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Simulation Modelling of Shunt Active Power Filter to Improve the Power Quality Using I-Cosψ Control Algorithm

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Abstract : The primary demand of the modern-day energy networks is to cope up with the power quality demands of the power grid facilities, this can be achieved by designing the effective power filters which reduces voltage and current harmonics. The following article is a comparative study on Instantaneous quadrature power theory and proposed I-Cos ψ control algorithm to derive the compensation currents of shunt active power filter (SAPF) which enhance the power condition of the system. In order to monitor the DC-link voltage a proportional–integral (PI) controller is preferred. By adopting MATLAB/Simulink platform the SAPF is designed for stable non-linear loads. The triggering pulses are generated by hysteresis current control technique to regulate the turn on and off of the voltage source inverter (VSI) switches. The simulation results demonstrate that the total harmonic distortion can be minimized relatively to a lower value by implementing the proposed current control algorithm.

***Keywords*:** Shunt active power filter (SAPF), Instantaneous quadrature power theory (P-Q Theory), I-Cos ψ control algorithm, proportional-Integral (P-I) controller, Mitigating the harmonics, Hysteresis current control technique, Point of common coupling (PCC), Total harmonic distortion (THD).

1. INTRODUCTION

The private and industrialised appliance of all the service companies across the globe [1-2] uses balanced or unbalanced non-linear electric gadgets which dependence on power electronic switches for its operation. The contamination of electrical energy distribution network is worst at employment stage due to non-linear loads like, variable speed and variable frequency drives, voltage controllers, electronic gadgets such as computers, printers, televisions, servers and telecom systems all of the which uses SMPS power conversion technologies. This results in the energy quality issues, e.g., harmonic overrefinement, voltage instability, unbalanced current, hissing noise [3]. The power loss in low-voltage distribution systems is due to harmonic distortion, poor power factor, electric heat dissipation, insulation hazards, tampering problems in communication systems and electric power system failure [4,5]. Hence, mitigation of energy quality problems has turned into a matter of discussion for the producers as well the consumers [6]. With the intention to pertain the direct inoculation of harmonic currents in to the energy grid, the Institute of Electrical and Electronics Engineering-Standards Association("IEEE-SA") superscribe that the total harmonic distortion (THD) of an electric power system, the IEEE criterion should be less than 5% [7,9]. The literature review reveals the most adequate technology to mitigate harmonic distortions is power filters. Consistently, to enhance the power condition at the power stations, series and shunt passive power filters are used. Since, non-linear loads in industrial firms are connected to a rigid energy system, it is demanding to model a passive filter to mitigate current harmonic disfigure. Above all, the passive filter has its innate flaw like its extensive size, reverberance with load impedance or supply impedance, unpredictability and inflexible [10]. To prevail the typical filter's drawbacks active power filters (APFs) which includes voltage source inverters (VSIs) are put forward as a substitute. APFs owns several features, including a rapid dynamic response, flexibility and predominant filtering accuracy, qualifying it as a fitting solution for power quality problems [11]. The current harmonics and quadrature power sensing methods, along with the compensation control algorithm defines the harmonic reduction competence capability of the shunt active power filter [12-14]. Among the compensation current control methods, I-Cos ψ algorithm is rarely implemented. For the extraction of fundamental and harmonic components many researchers have given out various techniques, for instance determining the reference

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compensation current and regulating the voltage across the DC-link capacitor. In order to restore the distorted currents at the non-linear loads linked at the point of common coupling (PCC), a reference current is estimated using current control algorithm. Gary W. et al. [15] recommended a methodology to cut back the harmonic current in the unstable voltage conditions. A system had been contemplated to lessen the inherent harmonics impact on the rectifier transformer by eliminating the current distortion along the supply side. [16-19].

The literature review presents a firm groundwork by allowing separate study on the shunt active power filter's modelling and regulation. Many researchers have ventured on boosting the energy quality in the balanced system. Yet, this paper describes the modelling and supervising shunt active power filter's (SAPF) using proportional–integral (PI) controller in detail. For reference current extraction by adopting both P-Q theory and I-Cos ψ control algorithm is designed using MATLAB/Simulink. By considering stable non-linear loads in a 3-ϕ, 3-wire network, harmonic current compensation technique is implemented.

2. METHODOLOGY

2.1 Performance and Configuration of Shunt Active Power Filter: An Overview

The composition of two circuitry: the control circuitry and the power circuitry which involves shunt active power filter shown in Figure 1[20,21]. The power circuitry is liable for generating the appropriate current compensation and it has a voltage source inverter (VSI) built on pulse width modulation (PWM) technique and1 a DC-link capacitor that stores energy, which also regulates and controls the DC voltage. Furthermore, to determine the instantaneous reference currents, the variation in the harmonic current is continuously tracked by the control circuitry and thereby controlling the power circuitry to incorporate the necessary distorted current. The dependency on the harmonic abstraction and technique to control current for the productivity of the harmonic current compensation will be considered in the later section[22]. The flow of current in the network before connecting the active power filters (APF) at the PCC is as referred in equation (1) [23]:

$$i_S = i_L = i_{1L} + i_H \tag{1}$$

i_S represents supply current, i_L refers to current in load, i_{1L} refers to the primary current element in load and i_H represents the current harmonic element in load.

While the shunt active power filter (SAPF) is equipped near PCC, a pair of supplementary current is present: compensated current produced using SAPF circuit that equals the harmonic current amplitude with a phase shift of 180°; and the current (i_{dc}) that is extracted through SAPF circuit from the supply to keep the potential difference across the capacitor (Vdc) at the set-point. Circulation of current in the electrical network is stated as follows,

$$i_S = i_L = [i_{1L} + i_H] - i_C + i_{dc} \tag{2}$$

i_C refers to the implanted compensation current also i_{dc} denotes current in the capacitor.

Conceptually, the potential difference across the capacitor of the DC-link decides the harmonious compensation current. For the generated compensation currents, i_C to be uniform with the harmonic currents, i_H extracted through nonlinear load, the potential across the DC-link should be managed at a constant range. Since, both the harmonic currents are equal in magnitude but opposite in phase angle they seem to cancel out each other, therefore restoring back the primary waveform with standard frequency, as in equation (3)[23]:

$$i_S = i_{1L} + i_{dc} \tag{3}$$

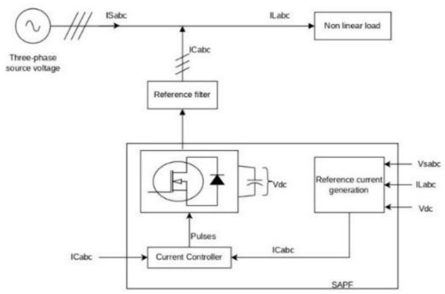

Fig.1 Shunt active power filter arrangement in Three-phase, three-wire system

2.2 Abstracting the Harmonic Currents:

2.2.1 Instantaneous quadrature power theory:

The prime object of this control algorithm is to measure the necessary current harmonics on the basis of the Clarke transformation used in time domine analysis of the instantaneous quadrature power theory, where 0-α-β stationary elements derived from a-b-c stationary reference elements. The following matrix representation shows the supply voltage and current transformation into 0-α-β correspondent [24]. Figure.2 represents the bond graph presentation on instantaneous quadrature power theory. Essentially,

$$\begin{bmatrix} v0 \\ v\alpha \\ v\beta \end{bmatrix} = \sqrt{2}/3 \begin{bmatrix} 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1 & -1/2 & 1/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} . \begin{bmatrix} va \\ vb \\ vc \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} i0 \\ i\alpha \\ i\beta \end{bmatrix} = \sqrt{2}/3 \begin{bmatrix} 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1 & -1/2 & 1/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} . \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} \tag{5}$$

As, v_a, v_b, and v_c are the a-b-c correspondent voltage in 3-ϕ, i_a, i_b, and i_c refers to the a-b-c correspondent current in 3-ϕ, v_0, v_α, and v_β represents the 0-α-β correspondent voltage in 3-ϕ, and i_0, i_α, and i_β are the 0-α-β correspondent current in 3-ϕ.

The zero-sequence component is neglected because as mentioned above, present article handles a 3-ϕ 3-wire network. The real and quadrature powers in the α-β correspondents, is denoted as.

$$\begin{aligned} S = P + j\,Q &= v_{\alpha\beta}\, i_{\alpha\beta}^{*} \\ &= (v_\alpha - j\, v_\beta)\,(i_\alpha + j\, i_\beta) \\ &= (v_\alpha i_\alpha + v_\beta i_\beta) + j\,(v_\alpha i_\beta - v_\beta i_\alpha) \end{aligned} \tag{6}$$

As, S denotes the apparent power, P is the real power, Q refers to quadrature power, and * refers to complex conjugate.

So, the following matrix represents instantaneous quadrature and real electric energy elements [24]:

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} v\alpha & v\beta \\ -v\beta & v\alpha \end{bmatrix} . \begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} \tag{7}$$

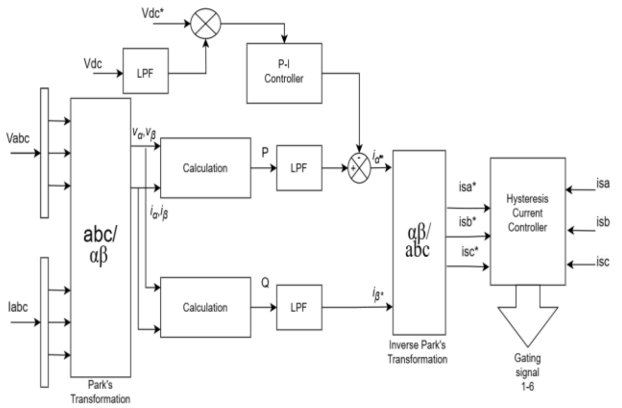

Fig.2 Bond graph of the P-Q theory

As in equation below, the AC and DC parts are decomposed from the instantaneous real and quadrature power when associated with the nonlinear load. The DC segment ($\bar{p}$) corresponds to the essential power component and also represents the energy transmitted to the load from the supply side, AC segment($\tilde{p}$) serves as the energy transaction between the load and the supply side. The high-order low-pass filter is involved in the circuit to extract the DC segment of the active power of the three-phase AC source, can be seen in Figure 2. On relating the instantaneous quadrature power element(Q), which is liable for the power flow among the phases at the load side, $\overline{q}$ and $\tilde{q}$, subsequently, shows the elementary portion and harmonic portion of the quadrature power [21].

$$P = \overline{p} + \tilde{p} \tag{8}$$

$$Q = \overline{q} + \tilde{q} \tag{9}$$

The AC portion ($\tilde{p}$) in real power and the entire quadrature power (Q) is necessary for the generation of the harmonics reference currents. The shunt active power filter preoccupies a slight portion of active power ($\overline{p}_{loss}$) from the 3-ϕ AC supply or from an independent energy source to restore the switching losses of voltage source inverter. Thereby, The AC portion ($\tilde{p}$) of the real power is in expression (10). So, matrix equation (11) shows calculation in the α- β correspondents to the compensation reference current and by using inverse Clarke transformation α-β correspondents are transformed back to the a-b-c correspondents, as shown in matrix equation (12).

$$\tilde{p} = P - \overline{p} + \overline{p}_{loss} \tag{10}$$

$$\begin{bmatrix} i\alpha * \\ i\beta * \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v\alpha & -v\beta \\ v\beta & v\alpha \end{bmatrix} \cdot \begin{bmatrix} \tilde{p} \\ Q \end{bmatrix} \tag{11}$$

$$\begin{bmatrix} ia * \\ ib * \\ ic * \end{bmatrix} = \sqrt{2}/3 \begin{bmatrix} -1/2 & \sqrt{3}/2 & 1/\sqrt{2} \\ 1 & 0 & 1/\sqrt{2} \\ 1/2 & -\sqrt{3}/2 & 1/\sqrt{2} \end{bmatrix} \cdot \begin{bmatrix} i\alpha * \\ i\beta * \\ i0 * \end{bmatrix} \tag{12}$$

2.2.2 I-Cos ψ control algorithm

The abstraction algorithm in deriving the reference currents, that can be accessed down the two categories: frequency dimension analysis and time dimension analysis. Algebraic transformations and circuit analysis is a simple control process in the time domain study. Also, the frequency dimension analysis should have a large memory for processing and is extra complex. The proposed harmonic current abstraction algorithm is a time dimension approach of I-Cos ψ control algorithm, MATLAB/Simulink can be used to assemble the simulation mode. Figure 3. represents the bond graph presentation of I-Cos ψ compensation current control algorithm.

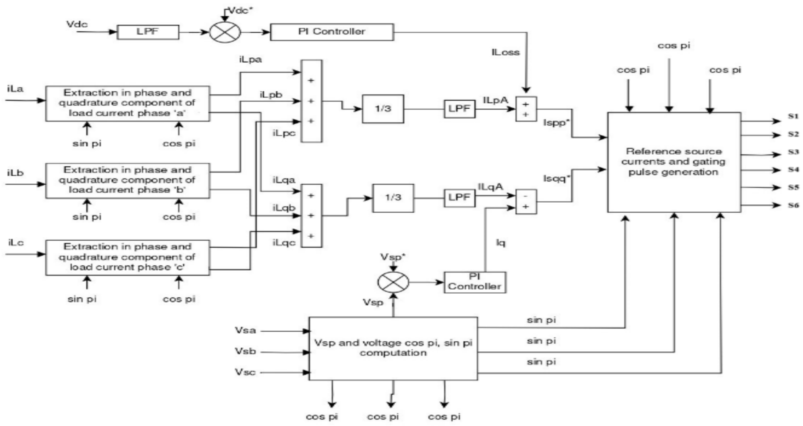

Figure.3 Bond graph of I-Cos ψ algorithm

Deriving the 3-phase supply voltages from the line voltage and

$$\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = 1/3 \begin{bmatrix} 2 & 1 & 0 \\ -1 & 1 & 0 \\ -1 & -2 & 0 \end{bmatrix} \cdot \begin{bmatrix} v_{sab} \\ v_{sbc} \\ 0 \end{bmatrix} \tag{13}$$

the phase amplitude voltage can be calculated using the 3-phase supply voltages as in equation 13 and 14.

$$V_{sp} = \sqrt{\frac{2}{3}(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)} \tag{14}$$

Where, v_{sa}, v_{sb}, v_{sc} are the phase voltages, v_{sab}, v_{sbc} are the line voltages, V_{sp} is the phase amplitude voltage.

On dividing equation 13 and 14 we get to derive the in-phase unit templates and quadrature unit templates are obtained by phase leading the each in-phase unit template by 90 degrees, as explained below.

$$u_{sa}=v_{sa}/V_{sp}\ ,\ u_{sb}=v_{sb}/V_{sp}\ ,\ u_{sc}=v_{sc}/V_{sp}$$

$$u_{sa}=\cos\Phi_{pa}\ ,\ u_{sb}=\cos\Phi_{pb}\ ,\ u_{sc}=\cos\Phi_{pc} \tag{15}$$

$$u_{saq}=(-u_{sb}+u_{sc})/\sqrt{3}\ ,\ u_{sbq}=(3u_{sa}+u_{sb}-u_{sc})/2\sqrt{3}\ ,$$

$$u_{scq}=(-3u_{sa}+2u_{sb}-u_{sc})/\ 2\sqrt{3}$$

$$u_{saq}=\sin\Phi_{qa}\ ,\ u_{sbq}=\sin\Phi_{qb}\ ,\ u_{scq}=\sin\Phi_{qc} \tag{16}$$

where, u_{sa} , u_{sb} , u_{sc} are the in-phase unit template and u_{saq} , u_{sbq} , u_{scq} are the quadrature unit template.

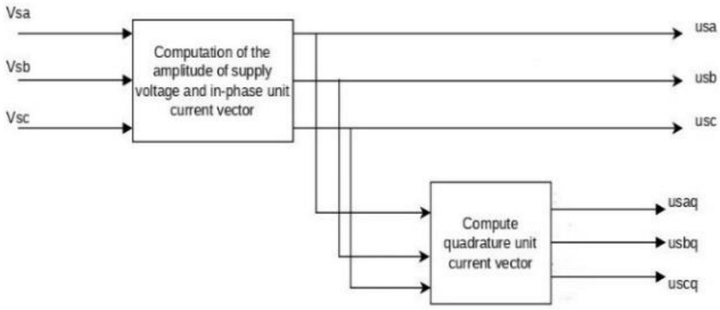

Fig.4 Unit Template based algorithm

The magnitude of real current component (I_{Lpa}) and quadrature current component (I_{Lqa}) of phase a is extracted from the load current (I_{La}) at the zero crossing of the in-phase unit template (cosΦ) and quadrature-phase unit template (sinΦ) of 3-Φ PCC voltage. A zero-crossing detector and sample and hold logic are included to abstract the in-phase and the quadrature load currents of phase a, likewise magnitude of real and quadrature elements of the other 2-Φ currents are determined.

To provide load balancing, the magnitude of real power (I_{LpA}) and quadrature power (I_{LqA}) elements of load currents is obtained by taking the average of the magnitude of real and quadrature elements of each 3-Φ currents.

$$I_{LpA}=(I_{Lpa}+I_{Lpb}+I_{Lpc})/3,\ I_{LqA}=(I_{Lqa}+I_{Lqb}+I_{Lqc})/3 \tag{17}$$

The magnitude of the fundamental real power (I_{spp}^*) and quadrature power (I_{sqq}^*) elements of reference supply current

$$I_{spp}^*=I_{Loss}+I_{LpA},\ I_{sqq}^*=I_q-I_{LqA} \tag{18}$$

Estimation of real power(i_{sp}^*) and quadrature power(i_{sq}^*) elements of reference supply current

$$i_{sap}^*=I_{spp}^*\cos\Phi_{pa},\ i_{sbp}^*=I_{spp}^*\cos\Phi_{pb},\ i_{scp}^*=I_{spp}^*\cos\Phi_{pc} \tag{19}$$

$$i_{saq}^*=I_{spq}^*\sin\Phi_{qa},\ i_{sbq}^*=I_{spq}^*\sin\Phi_{qb},\ i_{scq}^*=I_{spq}^*\sin\Phi_{qc} \tag{20}$$

Estimation of reference harmonic currents

$$i_a^*=i_{sap}^*+i_{saq}^*,\ i_b^*=i_{sbp}^*+i_{sbq}^*,\ i_c^*=i_{scp}^*+i_{scq}^* \tag{21}$$

2.3 Techniques to Control the Current:

For the effective performance of the filter switching states by defining the control pulses that can be derived by various control methods. Amid these methods, the gating signals to the voltage source inverter switches are generated by employing the hysteresis band current control method. Though there are many approaches to control the compensation current, but hysteresis current control technique is extensively pre-owned because of its absolute stable performance, easy circuit configuration, exactness, and quick counter. Through the hysteresis control technique, about the reference current the substantial current is held at the presumed range called the hysteresis band (HB). The reference current (i_a*, i_b*, i_c*) in comparison with substantial current (i_{Sa}, i_{Sb}, i_{Sc}) so as to conserve the substantial current within the hysteresis limit, based on the error produced, VSI switches are plugged in and out. The gate pulses generated to drive VSI are turned off or vice versa, when the substantial current surpasses the maximum limit of the hysteresis range. Generally, when the current at the output side wants to augment, the potential across the DC-link goes to the highest value, and when the current wants to decrease then voltage goes to the lowest value [25].

2.4 PI Controller:

Regulating the potential difference at the DC-link capacitor of the voltage source inverter in order to have a sustained DC voltage at the DC side of the inverter is a critical controlling factors of the shunt active power filter. Typically, active power filters that achieves the reference harmonic currents includes a capacitor at the DC side of the VSI to store energy. Conceptually, capacitor present at the DC side of the VSI should not consume any active power from the AC grid by holding its terminal voltage constant. Virtually, a small fraction of active power is consumed by VSI for its switching actions, as mentioned earlier [9]. Consequently, the error difference(vdc-vdc_ref) is furnished to the PI controller thereby, getting a constant DC-link voltage.

In order to regulate the AC voltage at the load side of a 3-phase system, the load voltage at the point of common coupling (PCC) is compared with the 3-phase reference phase voltage, the error signal is sent to PI controller and thereby maintaining a reference peak voltage at the PCC.

The transfer functions of the PI controller are given by the gains GPI(s). The amplitude of the source current is almost equal to the amplitude of the compensation current at high frequency operation of VSI. Hence, the current controller transfer function of a closed-loop system is presumed to be unity.

$$\mathrm{Gi(s)} = \frac{i_{s_{abc}}}{i_{abc}^{*}} \approx 1 \tag{22}$$

Where Gi(s) denotes the current gain; i_{Sabc} refer to the supply 3-ϕ current; i^*_{abc} represents the reference 3- ϕ current.

According to the step response of the closed-loop transfer function, the Kp and Ki value of the PI controller is represented by a block diagram in Figure 7. The controlled DC voltage gain of the closed-loop transfer function is obtained by Equation (23)

$$\frac{v_{dc}}{v_{dc\_ref}} = \frac{\frac{k_P k_i}{c}}{s^2+\frac{k_P}{c}s+\frac{k_P k_i}{c}} \tag{23}$$

v_{dc} is the DC voltage, v_{dc_ref} denotes the DC reference voltage, Kp is the proportional controller gain, Ki represents the integral controller gain, and C is the capacitor.

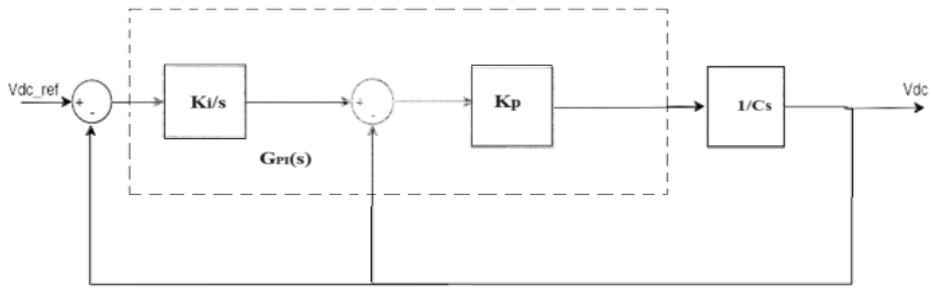

Figure.5 Closed-loop DC voltage regulation

The controlled DC voltage transfer function of the closed-loop system is same as the transfer function of the open-loop second-order system. On equating the Expression (23) along the Expression (24) which represents the standard second-order system gain the Kp and the Ki value can be decided.

$$H(s) = \frac{\omega_n^2}{S^2+2\xi\omega_n s+\omega_n^2} \tag{24}$$

ω_n refers to the natural damping frequency, and ξ represents damping factor. On trying to equate the Expression (23) and (24):

$$\frac{kp}{c} = 2\xi\omega_n \text{ and } \frac{k_P k_i}{c} = \omega_n^2$$

$$\text{hence, } k_P = 2\xi\omega_n c \text{ and } k_i = \frac{\omega_n}{2\xi}$$

3. Simulation results and discussion

The propounded current control technique with regard to SAPF is executed by employing MATLAB/Simulink power tool to mitigate harmonic currents due to the nonlinear loads. The Simulation exemplary includes (i) a 3-ϕ AC voltage supply, (ii) a non-linear load with a stable system, also (iii) the SAPF on P-Q theory and SAPF on proposed I-Cos ψ algorithm is modelled using standard system parameters by using MATLAB/Simulink and the experimental results are compared using Fast Fourier Transform.

Table 1. Network parameters

Parameter	Value
AC voltage source	380 $V_{ph\text{-}ph}$
Frequency	50Hz
Source impedance	Rs=0.1Ω, Ls=10mH
Filter impedance	Rs=0.0Ω, Ls=0.015mH
DC-link capacitance	1000µF, 400V
Kp	1.2
Ki	20

Table1, lists the system parameters for the simulation. By considering stable non-linear system, the effectiveness of both the SAPF control algorithm is studied and compared. The source current and the load current of the system with a stable non-linear load is non-sinusoidal it is seen in Figure.6. Figure.7, shows the Fast Fourier Transform of the stable system before connecting the shunt active power filter, in which the total harmonic distortion (THD) of the system source current is 24.59%, which implies that the source current involves harmonic components along with the fundamental component which is responsible for the disfigure of the source current.

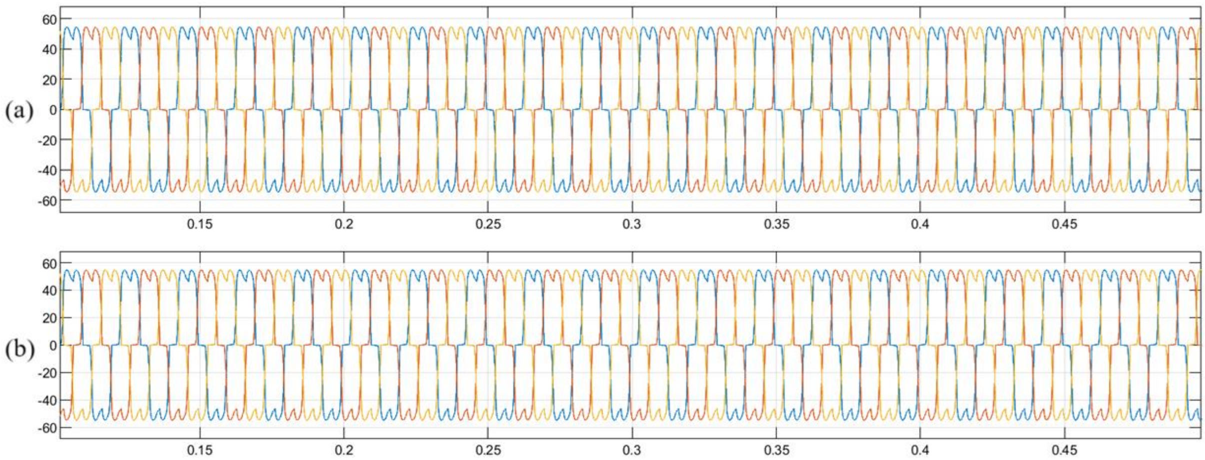

Figure.6 (a) supply current; (b) load current prior to the compensation

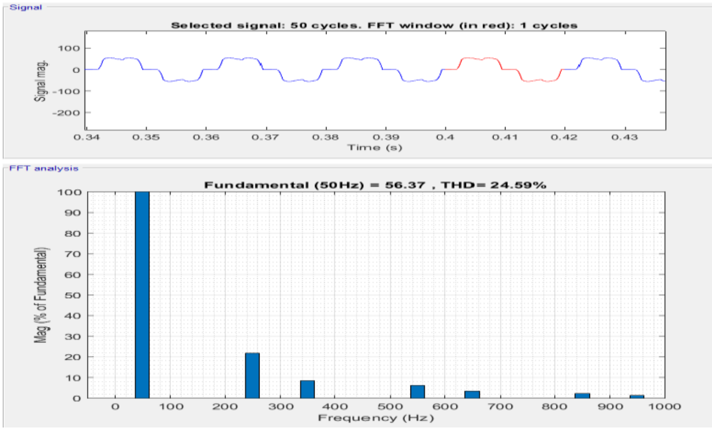

Figure.7 FFT analysis prior to compensation of a balanced system

To balance the significant THD, a shunt active power filter was used to conserve sinusoidal current, utilizing P-Q theory and I-Cos ψ control algorithm while removing harmonic distortion. Simulink model of the propounded SAPF using I-Cos ψ control algorithm is depicted in the figure.8. The disfigured source current is restored back to the sinusoidal waveform by the implimentation of shunt active power filter is shown in the figure.9.

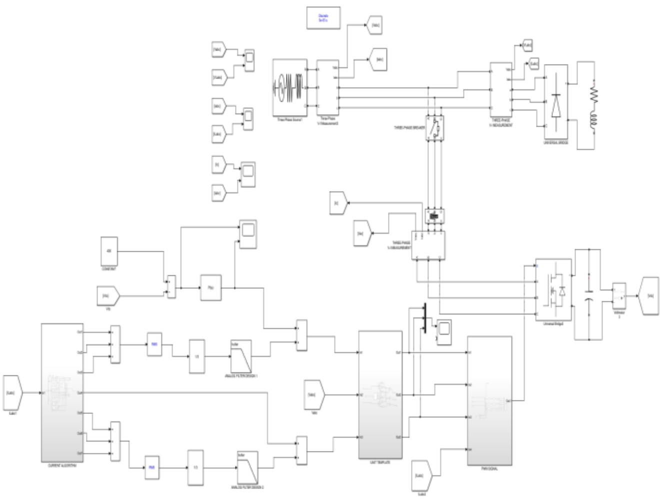

Figure.8 Simulink model of the proposed SAPF using I-Cos ψ control algorithm

The FFT analysis of the supply current for a stable non-linear load derived using P-Q theory is shown in the figure.10, the THD has reduced from 24.59% to 1.46%.

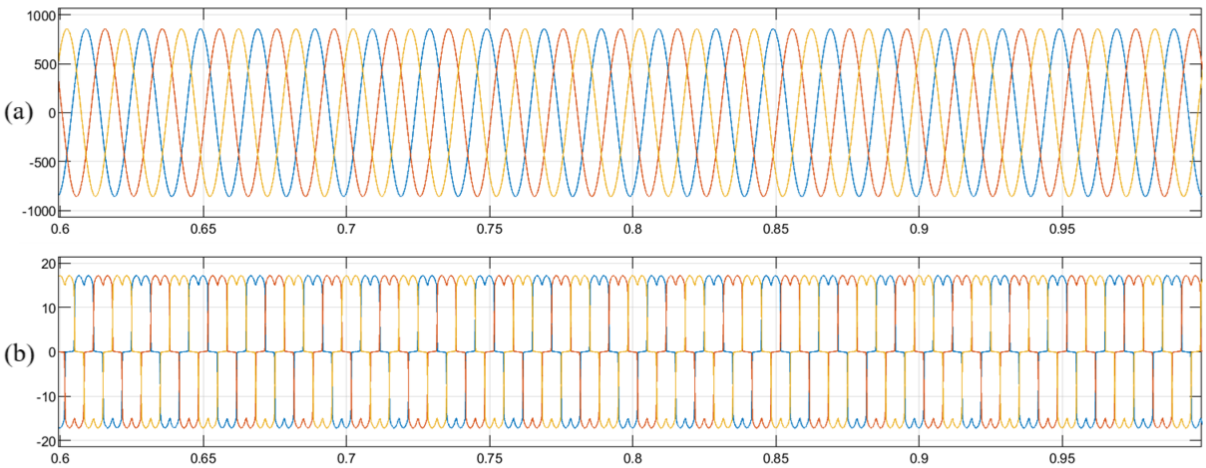

Figure.9 (a) supply current; (b) load current after compensation

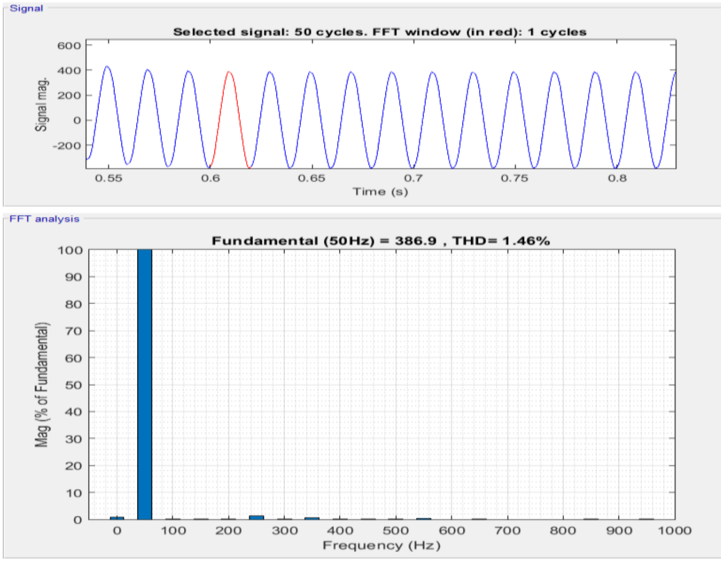

Figure.10 FFT analysis of the supply current after compensation of a stable system using P-Q theory

The FFT analysis of the supply current for a stable non-linear load derived using I-Cos ψ control algorithm is shown in the Figure.11, the THD has reduced significantly from 24.59% to 0.90%.

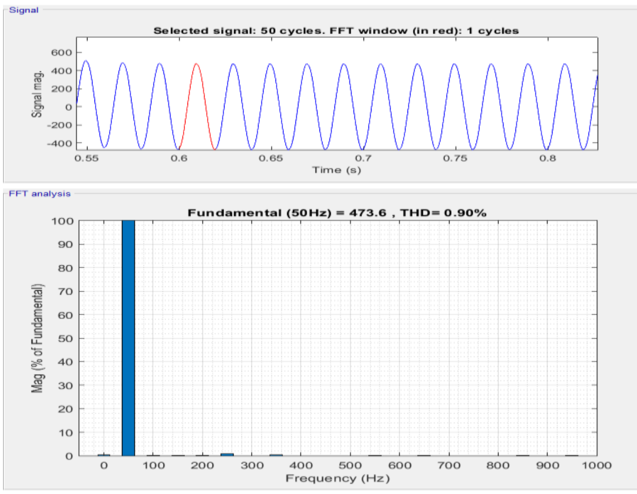

Figure.11 FFT interpretation of supply current after compensation of a stable system using I-Cos ψ control algorithm

Table 2. Total harmonic distortion (THDs) supply current

No	Load Depiction	% THD of the supply current
1	Non-linear load, stable network in absence of SAPF	24.59
2	Non-linear load, stable network in presence of P-Q theory based SAPF	1.46
3	Non-linear load, stable network in presence of I-Cos ψ control algorithm based SAPF	0.90

The harmonic spectrum of the supply current for stable grid using above mentioned control algorithms are synthesised and table 2 compares the results of the two- control algorithms.

4. CONCLUSION

The Shunt active power filter using different control algorithms to extract harmonic currents are studied and simulated using MATLAB/Simulink. Firstly, depicting P-Q theory based SAPF, this reduces the harmonic effect on the supply current from the THD 24.59% to 1.86%, this is an effective low THD for a balanced system. On considering the proposed I-Cos ψ based SAPF reduces the THD from 24.59% to 0.90%. Hence, from the table which depicts the THD of the supply current presents that I-Cos ψ based SAPF is more effective in deteriorating the power quality problems i.e., harmonic currents compensation, DC-link capacitor voltage regulation, reactive power compensation for balanced system.

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