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Power Quality Improvement using Parallel Connected FACTS Device with Simplified d-q Control

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Abstract

INTRODUCTION: Distribution network is mainly affected by the end user load nature. Ruinous influence on power system operation based on the type of load used by the end user and due to the presence of non-linear loads causes Harmonics in power system. The concept of reducing the harmful effect of harmonics on power system attracted the research attentiveness. OBJECTIVES: To reduce these harmonics and reactive power problems FACTS devices are found reliable. Out of various FACTS devices, Active Power Filter (APF) is one FACTS device which identifies and controls the harmonic contamination in power system with non-linear loads. This work mainly presents a parallel APF concept for the compensation of harmonics to improve the reliability of the system.
METHODS: The main contribution of this work is proposal of single control strategy for compensation of Power quality. Corrective back currents (for parallel APF) to compensate the identified harmonics are generated using modified d-q reference-based control methodology. RESULTS: The models are developed, and analysis is presented using MATLAB/SIMULINK software
CONCLUSION: d-q reference theory control strategy is explained in detail. Load current, Source Voltage and DC link voltage which are measured using various sensors and send to processor. modified d-q reference the signals to be measured are same

Keywords: FACTS, APF, Parallel APF, d-q theory, harmonics.

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1. Introduction

Power electronic based loads are used more in these modern days to enhance the load controllability. Devices like switch mode power supplies, variable speed drives, electronic fluorescent ballistic lamps, uninterrupted power supplies and magnetic cored devices. These equipments do not draw continuous currents from the supply source but instead draws abrupt short pulses. This phenomenon causes to generate harmonic currents that contaminate the power system. Harmonics degrade the system quality [1] and its efficiency.

Power quality [2-3] is important term in power system. Harmonic signal is a wave whose frequency is an integral multiple of fundamental quantity. Almost every signal contains harmonic frequencies. If a signal does not contain harmonics, it is pure sinusoidal waveform and if not pure, it contains harmonics. Harmonics are classified in to even and odd harmonics. Harmonic frequencies with multiples of two are called even harmonics and the other as odd harmonics. Even harmonics does not affect the power system but odd harmonics causes abrupt changes in the power system operation.

Passive filters (with inductors and capacitors) can minimize the harmonics [4-5], but with limited consignment. Passive filters tuned to particular frequency can nullify only one harmonic frequency at a time. As the order of harmonic frequency is less, size of the passive filter increases which eventually increases the cost of the filter, and vice-versa. It is stated that elimination of higher order odd harmonics is easier but dealing with lower order increases the complexity. Power electronic based custom power devices [6-7] are developed to deal with suppressing the harmonic frequencies in complete scale of order at once.

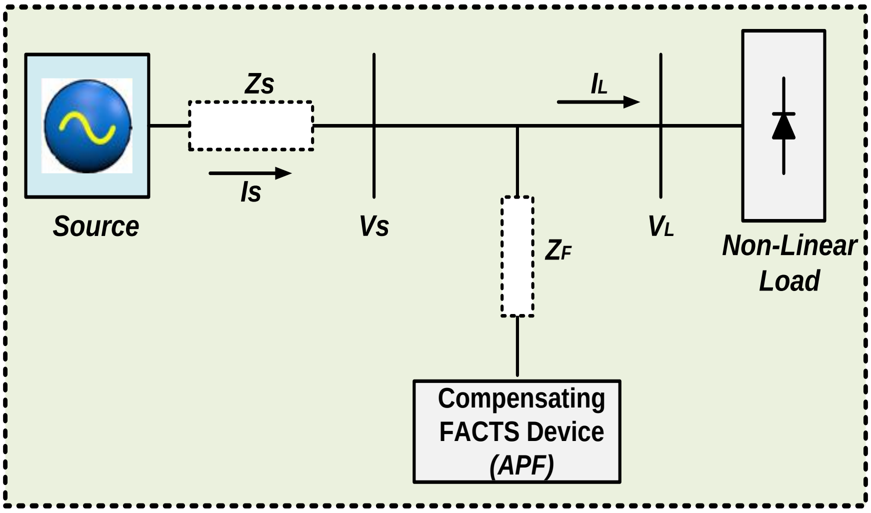

Figure 1. APF in power network

Active power filter (APF) [8-9] is onepower electronic based custom power device evolved to deal with harmonics in power system. APF is a Parallel compensating device connected in shunt to the PCC for harmonic compensation. APF identifies the harmonic quantity and generates corrective back (compensating) currents to compensate the identified harmonics. A single APF carries the complete load of compensating currents. This paper presents a parallel APF concept for the compensation of harmonics. Parallel APF [10] in power system increases the system reliability. Both the APFs share the load of generating compensating currents, and if any of the APF fails in operation, the other APF will be a backup to generate required compensatingcurrents. Corrective back currents (for parallel APF) to compensate the identified harmonics are generated using modified d-q reference based control methodology.

For High power and high voltage FACTS controller, people are preferring Multilevel to attain higher voltage and Parallel connected converters to handle high power. In single converter configuration even one device fail the entire system to be shut down. But in parallel configuration other converter will work and 50 % compensation will be done. For example ABB, Research center proposes Parallel configuration for High voltage FACTS devices.

2. APF for the Compensation of Harmonics in Power System

2.1. APF for Power Quality

Typical distribution system with loads like diodes and thyristor rectifiers deforms the source parameters by inducing harmonic frequency currents. Induction of harmonics worsens the power quality. Passive filters (with high pass and low pass filters) can improve power factor and eliminate harmonics. Elimination of harmonics using passive filters is effected by source impedance. Components of passive filter may come in to resonance with source impedance producing unwanted electro-magnetic interference issue. Active filters with power electronic technology can improve the power quality reliably.

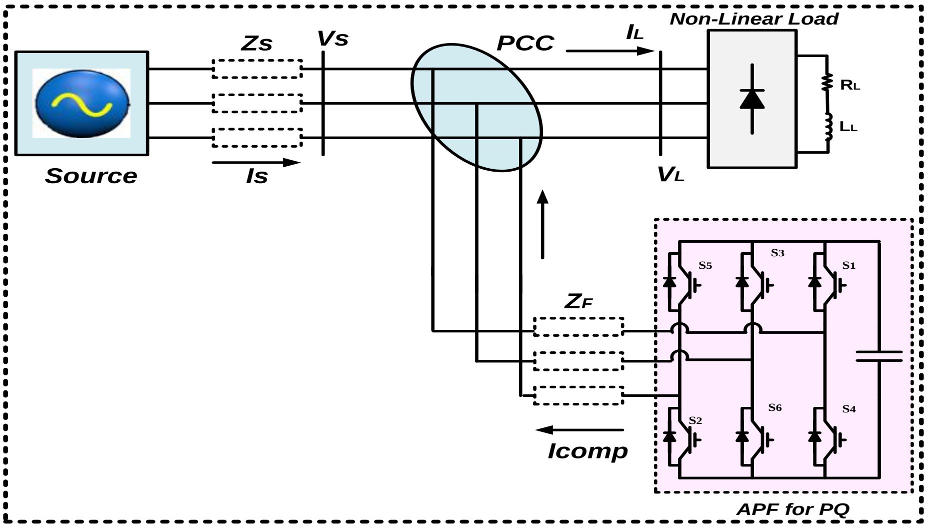

Figure 2. APF in power network with non-sinusoidal Load

Active power filter (APF) is onepower electronic based custom power device evolved to deal with harmonics in power system. Figure 2 illustrates theAPF connected in power network with non-linear load. APF is a parallel compensating device connected in shunt to the PCC for harmonic compensation. APF is connected through interfacing impedance, to PCC. Harmonics generated from non-linear load are compensated by currents from APF. APF identifies the harmonic quantity and generates corrective back (compensating) currents to compensate the identified harmonics to improve the power quality of power network.

2.2. d-q Reference based APF in Power Network

The compensating currents from APF are generated from d-q reference theory and the control flow algorithm is shown in figure 3. Three-phase load currents and voltages from the power network are taken as inputs ford-q reference theory. Three phase currents are transformed to balanced and stationary two-phase parameters using Clarkes' transformation (as defined in equations (1) and (2)) and further to rotating orthogonal system using Parks transformation (as defined in equations (3) and (4)).

$$I_\alpha = 2/3(I_a) - 1/3(I_b - I_c) \quad (1)$$

$$I_\beta = 2/\sqrt{3}(I_b - I_c) \quad (2)$$

$$I_d = I_\alpha cos\theta + I_\beta sin\theta \quad (3)$$

$$I_q = I_\beta cos\theta - I_\alpha sin\theta \quad (4)$$

DC voltage is controlled by comparing actual and reference DC voltage and further by processing through PI controller. The 'd' component obtained after Parks' transformation is passed through high pass filter and further compared to the output of DC voltage control and thus the obtained signal along with 'q'component and 'zero' component are processed for inverse Parks' transformation (as in equations (5) and (6)) and inverse Clarkes' transformation (as in equations (7), (8) and (9)) to generate three-phase reference APF currents. The sinusoidal angular displacement information required for forward and inverse transformations are sent from phase-locked loop (sensing voltage signal).

$$I_\alpha = I_d \cos(\theta) - I_q \sin(\theta) \quad (5)$$

$$I_\beta = I_q \cos(\theta) - I_d \sin(\theta) \quad (6)$$

$$I_a = I_\alpha \quad (7)$$

$$I_b = \frac{-I_\alpha + \sqrt{3}I_\beta}{2} \quad (8)$$

$$I_c = \frac{-I_\alpha - \sqrt{3}I_\beta}{2} \quad (9)$$

The reference three-phase reference APF currents are compared with actual APF currents using hysteresis controller and gate pulses for APF are generated. Complete representation of d-q reference frame theory based APF is shown in figure 4.

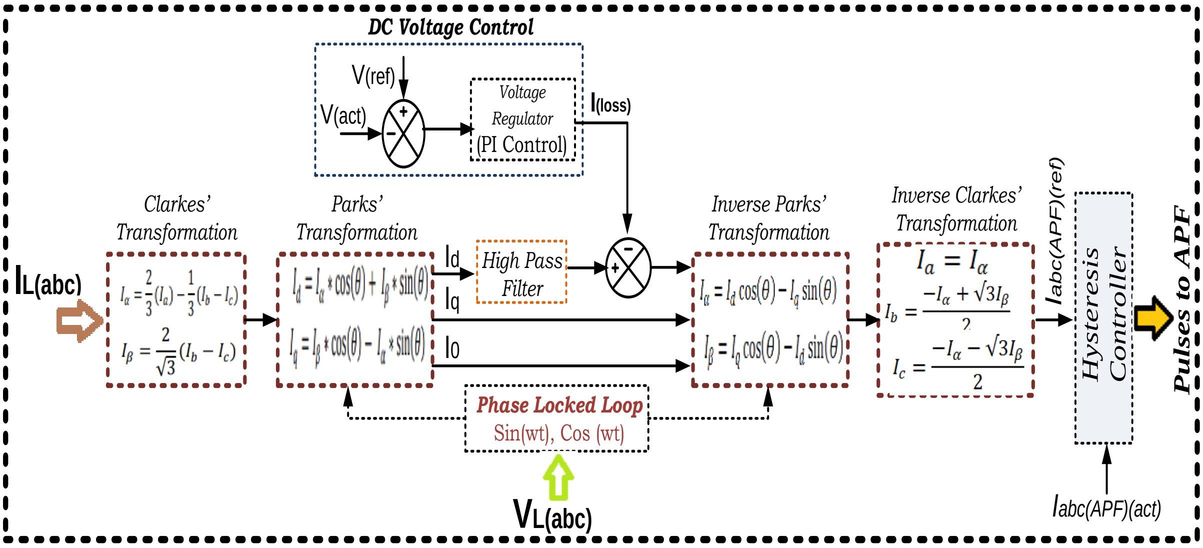

Figure 3. d-q reference theory for compensation of harmonics

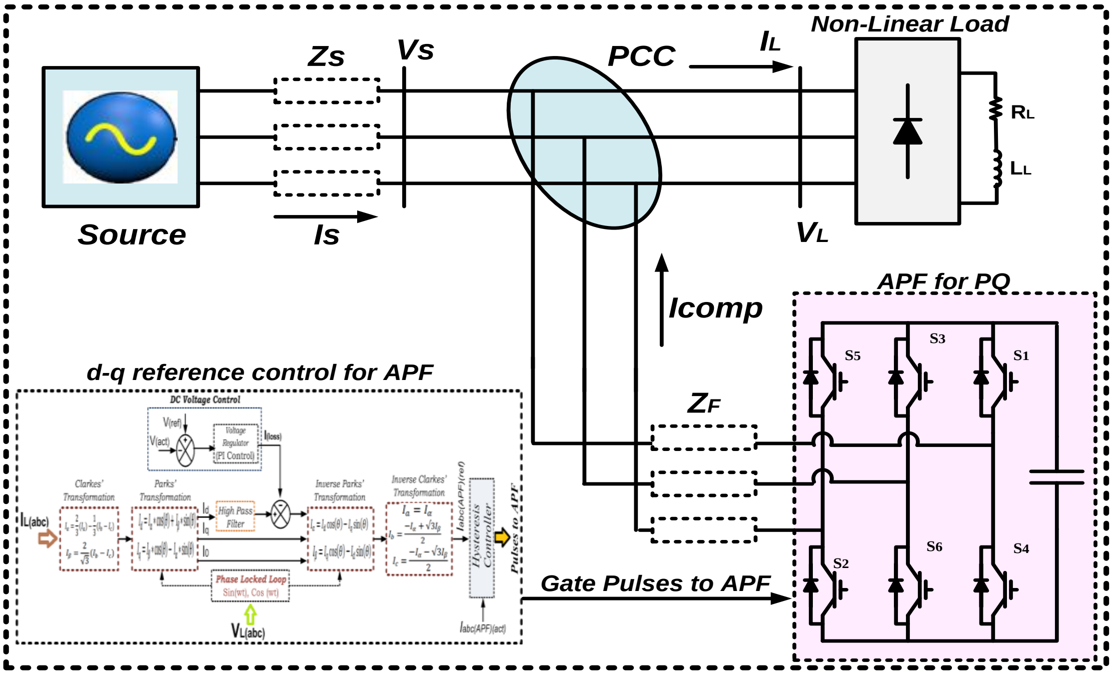

Figure 4. Complete representation of d-q reference frame theory based APF in power network.

3. Parallel APF for the Compensation of Harmonics

3.1. Parallel APF Configuration for Power Quality

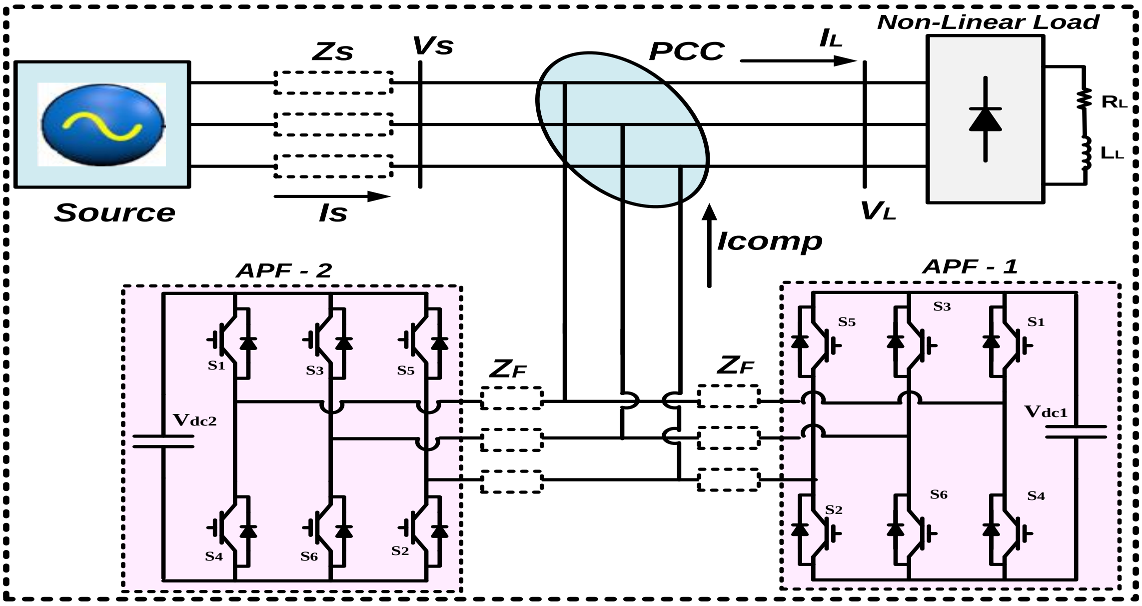

Figure 5. Parallel APF in power system

APF is a parallel compensating device connected in shunt to the PCC for harmonic compensation. A single APF in power system takes the complete load of generating compensation currents. If any problem identified in the APF, compensation process will become halt. To pursue the mentioned problem and increase the reliability in compensating system, parallel APF configuration is designed.

Figure 5 illustrates the parallel APF connected in power network with non-linear load. Two APFs in parallel are connected through interfacing impedances at PCC of power network. The complete load of generating compensation currents will be shared by two APFs and this decreases the burden and rating of each APF, eventually reducing the rating of switches in particular APF.

Switching losses are reduced with the presence of parallel APF configuration. Further, if one of the APF fails in operation, the other APF fills the gap and generates required compensating currents to power system. this phenomenon increases the reliability of the compensating system.

3.2. Modified d-q Reference based Parallel APF in Power Network

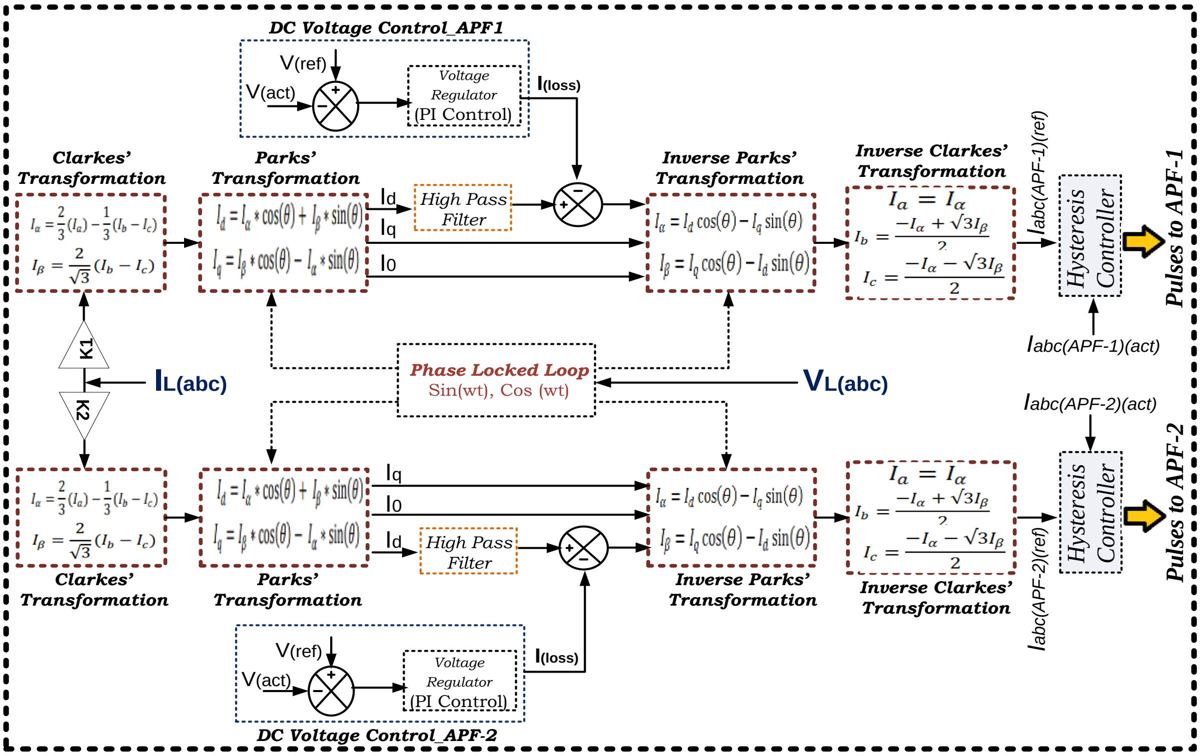

Figure 6. Modified d-q reference theory for parallel APF

The compensating currents from parallel APF are generated from modified d-q reference theory and the control flow algorithm is shown in figure 6. Procedure to generate gate pulses to APF-1 and APF-2 is similar. Three-phase load currents and voltages from the power network are taken as inputs ford-q reference theory. Three phase currents are transformed to balanced and stationary two-phase parameters using Clarkes' transformation (as defined in equations (1) and (2)) and further to rotating orthogonal system using Parks transformation (as defined in equations (3) and (4)) explained in the previous section.

DC voltage is controlled (differently for two APFs) by comparing actual and reference DC voltage and further by processing through PI controller.

Here in this control load current and source voltage are measure using voltage and current sensors. The accuracy of the data depends on quality of the sensors. Once the data collected it will be processed though DSP processor where our control strategy is defined.

The 'd' component obtained after Parks' transformation is passed through high pass filter and further compared to the output of DC voltage control and thus the obtained signal along with 'q' component and 'zero' component are processed for inverse Parks' transformation (as in equations (5) and (6)) and inverse Clarkes' transformation (as in equations (7), (8) and (9)) to generate three-phase reference currents for APF-1 and APF-2.

The reference three-phase reference APF-1 currents are compared with actual APF-1 currents using hysteresis controller and gate pulses for APF-1 are generated. The reference three-phase reference APF-2 currents are compared with actual APF-2 currents using hysteresis controller and gate pulses for APF-2 are generated. Complete schematic arrangement of parallel APF with modified d-q reference control is shown in figure 7.

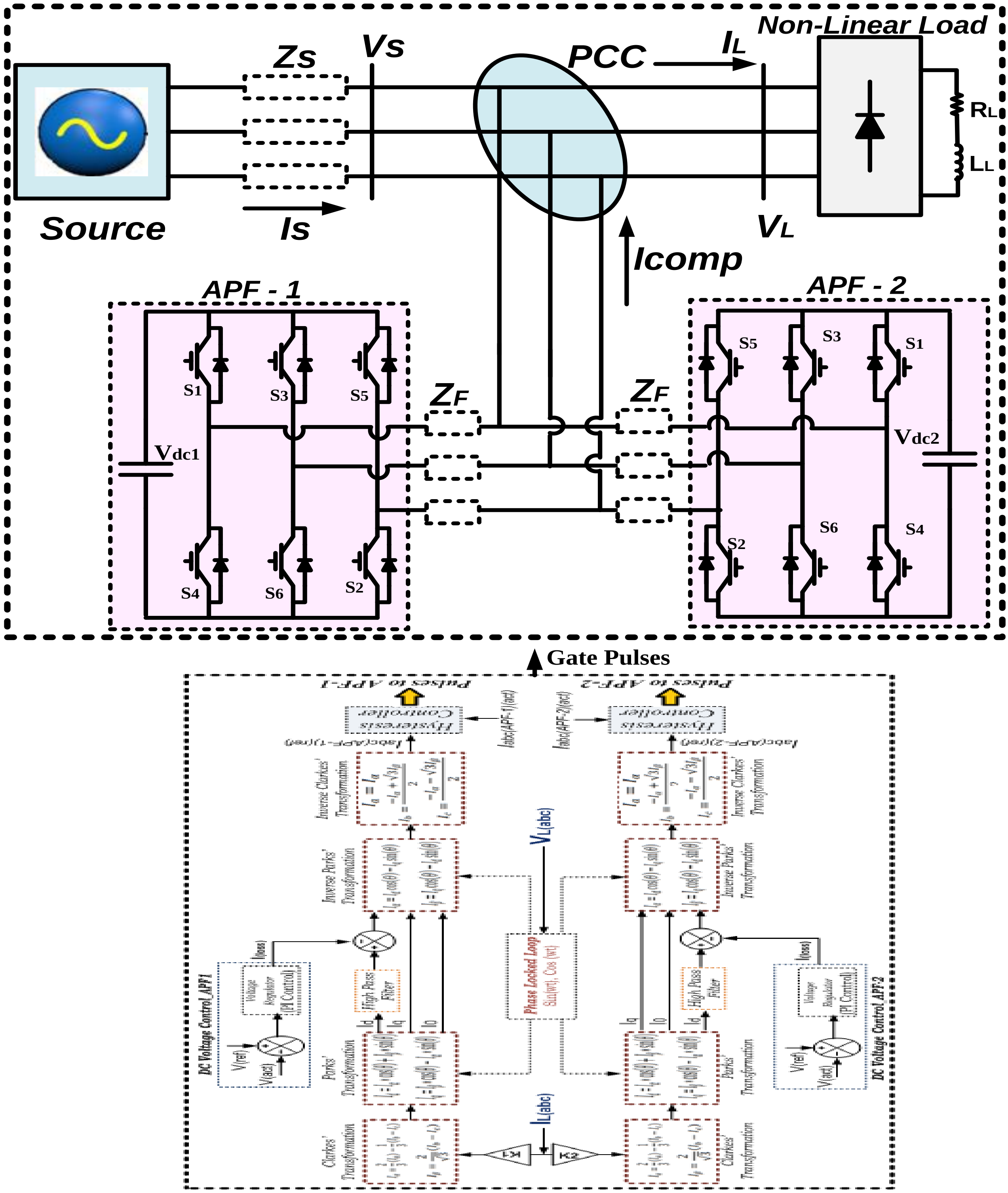

Figure 7. Complete arrangement of parallel APF with modified d-q reference control

4. Results Analysis

The application we considered here, is not very sensitive application. Yes if we have multiple sensing devices accuracy comes down, but here our aim is to bring down the THD less than 5 %. If it is 4 or 3 or 2 % the variation is very small.

Table-1 illustrates the system parameters used for developing the Simulink models.

Table 1. System parameters

Parameter	Value
Source Voltage	415V, 50 Hz
Source Impedance	0.1Ohms, 0.9mH
DC-Link Capacitor	4000µF
Interfacing Impedance	0.1Ohms, 5mH

4.1.Power System with Single APF

Source voltage with 320V is shown in figure 8. Figure 9 illustrates the source current with 12A. Source current is distorted by small magnitude even though the load is non-linear in nature.

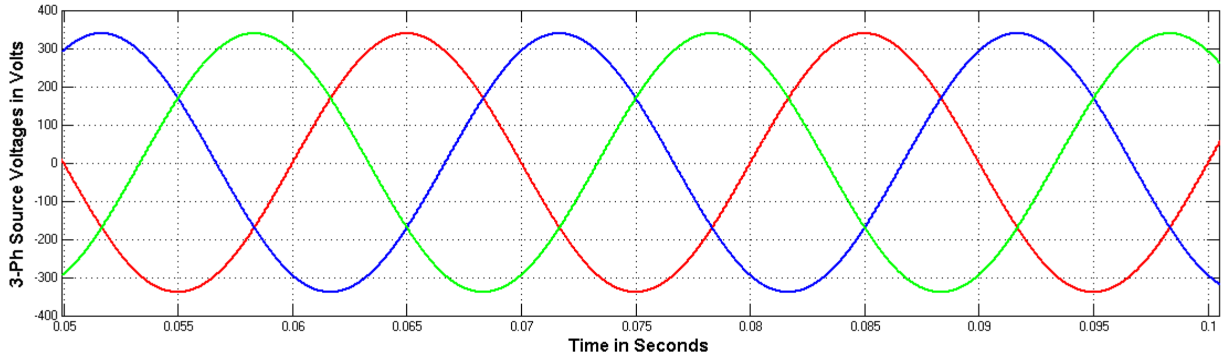

Figure 8. Source Voltage

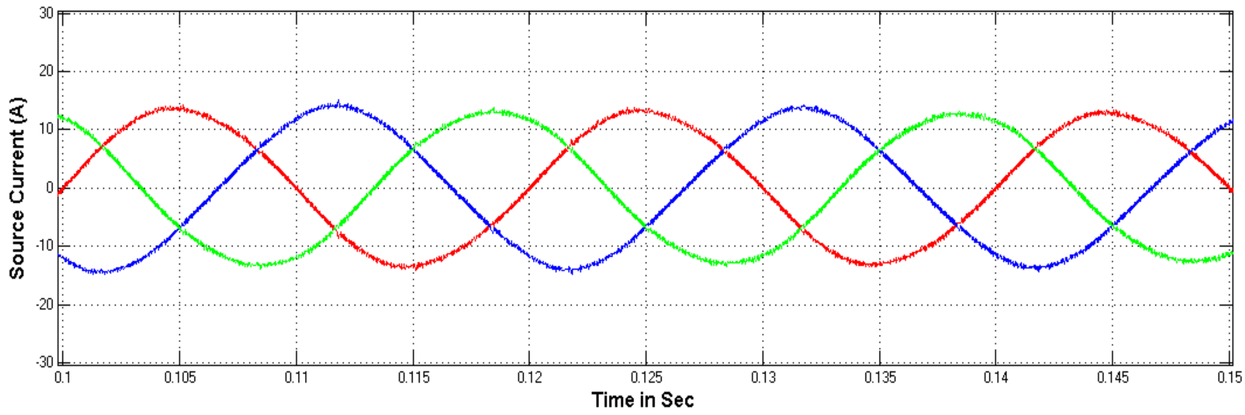

Figure 9. Three-phase source Currents

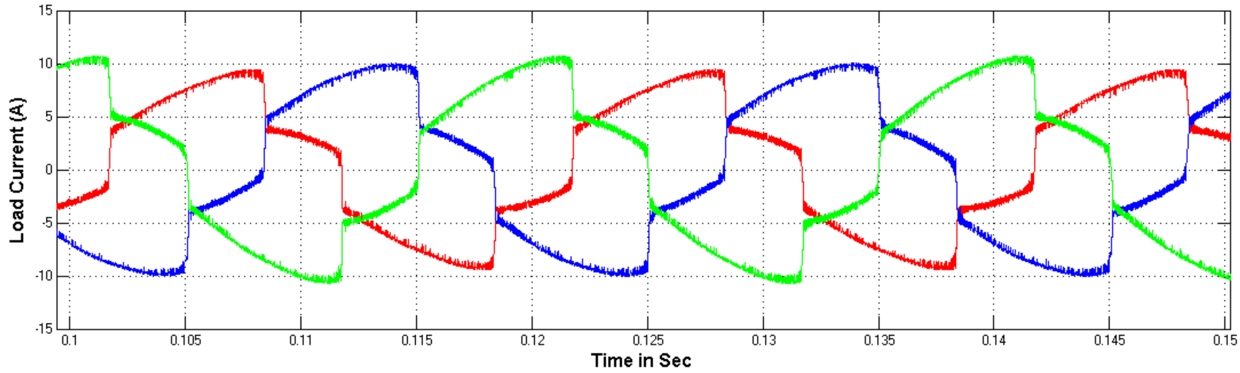

Figure 10. Three-phase load Currents

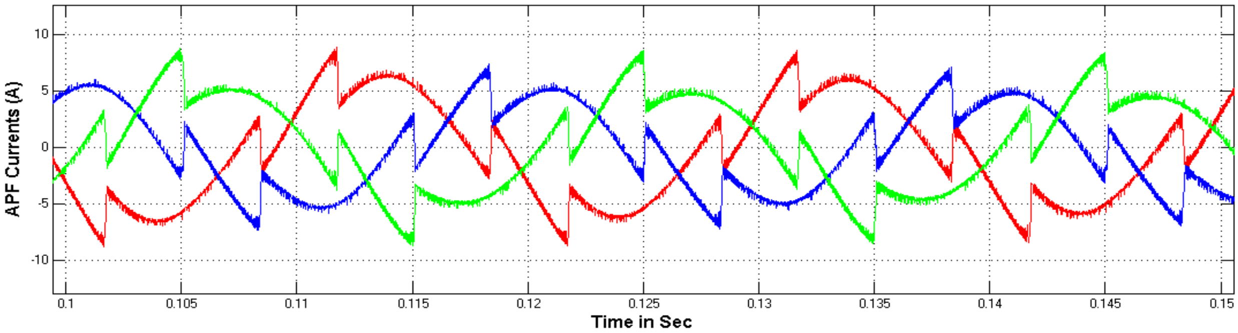

Figure 11. Filter Compensating currents from APF

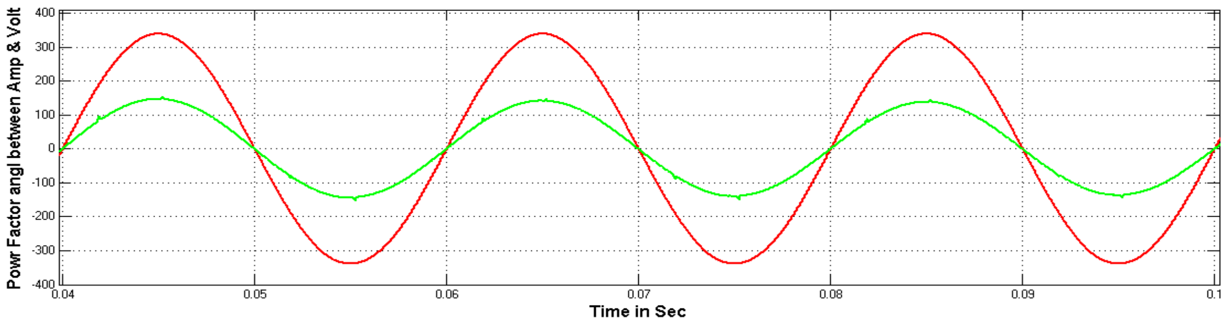

Figure 12. Source current and voltage phase angle

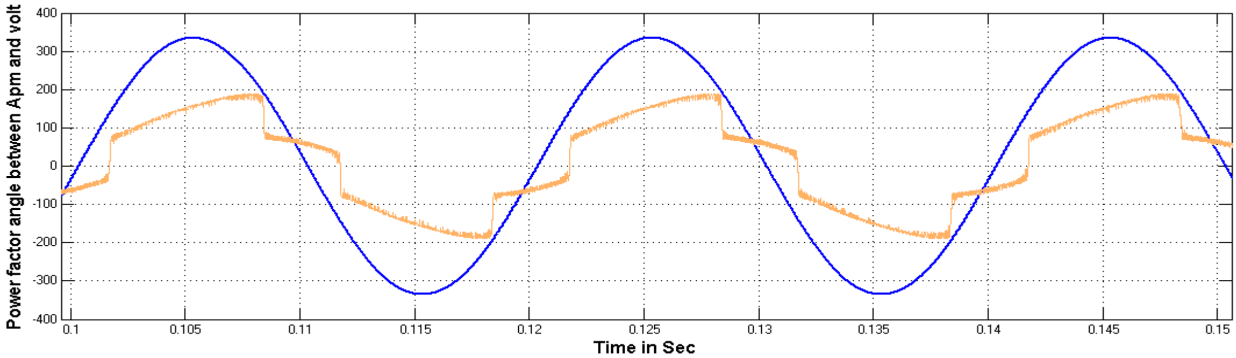

Figure 13. Load current and voltage phase angle

The three-phase load currents with 10 amps magnitude are shown in figure 10.Due to Nonlinear load Current is distorted.

Filter currents from APF are shown in figure 11. These filter currents compensate the harmonics in source current at PCC. Only single APF is present inthe power network and hence the total compensation currents are sent from single APF.

The phase angle difference between source current and voltage is shown in figure 12. Phase angle difference is almost zero which gives out nearly unity power factor. The phase angle difference betweenload current and voltage is shown in figure 13. Load current and voltage are displaced and yields very low power factor. Current signalsof load and source are added with gain for clear illustration.

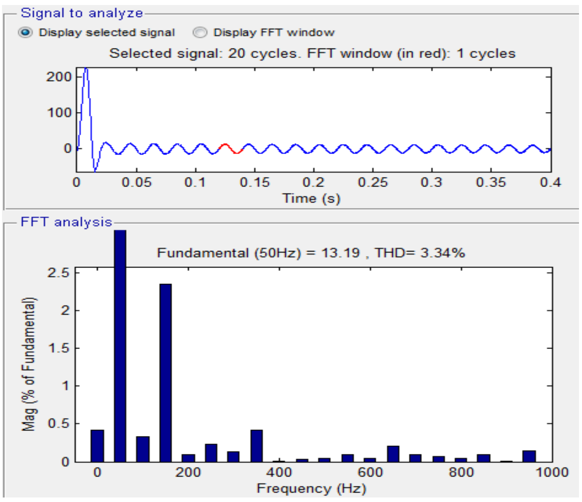

Figure 14. THD in source current

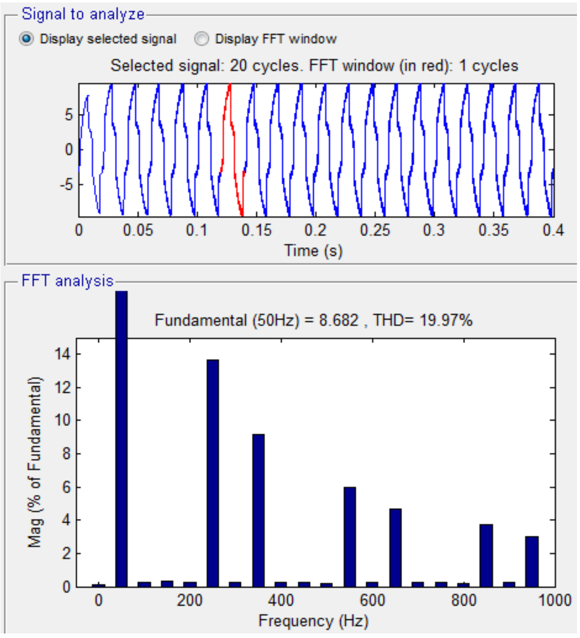

Figure 15. THD in load current

The harmonic distortions in Source side and load side currents are shown in figure 14 and figure 15 respectively. Load being non-linear distorts load current by 19.97%, while presence of APF forms the source current distorted by 3.34% with respect to fundamental.

4.2. Parallel APF with Equal Sharing

Source voltage with 320V is shown in figure 16. Figure 17 illustrates the source current with 12A. Source current is distorted by small magnitude even though the load is diode bridge load.

The three-phase load currents with 10 amps magnitude are shown in figure 18. Load current is distorted because the load is diode bridge.

Filter currents from APF-1 and APF-2 are shown in figure 19. These filter currents compensate the harmonics in source current at PCC. The control gain of load current input to control algorithm is set as ‘0.5’ for both APF-1 and APF-2. The totalcompensation current is shared among two APFs and compensation current of each APF is 5A (equal). Peak spike of compensation current is considered as reference for comparison.

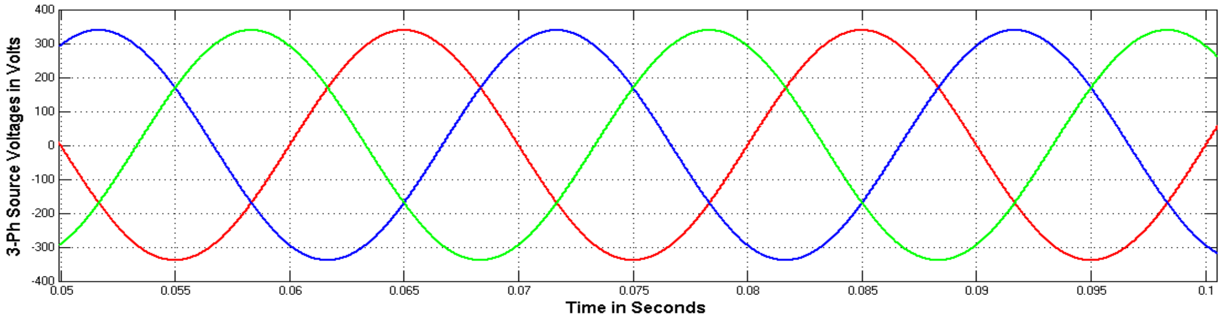

Figure 16. Source Voltage

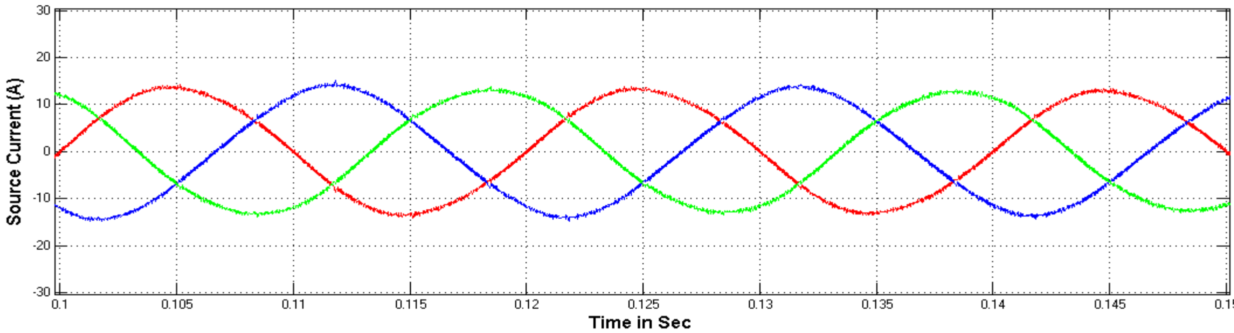

Figure 17. Three-phase source Currents

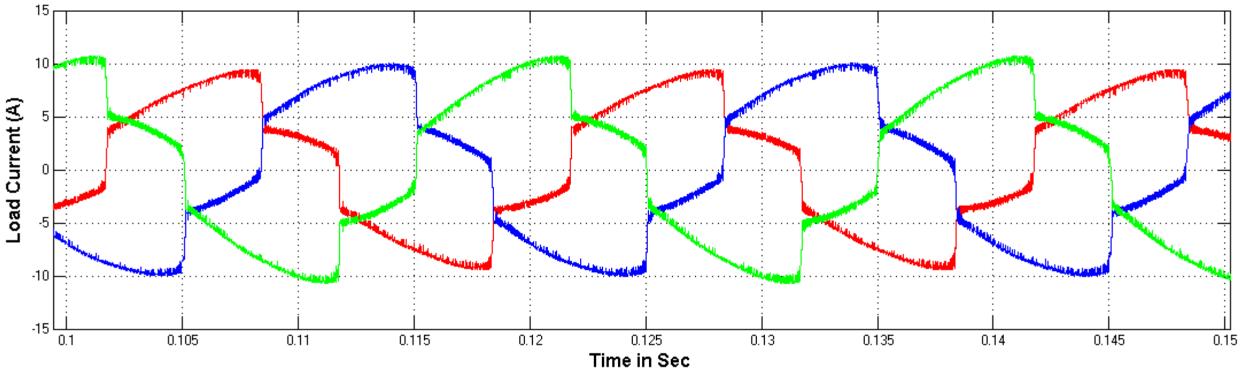

Figure 18. Nonlinear load current

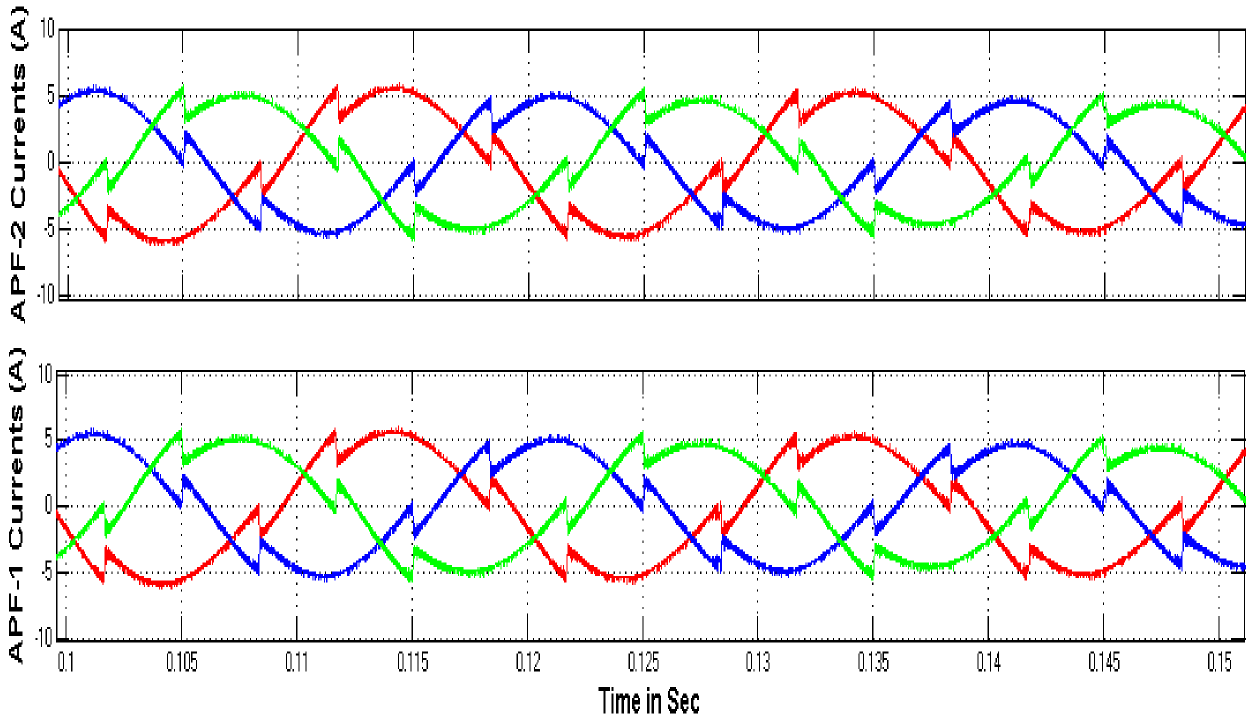

Figure 19. Filter currents from APF-1 and APF-2

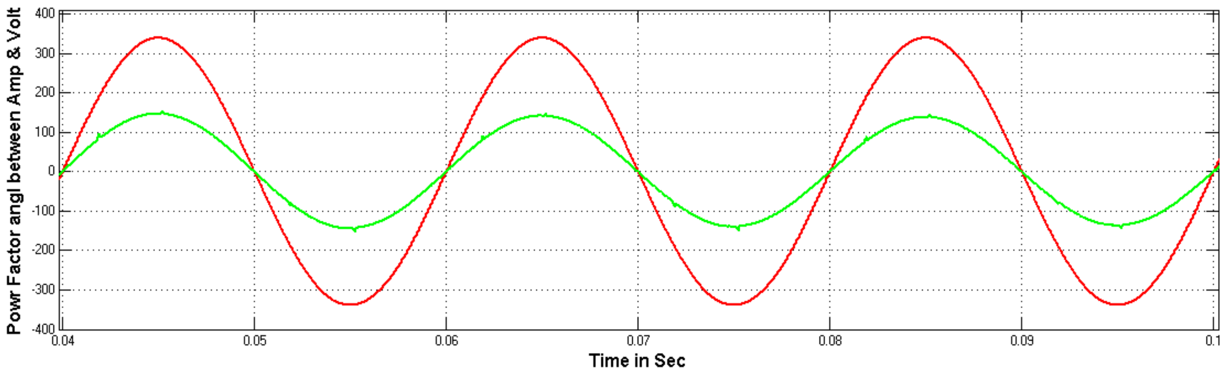

Figure 20. Source current and voltage phase angle

The phase angle difference between source current and voltage is shown in figure 20. Phase angle difference is almost zero which gives out nearly unity power factor. The phase angle difference betweenload current and voltage is shown in figure 21. Load current and voltage are displaced and yields very low power factor. Current signalsof load and source are added with gain for clear illustration.

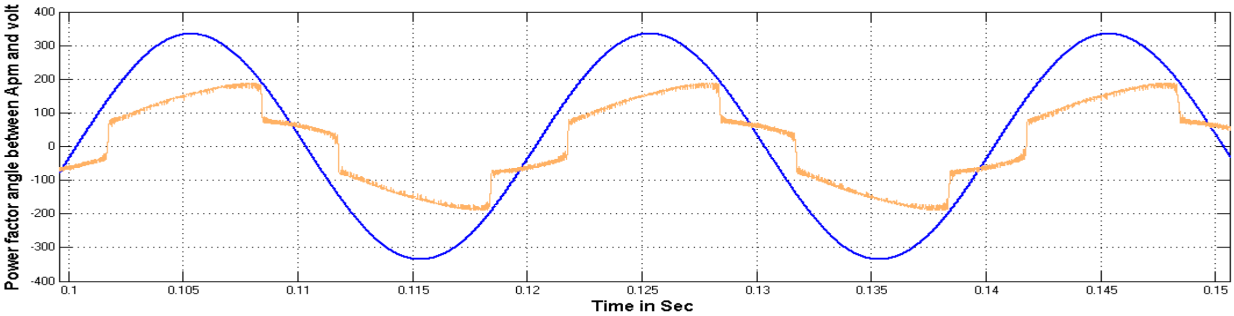

Figure 21. Load current and voltage phase angle

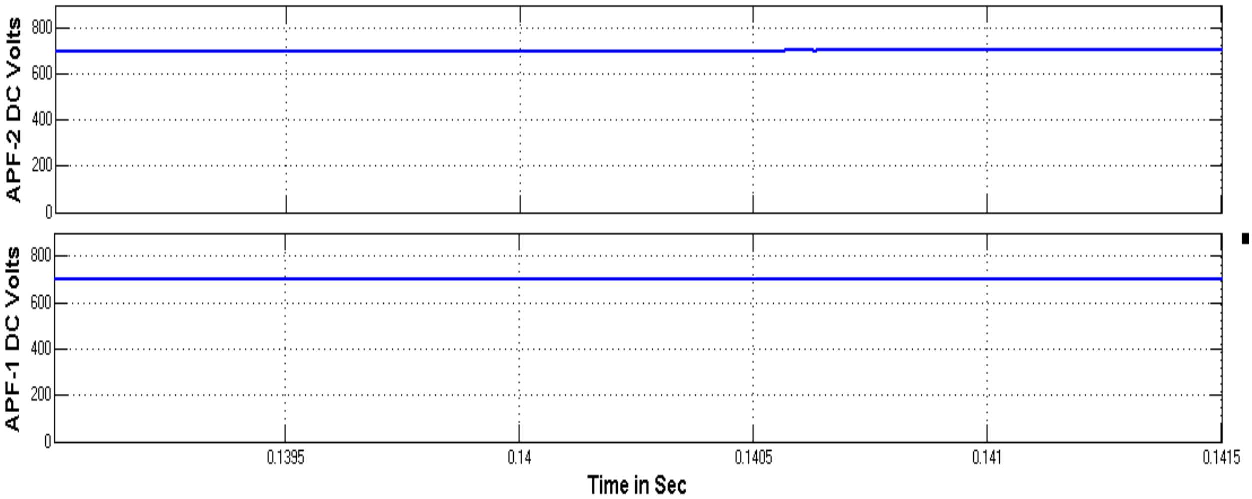

Figure 22. DC link Voltage of APF-1 and APF -2

The DC link voltage of APF-1 and APF-2 are shown in figure 22. Two APF's are driven with constant and equal DC link voltage of 700V.

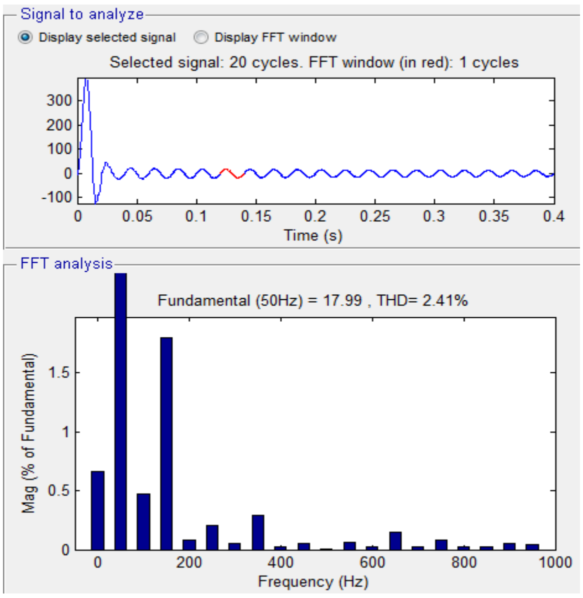

Figure 23. THD in source current

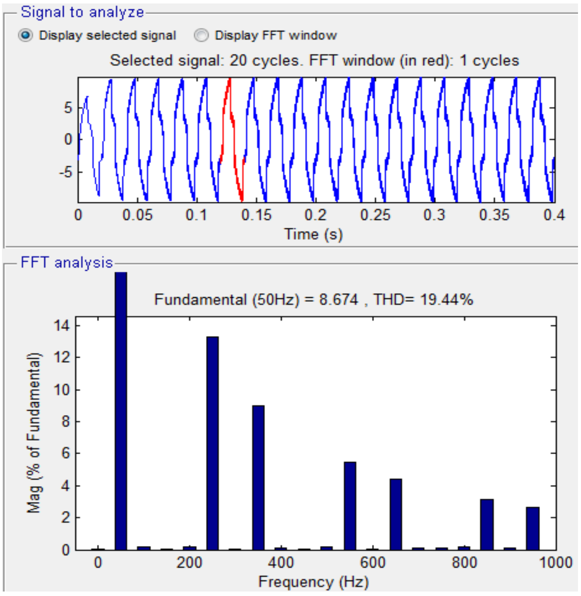

Figure 24. THD in load current

The harmonic distortion of source and load current are shown in figure 23 and figure 24 respectively. Load being non-linear distorts load current by 19.44%, while presence of APF forms the source current distorted by 2.41% with respect to fundamental.

4.3. Parallel APF with Unequal Sharing

Source voltage with 320V is shown in figure 25. Figure 26 illustrates the source current with 12A. Source current is distorted by small magnitude even though the load is diode bridge.

Filter currents from APF-1 and APF-2 are shown in figure 28. These filter currents compensate the harmonics in source current at PCC. The control gain of load current input to control algorithm is set as '0.75 and '0.5' for APF-1 and APF-2. The total compensation current is shared but unequal among two APF's, compensation current of APF-1 is 7.5A and of APF-2 is 2.5A. peak spike of compensation current is considered as reference for comparison.

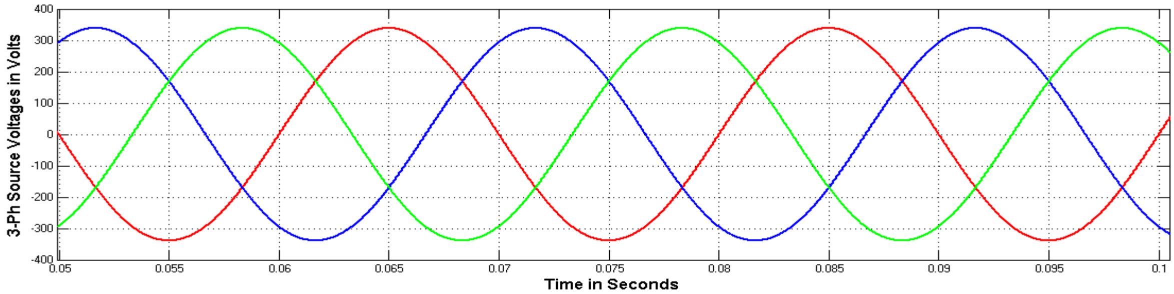

Figure 25. Source Voltage

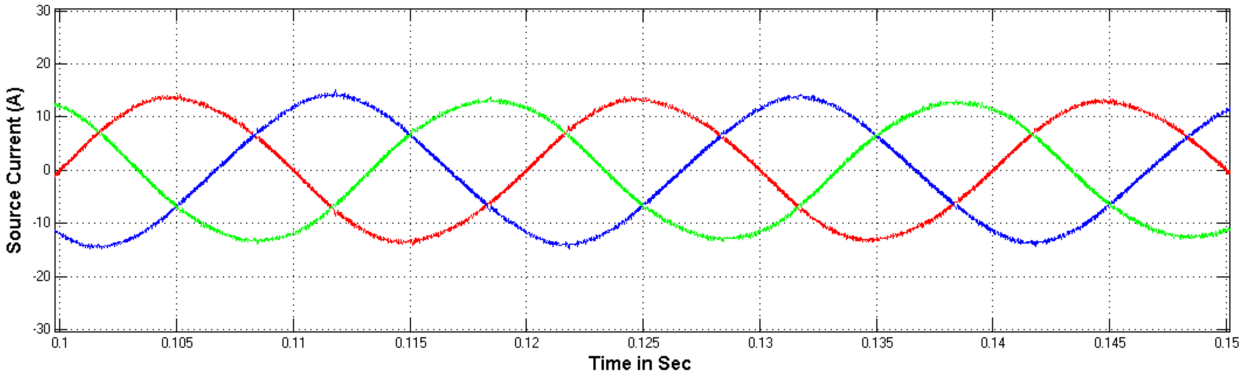

Figure 26. Three-phase source Currents

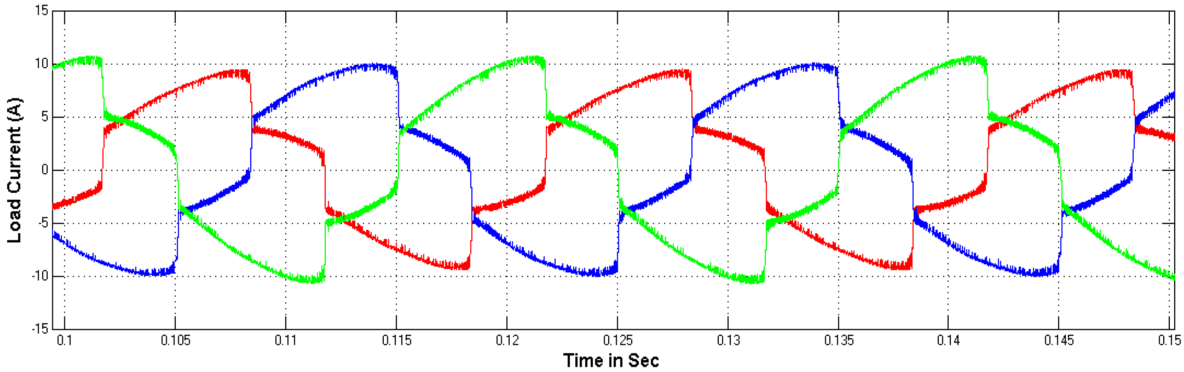

Figure 27. Nonlinear load Currents

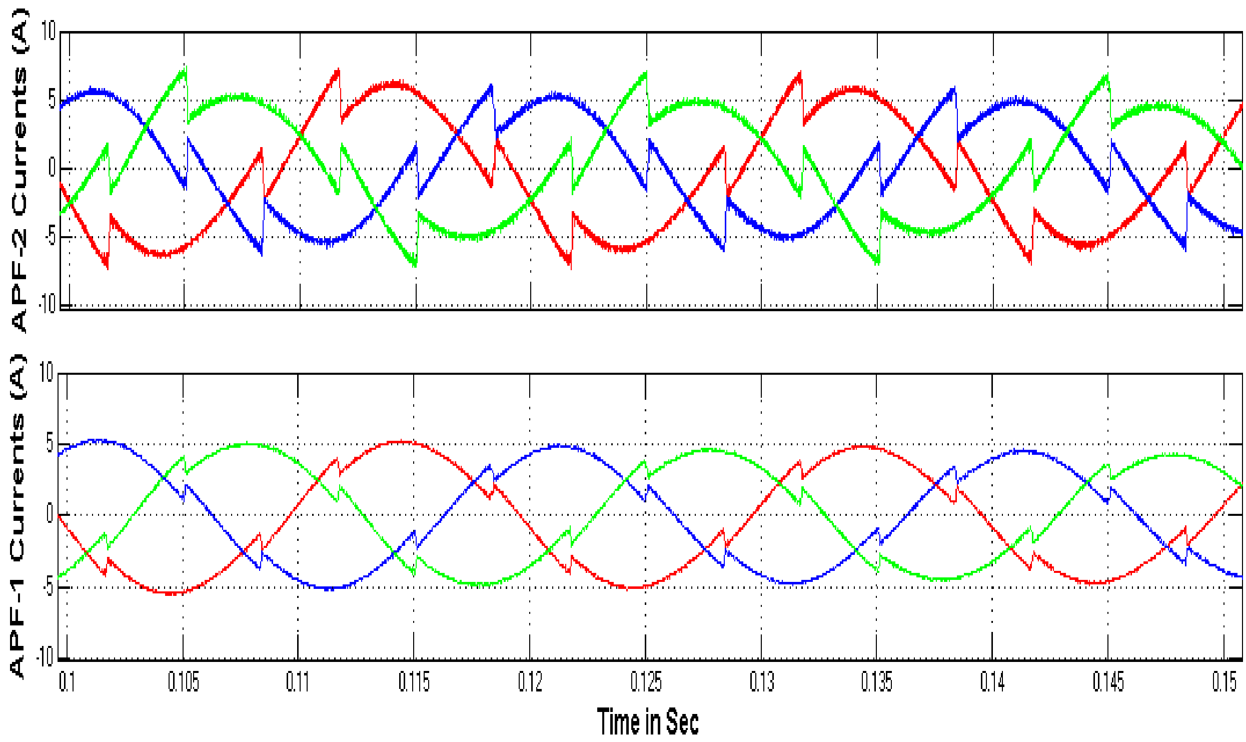

Figure 28. Filter currents from APF-1 and APF-2

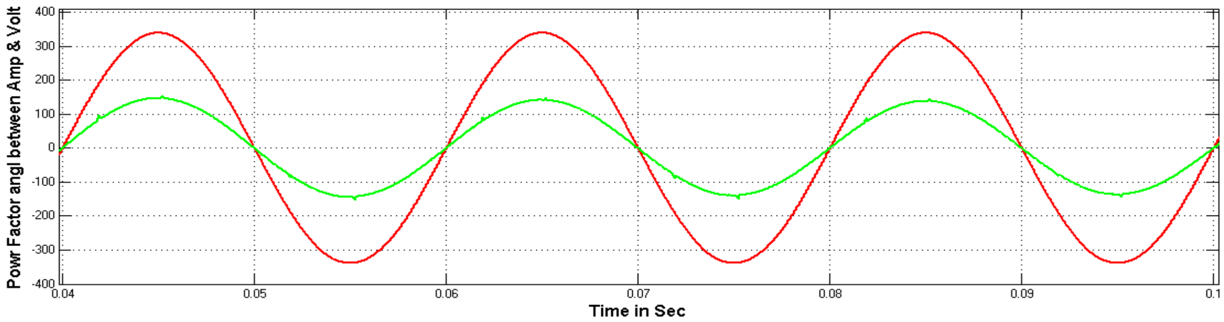

Figure 29. Source current and voltage phase angle

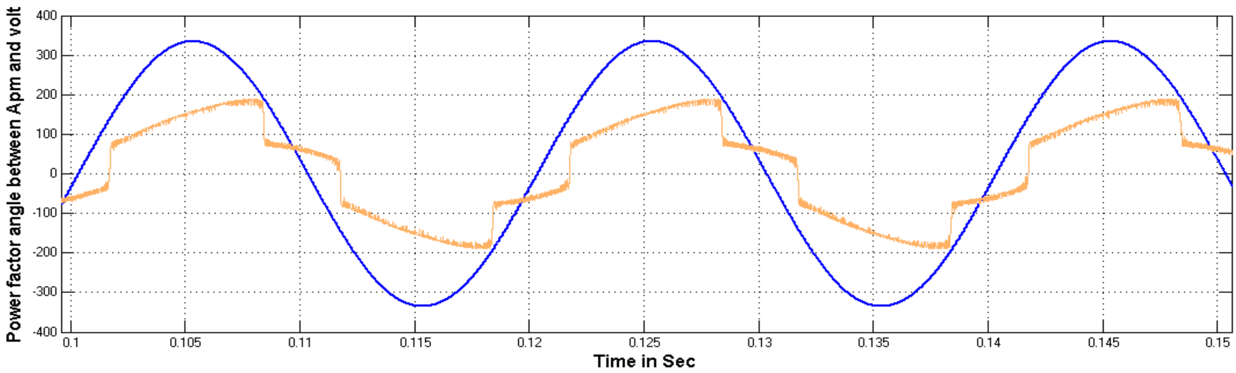

Figure 30. Load current and voltage phase angle

The phase angle difference between source current and voltage is shown in figure 29. Phase angle difference is almost zero which gives out nearly unity power factor. The phase angle difference between load current and voltage is shown in figure 30. Load current and voltage are displaced and yields very low power factor. Current signalsof load and source are added with gain for clear illustration.

The DC link voltage of APF-1 and APF-2 are shown in figure 31. Two APFs are driven with constant and equal DC link voltage of 700V.

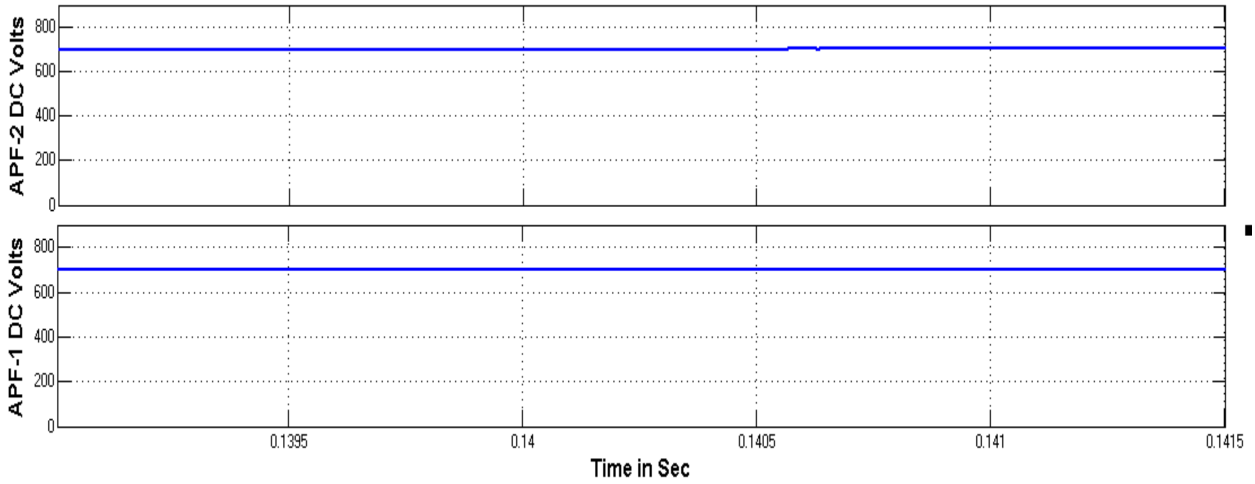

Figure 31. Load current and voltage phase angle

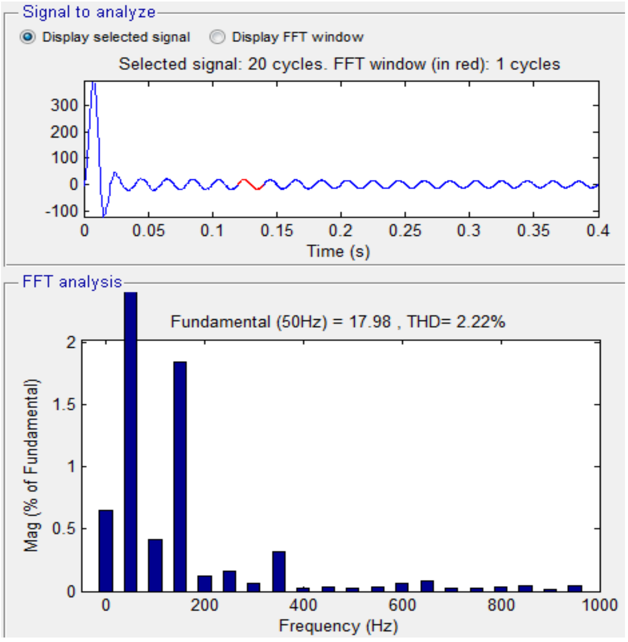

Figure 32. THD in source current

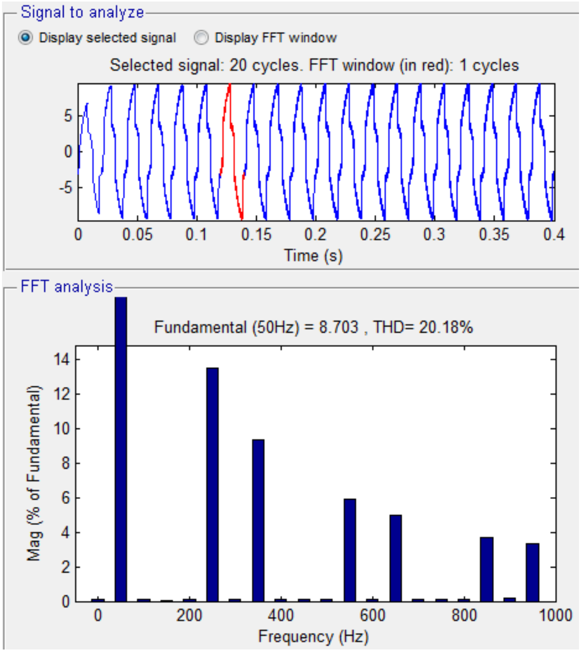

Figure 33. THD in load current

The harmonic distortion of source and load currents are shown in figure 32 and figure 33 respectively. Load being non-linear distorts load current by 20.18%, while presence of APF forms the source current distorted by 2.22% with respect to fundamental.

Table-2 illustrates the THD values of source current and load current. The source current is within standard limit and load current is distorted by huge magnitude since the load is non-linear.

Table2. Total harmonic Distortion analysis

	THD in Source Current	**THD in Load Current**
Single APF	3.34 %	19.97 %
Parallel APF – equal sharing	2.41	19.44
Parallel APF – unequal sharing	2.22	20.18

Conclusion

Duo to the power electronic control loads are main cause for production of harmonics and reactive power issues in power system network. Theses harmonics will affect the PCC connected other consumers and degraded the system efficiency. To improve this one can use FACTS controller in the network. This paper proposes the parallel APF configuration for harmonic compensation in power system. Single APF and parallel APF performances are presented and parallel APFs share the compensating load current and stress on the individual VSIs reduces with increased reliability.THD analysis is presented and in all the conditions, the source current THD is within specified limit of 5% due to the presence of APF. Load being non-linear in nature, load current is distorted by much higher. Control strategy (d-q reference based) for controlling parallel APF is illustrated to generate gate pulses to APFs. Here d-q reference theory is explained in detail. For control strategy we need Load current, Source Voltage and DC link voltage which are measured using various sensors and send to DSP processor. Even in the modified d-q reference the signals to be measured are same.

The advantage of using parallel APF circuit will recue the cost and increase the reliability of the power system network.

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