BEST: International Journal of Management Information Technology and Engineering (BEST: IJMITE)
ISSN (P): 2348–0513, ISSN (E): 2454–471X
Vol. 9, Issue 2, Dec 2021, 89–102

ENHANCEMENT OF POWER QUALITY USING SHUNT ACTIVE POWER FILTER

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ABSTRACT

This paper represents the technique for enhancement of power quality using Shunt Active Power Filter (SAPF) at load side of utility grid. The major objective of this paper is to introduce a suitable firing pulse generation method to obtain best harmonic compensation technique of shunt active power filter. Due to increasing use nonlinear load, harmonics at the load side of utility grid increased which cause harmonic losses. Proposed method of harmonic compensation using SAPF provides compensation current to the load so that source power factor can be maintained to unity. To achieve this purpose, hysteresis current control technique is used to obtain gate pulses to control voltage source inverter (VSI). The performance has been verified for nonlinear load using MATLAB/SIMULINK platform.

KEYWORDS: Power Quality, Instantaneous Reactive Power Theory, P–Q Theory, Shunt Active Power Filter, Hysteresis Current Control, Nonlinear Load, Harmonics

INTRODUCTION

In today's power distribution system, improving power quality is an important research area. This is due to the losses that it involves, which can be mitigated by a few methods. Because of the introduction semi – conductor devices and rapid advancement of power electronics technology, the use of non – linear loads have expanded so it is demanding the technology for implementation of power quality control.

From the past 20 years, use of passive and linear loads with smaller proportion of non – linear loads are increased in utility. With the increasing use of it, harmonics with poor input power factor cause adverse effect in the power system are also increased. Harmonics are a type of voltage and current distortion caused by drawing non – sinusoidal currents from ac mains [1], having a number of adverse effects on distribution system equipment and consumers, which cause a variety of problems, including excessive power loss in the distribution network as well as overhead and underground cables, transformers and rotating electric machines, electromagnetic interference in communication systems, operation of power protection device, overvoltage and shunt capacitor, error of measurement instrument and electrical and electronic equipment failures [2].

In distributed power systems and industries, guidelines for harmonics and reactive power regulation are hot topics so that are adopted increasingly. Power management has become smarter, more flexible, and efficient as a result of the widespread usage of power electronic products. However, due to the injection of current and voltage harmonics, they are causing power pollution. In integrated power systems, harmonic pollution causes problems. Researchers and engineers have begun to work on implementing harmonic controls using IEEE (Institute of Electrical and Electronics Engineer) 519-1992 principles. Customers will be required to pay soon to get facility of high-performance, high-efficiency, energy-saving, reliable and compact power electronics technologies. The continuous efforts of researchers and power electronics engineers will make possible to absorb increasing cost of loads which cause harmonic pollution.

SAPFs (Shunt Active Power Filter) are commonly utilized in the power system to adjust reactive power and current harmonics. They are also operated as a static VAR generator to improve and stabilize the voltage profile, compensates current harmonics by injecting current that is complimentary to the current produced by the non-linear load. Because of its easy construction and robustness, SAPFs are widely employed.

The main focus of this investigation has been on configuration compactness, control simplicity, and component rating reduction, all of which have resulted in overall cost savings. Based on these factors, a variety of power quality mitigator configurations have been designed to provide a detailed exposure to the design engineer in selecting a suitable configuration for a specific application within the restrictions of economy and desired performance.

Figure 1 explain block diagram of SAPF. The reference current consists of the harmonic components of the load current which the APF have to supply. This reference current is fed to a controller and switching signal is generated using PWM (Pulse Width Modulation) technique using Hysteresis Current Controller method to switch the IGBTs of the VSI in such a way that the SAPF will indeed produce the harmonic current required by the load [3]. To maintain a constant DC link voltage and effective compensation of harmonic current, a PI controller is used in the DC-link voltage control loop.

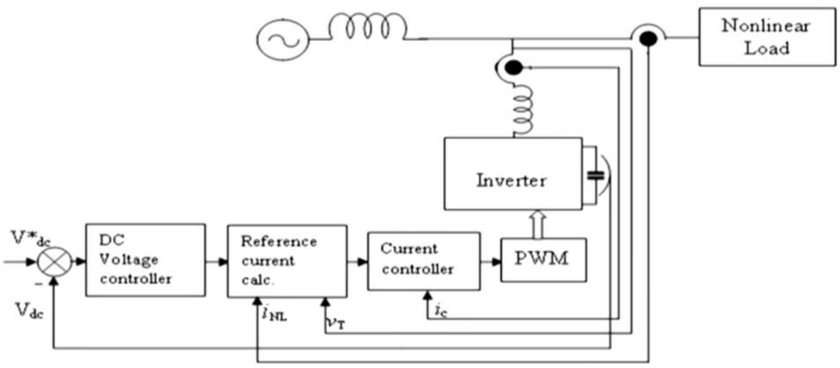


Figure 1: Block Diagram of SAPF.

The DC-link capacitor voltage, V_{dc} is compared with a reference DC voltage, V^*_{dc}. The error, $V^*_{dc} - V_{dc}$ is served as the input to the PI controller. With this, we can eliminate steady state error in the reference current signal tracking is eliminated. SAPF consists of two circuits :

- **Control Circuit**This circuit continually monitors the variation of harmonic current to identify the instantaneous reference compensation current. After identification, it regulates the power circuit to accurately synthesize the appropriate harmonic current. Efficiency of harmonic current compensation is mostly determined by harmonic extraction and current control technique [1].
- **Power Circuit**Main function of power circuit is to generate required compensating current. A PWM based VSI and a DC link capacitor are used to store energy in addition to maintain the DC voltage constant.

DESIGN OF CONTROL CIRCUIT

Before connecting SAPF at PCC, current flow in the power system can be written as :

$$i_s = i_L \; and \; i_L = i_{1L} + i_H \quad (1)$$

When SAPF is connected at PCC, eq. (1) can be written as following :

$$i_L = i_{1L} + i_H - i_C + i_{dc} \quad (2)$$

Where, i_s = Supply current, i_L = Load current, i_{1L} = Fundamental component of load current, i_H = Harmonic component of load current, i_C = Compensating current produced by SAPF (same magnitude as i_H but 180° phase shifted), i_{dc} = DC link current (exploited by SAPF to maintain V_{dc} constant)

The voltage across the DC link capacitor determines the harmonic compensating current. The compensation current generated by SAPF will be exactly similar to the harmonic current drawn by the non – linear load (i.e.$i_H = i_C$) when the voltage across the DC link capacitor is maintained to its predetermined level.

Now, by putting the value of i_H in eq. (2), we get,

$$i_s = i_{1L} + i_{dc} \quad (3)$$

A. Harmonic Extraction

The harmonic extraction is the technique of generating reference current from a distorted waveform. P–Q theory (IRP theory), d–q theory, PI controller, adaptive controller and many more theories have been created. Because of their accuracy, robustness and ease of computation, P–Q theory and d–q theory has been considered in more than 60% of research works.

In this research paper, we have considered P–Q theory (IRP theory) for the purpose of harmonic current extraction. Block diagram of IRP theory is shown in Fig. 2. Basically, IRP theory is time – domain analysis and based on Clark transformation.

We have considered 3 – Ø, 3 – wire system. So, zero sequence component is absent. The source voltage and source current of a – b – c coordinate can be transformed in to $\alpha - \beta - 0$ coordinates using eq. (4) and (5) respectively:

$$\begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} . \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (4)$$

and, $$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} . \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (5)$$

In the $\alpha - \beta$ coordinate, the complex sum of P and Q can be represented by,

$$S = P + jQ \quad (6)$$

$$= v_{\alpha\beta} i^*_{\alpha\beta} \quad (7)$$

$$= (v_\alpha - jv_\beta)\,(i_\alpha + ji_\beta) \quad (8)$$

$$= (v_\alpha i_\alpha + v_\beta i_\beta) + j(v_\alpha i_\beta - v_\beta i_\alpha) \quad (9)$$

Where, $*$ is the complex conjugate. Instantaneous P and Q components can be written in matrix form using eq. (10) as follows :

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (10)$$

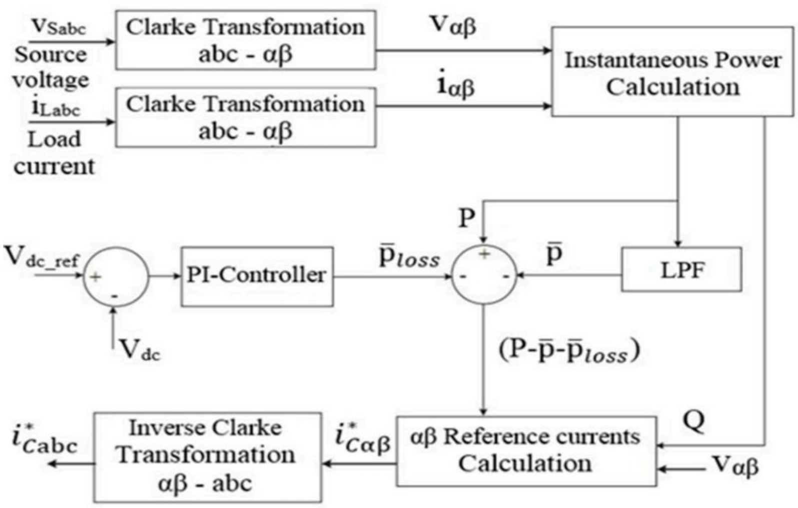


Figure 2: Block Diagram of Active and Reactive Power Theory.

In the presence of non – linear load, instantaneous P and Q components are divided into their AC and DC components, as shown in eq. (11) and (12), respectively. A high order LPF (low pass filter) is used to extract the DC component of the instantaneous real power, which is the only power that should be delivered by the three-phase AC source, as illustrated in figure 2 [4].

$$P = \bar{p} + \tilde{p} \quad (11)$$

$$Q = \bar{q} + \tilde{q} \quad (12)$$

Where, $\bar{p} =$ dc part of instantaneous P corresponds to power transmitted from source to load, $\tilde{p} =$ ac part of instantaneous P corresponds to energy exchanged between the source to load, $\bar{q} =$ fundamental component of Q, corresponds to energy circulation between load phases, $\tilde{q} =$ harmonic component of Q, responsible for energy circulation between load phases

The p and Q are required to generate the harmonic reference currents. The SAPF uses a small amount of real power ($\bar{p}_{loss}$) from the AC mains or an external power supply to recompose the switching losses of VSI and to maintain the DC link voltage at the desired level. As a result, $\tilde{p}$ is calculated using eq. (13).

$$\tilde{p} = P - \bar{p} + \bar{p}_{loss} \quad (13)$$

As a result, the compensating reference currents in $\alpha - \beta$ coordinates are calculated using eq. (14) and then converted in to a – b – c coordinates using an inverse Clark transformation, as indicated in eq. (15).

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} . \begin{bmatrix} \tilde{p} \\ Q \end{bmatrix} \quad (14)$$

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} . \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} \quad (15)$$

Current Control Technique

Several control techniques have been used in order to generate the control pulses responsible for defining the operation of switching states in designing SAPF. Among these methods, the hysteresis band current method is used in this work to generate the switching signals of VSI. This control method is widely employed among the various current control approaches due to its simplicity, quick response, precision and its unconditioned stability.

In this method, current is kept in a predefined band width, or the HB (Hysteresis Band), around the reference current as shown in figure 3. To keep the real current within the HB, the actual current is compared with the reference current, and the VSI switches are turned on and off in line with the error.

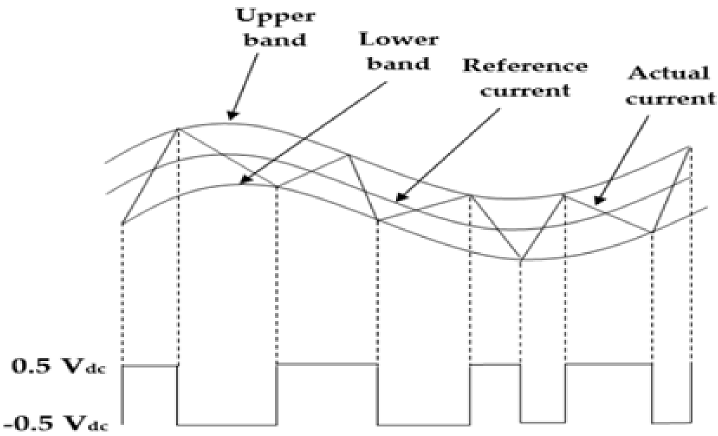


Figure 3: Hysteresis Current Control Technique.

The VSI output is turned off when the current error reaches the upper limit of the HB, or vice versa. When the output current needs to grow, the DC voltage typically goes to its highest value, and when the current needs to decrease, it goes to its minimum value [5].

PI Controller

By using DC link voltage regulation, one of the most important control phases of the SAPF is to maintain a constant DC voltage at the DC side of the VSI. These capacitors are used to store energy in filters that VSI use to generate harmonic reference currents. Theoretically, when power exchange between filter and the AC grid is zero, capacitor voltage should remain constant. The VSI consumes a small percentage of real power for its switching operation, as previously stated [6].

PI controller eliminates the steady state error in reference current signal tracking. Inner current control loop and outer voltage control loop of the PI controller of DC voltage are shown in figure 4. The gains $G_{PI}(s)$ and $G_{VSI}(s)$ represent transfer function of the PI controller and VSI, respectively.

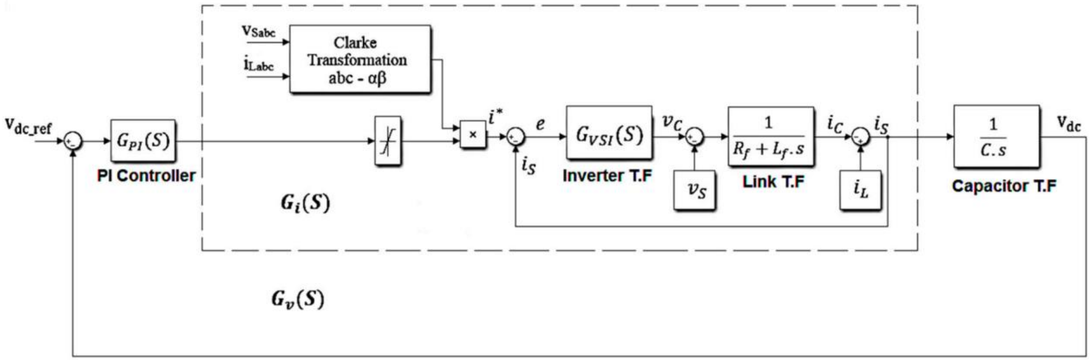


Figure 4: Inner Current Control Loop and Outer Voltage Control Loop.

The magnitudes of (i_{Sa}, i_{Sb}, i_{Sc}) are nearly equivalent to the magnitudes of $(i_{Sa}^*, i_{Sb}^*, i_{Sc}^*)$ when the VSI switches are operated at a high frequency. As a result, the current controller transfer function in close loop can be considered to be unity.

$$G_i(s) = \frac{i_{Sabc}}{i_{abc}^*} \approx 1 \tag{16}$$

Where, $i_{Sabc} = 3 - Ø$ source current, $i_{abc}^* = 3 - Ø$ reference current

The step response of the closed loop block diagram shown in figure 5 can be used to calculate the proportional gain (K_p) and integral gain (K_i) of the PI controller. As a result, the transfer function of eq. (17) is used to derive controlled closed loop DC voltage.

$$\frac{v_{dc}}{v_{dc}^*} = \frac{\frac{K_pK_i}{C}}{s^2 + \frac{K_p}{C}.s + \frac{K_pK_i}{C}} \tag{17}$$

Where, v_{dc} = DC voltage of capacitor, v_{dc}^* = DC reference voltage, C = Capacitor

Because DC voltage of closed loop control transfer function is in the form of 2nd order, the K_p and K_i can be calculated by equating open loop transfer function of eq. (17) with the general form of 2nd order transfer function, given by eq. (18).

$$H(s) = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \tag{18}$$

Where, ω_n = damping natural frequency, ξ = damping factor

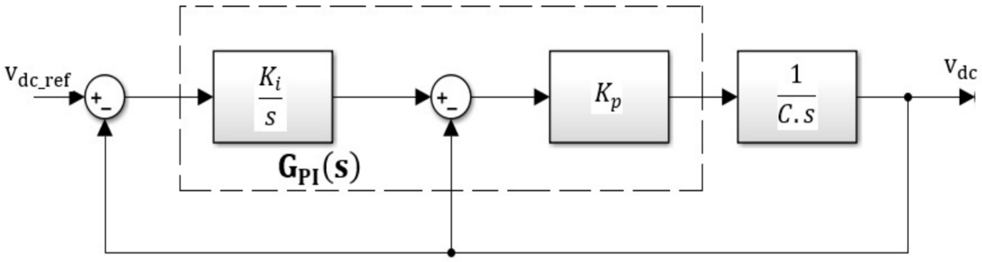


Figure 3: Close Loop for DC Link Voltage Control.

By equating eq (17) and (18), we get $\frac{K_p}{C} = 2\xi\omega_n$ and $\frac{K_pK_i}{C} = \omega_n^2$. Hence, $K_p = 2\xi\omega_n C$ and $K_i = \frac{\omega_n}{2\xi}$

Design of Power Circuit

Before compensation, harmonic current of the source current is given by eq. (19) [7].

$$I_h = \sqrt{I_{lrms}^2 - I_{l1}^2} \tag{19}$$

Where, I_h = RMS value of harmonic current, I_{lrms} = RMS value of line current, I_{l1} = RMS value of source current.

Thus, the current rating of SAPF should be capable of handling current at least equal to I_h.

DC bus voltage, $V_{DC} = 2\sqrt{\frac{2}{3}}V_{ll}$ (20)

Current of SAPF, $I_d = \frac{kVA\ rating\ of\ SAPF}{DC\ link\ voltage 2\omega V_{DCripple}}$ (21)

DC link capacitor, $C_{DC} = \frac{I_d}{2\omega V_{DCripple}}$ (22)

Now, selection of AC inductor is dependent up on current ripple, I_{crp} and we consider it as 10 % of I_d.

Inductor, $L_f = \frac{\sqrt{3}V_{DC}}{12 f_s I_{crp}}$ (23)

We have to select power electronic switches as per appropriate voltage and current ratings.

Voltage rating of switch, $V_{sw} = V_{DC} + V_d$ (24)

Current rating of switch, $I_{sw} = I_{crp} + I_p$ (25)

Where, V_d = spike in capacitance voltage during transient condition, I_p = peak current of SAPF

Matlab Implementation without Filter

Figure 6 and figure 7 show the circuit diagram of source connected to fully controlled rectifier with RL load and its MATLAB implementation respectively. Parameters of circuit implementation are listed in Table 1.

Table 1: System Parameter without Applying Filter

System Parameter	Value
Supply Voltage, V_s	$220*\sqrt{2}$ volts
Supply Frequency, f	50 Hz
Source Impedance, R_s, L_s	0.1 Ω, 0.01 mH
Smoothening Inductor, L_{smooth}	1 mH
Load Impedance, R, L	40 Ω, 10 mH

Here, smoothing inductor is used to provide delay in output current. The reactance provided by this is necessary in order to smooth the direct current wave shape, reduce losses and improve system performance. Apart from this, it reduces magnitude of ripple current in DC system.

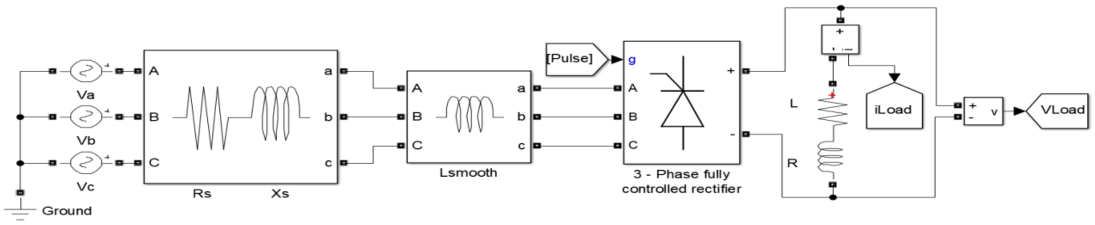


Figure 4: Circuit Diagram of Harmonic and Reactive Power Generated Load.

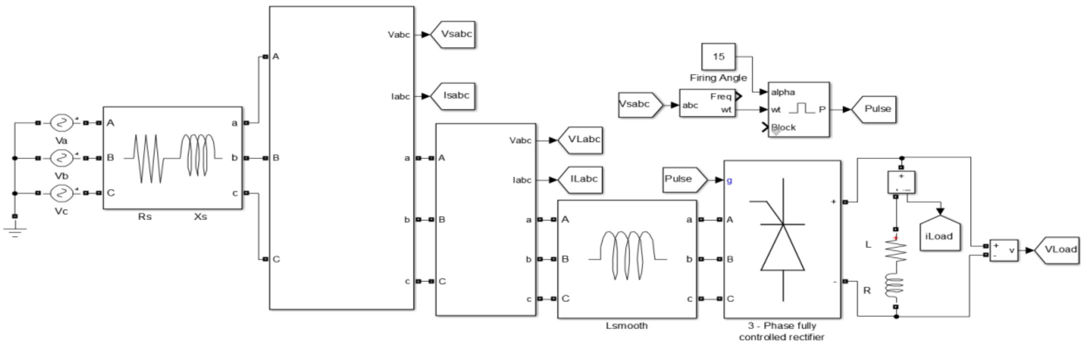


Figure 5: MATLAB Implementation of Harmonic and Reactive Power Generated Load.

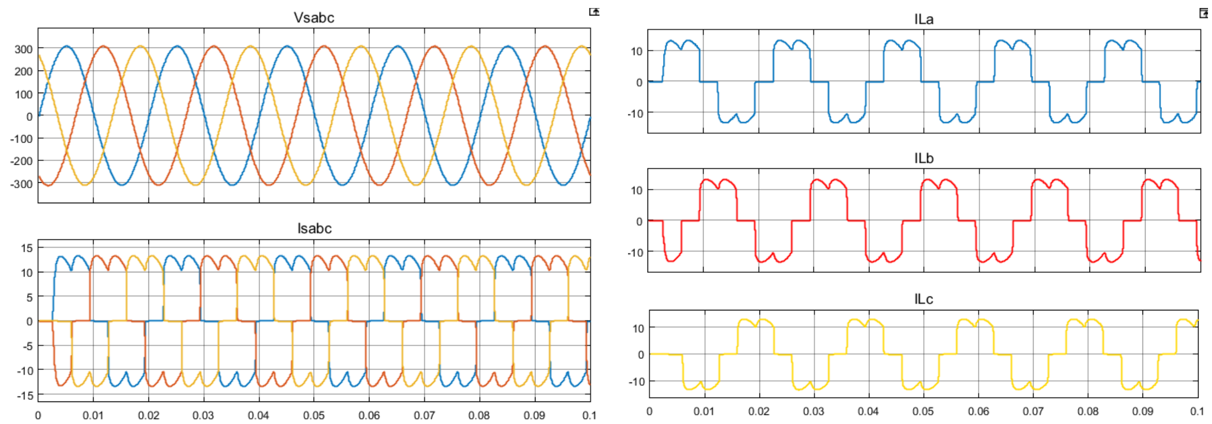


Figure 6: Waveform of V_sabc, I_sabc and I_Labc at alpha = 15.

Figure 8 shows waveform of source voltage, V_{sabc} and source current, I_{sabc}. In figure 9 FFT analysis of I_{sabc} is displayed. In the absence of filter, $I_{sabc} = I_{Labc}$ (figure 8 shows waveform of I_{Labc}). So, %THD in current waveform remains same.

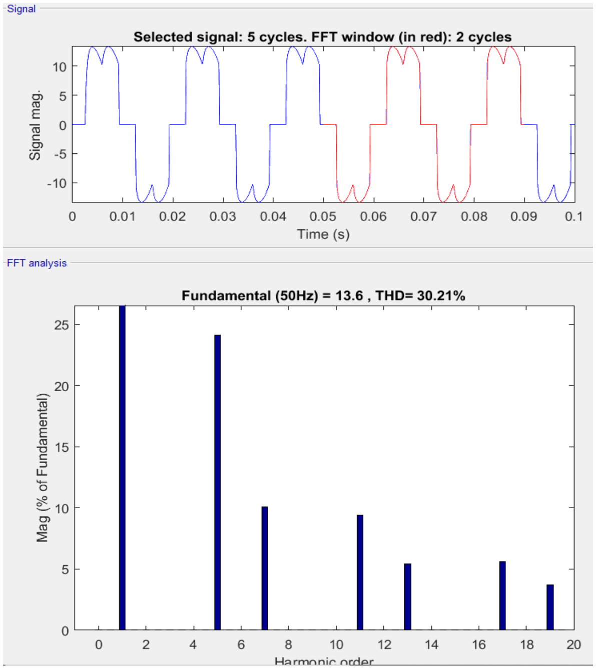


Figure 7: THD Analysis of I_Sabcat Alpha = 15° without Filter.

Table 2 shows % THD of source current, I_{sabc} and power factor at various firing angle. Load consumes active power of amount 7.1 kW and reactive power of 4 kVAR.

Table 2: Comparison of %THD at Various Values of Alpha without Filter

Firing Angle (α)	%THD	Power Factor
15°	30.21	0.9971
30°	32.60	0.9862
45°	37.36	0.9643
60°	48.94	0.9557

Design of Sapf

Implementation of a SAPF based fully controlled rectifier with RL load in MATLAB environment is shown in figure 10. % THD of the same circuit without connecting any filter component is listed in table 2. The design of SAPF is dependent upon reactive power requirement of load and reduction in % THD. System parameters for SAPF based on design are listed in table 3.

Table 3: System Parameters of SAPF

System Parameter	Value
Supply Voltage, V_s	$220*\sqrt{2}V$
Supply Frequency, f	50 Hz
Source Impedance, R_s, L_s	0.1 Ω, 0.01 mH
Smoothening Inductor, L_{smooth}	1 mH
Load Impedance, R, L	40 Ω, 10 mH
Capacitor,C_{dc}	4700 μF
Filter Impedance,R_f, L_f	0.1 Ω, 1 mH
Gain of PI controller, K_p, K_i	1.05, 0.01
Reference DC link voltage, V_{ref}	600 V

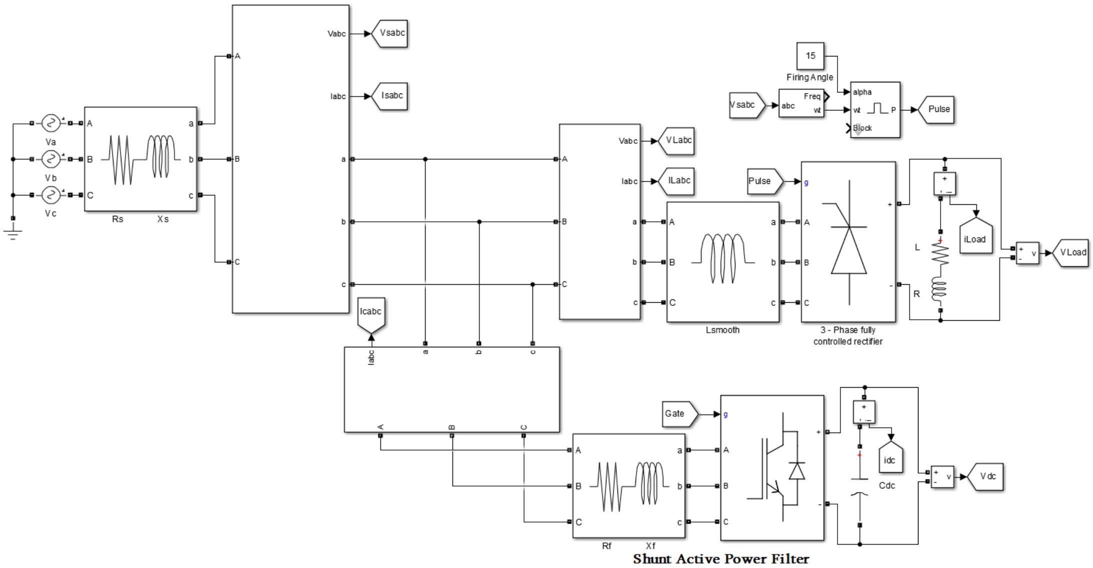


Figure 8: Circuit Diagram of Harmonic and Reactive Power Generated Load with SAPF.

Figure 11 shows control circuit for SAPF. Block diagram of the same was previously explained in figure 1. Harmonic extraction block and Current control technique using Hysteresis current controller and PI controller explained previously and its MATLAB implementation is shown in figure 12(a) and 12(b) respectively.

Figure 13(a) and 13(b) shows waveform of Clark's transformation of the source voltage and load current. Reference compensating current waveform in $\alpha\beta$ frame and its inverse Clark's transformed waveform are shown in figure 14(a) and 14(b).

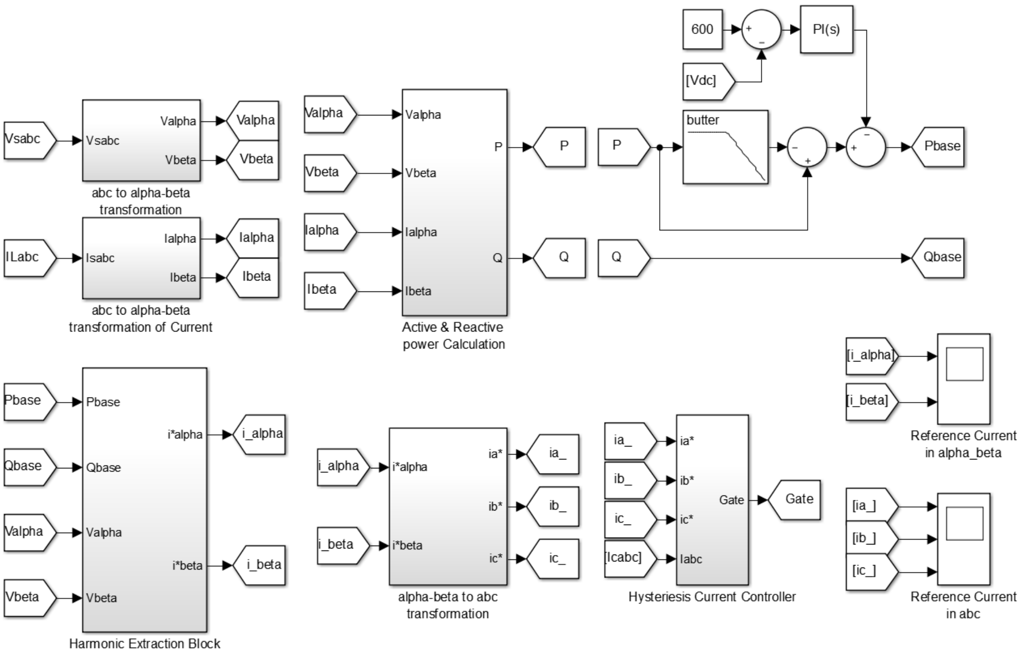
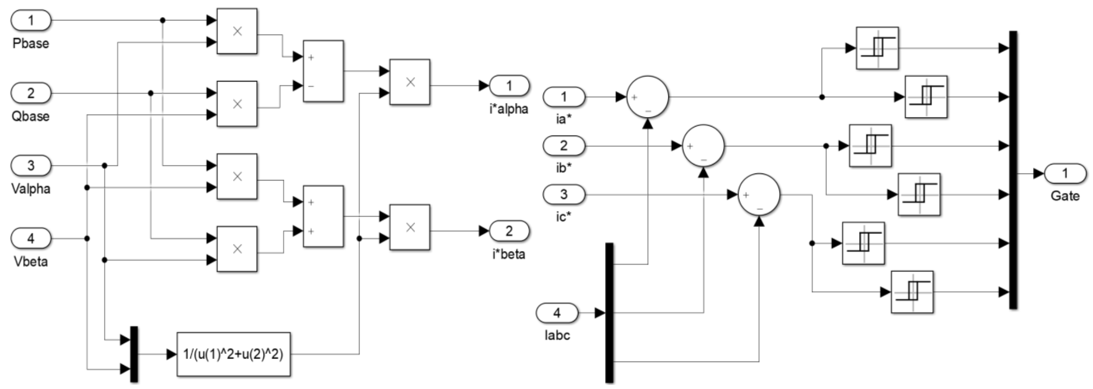
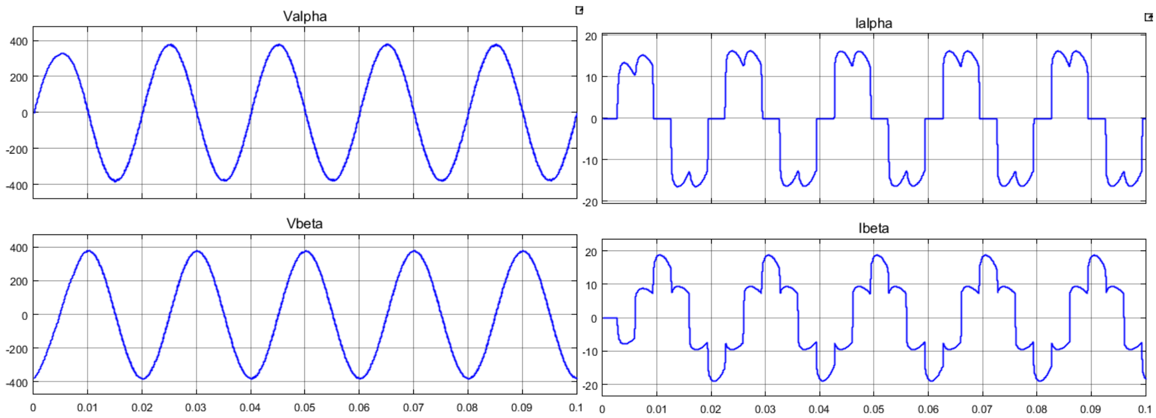


Figure 9: Control Circuit of SAPF.



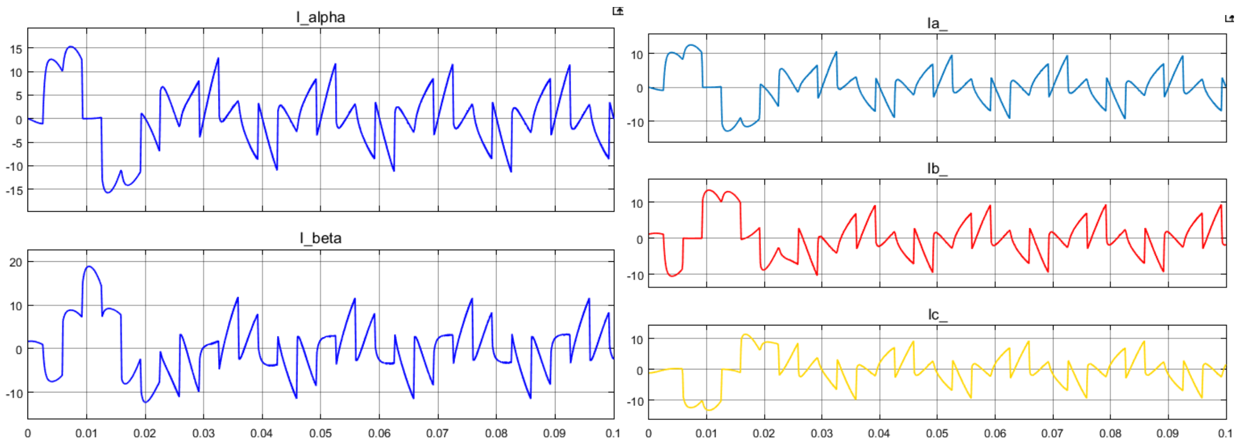
(a) (b)

Figure 10. (a) Harmonic Extraction Block, (b) Hysteresis Current Controller.



(a) (b)

Figure 11. (a): Clark Transformation of Voltage :V_α,V_β, (b) Clark Transformation of Current : I_α,I_β.



(a) (b)

Figure 12. (a): Compensation Current :I_α^*,I_β^*, (b) Reference Current : I_a^*,I_(b,)^*,I_c^* at Alpha = 15°.

Waveform of V_{sabc}, I_{sabc} *and* I_{Labc} are shown in figure. 15 with SAPF.

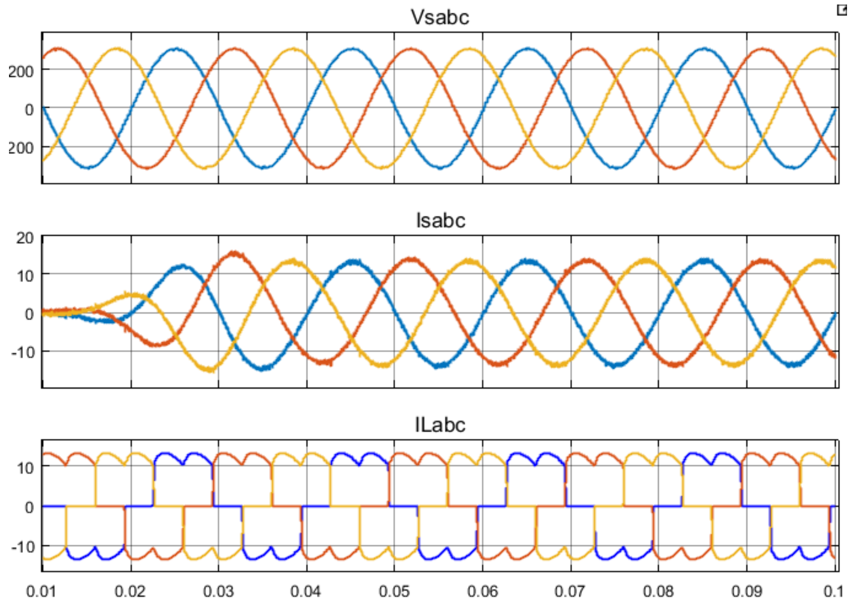


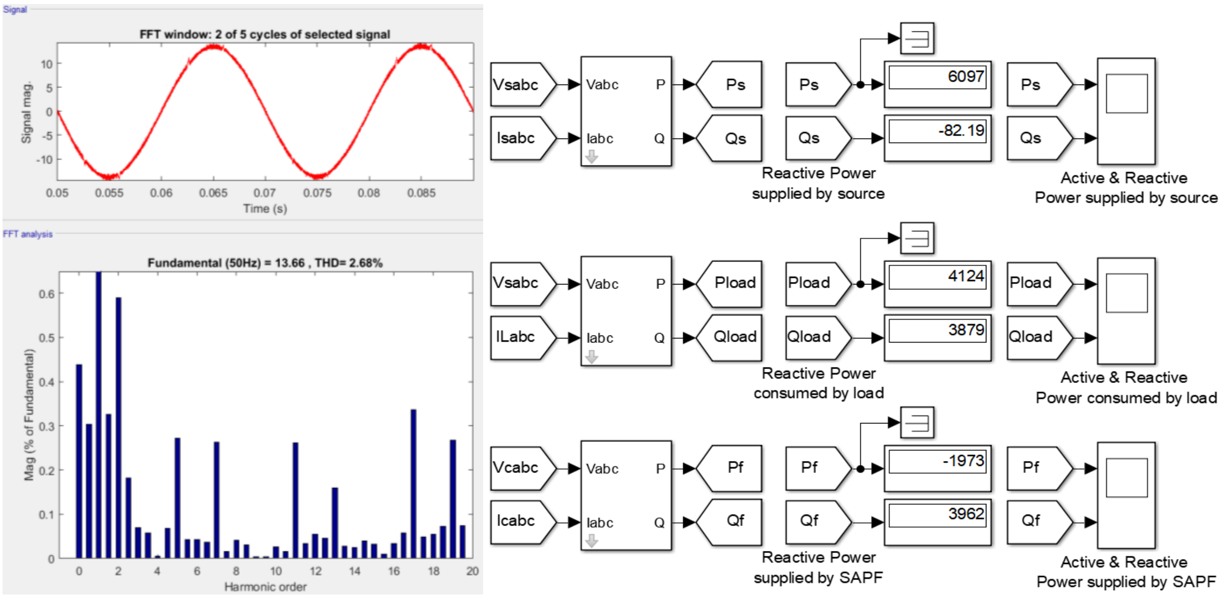
Figure 13: Waveform of V_sabc,I_sabc and I_Labc with SAPF at Alpha = 15.

Figure 16 and figure 17 shows THD analysis and waveform of load current with SAPF at firing angle of 15°.

Figure 18 indicates Active and Reactive power calculation in presence of SAPF. Here, Reactive power generated by SAPF is same as addition of Reactive power consumes by Load and Source.

Hence, we can say that reactive power is compensated and harmonic gets reduced (compare % THD of source current without filter and with SAPF at same alpha).

Table 4 shows % THD of source current, I_{sabc} and power factor at various firing angle.



(a) **(b)**

Figure 14.(a): THD Analysis of I_sabc at Alpha = 15° with SAPF,(b) Active and Reactive Power of Source, Load and SAPF.

Table 4: Comparison of %THD at Various values of Alpha without Filter

Firing Angle (α)	%THD	Power Factor
15°	2.68	0.9993
30°	5.45	0.9994
45°	5.24	0.9999
60°	7.17	1.0000

CONCLUSIONS

Power quality studies try to keep the current and voltage of a 3 – Ø power system as pure sinusoidal. Power supply should have constant value of RMS magnitude with constant frequency and phase shift of 120° between the adjacent phases. Due to the increasing use of non – linear load in industries, higher rating of motors, increasing use of power semi – conductor devices for conversion of voltage type (Rectifier : AC to DC converter, Inverter : DC to AC converter, Chopper : DC to DC converter, Voltage regulator : AC to AC converter, etc.) and voltage levels (Buck converter, Boost converter, Buck – Boost converter, etc.), voltage and/or current distortion occur and demand of reactive power increases. Due to effect of this, harmonics are introduced and power factor become poor in the system which cause deterioration in power quality. MATLAB/Simulink based model is prepared. Before connecting harmonic and reactive power compensation circuit at PCC, %THD for firing angle of 15°, 30°, 45° and 60° are 30.21 %, 32.60 %, 37.36 % and 48.94 % respectively.Once we connect SAPF at PCC, % THD for the firing angle of the same sequence can be reduced up to 2.68 %, 5.45 %, 5.24 % and 7.17 % respectively.

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