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Design and Analysis Three-Phase Shunt Active Power Filter in Mitigate Harmonic

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ABSTRACT

Nowadays, the power electronic equipment is extensively employed across industrial, commercial, and residential consumers which inject harmonic current in the power system. These harmonics detrimentally affect power quality, precipitating various power quality issues. Due to the detrimental effects of harmonic currents, there is considerable research interest in mitigating their impact on power systems. In this context, a shunt active power filter (SAPF) stands out as the most dependable solution. Its operation involves initial detection of harmonic currents within contaminated power systems, followed by the generation and injection of corrective mitigation currents to eliminate the detected harmonics. This paper critically discussing and analyse control techniques for three-phase shunt active power filters (SAPFs) aimed at enhancing power quality and mitigating current harmonics in nonlinear loads. The insights offered can serve as valuable guidance for selecting the optimal technique to synchronize SAPFs with connected power systems. Additionally, MATLAB/Simulink will be utilized to validate the efficacy of the shunt active power filter (SAPF) in harmonic mitigation.

1. Introduction

Currently, the utilization of electronic devices contributes significantly to the generation of harmonics within power distribution networks. This is primarily due to electronic equipment such as diode/thyristor rectifiers, AC controllers, and cycloconverters drawing non-sinusoidal currents from the utility source. Consequently, the currents consumed by these devices introduce harmonics, leading to a degradation in the overall power quality of the system. These harmonics cause several issues such as elevated Total Harmonic Distortion (THD), voltage distortion, increased power losses, and overheating of equipment [1-5]. Due to these negative impacts, it has become critical to control harmonic levels within the power system, which is why IEEE standard 519-1992 (now revised as IEEE

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standard 519-2014) was developed to limit THD to a maximum of 5% [6]. Harmonic filters have been widely used to mitigate these issues, particularly in environments where power quality is crucial [7,8].

Harmonic mitigation techniques can generally be categorized into passive and active approaches. Traditionally, passive filters composed of inductors, capacitors and resistors have been used to eliminate specific harmonic frequencies [9-11]. Despite their simplicity, passive filters are associated with several limitations, such as large size, inflexible compensation characteristics, and potential resonance problems that can worsen voltage distortion [12,13].

As a result, they are now largely being replaced by active power filters (APFs) [14,15], which offer dynamic harmonic compensation and better adaptability to varying system conditions. Among these, the shunt active power filter (SAPF) stands out due to its flexibility and effectiveness in compensating for current harmonics and improving power factor [16].

The operation of SAPFs is fundamentally based on detecting harmonic currents in contaminated systems and then injecting compensating currents to counteract these harmonics. This process relies heavily on control algorithms. Early methods, such as the Instantaneous Reactive Power Theory (PQ Theory) proposed by Akagi *et al.,* [7,12] are widely utilized for harmonic detection and compensation. PQ theory has been extensively developed and applied due to its ability to operate effectively in both steady-state and transient conditions. Alternatively, the Synchronous Reference Frame (SRF) method, also known as DQ theory [14,17] has gained prominence for its simpler computational requirements and improved performance in dynamic situations. This method transforms three-phase currents into a DQ reference frame, separating harmonic components from fundamental frequencies more effectively [18].

Several studies have focused on optimizing the performance of SAPFs through advanced control strategies. For instance, fuzzy logic-based control and Proportional-Integral (PI) controllers are increasingly employed to enhance the precision of harmonic extraction and reduce response times [19-24]. Fuzzy logic controllers are capable of handling system uncertainties and nonlinearities better than traditional linear controllers [25,26]. Moreover, combinations of control methods, such as the integration of fuzzy logic with hysteresis current control, have been proposed to further improve harmonic suppression and system stability [27-31].

Building upon these advancements, this paper presents a thorough investigation into the comparative effectiveness of various control methods for SAPFs, specifically targeting real-time harmonic mitigation in dynamic load conditions. By analyzing both PQ and DQ theories combined with controllers like space pulse-width modulation SPWM and Fuzzy Hysteresis, this research addresses the limitations of individual control strategies, providing a robust framework that enhances both stability and harmonic suppression efficiency. MATLAB/Simulink simulations validate the control algorithms, offering insights into optimal SAPF configurations for effective power quality management in nonlinear environments.

2. Methodology

2.1 Shunt Active Power Filter

Figure 1 illustrates a three-phase system comprising an AC source, a SAPF, and a nonlinear load. The SAPF's role is to detect harmonic signals and inject corrective current between the AC source and the nonlinear load, thereby reducing harmonics generated by the load and enhancing the system's power factor, as further depicted in Figure 7. The SAPF generates a harmonic current with the same magnitude but opposite phase to cancel out unwanted harmonics. Additionally, the SAPF provides reactive power to the load and maintains the source signal's sinusoidal waveform. Key control steps in this process include establishing the SAPF, harmonic extraction, current control, and voltage regulation.

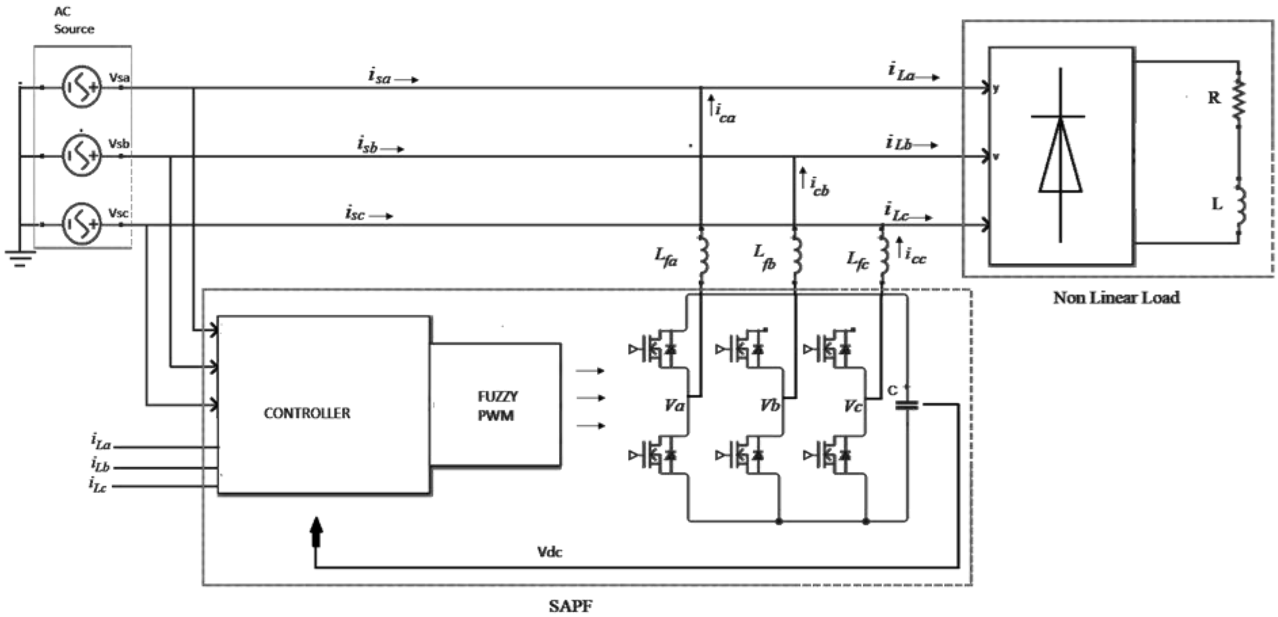

Fig. 1. Three phase shunt active power filter (SAPF) block diagram

The project starts by gathering the information regarding the studies that based on the harmonic extraction for control in Shunt active power filter. Based on the PQ and DQ theory for harmonic extraction, the equation obtained. This is including each of the parameter for other control algorithm in the SAPF.

Next, the equation based on the PQ theory and DQ theory and other control algorithm of the SAPF model is constructed in Simulink by using a MATLAB function block. The mathematical equation of the SAPF model needs to be check simultaneously if there are error detected in when running the simulation.

Last but not least, adjust the parameter in three phase SAPF until the desired result can achieved and try to get the lower percentage of harmonic for this system. The result of the harmonic value from PQ theory and DQ theory will compare with three-phase system without SAPF.

2.2 Instantaneous Reactive Power Method

The instantaneous power theory is usually known as PQ theory [12]. The main benefits of this approach are that it is easier to apply it in the sense of harmonic extraction. In this technique, the voltage supply and load current signal, IL will be transform to αβ frame by using Clarke transformation and the αβ frame will be applied to calculate the instantaneous power P and reactive Q power of the load. Then, the low pass filter is required to obtain desired harmonic component [14,15]. Finally, the extracted harmonic components iHαβ inverse back to three-phase load current, $Iabc$ via inverse Clarke-transformation to obtain desired reference current, $Iref$.

The method in harmonic extraction based on time domain which is the instantaneous reactive power also knows as PQ theory. In 1983, Akagi suggested a generalised principle of instantaneous reactive power in ac networks. This method will transform the voltage and current from ABC to αβ orthogonal coordinates. A circuit diagram of instantaneous reactive power method that design is shown in Figure 2.

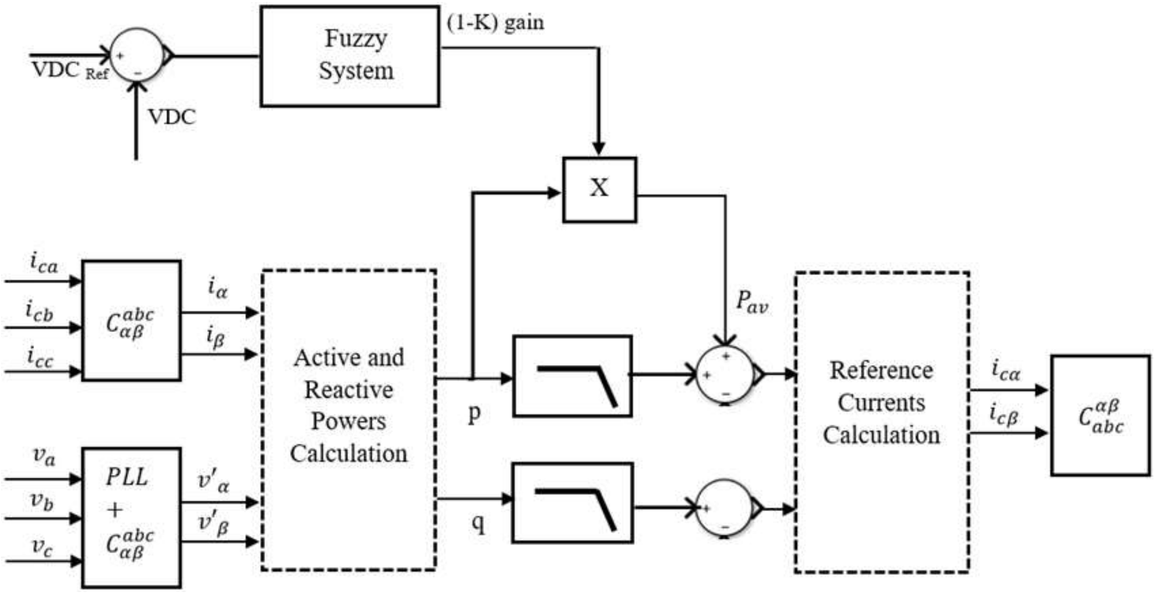

Fig. 2. Block diagram for the instantaneous active and reactive power theory

Another control strategy adopted in this project is the instantaneous reactive power also knows as PQ theory. In the PQ method, the three-phase voltages and currents in the a-b-c coordinates will transform to α-β-0 orthogonal coordinates using Clark transformation. The Clark transformation for voltages source and load current can expressed by the following Eqs. (1) and (2).

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} . \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} . \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{2}$$

Then, the voltage source, Vs and current load, IL in terms α and β will be applied to find the reactive Q and instantaneous active P power for the load. However, the value P and Q power can be expressed by this Eq. (3).

$$\left[\begin{bmatrix} P \\ Q \end{bmatrix}\right] = \left[\begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix}\right] . \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \tag{3}$$

Then, desired harmonic component, will transform back to a-b-c component *via* inverse Clark transformation to generate the reference current, for shunt active power filter to mitigate the harmonic. The inverse Clark transformation can express by the following Eq. (4).

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} . \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \tag{4}$$

2.3 Synchronous Reference Frame Method

According to Akagi *et al.,* [7] the SRF algorithm also known as DQ theory is the best algorithm as it provides simple design structure with increased speed, reduced computational burden and also easier to implement. In this algorithm, the three-phase load current $Iabc$ will convert into direct-quadrature-zero (dq0) frame by using Park transformation matrix. Then the d and q component of current are to fed to low pass filter to separate fundamental component and harmonic component [7,9]. In the SRF algorithm, the Phase Locked Loop (PLL) synchronization system is using to automatically evaluate the phase angle of the fundamental positive sequence and the system frequency of the three-phase voltage source signal [10]. Finally, the DQ frame will inverse back to the three-phase load current, $Iabc$ *via* inverse Park- transformation to generate desired reference current, Iref.

The harmonic extraction algorithm is time domain based synchronous reference frame (DQ theory) method, in which three-phase load current will convert to the DQ synchronous reference frame. So, that harmonic component and fundamental component can been separate using low pass filter (LPF). A Figure 3 shows the block diagram of SRF method block diagram.

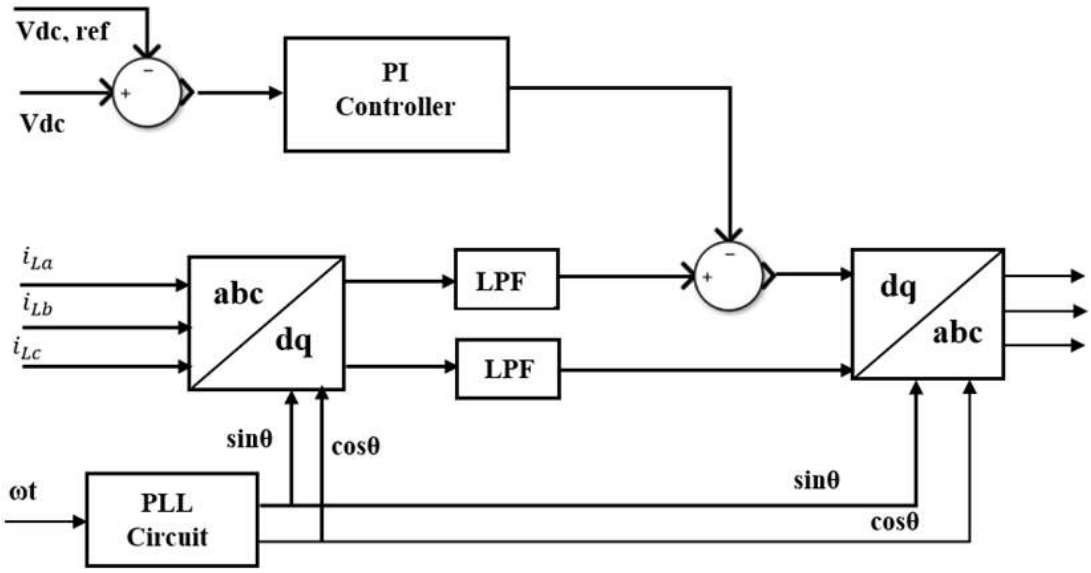

Fig. 3. Block diagram for synchronous reference frame method

The control strategy adopted in this study is the synchronous reference frame also known as DQ theory. In this method, Park Transform is using for the load current iLa, iLb and iLc to convert which is from the A-B-C reference current to DQ synchronous reference frame. In order, to separate the sequence component which is fundamental positive and negative sequence components of instantaneous currents id and iq [11]. The following Eq. (5) for park transformation.

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} cos\theta & cos\left(\theta - \frac{2\pi}{3}\right) & cos\left(\theta + \frac{2\pi}{3}\right) \\ -sin\,\theta & -sin\left(\theta - \frac{2\pi}{3}\right) & -sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \cdot \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{5}$$

However, the DQ frame will transfer back to ABC frame using inverse transformation from park transformation and follow to the current control algorithm to generate the reference current, $Iref$. The inverse transformation to translate current from the DQ frame to the ABC frame by following this Eq. (6).

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & -sin\theta \\ cos\left(\theta - \frac{2\pi}{3}\right) & -sin\left(\theta - \frac{2\pi}{3}\right) \\ cos\left(\theta + \frac{2\pi}{3}\right) & -sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} . \begin{bmatrix} I_d \\ I_q \end{bmatrix} \tag{6}$$

2.4 PI Controlled for DC- Link Regulation Algorithm

For the DC- link regulation algorithm, the PI controlled has been used widely by researcher for shunt active power filter to reduce harmonic in power system. The PI controlled based on DC-link voltage regulation used to set the reactive power compensation and amplitude of reference for harmonic [12]. Basically, the output of the controlled is forwarded to generate reference current signal for SAPF. The input for PI controlled is from the error between DC reference side voltage and dc voltage, Vdc. It is expressed by this Eq. (7).

$$e\,(t) = Vdc_{ref} - Vdc \tag{7}$$

2.5 SPWM for Current Control

The SPWM based on current control algorithm that used in this study for PQ and DQ method is shown in Figure 4. Besides, to generate the switching pulses with different duty-cycle, the SPWM signal must been generated by comparing the error signal from PI controller. Therefore, the reference current signal will be generated as the desired injection current in system to reduce harmonic from the switching pulse in the SAPF. This method can ensure constant 40 switching frequency and regulate the current tracking error with fast dynamic response. Finally, the switching states of the power switching devices are determined by gating signals Sa, Sb and Sc as described in Table 1 [13].

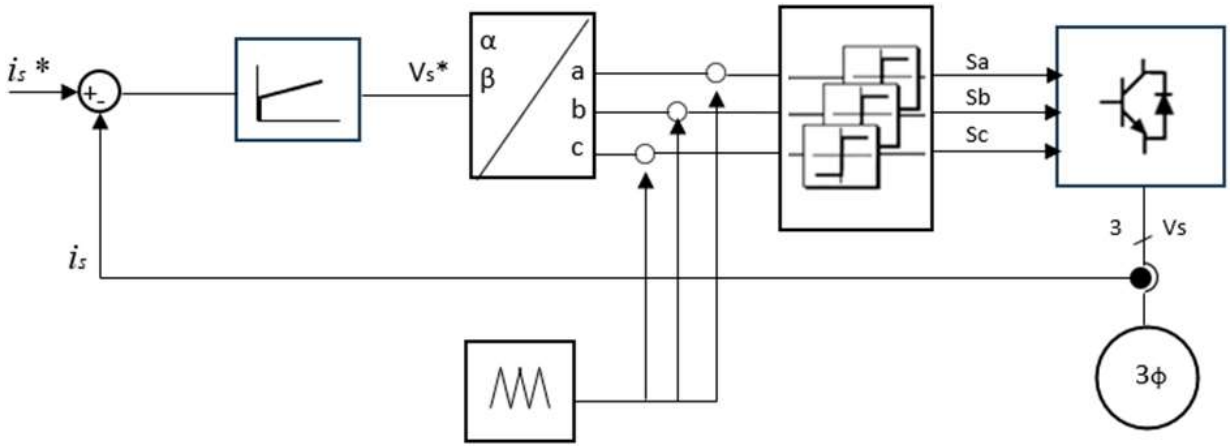

Fig. 4. Block diagram for SPWM current control scheme

Table 1
Condition the power switching in active power filter

Switching	Condition
Sa	1, if S1 ON and S4 Off
	0, if S1 Off and S4 ON
Sb	1, if S2 ON and S5 Off
	0, if S2 Off and S5 ON
Sc	1, if S3 ON and S6 Off
	0, if S3 Off and S6 ON

2.6 Fuzzy Hysteresis for Current Control

Figure 5 shown the block diagram for combination from two current control which is hysteresis controlled and fuzzy controlled. According to Figure 5, the hysteresis fuzzy current control has been applied to generate the signal of switching 41 for the IGBT. However, the hysteresis fuzzy control can be enhancing the performed of the SAPF. Normally, the hysteresis band controlled always been applied in current control algorithm because this method simple and easy to implement in circuit but this method will generate high frequency for switching and can't been control. However, this problem can also induce significant losses for switching and give impact to power transistor. So that, the fuzzy logic control has been combine with hysteresis band control to reduce disadvantage on hysteresis band control and also to ensure proper switching. In the fuzzy logic, the three steps have been followed which is Fuzzification, Rule base and inference engine and Defuzzification to ensure the fuzzy can been execute (Figures 6 to 8). Table 2 shows the Fuzzy Rule for current control.

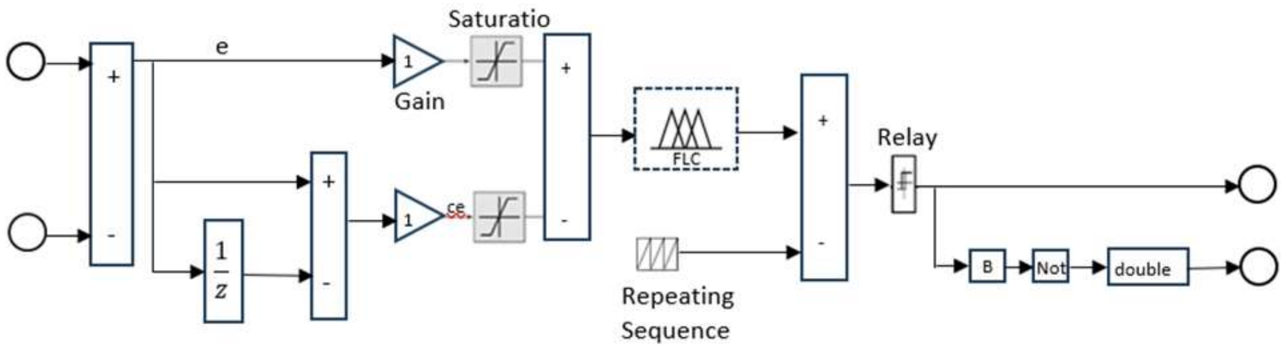

Fig. 5. Proposed block diagram for fuzzy logic based hysteresis current control scheme

Table 2
Fuzzy rule for current control

ΔE \ E	NL	NM	EZ	PM	PL
NL	PL	PM	PM	PM	PL
NM	PL	PM	PS	PM	PL
EZ	PVL	PM	PSV	PM	PVL
PM	PL	PM	PS	PM	PL
PL	PL	PM	PM	PM	PL

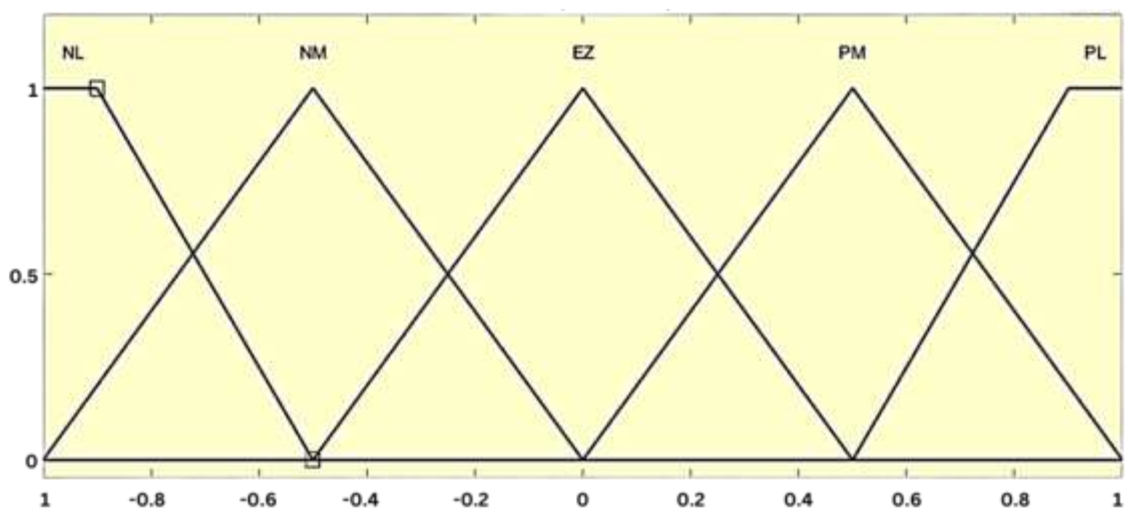

Fig. 6. Variables "error" for fuzzy input 1

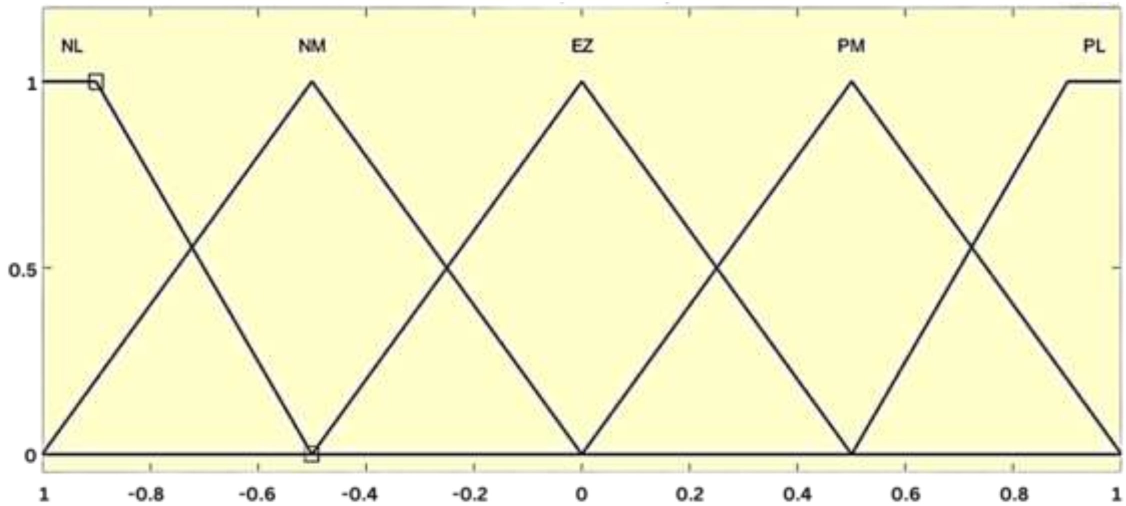

Fig. 7. Variables “change of error” for fuzzy input 2

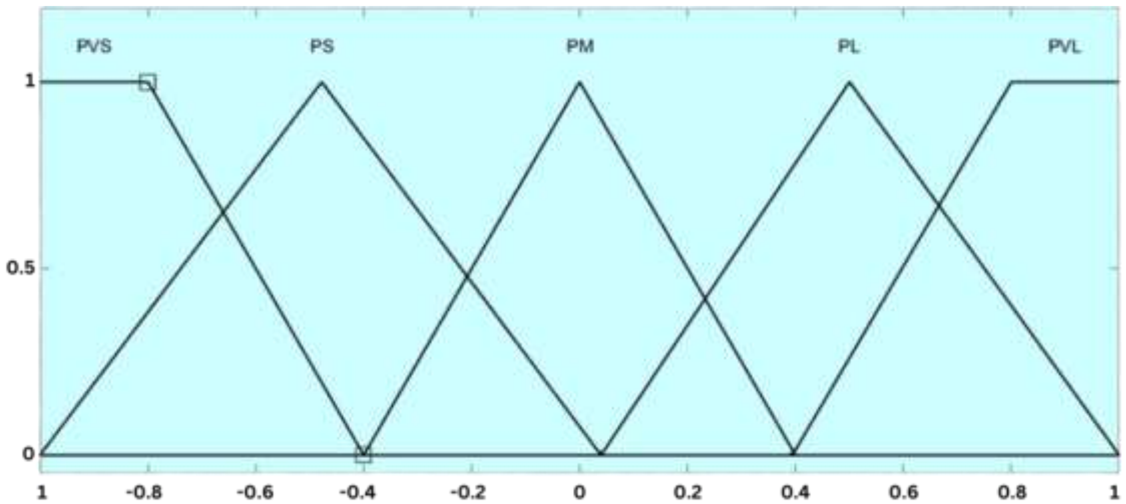

Fig. 8. Variables “output” for fuzzy output

3. Simulation Results

The simulation result from MATLAB/Simulink for three-phase SAPF are obtained based on the response of the percentage harmonic in system (Figure 9). The result from simulation using PQ and DQ theory and also using PI controlled will elaborates in this paper. Finally, the result for THD% will been analysis for this reference model with SAPF and without SAPF.

The reference model is for three phase system without SAPF. The Table 3 shows the parameter that been used for this SAPF. Each of the parameter’s value are defined in MATLAB/Simulink when established the model.

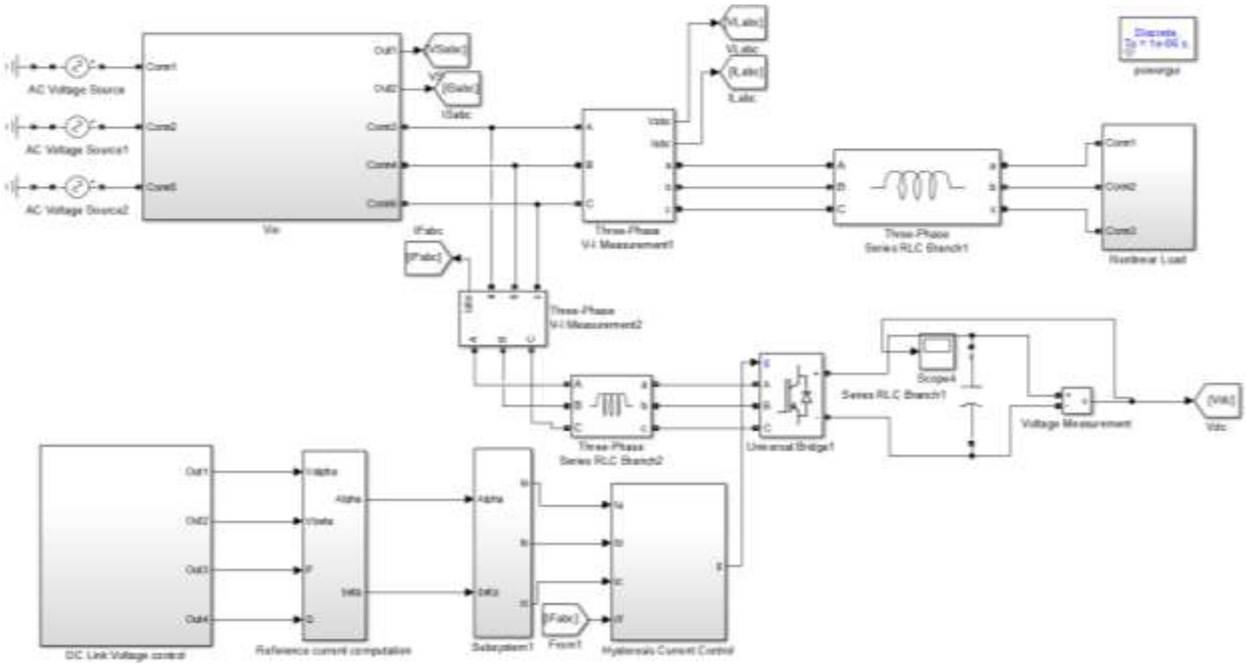

Fig. 9. MATLAB/Simulink for three-phase shunt active power filter (SAPF)

Table 3
Circuit parameter of system

Quantity	Value
Voltage Source	311V
Supply Frequency	50Hz
Line Inductor	19.6µH
Line Resistence	0.25mΩ
RL load	R=6.5Ω , L=20mH
Injection Inductor	3mH
DC-link capacitor	1600µF
DQ theory (KP and KI)	KP = 0.2, KI = 30
PQ Theory (KP and KI)	KP = 100, KI = 0.6

The load current THD with a rectifier load is 22.65 %. In this project, has few methods which is control algorithm that applied in active power filter to improve this system to reduce harmonic. The control algorithm that have been applied in APF are: -

i. PQ theory (Harmonic extraction) with SPWM (Current Control)
ii. PQ theory (Harmonic Extraction) with Fuzzy Hysteresis (Current Control)
iii. DQ theory (Harmonic Extraction) with SPWM (Current Control)
iv. DQ theory (Harmonic Extraction with Fuzzy Hysteresis (Current Control)

The desired output response for voltage waveform, current source and THD % for the three-phase reference model without SAPF are shown in Figure 10. The result of the percentage of THD% in reference model will show in MATLAB/Simulink by using the FFT analysis tool. When the reference model not connect with SAPF, the current will produce bigger the percentage of harmonic which is 22.65%. However, the supply current signal will become non-sinusoidal from sinusoidal.

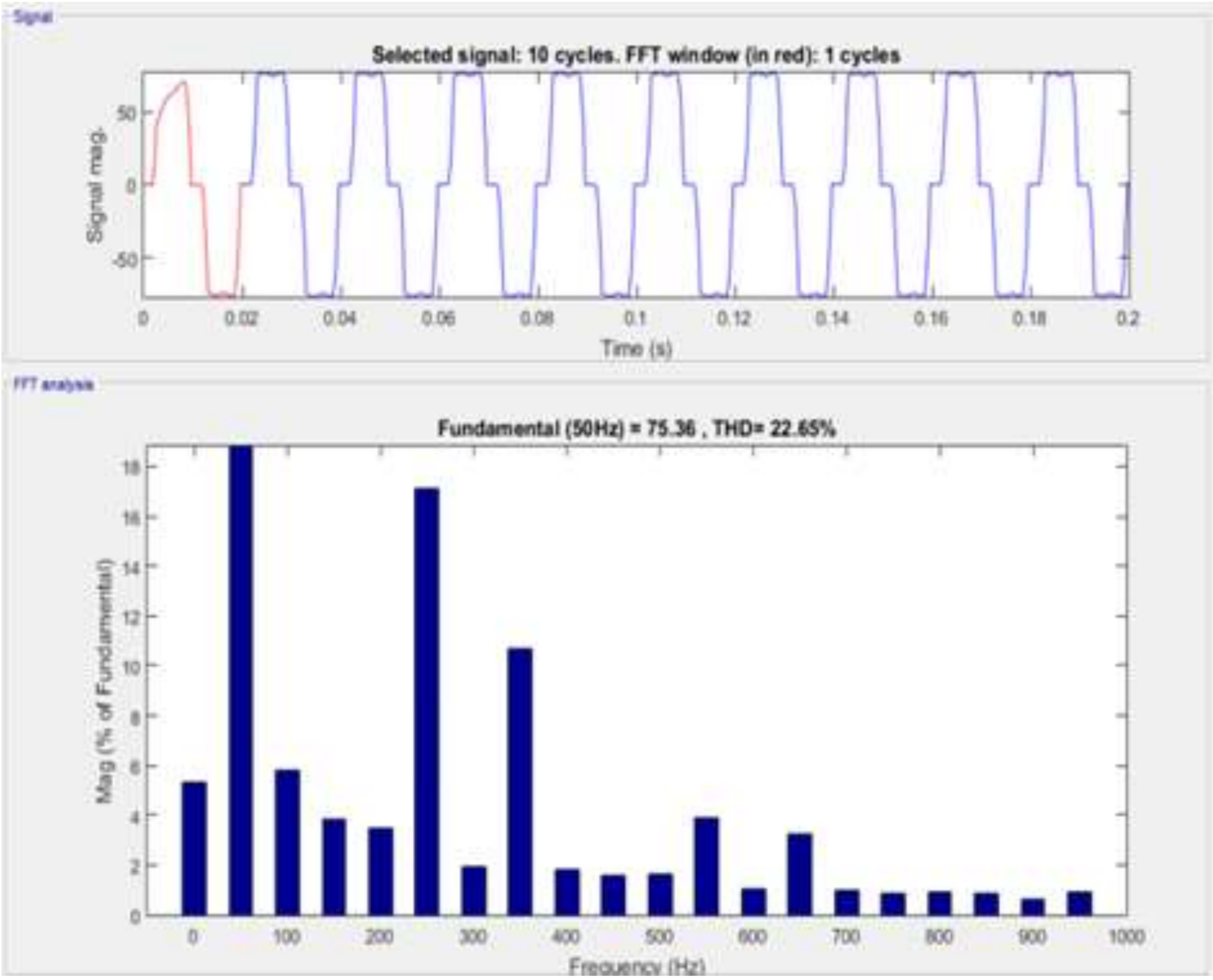

Fig. 10. Harmonic percent without SAPF

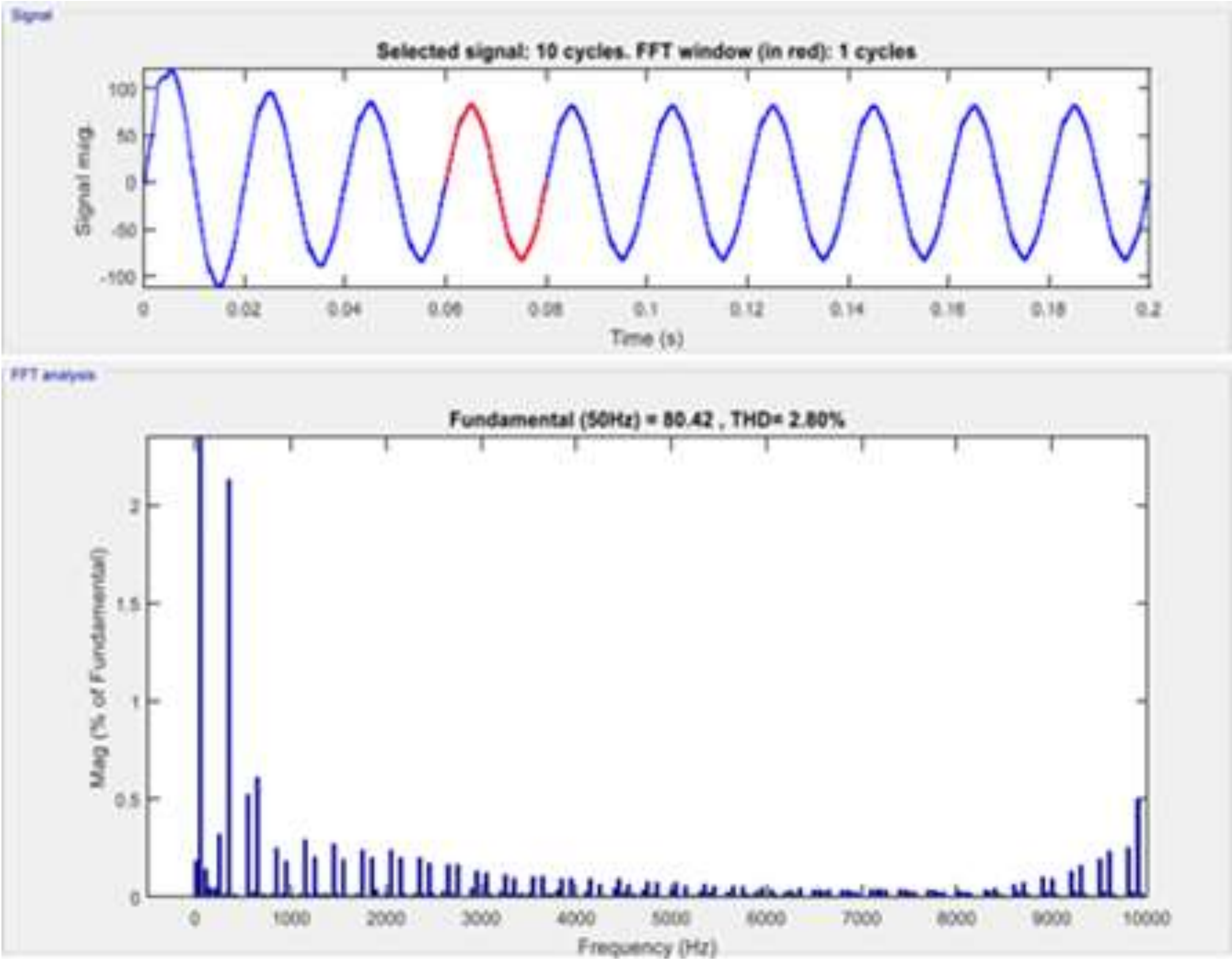

Fig. 11. Harmonic percent for PQ theory using PI and SPWM

The desired output response for current source and THD% for three-phase SAPF using PQ theory using PI and SPWM are shown in Figure 11. The FFT analysis tool in MATLAB software will show the percentage of THD%. However, according to IEEE Std. 519-1992, "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems", 1993 said that the THD% should be less than equal 5%. When SAPF using PQ theory with PI controlled is connect in the three-phase model the THD% become 2.80%. Meanwhile Figure 12 shown that the THD% for PQ theory using hysteresis Fuzzy method. The THD become 2.57% for this proposed current control.

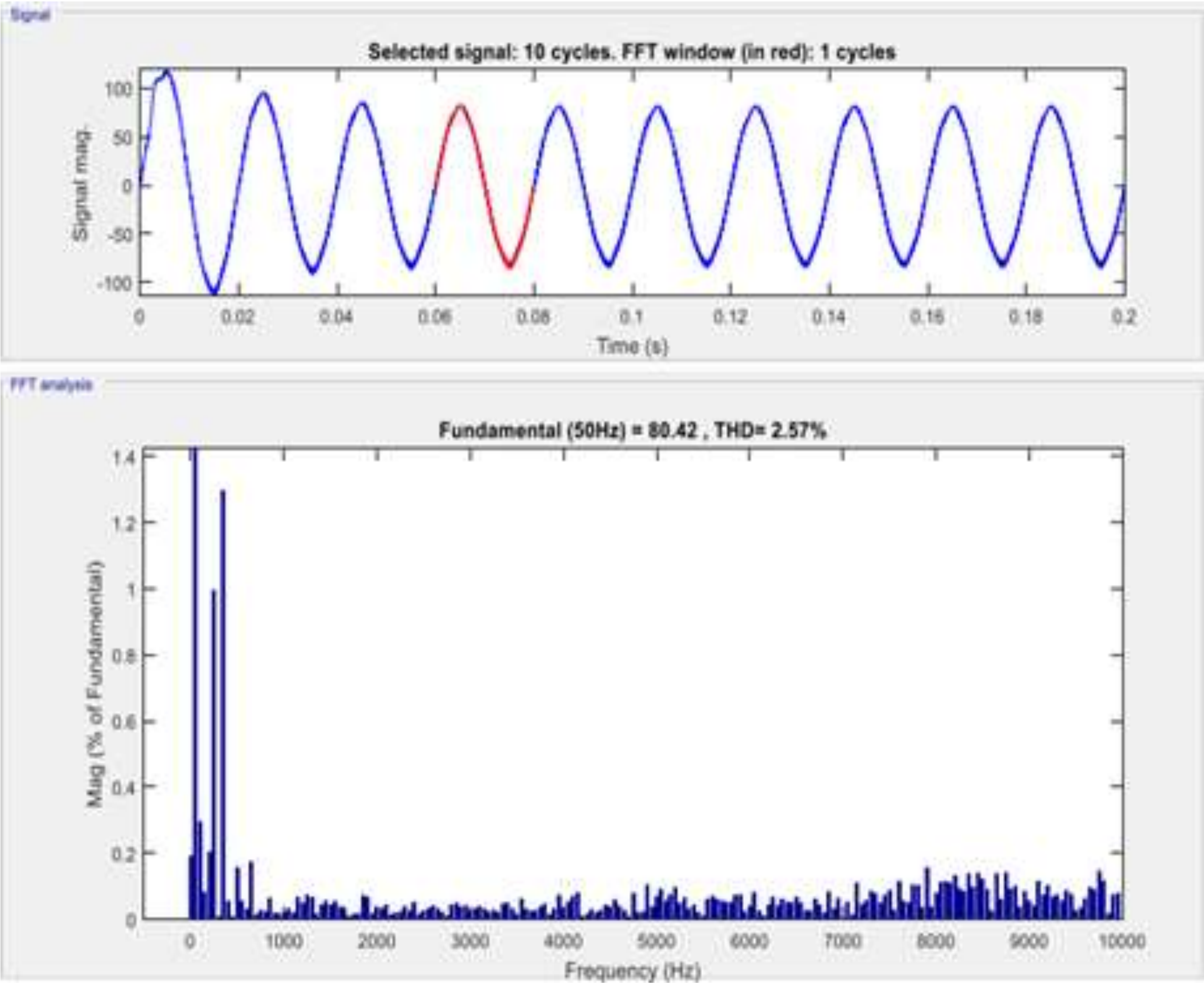

Fig. 12. Harmonic percent for PQ theory using hysteresis fuzzy

For the DQ theory analysis, the desired output response for current source and THD% for three-phase SAPF using DQ theory with PI controlled and SPWM are shown in Figure 13, the THD become 3.32% meanwhile Figure 14 shown the result analysis of three-phase shunt active filter using DQ theory with Fuzzy Hysteresis, the THD become 2.81%.

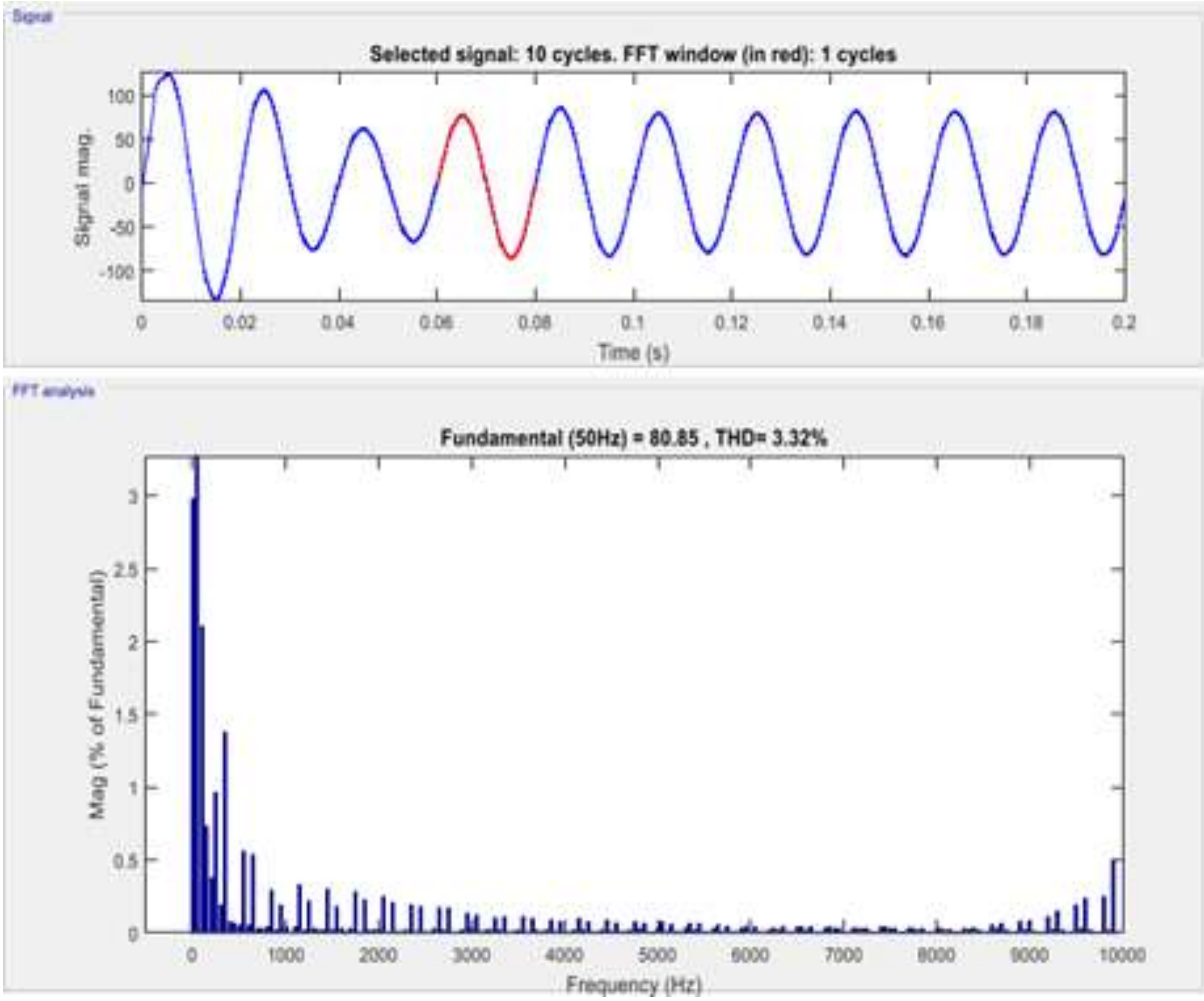

Fig. 13. Harmonic percent for DQ theory using PI and SPWM

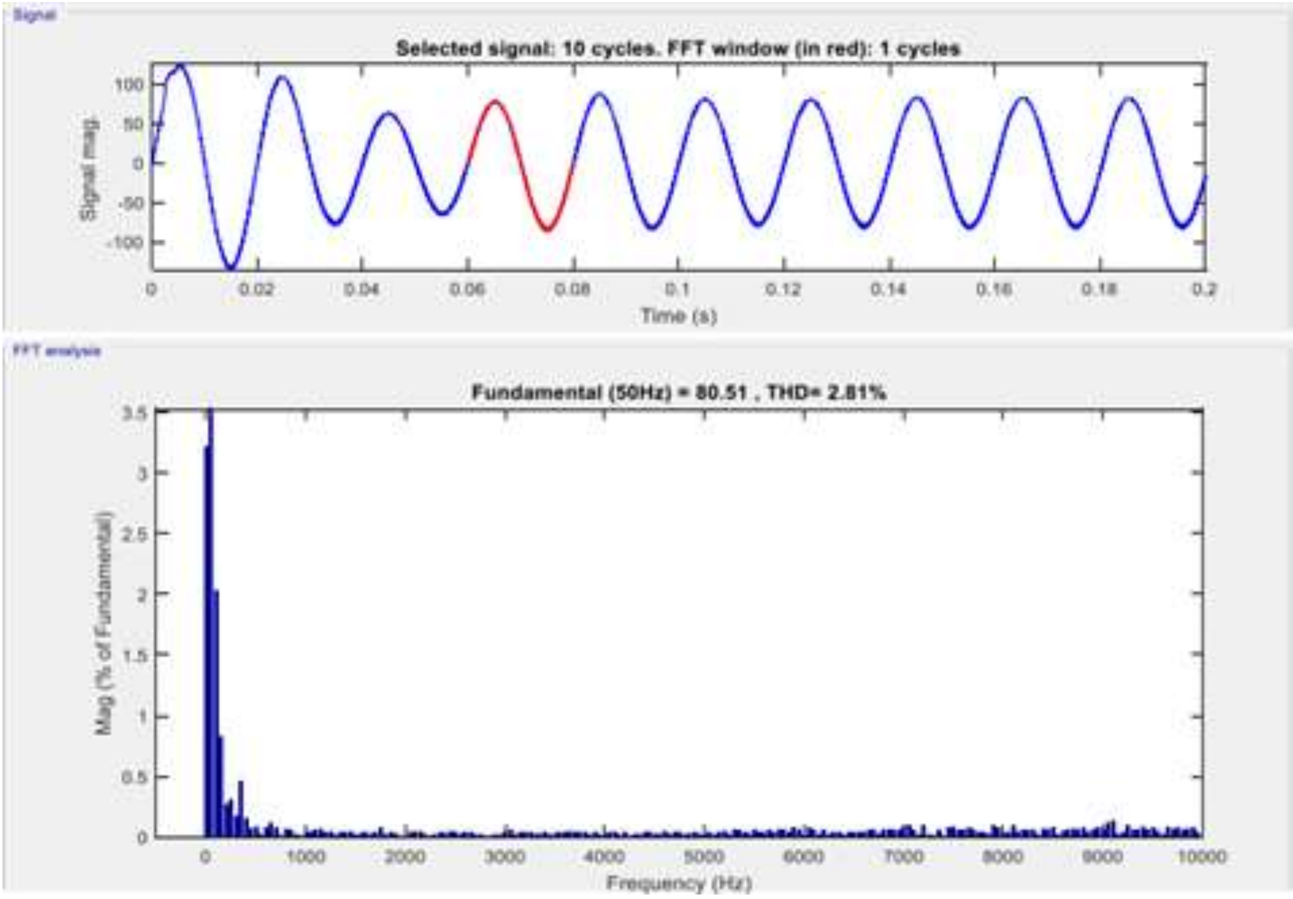

Fig. 14. Harmonic percent for DQ theory using Fuzzy Hysteresis

From analysing the simulation results with different controller combinations, it shown that the proposed complete fuzzy control gives a better harmonic mitigation and the filter performance is improved. The simulation results and its comparison with conventional control techniques are given in Table 4.

Table 4
Source current THD comparison of different control techniques

Harmonic Extraction	Current Control	Source Current THD%
Without filter		22.65%
PQ Theory	SPWM	2.80%
	Fuzzy Hysteresis	2.57%
DQ Theory	SPWM	3.32%
	Fuzzy Hysteresis	2.81%

4. Conclusions

In conclusion, this study advances the field of harmonic mitigation by implementing a comprehensive approach to control three-phase shunt active power filters (SAPFs). Unlike traditional methods, this work integrates both PQ and DQ theories for harmonic extraction, and further enhances these techniques through the use of fuzzy logic and Proportional-Integral (PI) controllers.

This dual-algorithm approach not only provides flexibility but also optimizes harmonic suppression under varying power conditions. The proposed combination of Fuzzy Hysteresis and SPWM controllers introduces a novel hybrid solution that enhances real-time response and improves stability, which are critical for power systems facing dynamic loads.

This study lies in its multi-technique comparison, providing a unique evaluation of various control methods within SAPF systems. This comparative analysis reveals that the integration of Fuzzy Hysteresis control offers superior harmonic reduction and rapid response, surpassing the performance of conventional control algorithms. Through MATLAB/Simulink simulations, this study successfully demonstrates that the proposed SAPF configuration meets and exceeds IEEE 519-2014 standards for THD reduction, presenting a viable path forward for optimizing power quality in nonlinear systems. The insights gained from this research contribute a novel framework for selecting optimal SAPF configurations, paving the way for future advancements in power filter design.

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