

Research Article

PI-Controlled Shunt Active Power Filter for Effective Elimination of Harmonics in Transmission System Based on PQ Theory

Janardhanarao K^{†*}, Sudhakar Kothuru[‡] and Vijay Kumar B[‡]

[†]Electrical Department, IIT Roorkee, Roorkee, India

[‡]Electrical and Electronics Engineering, Navodaya Institute of Technology, Raichur, India

Accepted 07 March Feb 2015, Available online 15 March 2015, Vol.5, No.2 (April 2015)

Abstract

Harmonics are developed in transmission and distribution system with use of huge quantity of non-linear (transformer etc.), power electronic equipments (bridge rectifier, power converters etc.), in industrial and even house-hold electrical equipments. This will lead to damage either supply system or non-linear loads. In order to protect the supply system from current harmonics, we have to use the active power filters. These are used to compensate the reactive power compensation, but the performance of active power filters are based on various control strategies. This paper presents the complete examination to estimate the working of SHAF for generating the current references under steady and transient for balanced, unbalanced and non-sinusoidal conditions by using PI controller. The P-Q theory and synchronous reference frame theory, which are widely used in SHAF. The most validate results obtained by simulation with matlab/simulink software are carried out with PI controller for P-Q control theory for various voltage conditions like balanced, unbalanced and non-sinusoidal conditions and dynamic load changes.

Keywords: Voltage source inverter, Current source inverter, Harmonics Compensation, SHAF, P-Q control technique, PI- controller.

1. Introduction

Nowadays by the improvement of semiconductor and power electronic technology, the conventional use of non-linear loads is greater than before. So that the quality of power deteriorates with the extensive use of non-linear loads in both transmission and distribution systems. In generally power quality says that as quality of current and/or voltage. It can be defines that “the measure, analysis and improvement of the bus voltage with sinusoidal waveform at rated voltage and constant frequency” (H. Akagi *et al*, 1983). When the non-linear loads such as transformers, arc furnaces, power converters, static VAR compensators, adjustable drives and pulse width modulated drives etc, are increases, As a result of increasing non-linear loads to produce harmonic currents or circulating currents. These current harmonics causes to damage the source and/or non-linear loads. By the cost point of view we have to secure our source, for the purpose we are going to use filters (H. Akagi *et al*, 1983).

Recently, we are using active power filters instead of passive power filters, why because the passive power filters having some disadvantages (IEEE Std. 519-1992, 1993). It is well-known that in three phase

three wire system, the zero sequence power is nil because of absence of neural conductor. Consequently the unnecessary current harmonics are going through the ground. In Such situation a perfect compensator is important to eliminate such consequences caused by harmonics (IEEE Std. 519-1992, 1993). However a lot of control techniques have been developed although the P-Q theory, synchronous reference frame theory (H. R. Silva *et al*, 2001; H. Akagi *et al*, 1984) are always leading. The present paper describes on P-Q theory through PI controller. To monitor the current observations, effective simulations are taking by means of PI controller for P-Q theory for different voltage situations like balanced, unbalanced and non-sinusoidal conditions and dynamic load changes.

2. Classification of shunt active power filters

According converter type, the shunt active power filters are classified into two types. Those are current source converter type shunt active power filter and voltage source converter type shunt active power filter as shown in Fig: 1 (H. R. Silva *et al*, 2001).

The main difference between these two topologies is energy storage element connected at DC link side. In CSC type shunt active power filter, the converter is formed by six controllable switches in series with

*Corresponding author: Janardhanarao K

diodes and $L_f C_f$ filter is connected in between the PWM converter and supply mains and it is used to suppress ripples in output of the converter. In VSC type shunt active power filter, the converter is formed by six controllable switches in shunt with diodes and L_f filter is connected in between the PWM converter and supply mains and it is used to suppress ripples in output of the converter (H. R. Silva *et al*, 2001; IEEE Std. 519-1981, 1981).

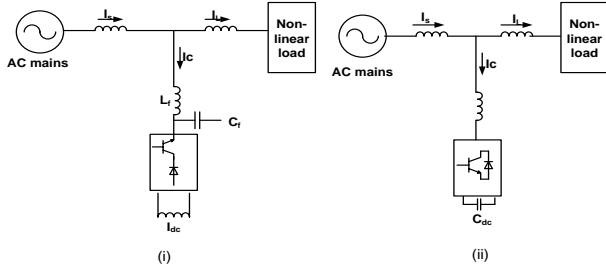


Fig. 1. (i) CSC and (ii) VSC type shunt active power filter

This paper presents the VSC type shunt active power filter. Basically the shunt active power filter is connected at point of common coupling, the basic principle of the active power filter is injected the reference harmonic currents in phase opposition to current harmonics produced by the non-linear loads. Due to that cancellation of current harmonics, we will get sinusoidal waveform at point of common coupling.

3. Methodology of 3-phase, 3-wire shunt active power filter

3.1. Instantaneous real active and reactive power method

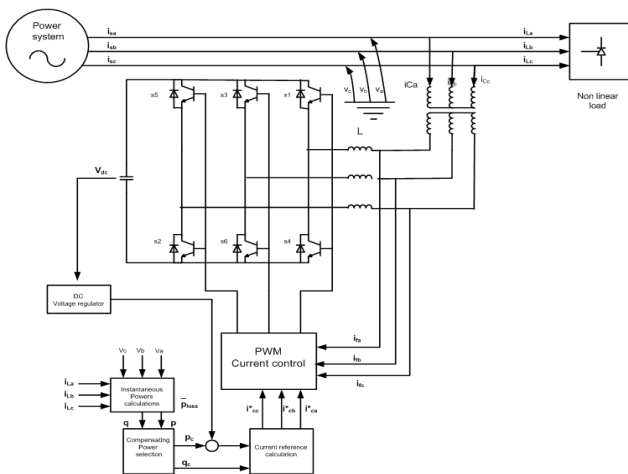


Fig. 2. The basic block diagram of three phase three wire shunt active power filter

The basic block diagram of 3-phase, 3-wire shunt active power filter is shown in Fig: 2 (J. Alfonsa *et al*, 2000). Here the source is connected to the non-linear load, these non-linear loads always generates current harmonics. Due to these current harmonics, distorted waveform is appeared at point of common coupling. For getting sinusoidal waveform at point of common

coupling we have to connect the shunt active power filter (H. Akagi *et al*, 1984; IEEE Std. 519-1981, 1981). These shunt active power filter consists of L_f filter and voltage source converter which is having six controllable switches in parallel with the diodes. Here the shunt active power filter takes the harmonic currents information from the non-linear load, it gives the information to the PWM circuit, these PWM circuit generates the gating signals to the voltage source inverter. In the voltage source inverter, the switches are operating according to the generation of gating signals (R.M. Stephan *et al*, 1998; F. Z. Peng *et al*, 1998).

The output of the voltage source inverter is passing through the L_f filter. These L_f filter is used to add the reference signals in phase opposition to the actual current harmonics generated by the non-linear load. These shunt active power filter can be operated with the help of real and reactive power control strategy.

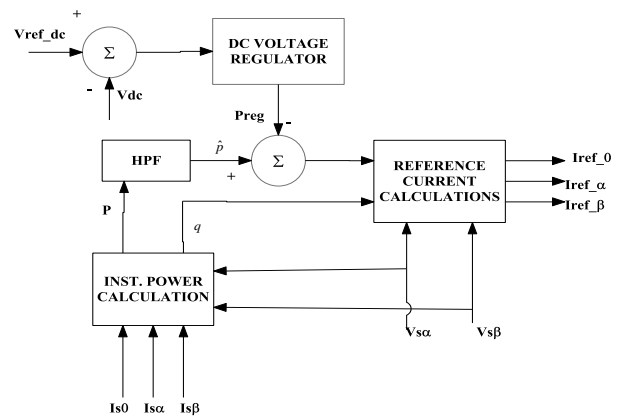


Fig. 3.Active filter controller block diagram

The operation of real and reactive power control strategy is based on active filter controller block diagram as shown in Fig: 3 (H. Akagi *et al*, 2007). Former days the calculations of power flow were consequential from the average powers or root mean square values of voltages and currents. Akagi, H, proposed one method for calculating reference compensation currents called the instantaneous P-Q method (i.e., instantaneous real active and reactive power theory) (T. Kawabata *et al*, 1997). These reference compensation currents are required to inject into the network, where non-linear loads are connected. This P-Q theory is based on time domain analysis. By using of this P-Q theory, information of both load line currents and source voltages converters α - β -0 coordinates with the help of instantaneous power calculation (J. Alfonsa *et al*, 2000). So the P-Q theory has been used the transformation called Clarke transformation. It is used to plot the three phase supply/source instantaneous voltages and output/load line currents into α - β -0 coordinates. The transformation matrices C and C^{-1} for transformation of Clarke and back transformation are given respectively in equations (L. S. Czarnecky, 2004).

$$\begin{pmatrix} V_{in0} \\ V_{in\alpha} \\ V_{in\beta} \end{pmatrix} = C \begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} \tag{1}$$

$$\begin{pmatrix} V_{in0} \\ V_{in\alpha} \\ V_{in\beta} \end{pmatrix} = \sqrt{2}/3 \begin{pmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{pmatrix} \begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} \tag{2}$$

$$\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} = C^{-1} \begin{pmatrix} V_{in0} \\ V_{in\alpha} \\ V_{in\beta} \end{pmatrix} \tag{3}$$

$$\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} = \sqrt{2}/3 \begin{pmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{pmatrix} \begin{pmatrix} V_{in0} \\ V_{in\alpha} \\ V_{in\beta} \end{pmatrix} \tag{4}$$

The equations (1), (2), (3), and (4) are shown above. These are given as voltage wave but they are also applicable for current waves. Here “0” represents the zero sequence component of voltage wave/current wave. In three phase three wire system, zero sequence components can’t flow. So that zero sequence components, from above equations (1), (2), (3) and (4) are eliminated and the α - β axes transforming into three phase balanced -linear system.

$$\begin{pmatrix} P_r \\ Q_r \end{pmatrix} = \begin{pmatrix} V_{in\alpha} & V_{in\beta} \\ V_{in\beta} & -V_{in\alpha} \end{pmatrix} \begin{pmatrix} I_{op\alpha} \\ I_{op\beta} \end{pmatrix} \tag{5}$$

Rearranging equation (5)

$$\begin{pmatrix} I_{op\alpha} \\ I_{op\beta} \end{pmatrix} = \frac{1}{V_{in\alpha}^2 + V_{in\beta}^2} \begin{pmatrix} V_{in\alpha} & V_{in\beta} \\ V_{in\beta} & -V_{in\alpha} \end{pmatrix} \begin{pmatrix} P_r \\ Q_r \end{pmatrix} \tag{6}$$

$$P_r = \bar{P}_r + \tilde{P}_r \tag{7}$$

$$Q_r = \bar{Q}_r + \tilde{Q}_r \tag{8}$$

From equations (7) and (8), P_r be the instantaneous real power is the sum of average and oscillating real powers and Q_r be the instantaneous imaginary power is the sum of average and oscillating reactive powers. For linear load, P_r and Q_r are having only DC/constant/average values. However if load may be bridge rectifier as a non-linear load, the current waveform should enclose not only the 50 Hz/fundamental frequency component but also the multiple of 50 Hz/fundamental frequency components.

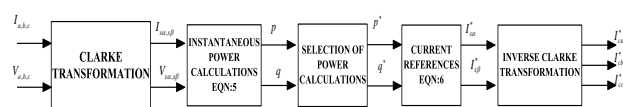


Fig. 4. Calculation of current reference based on P-Q theory

Then the instantaneous P_r and Q_r should include constant dc or average component and fluctuating or oscillating component as decomposing in equations (7) and (8). The average component of real P_r and reactive

Q_r can't exist as reference powers so that oscillating components of real P_r and imaginary power Q_r must have to be chosen as reference powers, if the shunt active power filter is deliberate for compensation current harmonics or circulating currents. From the active power filter controller block diagram, the low pass filter (LPF) is used to absorb the average/constant dc component/elements and selecting the fluctuating/oscillating component/ elements in equations (7) and (8) and back transformation is used to get the desire compensation reference currents (i_{ca}^* , i_{cb}^* , i_{cc}^*) in the form of a - b - c coordinates in Fig: 4 (H. Akagi *et al*, 2007).

3.2 Importance of DC capacitor

The voltage of DC capacitor may be restricted by a DC voltage regulator. A low-pass filter is used, it anesthetized to the fundamental (50Hz) voltage frequency oscillations (R. Arseneau *et al*, 1996; E.H. Watanabe *et al*, 1995). The clean voltage variation occurs, according to the subsequent equations regulation of voltage (ϵ_r) is given as,

$$\epsilon_r = -1; \quad V_{dc} < -0.05V_{dc_ref} \tag{9}$$

$$\epsilon_r = \frac{V_{dc}}{-0.05V_{dc_ref}}; \quad -0.05V_{dc} \leq V_{dc} \leq -0.05V_{dc_ref} \tag{10}$$

$$\epsilon_r = 1; \quad V_{dc} > 0.05V_{dc_ref} \tag{11}$$

4. Construction of PI Controller

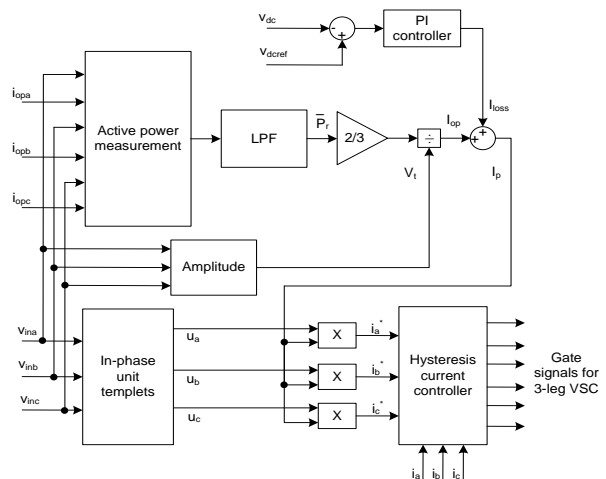


Fig. 5. Generating gate signals for shunt active filter

The above Fig: 5 (A. M. Massoud *et al*, 2004) shows that PWM control circuit of shunt active power filter based on generation of current reference contains active power measurement, PI-controller, low pass filter, reference current generator and hysteresis current controller. Here the load currents (I_{opa} , I_{opb} , I_{opc}) the voltages at point of coupling (V_{ina} , V_{inb} , V_{inc}) and DC link voltage V_{dc} are sensed signals, and these are used as feedback signals. The bigger current references are getting as a result of modifiable the dc link voltage (A. E. Emanuel, 2004). The error signal is obtained

from comparing the actual dc link voltage with V_{ref_dc} (reference DC voltage). The DC bus error voltage is given as,

$$V_{dcerr} = V_{dc} - V_{dc_{ref}} \tag{12}$$

Here the PI – controller is used for DC bus control. So When the error signal is flowing by the way of PI controller, its controls the DC bus current signal, which will give the greater value of supply current included with the controller and is thus made accessible at zero crossing only. The output result of the PI controller is greater value of supply current that is the classified into of two elements/components. Those are, (i). Fundamental element/ component of active output/load current of SHAF and, (ii). Loss element / component of active output/load current of SHAF.

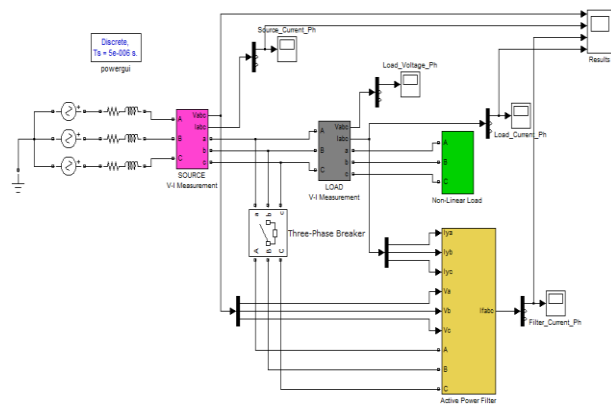


Fig: 6. Simulation diagram for three phase three wire shunt active power filter connected with three phase circuit breaker

The greater value of the current is multiply with sinusoidal waveform in phase with input/source voltage to get compensating reference current waves. These compensating reference currents compared with the help of actual current waves in the hysteresis band, which will give the slip-up signal to the modulation technique (H. Akagi *et al*, 1983; H. R. Silva *et al*, 2001). Then this error signal will choose the action of voltage source inverter switches, these are generates the reference harmonic currents injected with the help of voltage source inverter.

5. Performance of system

The experimental analysis of three phase three wire SHAF is given in below simulation using SIMULINK/MATLAB Fig: 6. The experimental performance of the three phase three wire SHAF is describing with the help of circuit breaker and dynamic load conditions for various conditions of steady and transient for balanced, unbalanced and non-sinusoidal conditions and the effective simulations are carried out for SHAF for PI controller with P-Q theory.

5.1 Simulation for balanced three phase three wire SHAF

The simulations are implemented for balanced three phase voltage condition of shunt active power filter for three phase three wire system. These simulation results are showing at steady and transient conditions at two situations, those are (i).With shunt active power filter, (ii).Without shunt active power filter. The system is having three phase voltage of $220\sqrt{3}$ V, with frequency of 50 Hz and is connected to controlled RL-load bridge rectifier (R=45 ohms and L=50 henrys). From the simulation results, 0.2 to 0.3 sec, the circuit breaker is going ON, in this period the shunt active power filter is connected to the system as a result supply/source current of phase A is becomes sinusoidal waveform.

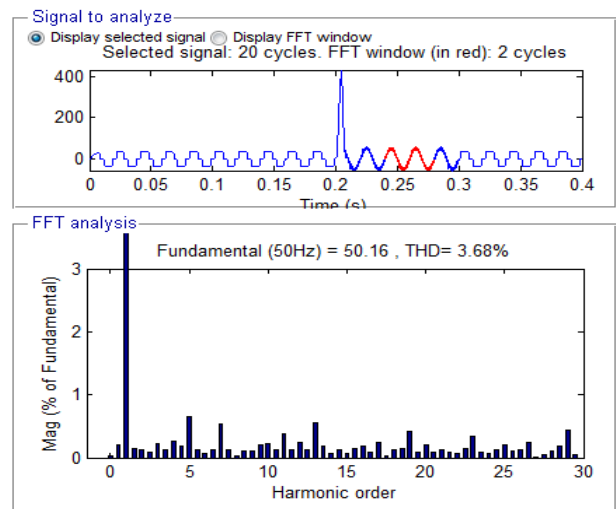
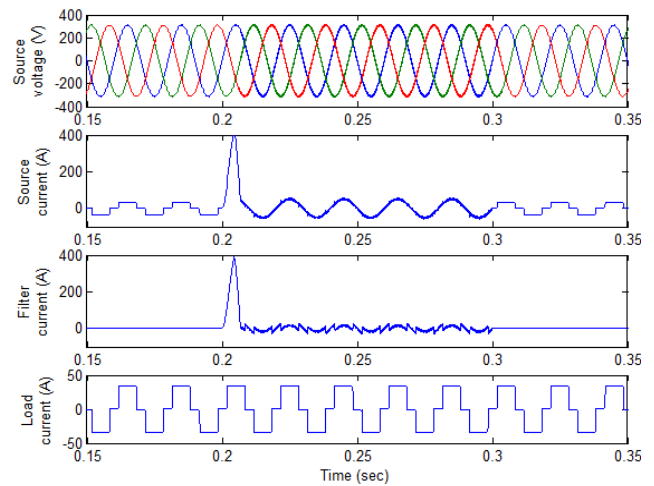


Fig: 7. Simulation results for balanced three phase three wire system and FFT analysis for source current for phase A.

At rest of the time the circuit breaker is going to OFF, in this period shunt active power filter is disconnected from the system, As a result the supply/source current of phase A becomes non-sinusoidal is same as the output/load current. Finally from the FFT analysis the total harmonic distortion of the supply/source current

of phase A is decreased to 3.68% of fundamental supply/source current of phase A as shown in Fig: 7.

5.2 Simulation for unbalanced three phase three wire SHAF

The below Fig: 8 shows the experimental results under unbalanced three phase voltage condition of shunt active power filter for three phase three wire system. These simulation results are showing at steady and transient conditions at two situations, those are (i).With shunt active power filter, (ii).Without shunt active power filter. The system is having one of the three phase voltage of 220 V, with frequency of 50 Hz and is connected to controlled RL- load bridge rectifier (R=45 ohms and L=50 henrys).

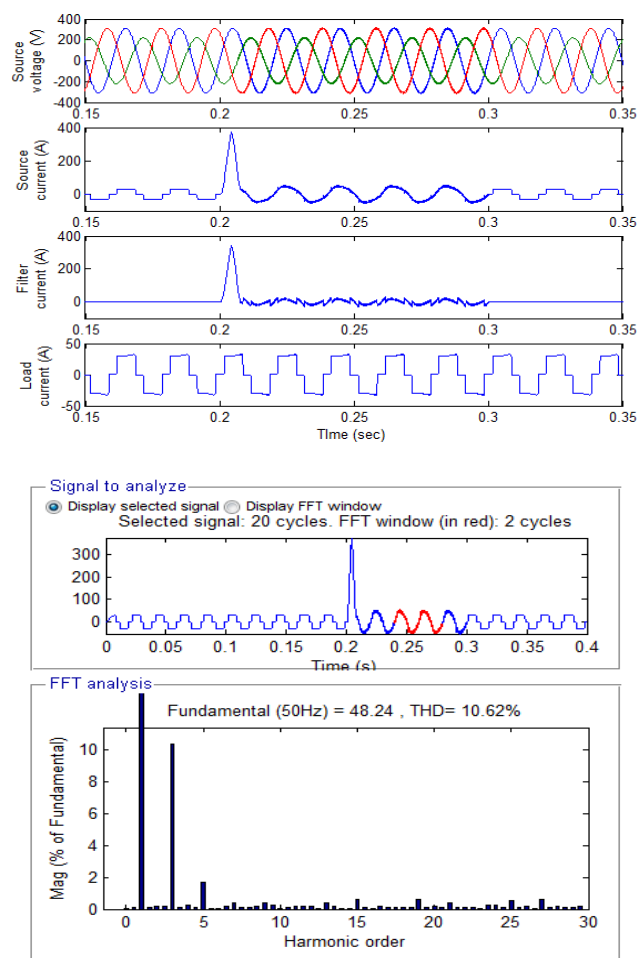


Fig: 8. Simulation results for unbalanced three phase three wire system and FFT analysis for source current for phase A

From the simulation results, 0.2 to 0.3 sec, the circuit breaker is going ON, in this period the shunt active power filter is connected to the system as a result supply/source current of phase A is becomes sinusoidal waveform. At rest of the time the circuit breaker is going to OFF, in this period shunt active power filter is disconnected from the system, As a result the supply/source current of phase A becomes

non-sinusoidal is same as the output/load current. Finally from the FFT analysis the total harmonic distortion of the supply/source current of phase A is decreased to 10.62% of fundamental supply/source current of phase A as shown in Fig: 8.

5.3 Simulation for non-sinusoidal three phase three wire SHAF

Fig: 9 below shows the simulation results under non-sinusoidal three phase voltage condition of shunt active power filter for three phase three wire system. These simulation results are showing at steady and transient conditions at two situations, those are (i).With shunt active power filter, (ii).Without shunt active power filter.

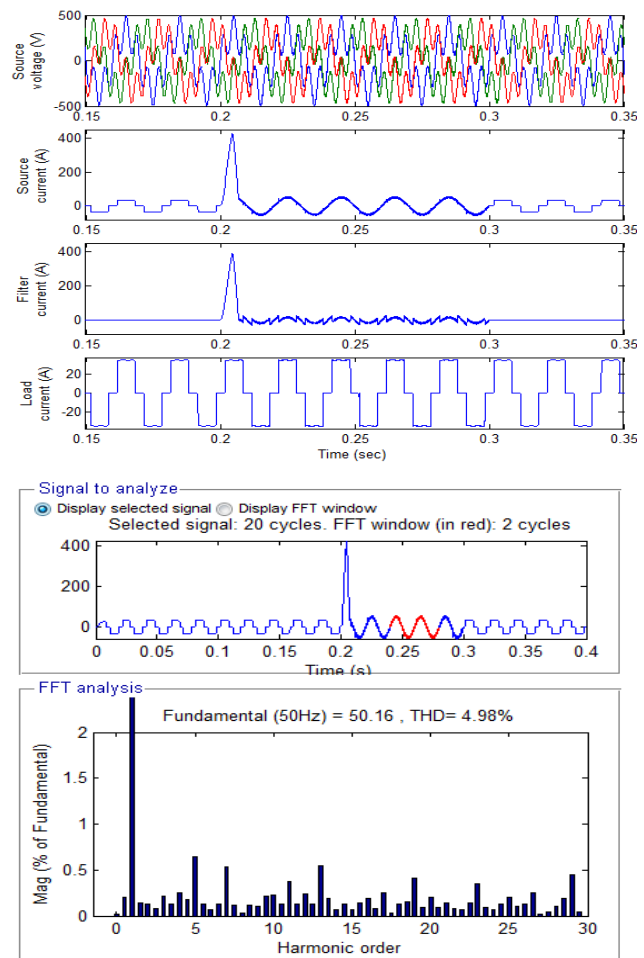


Fig: 9. Simulation results for non-sinusoidal three phase three wire system and FFT analysis for source current for phase A

The system is having three phase voltage with frequency of 50 Hz and is connected to controlled RL-load bridge rectifier (R=45 ohms and L=50 henrys). From the simulation results, 0.2 to 0.3 sec, the circuit breaker is going ON, in this period the shunt active power filter is connected to the system as a result supply/source current of phase A is becomes sinusoidal waveform.

At rest of the time the circuit breaker is going to OFF, in this period shunt active power filter is disconnected from the system, As a result the supply/source current of phase A becomes non-sinusoidal is same as the output/load current. Finally from the FFT analysis the total harmonic distortion of the supply/source current of phase A is decreased to 4.98% of fundamental supply/source current of phase A as shown in Fig: 9.

5.4 Simulation for balanced three phase three wire SHAF with dynamic load changes

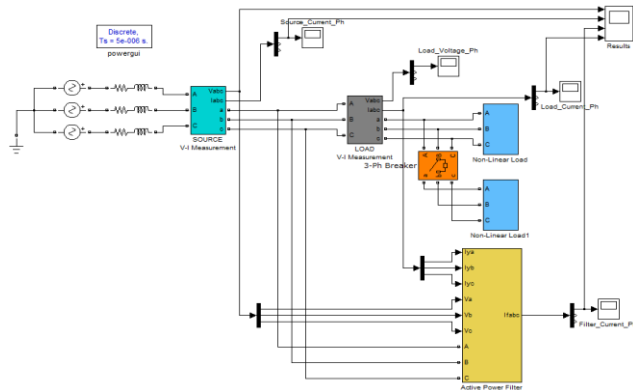


Fig: 10. Simulation diagram for three phase three wire shunt active power filter connected with three phase circuit breaker.

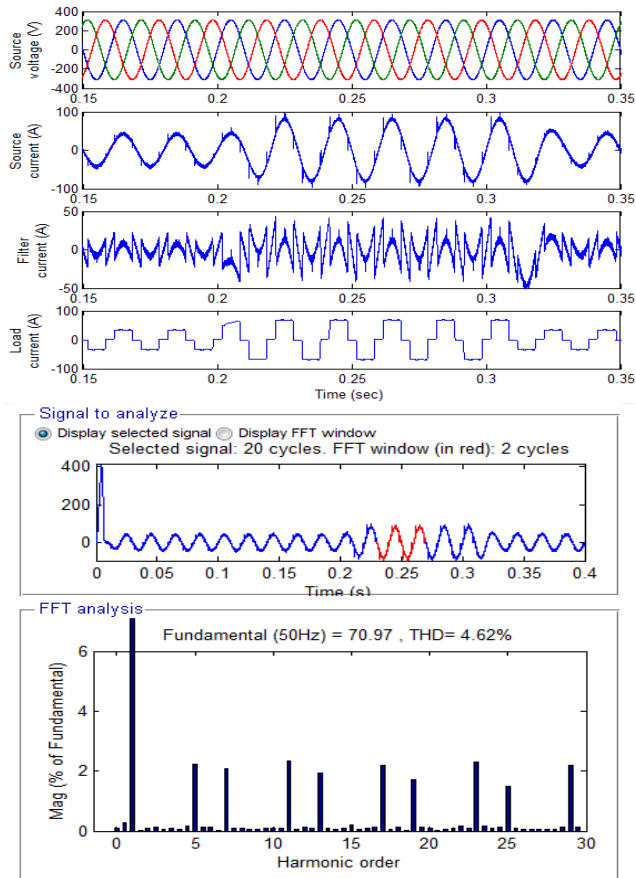


Fig: 11. Results for balanced three phase three wire system with dynamic load changes

The Fig: 11 shows the simulation results under balanced three phase voltage condition of shunt active power filter for three phase three wire system. These simulation results are showing at steady and transient conditions at two situations, those are (i). with additional dynamic load, (ii). without additional dynamic load. The system is having three phase voltage of $220\sqrt{3}$ V with frequency of 50 Hz and is connected to controlled RL- load bridge rectifier ($R=45$ ohms and $L=50$ henrys). From the simulation results, 0.22 to 0.32 sec, the dynamic load is connected to in parallel to the actual load, in this period the load draw more current than actual current as shown in Fig: 10, and the rest of the period, load draw the actual current. Finally from the FFT analysis the total harmonic distortion of the supply/source current of phase A is decreased to 4.62% of fundamental supply/source current of phase A as shown in Fig: 11.

5.5 Simulation for unbalanced three phase three wire SHAF with dynamic load changes

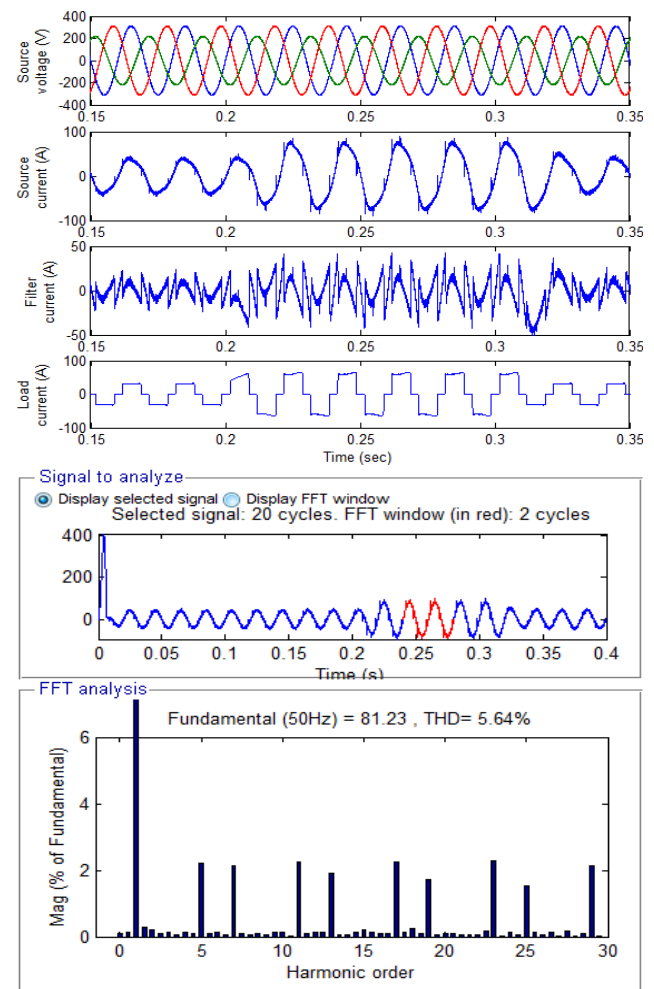


Fig: 12. Simulation results for unbalanced three phase three wire system with dynamic load changes and FFT analysis for source current for phase A.

The Fig: 12 shows the simulation results under unbalanced three phase voltage condition of shunt

active power filter for three phase three wire system. These simulation results are showing at steady and transient conditions at two situations, those are (i).With additional dynamic load, (ii).Without additional dynamic load

The system is having one of the three phase voltage of 220 V with frequency of 50 Hz and is connected to controlled RL- load bridge rectifier (R=45 ohms and L=50 henrys). From the simulation results, 0.22 to 0.32 sec, the dynamic load is connected to in parallel to the actual load, in this period the load draw more current than actual current as shown in Fig: 11, and the rest of the period, load draw the actual current. Finally from the FFT analysis the total harmonic distortion of the supply/source current of phase A is decreased to 5.64% of fundamental supply/source current of phase A as shown in Fig: 12.

5.6 Simulation for non-sinusoidal three phase three wire SHAF with dynamic load changes

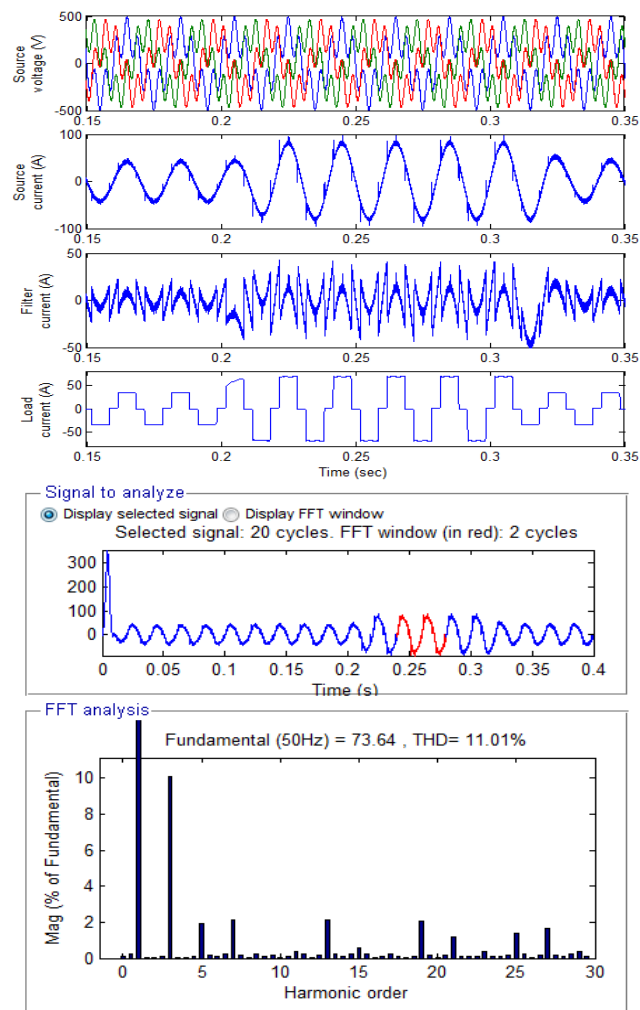


Fig: 13. Simulation results for non-sinusoidal three phase three wire system with dynamic load changes and FFT analysis for source current for phase A

The Fig: 13 shows the experimental results non-sinusoidal three phase voltage condition of shunt

active power filter for three phase three wire system. These simulation results are showing at steady and transient conditions at two situations, those are (i).With additional dynamic load, (ii).Without additional dynamic load.

The system is having three phase voltage with frequency of 50 Hz and is connected to controlled RL-load bridge rectifier (R=45 ohms and L=50 henrys). From the simulation results, 0.2 to 0.3 sec, the dynamic load is connected to in parallel to the actual load, in this period the load draw more current than actual current as shown in Fig: 13, and the rest of the period, load draw the actual current. Finally from the FFT analysis the total harmonic distortion of the supply/source current of phase A is decreased to 11.01% of fundamental supply/source current of phase A as shown in Fig: 13.

Conclusions

In this paper when the load may be balanced/unbalanced, linear/nonlinear, the source must be sinusoidal. Because of this we can proposed this shunt active filter with PQ theory done in various types of conditions, those are balanced, unbalanced and non-sinusoidal conditions under the PI-controller by the using of simulink/matlab software. This was useful to get the constant power supply and sinusoidal current waveform at point of common coupling. This construction of three phase three wire shunt active power filter with PQ theory is cost-effectiveness for allowing more number of low pass filters to removing the reactive currents, circulating currents, neutral/zero sequence currents and improving the power factor at input of the system.

References

- H. Akagi, Y. Kanazawa, A. Nabae (1983), Generalize theory of the Instantaneous Reactive Power in Three-Phase Circuits, *IPEC'83 - Int. Power Electronics Conf., Tokyo, Japan*, pp. 1375-1386.
- IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems, *IEEE Std. 519-1992*.
- H. R. Silva, J. S. Martins J.l. Afonso (2001), Active filters for power quality improvement, *IEEE power Tech, Porto, Portugal* [18], pp. 10-13.
- A. Nabae, H. Akagi, Y. Kanazawa (1984), Instantaneous Reactive Power Compensator Comprising Switching Devices without Energy Storage Components, *IEEE Trans. Industry Applic.*, vol. 20, no.3, pp. 625-630.
- Guide for Harmonic Control and Reactive Power Compensation of Static Power Converter, *IEEE Std. 519-1981*.
- R. M. Stephan, M. Aredes, E. H. Watanabe (1998), New concepts of Instantaneous Active and Reactive Powers in Electrical Systems with generic loads, *IEEE Trans. Power Delivery*, vol. 8, no 2, pp. 697-703.
- F. Z. Peng, G. Ott, and D. J. Adams (1998), Harmonic and Reactive Power Compensation Based on the Generalized reactive Power Theory for Three Phase Four Wire System, *IEEE Transl. Power Electronics.*, vol.13, no. 5, pp. 1174-1181.

- Alfonsa J., Couto C., Martin J. (2000), Active Filters with Control based on the p-q theory, *IEEE Industrial Electronics Society Newsletter*, vol.47, no. 3, ISSN. 0746-1240, pp.5-10.
- Kawabata T, Y komastu (1997), Characterisitcs of three phase active power filter using Extension pq theory, *Industrial Electronics, ISIE 1997, proceedings of the IEEE international symposium*.
- L.s. czarnecky (2004), On some Misinterpretations of the reactive power p-q theory, *IEEE Tran. On Power Electronics*, Volume 19, Issue 3, pp. 828-836.
- Arseneau, R., Baghzouz, Y. et al (1996), Practical definitions for powers in systems with nonsinusoidal waveforms and unbalanced loads: a discussion, *Power Delivery, IEEE Transactions on*, vol.11, no.1, pp.79-101.
- E. H. Watanabe, M. Aredes (1995), New control algorithms for series and shunt three phase four wire active power filter, *IEEE Trans.power Delivery*, vol 10, no.3, pp. 1649-1656.
- A. E. Emanuel (2004), Summary of IEEE Standard 1459: definitions for the measurement of electric power quantities under sinusoidal, nonsinusoidal, balanced, or unbalanced conditions, *IEEE Trans.Ind.Appl*, vol.40, no.3, pp. 869-876.
- H. Kawahira, T. Nakamura, S. Nakazawa (1983), Active Power Filters, *IEEE IPEC - Tokyo*, pp.981-992.
- L. Benchaita, S. Saadate, A. Salemnia (1999), A comparison of voltage source and current source shunt active filter by simulation and experimentation, *IEEE Trans. on Power Systems*, Vol. 14, No. 2, pp. 642-647.
- C. A. Quinn, N. Mohan (1992), Active filtering of harmonic currents in three-phase, four-wire systems with three-phase, single-phase nonlinear loads, in *Proc. IEEE APEC'92*, pp. 829-836.
- H. Akagi, et al (2007), Instantaneous Power Theory and Applications to Power Conditioning, *Book IEEE Press*, pp. 41-102.
- A. M. Massoud, S. J. Finney, et al (2004), Review of Harmonic Current Extraction Techniques for an Active Power Filter, *International Conf. on Harmonics and Quality of Power*, Vol. 1, pp. 154-159.
- H. Akagi (2005), Active Harmonic Filters, *Proceedings of the IEEE*, Vol. 93, No. 12, pp. 2128-2141.