Shunt Hybrid Active Power Filter Based on Two Compensation Strategies with PI and Fuzzy Logic Controllers

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Abstract—**Industrial designs have tremendously changed within the last decade, with its time and nonlinear variation loads in power frameworks spectrum expanding widely. This revolution has resulted in increased quality control problems such as current unbalance, current and voltage harmonics, flicker and poor power factor in control frameworks. The aim of this paper is to address this problem through the development of Synchronous Reference Frame and Reactive Power (SRF and P-Q) control methods. The DC voltage was regulated to its set reference for providing the current reference using proportional-Integral (PI) and fuzzy logic controllers. From the results, Fuzzy logic control was shown to achieve an adequate DC capacitor energy storage optimization, the sinusoidal type of the current and the change of the power factor. A low Total Harmonic Distortion (THD) that met the suggestions of IEEE-519 standard on symphonious levels was achieved with the proposed method.**

Index Terms—**Total Harmonic Distortion; Shunt Hybrid Active Power Filter; P-Q Control Strategy; SRF Control Strategy; PI Controller; Fuzzy Logic Controller**.

I. INTRODUCTION

The utilization of variable solid state switching devices in home and commercial appliances is growing tremendously as represented in personal computers, rectifies, uninterruptable power supply (UPS), microwave oven and so on. This increase has led to a great expansion of the harmonic levels in the power network [1]. These harmonics are the main reason for the imperfections experienced in control misfortunes, poor influence factor, inordinate over warming in the transformer winding and ineffective power system [2]. Despite the efforts made by utilities and costumers to improve the control quality in a controlled framework through various compensators such as passive filters and static compensators, there are still issues with all the compensators such as high introductory costs, the necessity of high power converter evaluations, and high running expenses [3].

The dynamic power channel (APF) is one of best compensators that has shown great capability in consonant disposal [4] through their ability to remunerate most wonders of power quality such as current-voltage harmonics and the imbalances when they are well controlled. Generally, these filters generate similar signals but in opposite direction to the system for the compensation of any disturbances [5]. Till now, several APF control techniques have been proposed, but despite the creation of few control systems, yet, two control strategies which are instantaneous active and reactive power (P-Q) strategies and synchronous reference frame (SRF) technique still stand out [6].

This study utilized the SRF technique and instantaneous active and reactive power (P-Q) strategies to ensure the shaping of AC current and regulation of DC voltage in a three-phase shunt hybrid active power filter. In this paper, therefore, a proposal of the proportional-integral (PI) controller and fuzzy logic control schemes is made for harmonic current and maintenance of DC voltage for the improvement of the shunt HAPF performance. The switching signals for the three-phase voltage source inverter were generated with hysteresis current controller (HCC) due to the simplicity, robustness and fast dynamic response of its implementation [7].

II. THREE-PHASE SHUNT HYBRID ACTIVE FILTER MODELLING

The configuration of the shunt hybrid power filter in connection to the power framework for the nourishment of the nonlinear burdens is demonstrated in Figure 1. There are three-stage voltage source inverters in the SHPF arranged in association with a fifth tuned detached channel. The nonlinear burdens (diode connects rectifiers with R-L stack) are associated to regularly couple, which speaks to the point of common coupling that represents the expected industrial loads to be compensated.
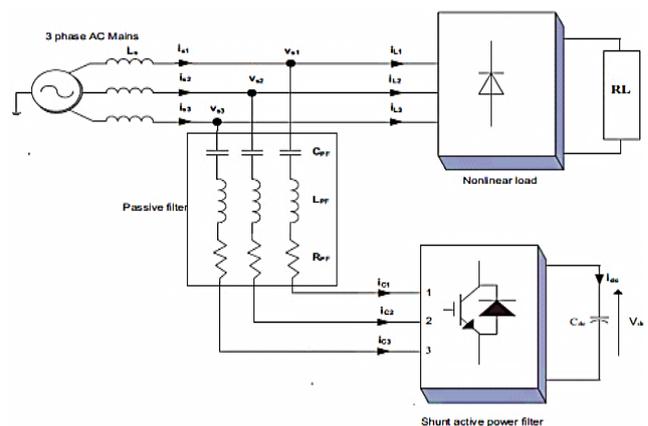
Figure 1: The configuration of the shunt hybrid power filter

III. Current Control Methods Of Shunt Hybrid Active Power Filter

The most important aspect of active filter control is the estimation of the compensating signal. It greatly influences the compensation objectives, active filter rating and its transient, as well as its performance in a steady state. The estimation of the reference signal is initiated through the detection of the current signal/essential voltage to collect accurate system variable information. The voltage of the AC source and the DC-bus voltage of the APF voltage are the variables to be sensed. The typical current variables are AC source current, load current, and compensation current. From these system variables, the estimation of the compensation reference signals in terms of voltage or current is made in a frequency-domain or time-domain approach. In this paper, the SRF and P-Q methods are used.

A. The P-Q Theory

Akagi et al. [1, 2] proposed a general theory for three phase's systems instantaneous reactive power known as momentary power theory or P-Q theory in 1983. This theory relies on quick esteems in three-stage control frameworks with or without nonpartisan wire. It is also substantial for brief operations or enduring state and for non-specific voltage and current waveform as well. The theory involved an algebraic transformation of the three-phase currents and voltages from the a-b-c coordinates to the α-β-0 coordinates, followed by the calculation of the instantaneous power component using p-q theory.

$$\begin{bmatrix} P_O \\ P \\ q \end{bmatrix} = \begin{bmatrix} V_O & 0 & 0 \\ 0 & V_\alpha & V_\beta \\ 0 & -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} P \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \tag{2}$$

$$P = \tilde{P} + \bar{P} \tag{3}$$

$$q = \tilde{q} + \bar{q} \tag{4}$$

$$P_0 = V_0 I_0 \tag{5}$$

where:

i. p and q represent the active power and imaginary power of a three-phase system respectively. p is a total source-to-load instantaneous energy flow per second in the steady state and transient state while q is proportional to the quantity of the energy exchange between the system phases and it has no effect on the power transfer between the load and the source.

ii. P_0 is the active power with no sequence component.

iii. $\bar{P}$ is the normal quick genuine power estimate that is exchanged from the power source to the heap, and it is the major power part to be provided by the power source and because of key dynamic current.

iv. $\tilde{P}$ is the alternating value of the instantaneous real power that is exchanged through the a-b-c coordinates between the power source and the load. Since energy transference from the power source to load is not involved in the alternating value of the instantaneous real power, it must be adjusted.

v. $\bar{q}$ is the immediate value of the instant imaginary power which is exchanged between the system phases,

and the power of the power between the sources of energy and the load determines the selection of the compensation power, due to the fact that the instant imaginary power is the average value compensation and the basic reactive current

vi. $\tilde{q}$ is the alternating value of the exchanged instantaneous imaginary power between the system phases and it does not imply the energy transferred.

vii. Since there is no need for the alternating value of the instantaneous imaginary power, it ought to be compensated. It is also due to harmonic currents. These powers are explained in Figure 2
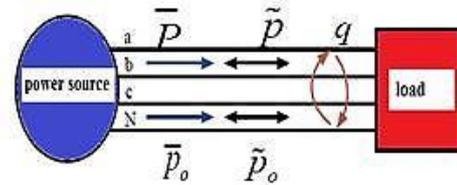
Figure 2: Difference between load power and source power

B. Synchronous Reference Frame (SRF) Theory

The SRF theory is used to acquire remunerating current reference signal. This controlled procedure involves the sensing and transformation of three-phase load currents from the a-b-c reference frame to d-q coordinates (DC components) using Park's transformation. Figure 3 showed the passing of these load current d-q components through the low-pass filter.
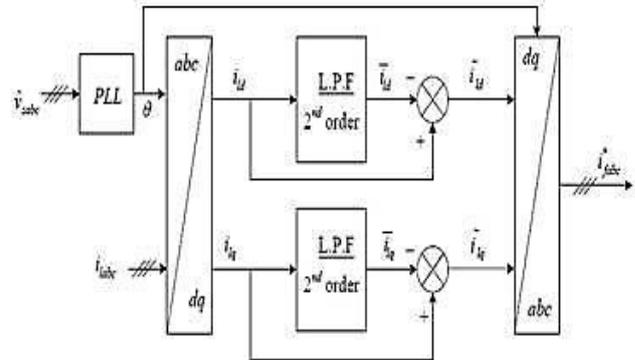
Figure 3: The principle of the synchronous reference frame method

Only the fundamental low-frequency components will be passed, while the harmonic component is stopped. A subtraction of the fundamental component from the non-filtered signal results in harmonic components in load current. The consonant current segment data in a-b-c reference outline is achieved by changing these parts in the d-q reference to a-b-c reference outline using backwards Park's transformation.

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} I_{La} \\ I_{Lb} \\ I_{Lc} \end{bmatrix} \tag{6}$$

The decomposition of the above-calculated currents into fundamental and harmonic components can be achieved as follows:

$$Id = Id_{dc} + Id_h \tag{7}$$

$$Iq = Iq_{dc} + Iq_h \qquad (8)$$

In the d-q reference frame, the fundamental component of load current will appear as DC quantity. Thus, Id_DC= Id1 and Iq_DC = Iq1. A subtraction of the harmonic current signal from the total load current will give the harmonic component of load current, i. e.

$$Id_h = IL - LPH \ (Id) \qquad (9)$$
$$Iq_h = IL - LPH(Iq) \qquad (10)$$

These load current d-q components are passed through low pass filter which allows the passage of low-frequency components. Subtracting the basic segment from the non-separated flag will give the reference remunerating signal in the d-q reference, while the subsequent flag in the d-q reference outline is changed into an a-b-c reference outline using the Converse stop's transformation, given as:

$$\begin{bmatrix} I_{f^*a} \\ I_{f^*b} \\ I_{f^*c} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \sin\theta \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} I_{dh} \\ I_{qh} \end{bmatrix} \qquad (11)$$

These signals were synchronized to the PCC voltages using a three-phased PLL (phase locked loop), and to extract the DC components of I_{ld} and. I_{lq}, this d–q current components are passed through low-pass filters (LPFs). The d-axis and q-axis currents are comprised of the fundamental and harmonic components as follows:

$$I_{ld} = I_{dDC} + i_{dAC} \qquad (12)$$
$$I_{lq} = I_{qDC} + i_{qAC} \qquad (13)$$

These reference streams, figured ebbs and flows are given to the hysteresis current controller (HCC) for the creation of the gating heartbeats that controls the source inverter. A major advantage of the synchronous reference frame method is that the supply voltage information does not need to be supplied as obtainable with the p-q method. The issue of imbalances in the mains supply cannot be overcome using the synchronous reference frame-based filtering.

C. Hysteresis Current Control

This is a way of generating the required activation heartbeats through contrasting the input signal and reference current, and it is used to control the source inverter. This technique concurrently controls the voltage source inverter switches; swinging the current through the inductor in different directions and taking after the reference current. The HCC demonstrated in Figure 4 is the least complex control strategy currently used in this area.

D. PI DC Voltage Controller

There is a need to deal with a little measure of power streaming into DC capacitor to control DC bus voltage, consequently compensating for the conduction and exchange misfortunes. There is no need for the DC link voltage control circle to be as quick as when it responds to the relentless state working condition. The real DC interface voltage is contrasted while the voltage is connected to a PI controller via a link DC. To maintain the DC-link voltage at the settled reference esteem, the DC-connect capacitor requires a
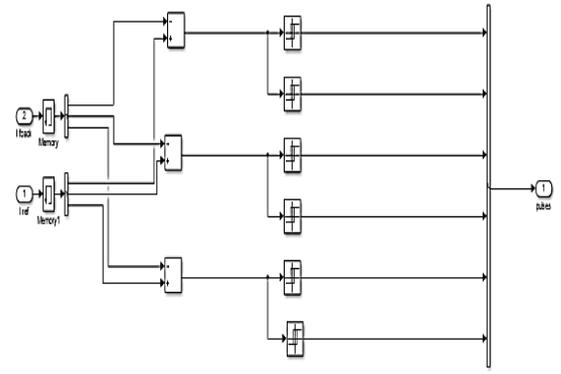
Figure 4: The hysteresis current control circuit

specific real power measure which directly corresponds to the difference between the real voltages and the reference. The control flag which originates from the PI controller to the direct DC interface voltage can be communicated as:

$$P_{dc-link} = K_p(V_{dc-ref} - V_{dc}) + K_i \int (V_{dc-ref} - V_{dc})dt \quad (14)$$

where K_p and K_i are proportional and integral gains of the PI controller.

An expansion of the proportional gain (K_p) minimizes the rise time and steady-state error, but can cause an increase in the settling time and overshoot. Similarly, an increase of the necessary pick up (K_i) reduces the relentless state mistake, but can lead to overshoot and settling time. Figure 5 showed the block diagram of PI controller.
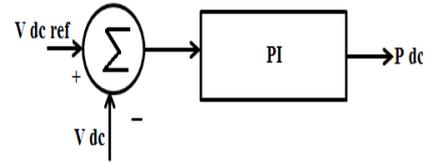
Figure 5: The block diagram of PI controller

E. Fuzzy Logic Dc Voltage Controller

In the past four decades, Fuzzy logic has been popular due to its points of interest of power against parameter variety, customization, ubiquity, etc. Fuzzy modelling has provided the ability to specify the approximate relationships between inputs and desired outputs at a point when the framework is inadequately comprehended or excessively mind-boggling, making it impossible to be portrayed in exact numerical terms. These relationships are presented as a set of Fuzzy IF-THEN rules, where the motive is to approximately, represent the state of the system and consequently provide a range of potential responses. The Fuzzy logic controller is used in this paper to maintain the DC transport voltage steadily at the reference esteem. In Fuzzy logic, a set of Fuzzy theory is used, with variables being a member of one or more sets in a specified manner. Fuzzy logic mimics the human reasoning process in computing, making decisions based on vague and incomplete data, as well as in quantifying imprecise information; yet, through the application of the "defuzzification" process, can arrive at definite conclusions with a defined level of participation. Figure 6 showed the block diagram of a Fuzzy logic controller (FLC) which basically comprises of three squares, which are fuzzification, inference, and defuzzification.
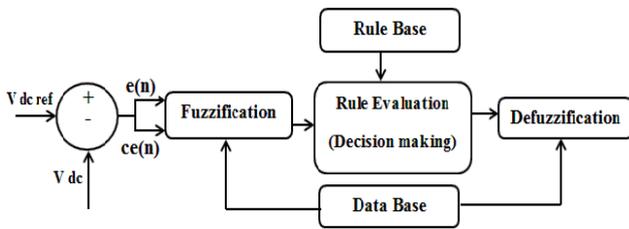
Figure 6: The block diagram representation of a fuzzy logic controller

IV. SIMULATION RESULTS

The use of Simulink for the execution of shunt HAPF with respect to the synchronization of the reference frame method (SRF) and p-q method with PI and Fuzzy controllers under perfect sources of voltage was investigated. The parameters of the framework are source voltage = 380 V, source impedance Rs = 0.2 mΩ, recurrence f = 50 Hz, Ls = 15 µH, Lf = 120 µH, DC voltage capacitor VDC_ref = 700 V, CDC = 2000 µF, channel impedance Rf=8 mΩ, nonlinear load Rl = 60 Ω, Ll = 0.5 H with diode rectifier and additional unbalanced loads (40 Ω + 0.005 H, 20 Ω + 0.001 H and 15 ω + 0.01 H).

The nonlinear load which comprised of a three-phase diode rectifier, RL, and an additional nonlinear load at 0.08s was fed by sinusoidal and symmetrical mains phase voltages. Figure 5 illustrates the system result before the application of the shunt HAPF; the THD of the load current before and after 0.08s was 30.12 % and 33.57 %, respectively. The shunt HAPF with the proposed Fuzzy logic and PI controllers was simulated and demonstrated. The proposed controller reenacted with the balanced and unbalanced nonlinear loads with the sinusoidal states of the source voltages. The THD of the current that uses FFT was about 7.72 % with a PI controller (Figure 8) and 4.2 % with a Fuzzy logic controller (Figure 9). Besides, Fuzzy logic controller maintained the VDC as consistent reference esteem (700v). More details of the results are presented in Table 1.
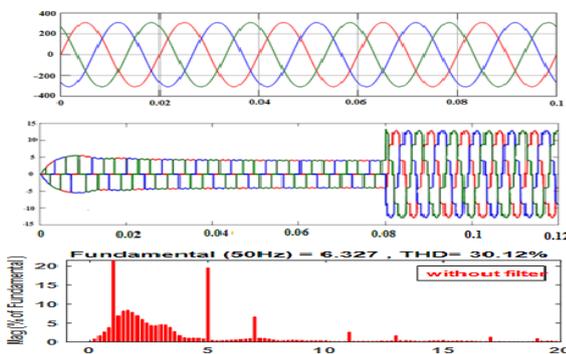
Figure 7: The simulated result without filter.
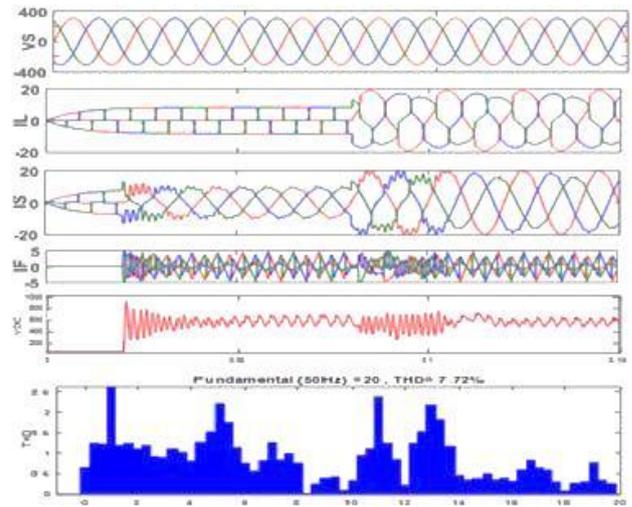
Figure 8: The simulated results based on P-Q theory with PI controller
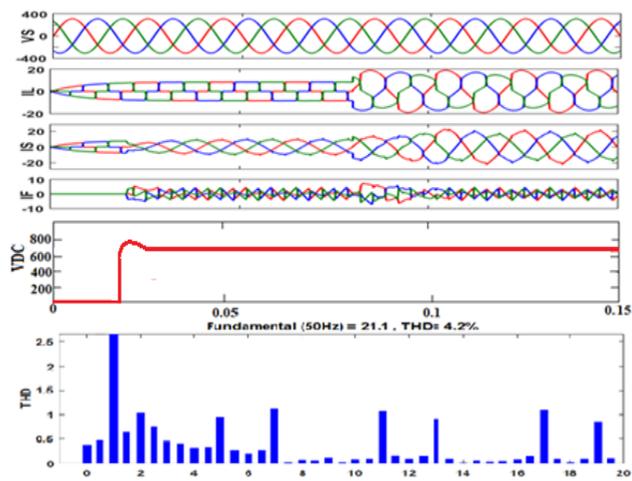
Figure 9: The simulated results based on P-Q theory with fuzzy logic controller.

The waveform of the voltage and current at the source and load sides are demonstrated in Figures 10 and 11. The load current had a THD of 30.12 % and a power factor of 0.84, while with PI and Fuzzy logic controllers, the THD of the source current reduced to 3.33 % and 1.17 % respectively, with a unity power factor after shunt HAPF remuneration using the SRF strategy. In addition, the simulation aftereffects of the proposed shunt HAPF under the transient condition of changing nonlinear load at 0.08s. An excellent dynamic response of T = 0.01s was achieved with the filter equipped with the Fuzzy logic controller. Finally, the Fuzzy logic controller can be said to have an excellent performance because based on Figures 7 and 9, the shunt HAPF excellently tracked the reference current with a consistent DC voltage of capacitor with little ripple (700v). More details of the reproduction results are presented in Table 1.

Table1
Comparison of The Two Techniques with Pi and Fuzzy Logic Controllers.

| Performance system | | Harmonic orders | | | | | | | | | | PF | Time | V DC |
Without filter		3th	5th	7th	9th	11th	13th	15th	17th	19th	THD %			
With filter	PI	0.92	2.90	1.25	0.39	2.38	2.18	0.50	0.92	0.75	7.72	0.91	0.05	*weak*
(P-Q theory)	FLC	0.44	0.95	1.02	0.11	1.06	0.90	0.04	1.01	0.76	4.20	0.98	0.02	*very good*
With filter (SRF theory)	PI	0.04	1.01	0.90	0.03	0.93	0.81	0.03	0.84	0.70	3.33	0.94	0.05	*good*
	FLC	0.13	0.03	0.23	0.03	0.51	0.44	0.03	0.50	0.40	1.17	0.99	0.01	*excellent*
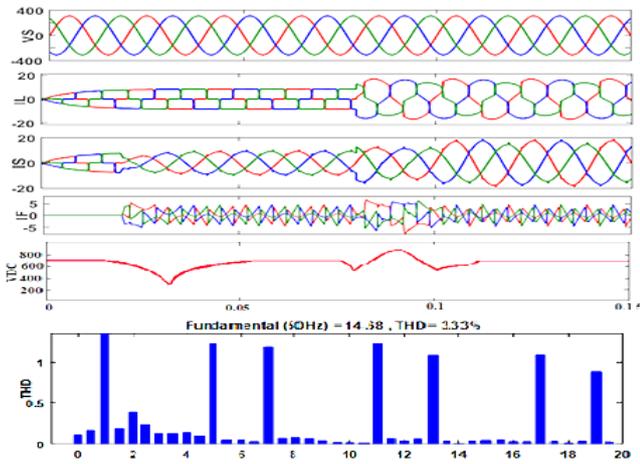
Figure 10: The simulated results based on SRF theory with PI controller.
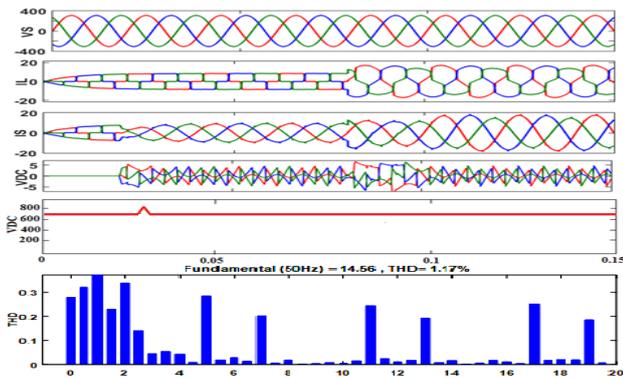
Figure 11: The simulated results based on SRF theory with fuzzy logic controller

V. CONCLUSION

In this study, two control techniques were developed and verified with a three-phase-three-wire shunt hybrid power filter. Despite the two methods with Fuzzy logic controller being competent to recompense the current harmonics in the 3-stage-3-wire system, the overall execution of the SRF theory with Fuzzy logic controller was better compared to the p-q theory with Fuzzy logic controller in terms of THD, time response and constant VDC

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