_{Loss} \\ -q \end{bmatrix} \quad (7)$$

Actual reference signal is given by α-axis component, the $i^*_{c\alpha}$ gives the required reference current signal and expressed as (8).

$$i^*_{c\alpha} = \frac{1}{V_\alpha^2 + V_\beta^2} [V_\alpha(p + \mathrm{p}_{\mathrm{dc}}) + P_{Loss} - V_\beta\, q] \quad (8)$$

Figure 5 represent implementation of single-phase active and reactive power theory for reference current calculation in terms of block diagram. Source voltage and load current are converted in α-β component and then instantaneous real and reactive power is calculated. Harmonics and fundamental component ae separated using filter and finally reference compensation current is determined using single phase p-q theory described.

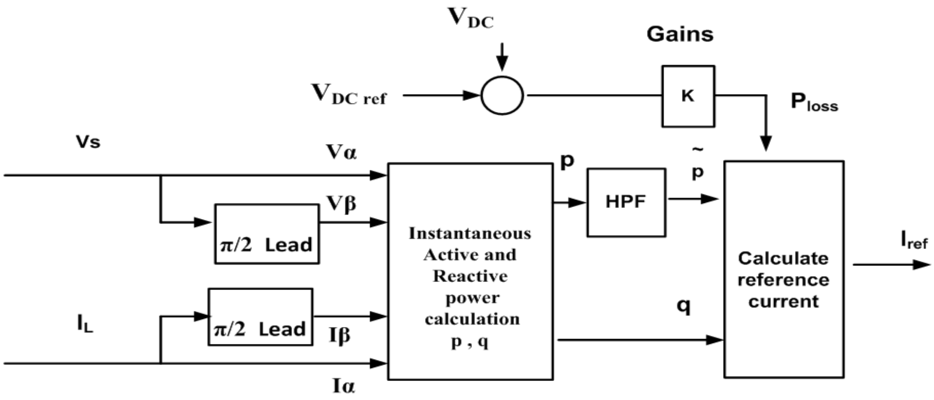

Figure 5. Block diagram representation of single-phase p-q theory

4.2. DC voltage control applied to shunt active filter

The DC linked capacitor has to recompense the switching losses of APF converter along with active power need during dynamic load condition. This reduces V_{dc} from its reference value V_{dc_ref}. It is essential to regulate DC voltage to ensure effective operation of APF or else capacitor will remain discharged. To regulate real power loss component P_{loss} must be added in the final reference current. Thus, final reference signal should have harmonic component, reactive power component and loss component to control injected current by APF.

Traditionally PI controller is used for DC voltage control which requires tuning of PI gains. In this work DC linked voltage is monitored by designing FLC [31]. The basic block diagram of FLC developed for APF is as shown in Figure 6. The error between $V_{dc\ ref}$ and V_{dc} and the change in error is given as input to the FLC. For each input and output total seven fuzzy sets are formed with linguistic value like positive small (PS), positive medium (PM), negative small (NS) using gaussian and triangular membership functions for input and output respectively as shown in Figures 7 and 8.

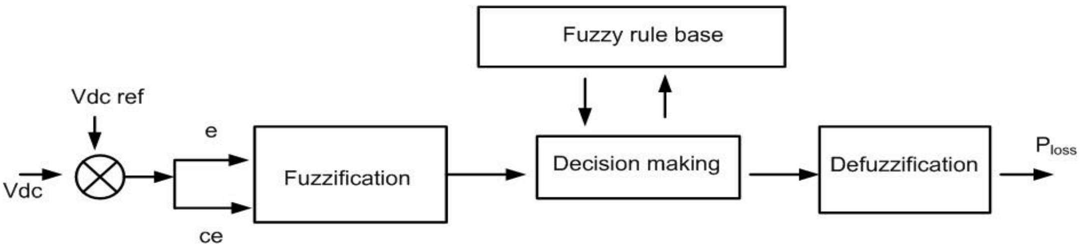

Figure 6. FLC designed for shunt active filter

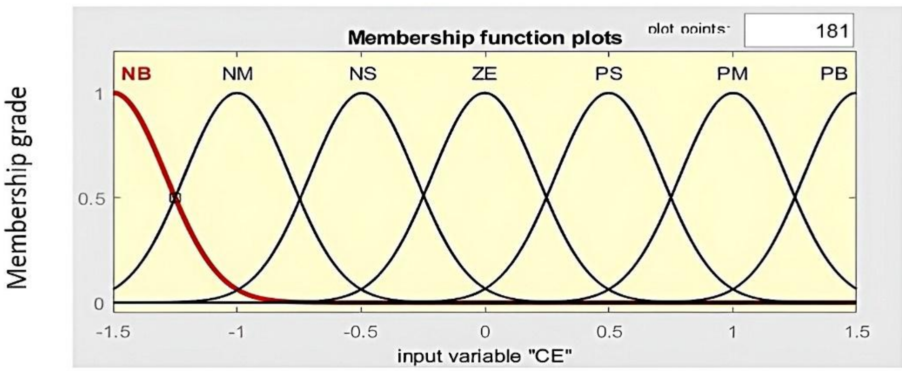

Figure 7. Input variable MF

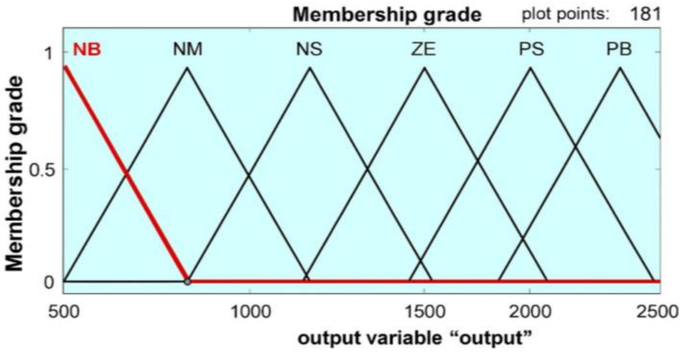

Figure 8. Output variable MF

The fuzzy control scheme is implemented in three steps of fuzzification, execution of rules and defuzzification. In fuzzification process, the numerical values are converted in fuzzy values. Fuzzy rule base system defines control rules mapping input and output relation using minimum AND operator. Fuzzy inference system (FIS) stored a total 49 rules. In fuzzy based system the control laws are presented in IF THEN rules. FIS activates the rules based on the input values and generates outputs. Table 2 represents the rule base crated in matrix form. The activated fuzzy rules generate fuzzified output which is essential to convert in the form required by real system. This is done with the defuzzification method. Here centroid defuzzification method is applied. In this work, Mamdani fuzzy model is used which is more popular.

Table 2. Control rule base for proposed fuzzy controller

CE	E						
	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	PB	NS	ZE
NM	NB	NB	NM	PB	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. Generation of gate pulses for switching devices

The current provided by the APF at the connection point is regulated by switching inverter switches. In this work, the current control loop is controlled by the phase opposition disposition pulse width modulation (POD-PWM) method. It compares reference signals and four carrier signals and generates signals HIGH(H) or LOW(L) for switching devices to generate corresponding voltage levels. The uppermost carrier wave above zero generates $+V_{dc}$ and below zero by symmetry generates $-V_{dc}$. Similarly, the middle carrier waves above zero generate $+V_{dc}/2$ and below zero generate $-V_{dc}/2$ level. When the reference level is between middle carriers it generates a zero voltage level. Switching control conditions are stated Table 3.

Table 3. Control signal for switching devices

Conditions	Switching states	Voltage levels
$I_{ref} \geq C1$	$SW_1 = H, SW_2 = L, SW_3 = L, SW_4 = H, SW_5 = L$	$+V_{dc}$
$I_{ref} \geq C2$	$SW_1 = L, SW_2 = L, SW_3 = L, SW_4 = H, SW_5 = H$	$+V_{dc}/2$
$C3 < I_{ref<}C2$	$SW_1 = L, SW_2 = L, SW_3 = L, SW_4 = L, SW_5 = L$	0
$I_{ref} \geq C3$	$SW_1 = L, SW_2 = L, SW_3 = H, SW_4 = L, SW_5 = H$	$-V_{dc}/2$
$I_{ref} \geq C4$	$SW_1 = L, SW_2 = H, SW_3 = H, SW_4 = L, SW_5 = L$	$-V_{dc}$

5. RESULTS AND DISCUSSION

The performance of the developed shunt active filter is demonstrated with the MATLAB/Simulink platform. Figure 9 shows the APF system developed for reducing current harmonics in the polluted distribution network due to nonlinear load.

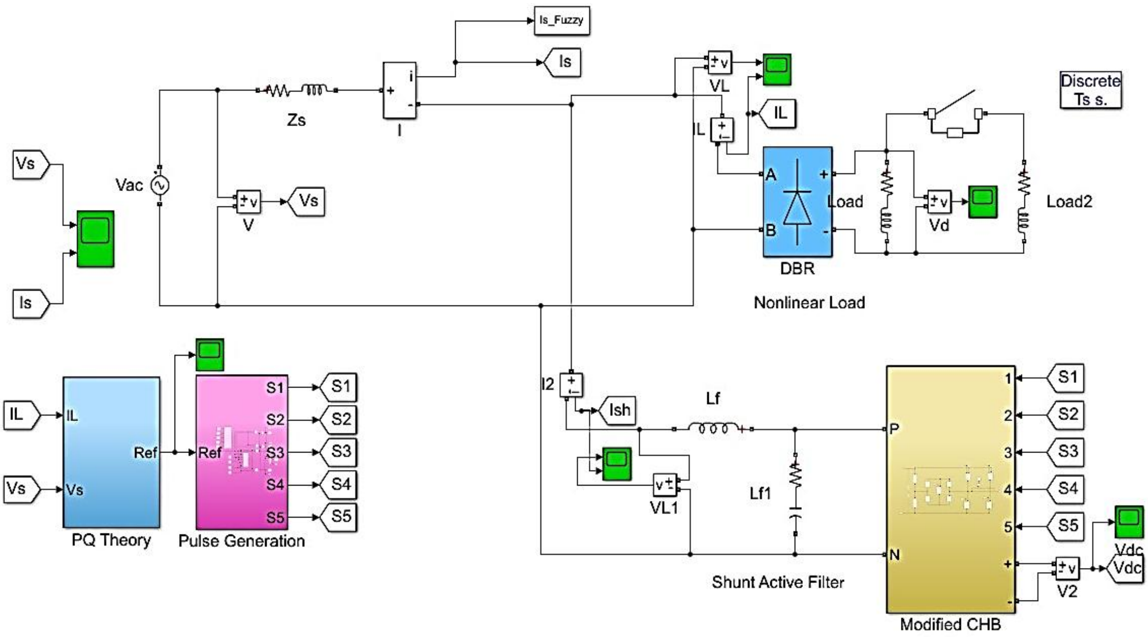

Figure 9. Shunt active filter Simulink model

Table 4 shows the values of the system components used for simulating the distribution system with APF. The simulation is done for single-phase system by assuming a balanced three-phase system. The system can be developed for three phases by adding ±120^0 phase shift for other phases.

Table 4. System parameters

Name of the parameter	Values
Supply system	230 V, 50 Hz
DC link voltage	Vdc=440 V, C1=C2=3000 μF
Nonlinear load (diode bridge rectifier with R-L type load)	R=5 Ω L=20 mH
Switching frequency for carrier signal	5 KHz

Figure 10 shows the source current waveform, and Figure 11 shows distortion measurement of source current under nonlinear load condition in terms of total harmonic distortion (THD) without the application APF at the coupling point. It is seen that without filtering the current on the source side is distorted and the THD is 34.15%. It is seen that after the application of an active filter, the THD is reduced to 2.31% from 34.15%.

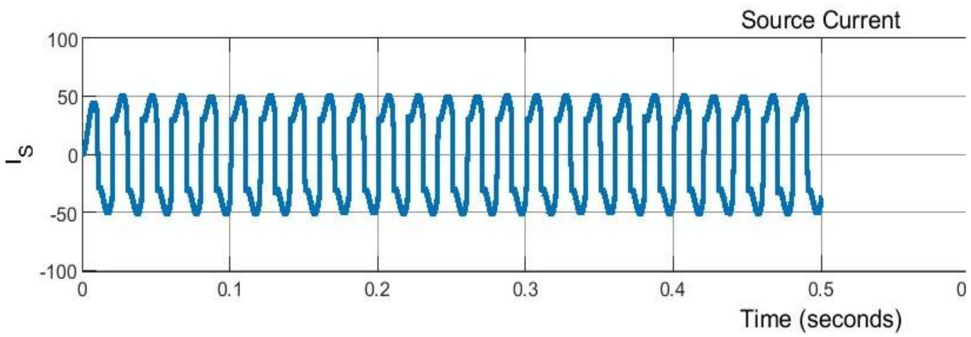

Figure 10. Supply current waveform before filtering action

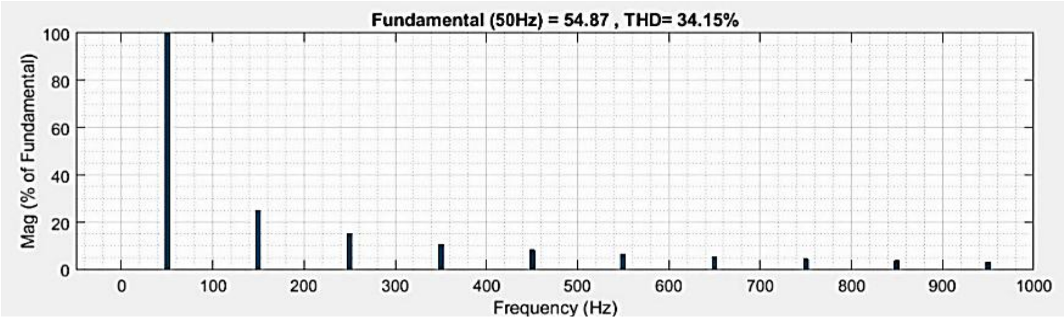

Figure 11. Supply current with THD before filtering action

Figure 12 shows the improved supply waveform which is near to sinusoidal shape and Figure 13 shows a THD spectrum of source current becomes 2.31%. Figures 14 and 15 show the switching signal produced during POD-PWM techniques for SW_1, SW_2, SW_3, and SW_4.

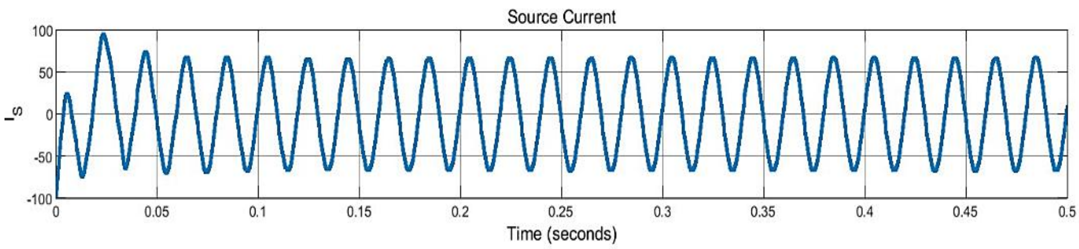

Figure 12. Supply current waveform after filtering action

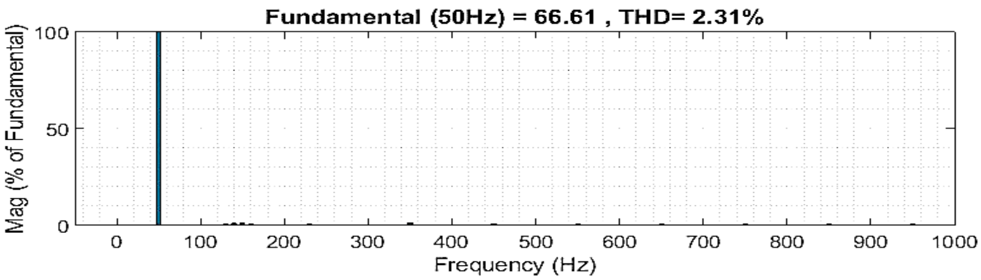

Figure 13. Supply current with THD after filtering action

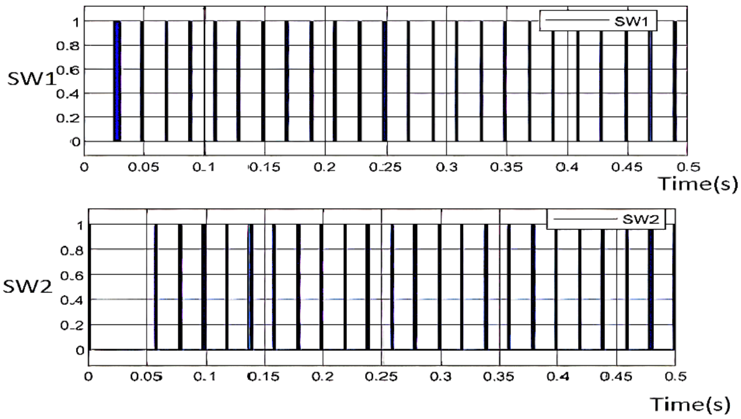

Figure 14. Switching signals during POD-PWM techniques for SW_1 and SW_2

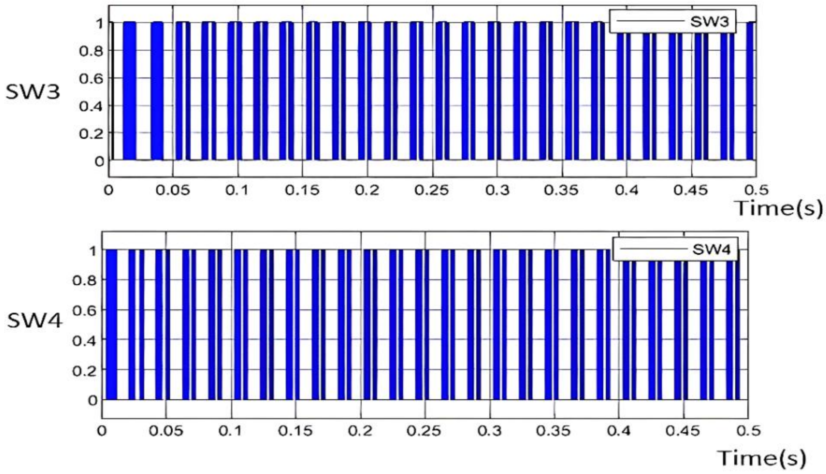

Figure 15. Switching signals during POD-PWM techniques for SW_3 and SW_4

6. CONCLUSION

In this research, a shunt APF was successfully developed using a five-level inverter with a reduced number of switches to mitigate harmonics in the distribution network. By implementing artificial intelligence through a FLC, the APF demonstrated significant improvements in power quality, meeting the compliance requirements set by utilities and regulatory bodies. Harmonic identification was effectively achieved using the single-phase adaptation of the p-q theory originally designed for three-phase systems. The POD-PWM switching technique delivered satisfactory performance, reducing the THD of the source current from 34.15% to 2.31%, in adherence to the IEEE-519 standard. The results confirm that the developed APF significantly reduces current harmonics. Moreover, the fuzzy logic control approach, leveraging human knowledge through IF-THEN rules, proved to be a robust alternative to complex mathematical modeling, making it an excellent choice for controlling the APF efficiently. This article highlights the potential of combining advanced inverter technology with intelligent control systems to enhance power quality in polluted distribution networks.

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AUTHOR CONTRIBUTIONS STATEMENT

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Babasaheb Rajaram Patil	✓			✓		✓	✓			✓		✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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