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A Critical Evaluation of Power Quality Features using Dual APF under Grid Interfaced DG Scheme

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Abstract

This paper presents the concept of power quality enhancement reducing the harmonic distortion with power distribution system consisting of balanced and unbalanced non-linear type of loads. This paper presents power quality enhancement using dual active power filters (APF's) under grid connected distributed generation scheme. Acive power filters effectively generate compensating signals for harmonic abolition and this paper presents APF for compensating currents to be induced in to distribution grid for harmonic elimination under balanced and unbalanced non-linear load conditions. Distributed generation (DG) feeds the grid and the scheme of grid interfaced DG was explained. APF is controlled using instantaneous P-Q theory and DG inverter is controlled using simple control strategy. Proposed system was developed and the results are obtained using MATLAB/SIMULINK software.

Keywords: *dual APF, harmonics, power quality, grid interfacing, distributed generation*

1. Introduction

Electric power systems worldwide are rapidly undergoing a transition from regulated to the deregulated structure. Majority of the electric power generation is from conventional fossil fuels like coal, natural gas etc. Although investment in major capital projects such as generation are sufficiently encouraged, the rate at which these investments are implemented may be mismatched with the power demand growth rate [1]. The other problem with these massive investments is environmental issues. These investments require large areas of land to be cleared. Placing power generating stations right-of-the-way for transmission or distribution lines which generally changes the ecosystem of the places where the investment is going to be located increases transmission losses. To overcome these disadvantages, installation of minor power generation equipment at load facilities in power distribution system called distributed generation (DG) [2-4] which do not need much investment but also can offer environmental, technical and economic assistance can serve the purpose to increase the system performance in power distribution system. Distributed generation generally means more than one power source feeding the same loads including sources at multiple locations but it can also mean stand alone or isolated generation at the point of use [5-6]. Position and sizing of distributed generation can affect the system performance and in order to obtain extent benefits from DG, these parameters should be given atmost priority. Multiple generation sources tied together means that sufficient power can be made available for the entire load where no one generator is sufficient by itself. This allows sufficient redundancy to take units off line for maintenance or where one or more fail and also there can be additional reserve capacity for unexpectedly large loads.

Power electronic appliances are used widely in industrial, commercial and consumer environment. These appliances generate harmonics and reactive power in the utility system. The improvement of power quality by reducing harmonics has become an important issue nowadays [7-8]. Conventionally, passive LC filters have been used to eliminate line current harmonics and to improve the power factor. But the passive filters have many disadvantages, such as fixed compensation, large size and resonance problems. To solve above mentioned problems, active power filters were introduced (Figure 1).

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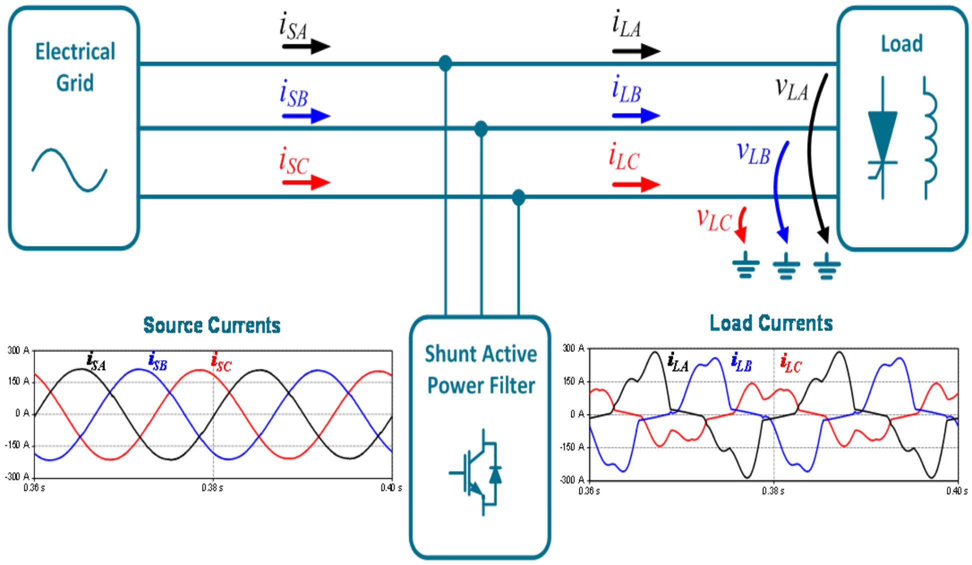

Figure 1. Shunt active power filter

Power quality can be defined as the interaction of electrical power with electrical equipment. If electrical equipment operates correctly and reliably without being damaged or stressed, we would say that the electrical power is of good quality. On the other hand, if the electrical equipment malfunctions, is unreliable, or is damaged during normal usage, we would suspect that the power quality is poor. Power quality determines the fitness of electrical power to consumer devices. The presence of harmonic waveforms in power system is the main cause of power quality problems. Harmonics have a number of undesirable effects on the distribution system. It causes excessive voltage distortion, increased resistive losses or voltage stresses, reductions in ac motor efficiency and product quality etc in the power system.

With the widespread use of harmonic generating devices, the control of harmonic currents to maintain a high level of power quality is becoming increasingly important. An effective way for harmonic suppression is the harmonic compensation by using active power filter [9-12]. Active power filters are considered as a feasible solution for reducing current harmonics and reactive power due to their small size, no requirement for tuning and stable operation.

This paper presents the concept of power quality enhancement reducing the harmonic distortion with power distribution system consisting of balanced and unbalanced non-linear type of loads. This paper presents power quality enhancement using dual active power filters (APF's) under grid connected distributed generation scheme. Acive power filters effectively generate compensating signals for harmonic abolition but this paper describes APF for compensating currents to be induced in to distribution grid for harmonic elimination under balanced and unbalanced non-linear load conditions. Distributed generation (DG) feeds the grid and the scheme of grid interfaced DG was explained. Dual APF is controlled using instantaneous P-Q theory and DG inverter is controlled using simple controlled strategy. Proposed system was developed and the results are obtained using MATLAB/SIMULINK software.

2. APF for Harmonic Suppression in Grid-Tied DG Scheme in Distribution Network

2.1. APF in Grid-Tied DG in Distribution System with Balanced Non-Linear Load

The main power distribution system consists of main source with source impedance. The load is of non-linear nature and draws only non-linear components of currents from source currents leaving out harmonics in source currents. Harmonics in source components affects the functioning of other sensitive loads in the system and creates unwanted situation in power distribution system.

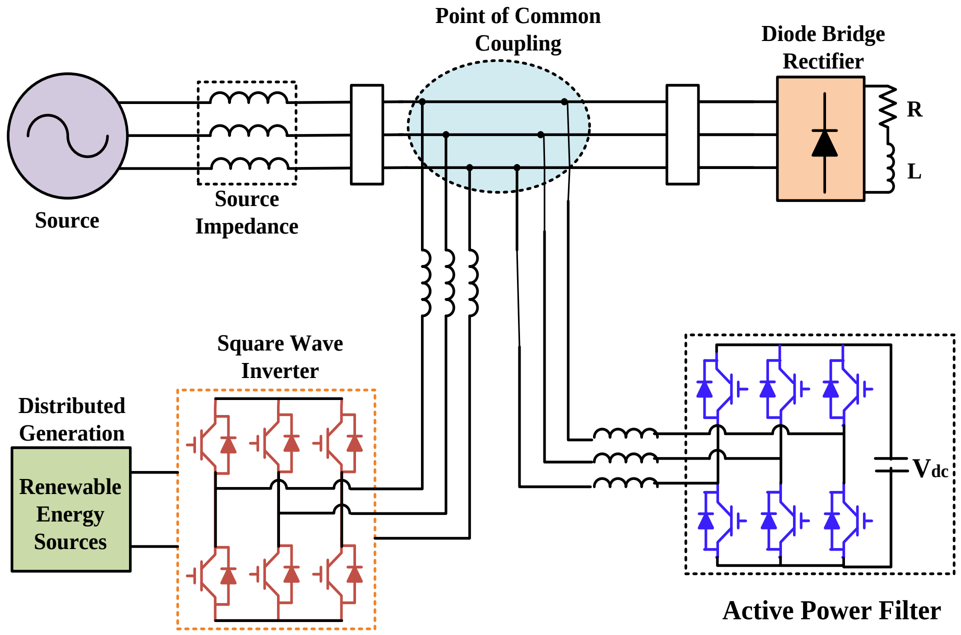

Figure 2. APF in grid-tied DG in distribution system with balanced non-linear load

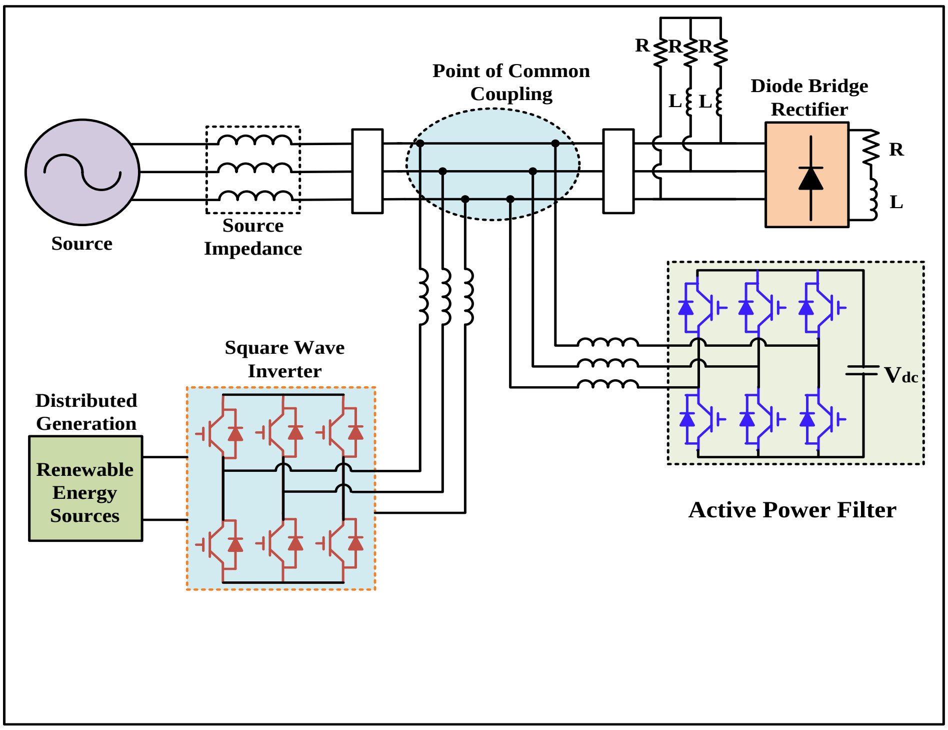

Figure 3. APF in grid-tied DG in distribution system with unbalanced non-linear load

Active power filters are a type of FACTS controllers connected in power system to suppress harmonic distortion in source components by inducing compensating signals in to distribution system. A single APF placed in distribution system is responsible to suppress the complete harmonic distortion in source components which in turn increases the stress and load on APF. Two parallel APF's instead of single APF in power distribution system can serve better than aforementioned single APF reducing the stress and load on individual APF's. Two parallel APF's share the load for sending compensating currents in to power distribution system. Two parallel APF configuration connected at PCC in power distribution system with balanced non-linear load is shown in Figure 2. Each APF is interfaced to distribution system through filter circuit. Each APF consists of voltage source converter driven with a small DC source. Two APF's are controlled with a common control strategy sending gate pulses to voltage source converters. In this context, the second APF is used as DG interfacing inverter.

2.2. Dual APF in Grid-Tied DG in Distribution System with Unbalanced Non-Linear Load

A three-phase power system is called balanced or symmetrical if the three-phase voltages and currents have the same amplitude and are phase shifted by 120° with respect to each other. If either or both of these conditions are not met, the system is called unbalanced or asymmetrical. Unbalance in any system can cause serious damages. APF in grid-tied DG in distribution system with unbalanced non-linear load is shown in Figure 3. The parallel APF's compensate the unbalance in the system and makes source current to be balanced.

3. Control Strategies for DG inverter and APF

3.1. Instantaneous P-Q Control Theory for APF

Instantaneous active and reactive power theory is a general theory to control a voltage source converter to produce gate pulses for harmonic suppression at point of common coupling inducing compensating signals. This theory was developed by Akagi in 1980's. This theory is also called as instantaneous power theory or P-Q theory. The schematic control flow of P-Q theory is shown in Figure 4.

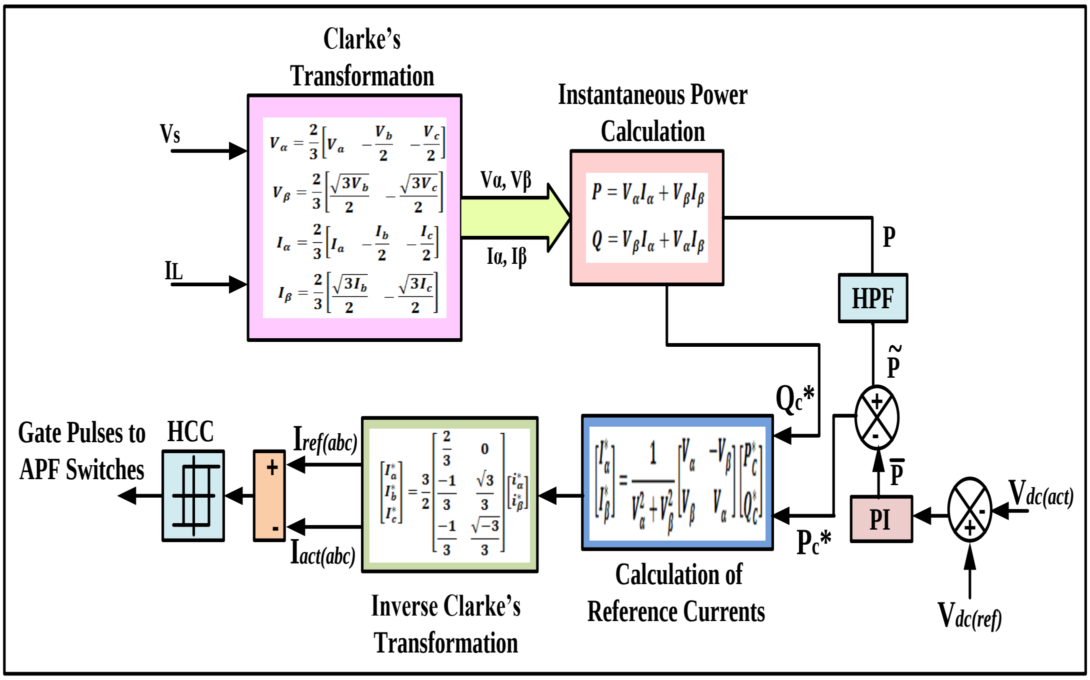

Figure 4. Instantaneous P-Q control theory for Dual APF

Instantaneous active and reactive power theory is a general theory to control a voltage source converter to produce gate pulses for harmonic suppression at point of common coupling inducing compensating signals. This theory was developed by Akagi in 1980's. This theory is also called as instantaneous power theory or P-Q theory. The schematic control flow of P-Q theory is shown in Figure 4.

Instantaneous active and reactive power theory involves the transformation of stationary a-b-c frame to orthogonal stationary α-β frame by using Clarke's transformation.

$$V_{\alpha\beta} = \frac{2}{3}\begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (1)$$

$$I_{\alpha\beta} = \frac{2}{3}\begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} I_{la} \\ I_{lb} \\ I_{lc} \end{bmatrix} \quad (2)$$

$$V_\alpha = \frac{2}{3}\left[V_a \quad -\frac{V_b}{2} \quad -\frac{V_c}{2}\right] \quad (3)$$

$$V_\beta = \frac{2}{3}\left[\frac{\sqrt{3}V_b}{2} \quad -\frac{\sqrt{3}V_c}{2}\right] \quad (4)$$

$$I_\alpha = \frac{2}{3}\left[I_a \quad -\frac{I_b}{2} \quad -\frac{I_c}{2}\right] \quad (5)$$

$$I_\beta = \frac{2}{3}\left[\frac{\sqrt{3}I_{lb}}{2} \quad -\frac{\sqrt{3}I_{lc}}{2}\right] \quad (6)$$

Three-phase voltage signals in a-b-c frame is converted to α-β frame as indicated in Equation (1) and three-phase current signals in a-b-c frame is converted to α-β frame as indicated in Equation (2).

Voltages and currents in α-β frame are sent for instantaneous power calculations. Active and reactive powers are calculated from α-β frames of voltage and currents as in (7) and (8) represented as (9).

$$P = V_\alpha I_\alpha + V_\beta I_\beta \quad (7)$$

$$Q = V_\beta I_\alpha - V_\alpha I_\beta \quad (8)$$

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix}\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \quad (9)$$

P and Q are the instantaneous active and reactive powers.

The calculated instantaneous active power is passed through a high pass filter to obtain AC component of active power ($\tilde{P}$). Actual DC link voltage is measured and compared with reference DC link voltage and the error is damped using a simple PI controller to obtain power loss P_{loss} component ($\bar{P}$). The obtained power loss component is compared with AC component of power to obtain reference compensating active power component as (10).

$$P_C^* = \tilde{P} - \bar{P} \quad (10)$$

The reference active power and reactive power components are sent for calculation of reference currents in α-β frame with (11) and are converted to a-b-c coordinates using inverse Clarke's transformation as in (12).

$$\begin{bmatrix} I_\alpha^* \\ I_\beta^* \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2}\begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix}\begin{bmatrix} P_C^* \\ Q_C^* \end{bmatrix} \quad (11)$$

$$\begin{bmatrix} I_a^* \\ I_b^* \\ I_c^* \end{bmatrix} = \frac{3}{2}\begin{bmatrix} \frac{2}{3} & 0 \\ \frac{-1}{3} & \frac{\sqrt{3}}{3} \\ \frac{-1}{3} & \frac{\sqrt{-3}}{3} \end{bmatrix}\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} \quad (12)$$

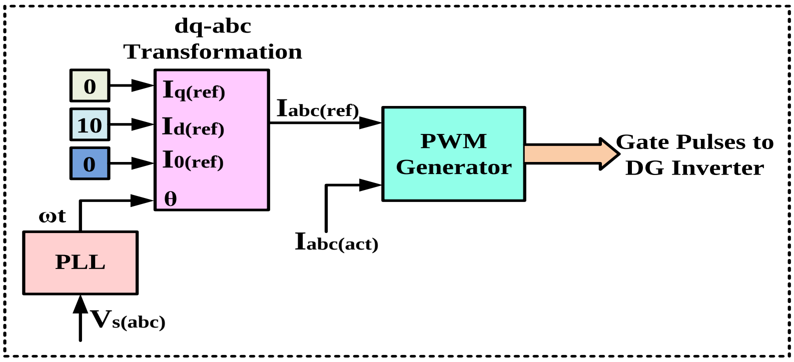

Figure 5. Control strategy for DG inverter

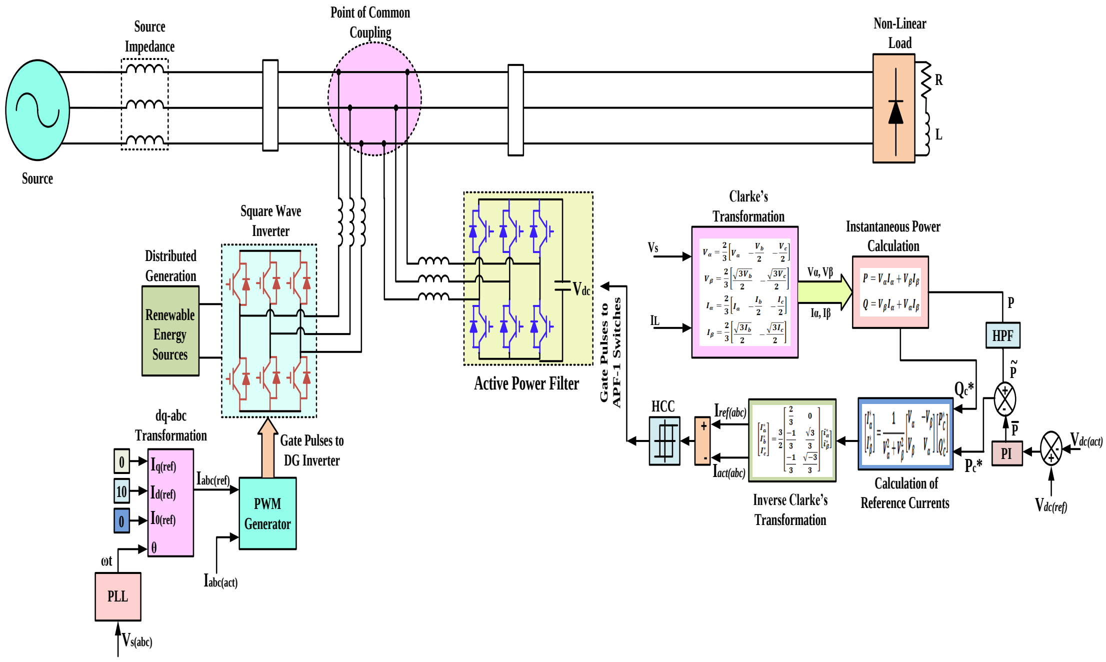

Figure 6. Complete schematic arrangement of DG integration to grid with parallel inverter for harmonic suppression with their respective control strategies

Where I_a^*, I_b^* and I_C^* are the reference currents obtained from inverse Clarke's transformation. The reference current signals in three co-ordinate system are compared with actual currents and the error signal is sent to hysteresis current controller which produces gate pulses to two parallel APF's. The currents from parallel voltage source converters (APF) sends compensating signals to point of common coupling to reduce the harmonic distortion in power distribution source components.

3.2. Control Strategy for DG Inverter

Control strategy for controlling DG inverter placed after DG to invert power from DC type to AC type is shown in Figure 5. Source voltage is sent to PLL to obtain the information regarding phase angle (Table 1). In this simple control strategy to control DG inverter, the reference values of $I_{q(ref)}$, $I_{0(ref)}$ are set to zero as no reactive power is fed to grid. Only active power is fed from DG to grid and thus $I_{d(ref)}$ is set to a fixed value. The reference values are fed to dq-abc transformation (inverse Clarke's transformation). The output of inverse transformation yields three-phase reference current signals. The obtained reference current signals are then compared with actual current signals. The error signal is fed to simple PWM generator to produce pulses to DG inverter. The complete schematic arrangement of DG integration to grid with two parallel inverters for harmonic suppression with their respective control strategies were shown in Figure 6.

4. Results and Discussions

4.1. Power Distribution System with Balanced Non-Linear Load

Three-phase source voltage and source currents are shown in Figure 7 and Figure 8 respectively for Distribution system with balanced non-linear load. Source voltage is maintained with peak 360V and source current is at 20A peak initially up to DG disconnection. When DG is connected at 0.1 sec, the main source current drops to 10A and DG feeds required current to load. Load current of balanced 20A is shown in Figure 9 and as load is of non-linear type, load current is distorted but balanced. Load current is maintained with constant peak even with source current reduction indicating required load current is fed from DG.

Table 1. System Parameters

Parameter	Value
Source Impedance (Zs)	0.1 + j0.28 Ω
Load Impedance	30 + j9.42 Ω
Source Voltage	415 V phase-phase
Fundamental Frequency	50 Hz
DC Link voltage	800 V
Filter inductance	22.5 mH

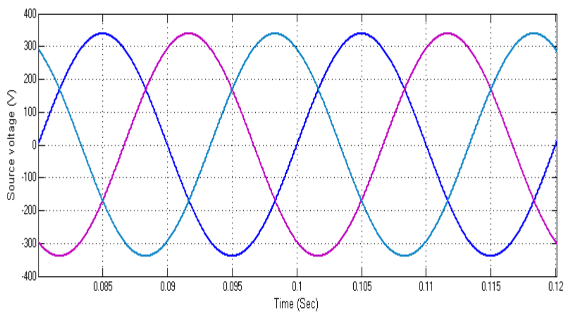

Figure 7. Three-phase Source voltage

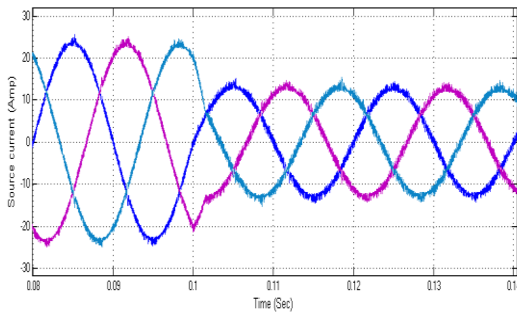

Figure 8. Three-phase Source currents

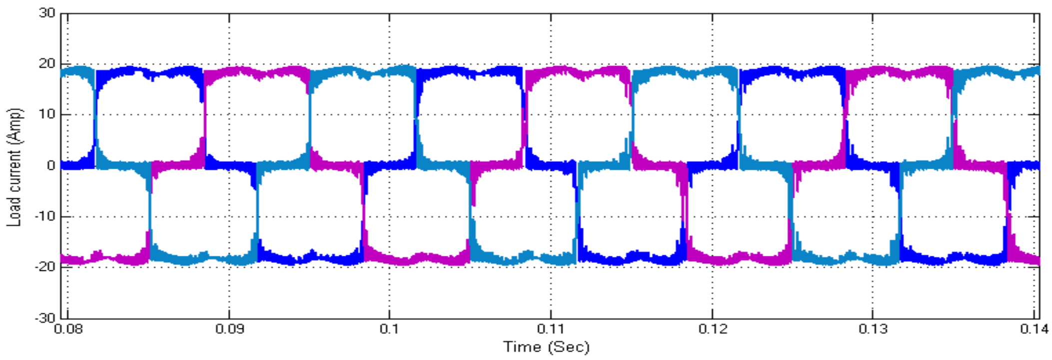

Figure 9. Three-phase Load currents

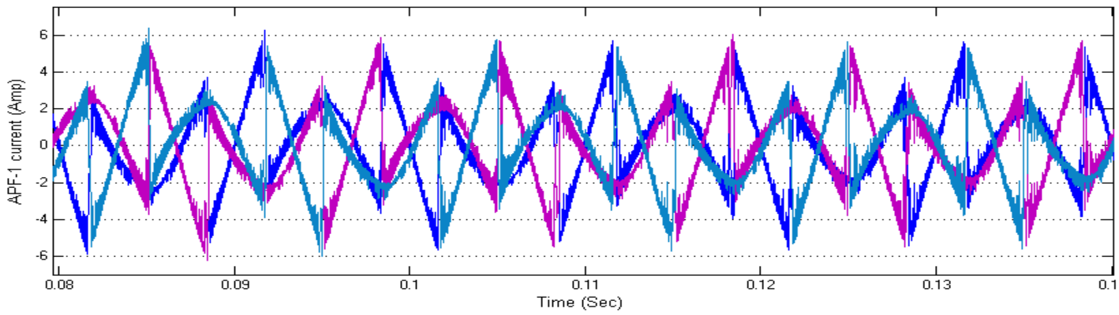

Figure 10. APF Compensation current

Three-phase compensating signals from parallel APF's are shown in Figure 10. Figure 10 represents the compensating signals induced from APF.

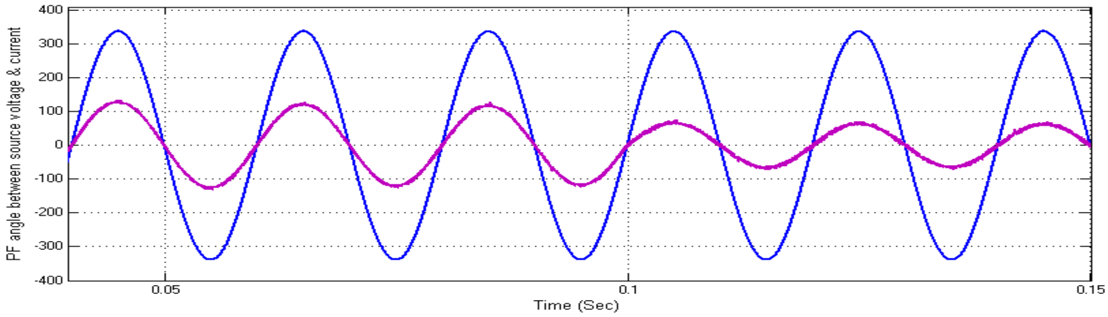

Figure 11. Power factor angle between source voltage and current

Power factor angle between source voltage and current is represented in Figure 11. The phase angle difference between source voltage and current is zero and thus power factor is maintained nearer unity.

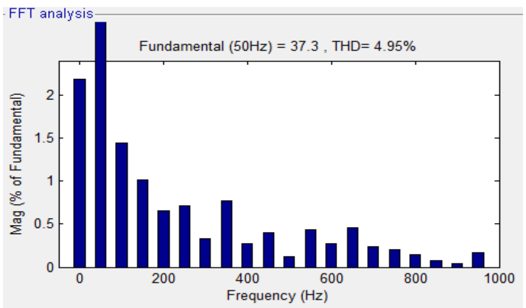

Figure 12. Source current THD

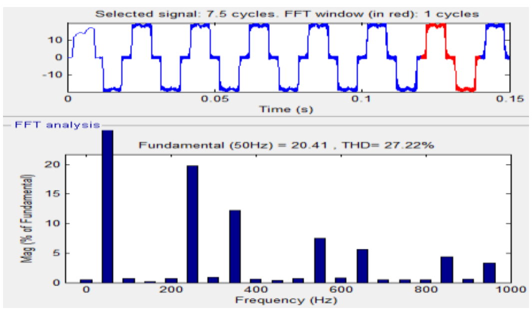

Figure 13. Load current THD

Harmonic distortion in source current is shown in Figure 12 and distortion in load current is shown in Figure 13. Harmonic distortion in load current is 27.22% and distortion in source current is maintained at 4.9% which is within nominal limit.

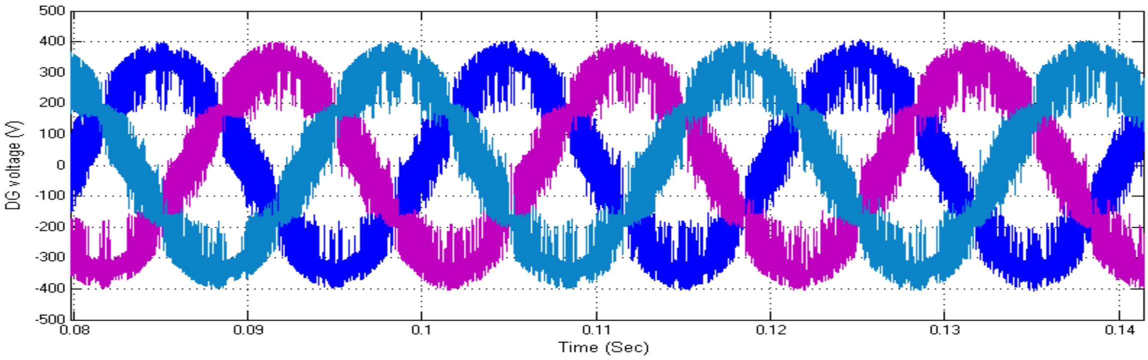

Figure 14. DG generated voltage after filtering

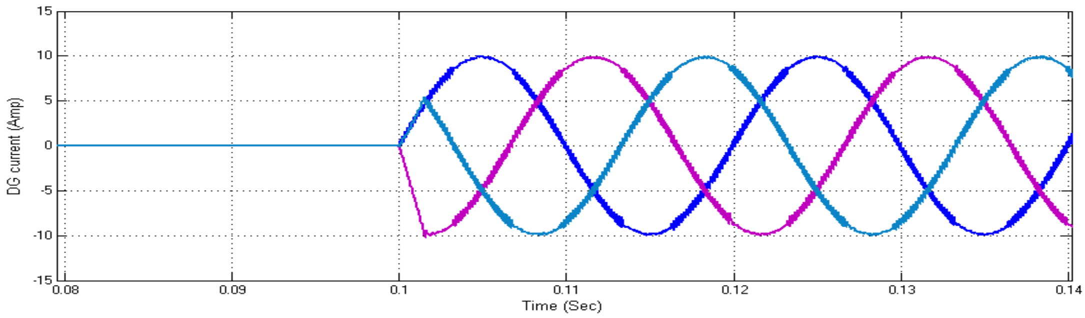

Figure 15. DG generated current after filtering

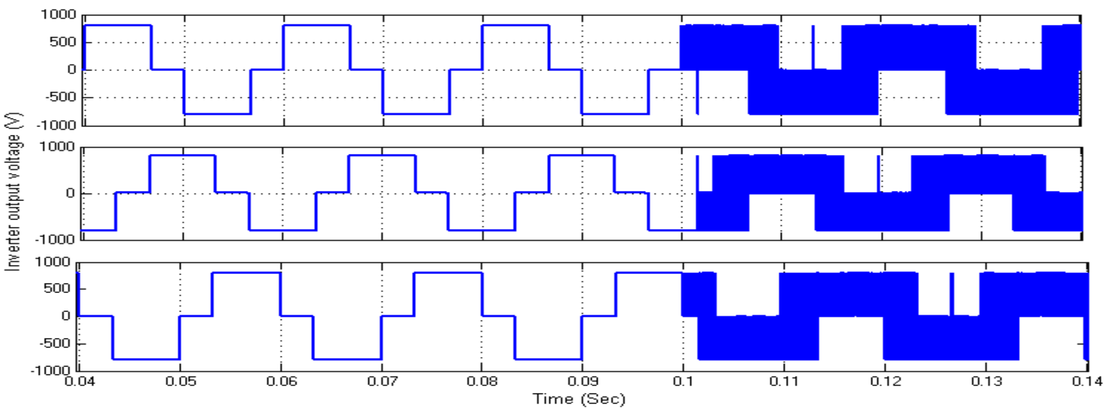

Figure 16. DG generated voltage before filtering

Output voltage of inverter of distributed generation after filtering is shown in Figure 14. Currents fed to distribution system from DG are shown in Figure 15. DG current remains zero up to switching of DG till 0.1 sec. DG current of 10A is fed to grid to feed the load after 0.1 sec as soon as DG was switched with reduction of main source current in power distribution system. DG inverter output voltage in three phases before filtering is shown in Figure 16.

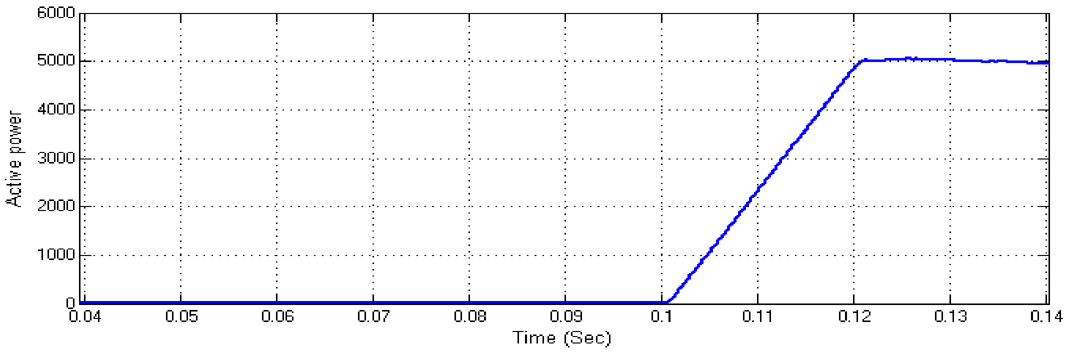

Figure 17. Injected active power into the grid from DG

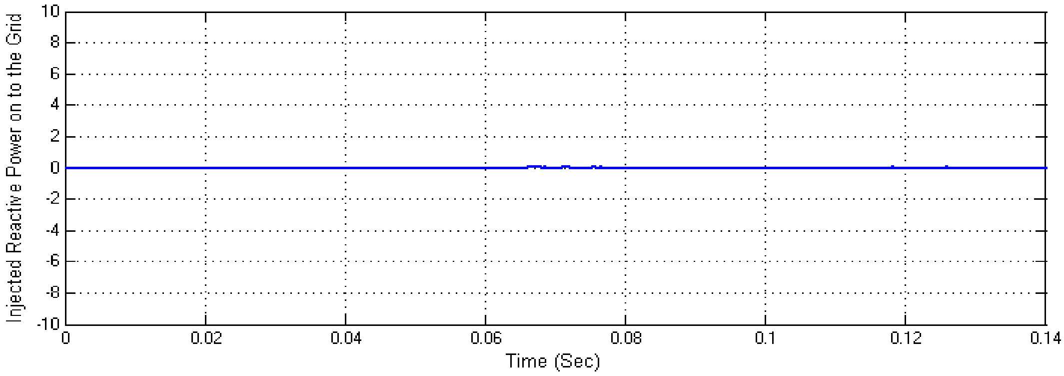

Figure 18. Injected reactive power into the grid from DG

Active power fed from DG is shown in Figure 17 and reactive power from DG is shown in Figure 18. DG is switched in to power distribution system at instant 0.1 seconds. The active power from DG remains zero up to 0.1 sec and after switching of DG in to system; active power of 5KW is fed from DG to grid. Reactive power from DG is zero indicating no reactive power feeding to grid or absorption from grid.

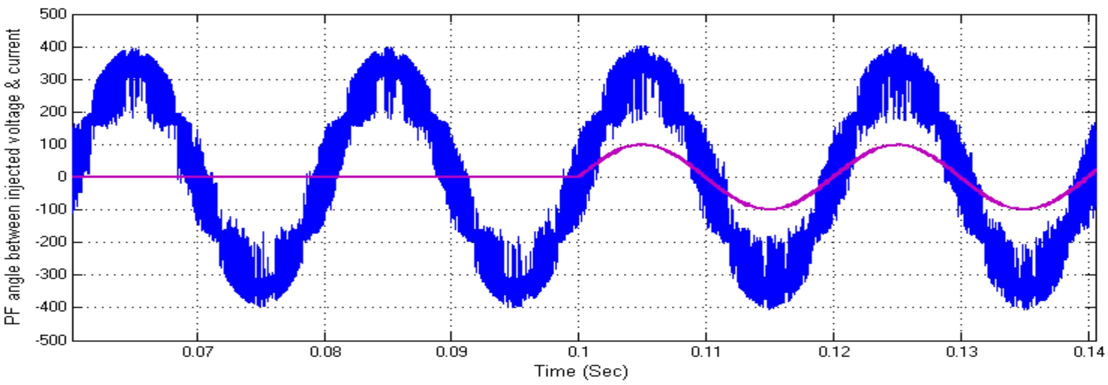

Figure 19. Power factor angle between injected voltage and current

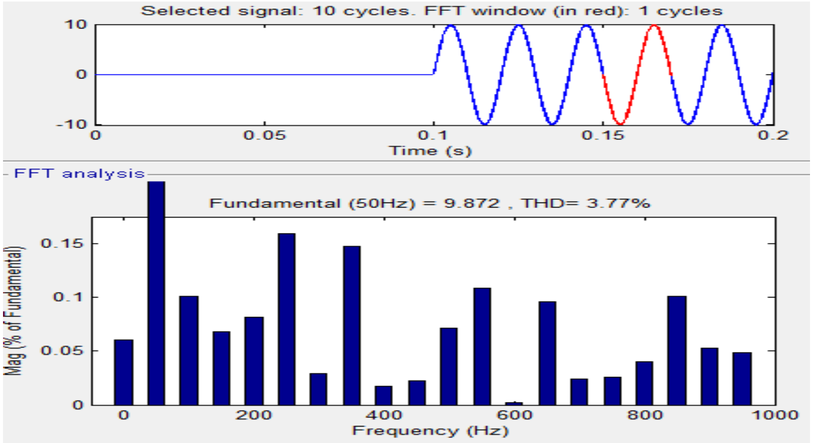

Figure 20. THD of injected current from DG

Power angle between induced voltage and current from DG after switched ON to grid is shown in Figure 19. The phase angle is zero and hence power factor is maintained nearer unity while feeding power to grid from DG. Harmonic distortion in DG injected current is 3.77% as shown in Figure 20 and is maintained within nominal value of limit.

4.2. Power Distribution System with Unbalanced Non-Linear Load

Three-phase source voltage and source currents are shown in Figure 21 and figure 22 respectively for Distribution system with unbalanced non-linear load. Source voltage is maintained with peak 360V and balanced source current is at 20A peak initially up to DG disconnection. When DG is connected at 0.1 sec, the main source current drops to 10A and DG feeds required current to load. Load current of unbalanced is shown in Figure 23 and as load is of non-linear unbalanced type, load current is distorted.

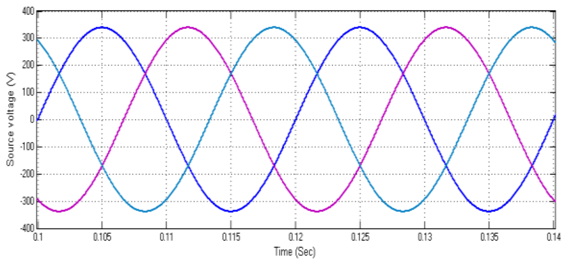

Figure 21. Three-phase source voltage

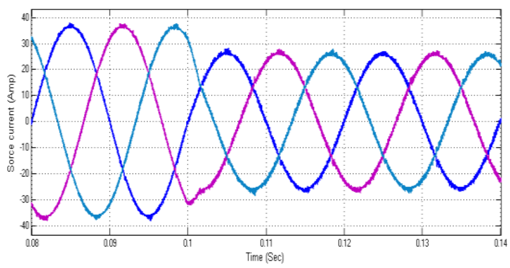

Figure 22. Three-phase source current

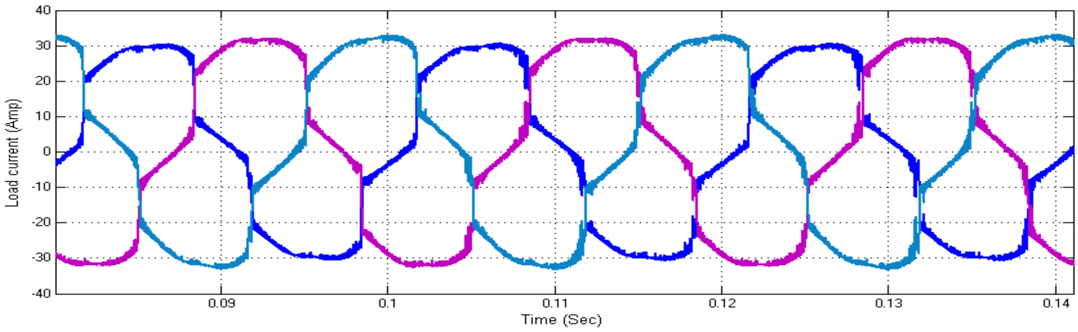

Figure 23. Three-phase Load current

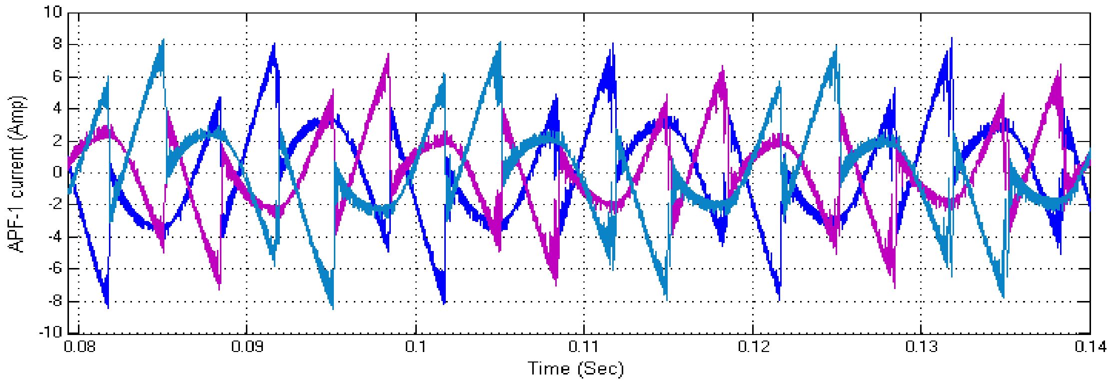

Figure 24. APF Compensation current

Three-phase compensating signals from parallel APF is shown in figure 24. Figure 24 represents the compensating signals induced from APF.

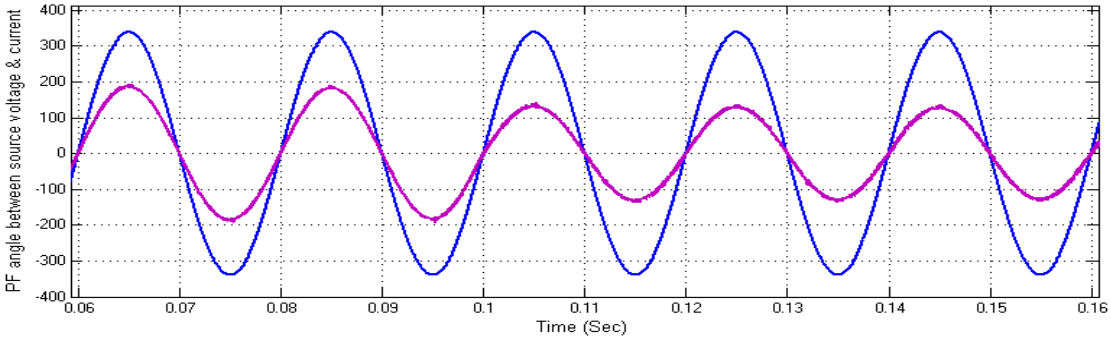

Figure 25. Power factor angle between source voltage and current

Power factor angle between source voltage and current is represented in figure 25. The phase angle difference between source voltage and current is zero and thus power factor is maintained nearer unity.

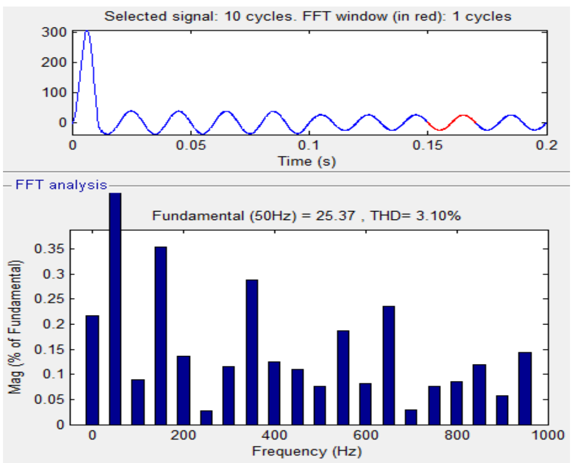

Figure 26. Source current THD

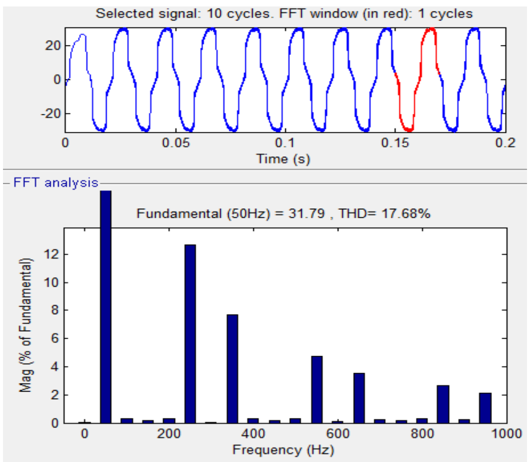

Figure 27. Load current THD

Harmonic distortion in source current is shown in figure 26 and distortion in load current is shown in Figure 27. Harmonic distortion in load current is 17.68% and distortion in source current is maintained at 3.18% which is within nominal limit.

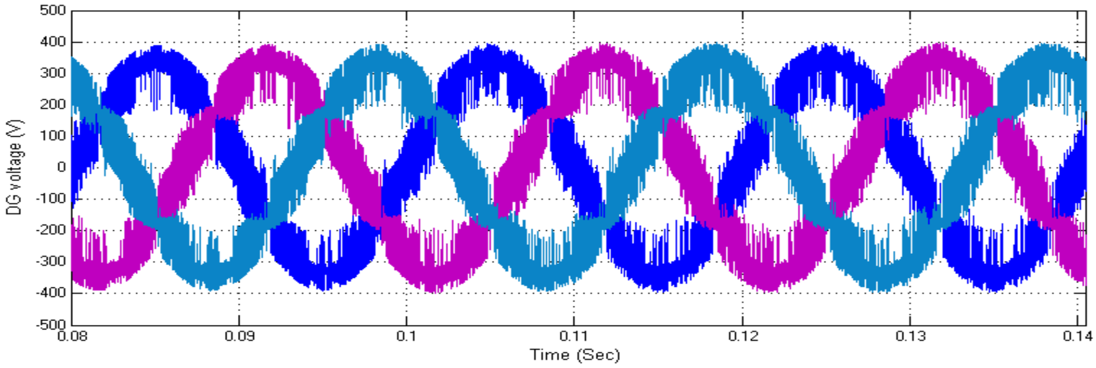

Figure 28. DG generated voltage after filtering

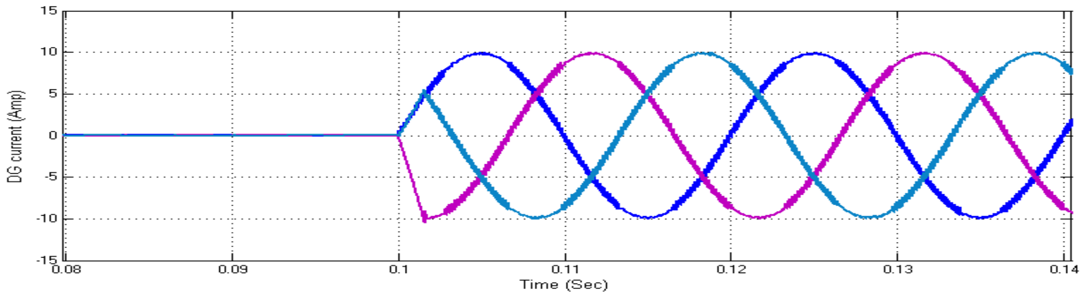

Figure 29. DG generated current after filtering

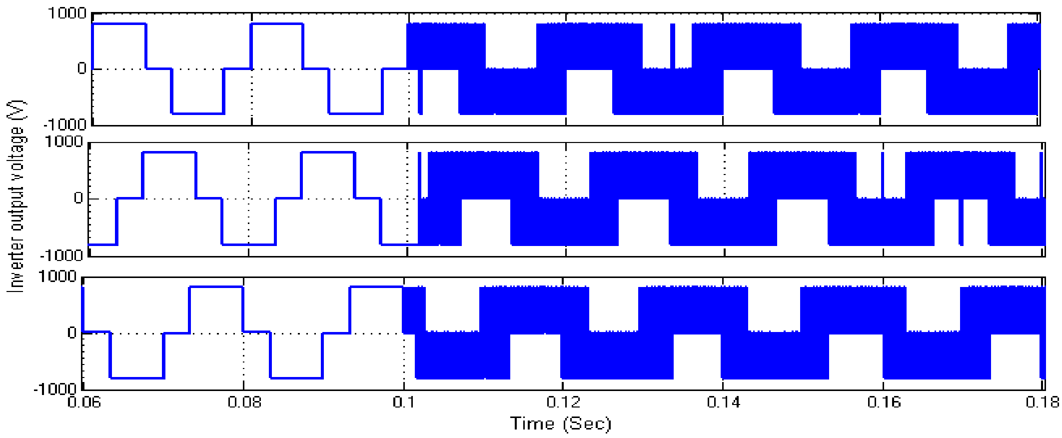

Figure 30. DG generated voltage before filtering

Output voltage of inverter of distributed generation after filtering is shown in Figure 28. Currents fed to distribution system from DG are shown in Figure 29. DG current remains zero up to switching of DG till 0.1 sec. DG current of 10A is fed to grid to feed the load after 0.1 sec as soon as DG was switched with reduction of main source current in power distribution system. DG inverter output voltage in three phases before filtering is shown in Figure 30.

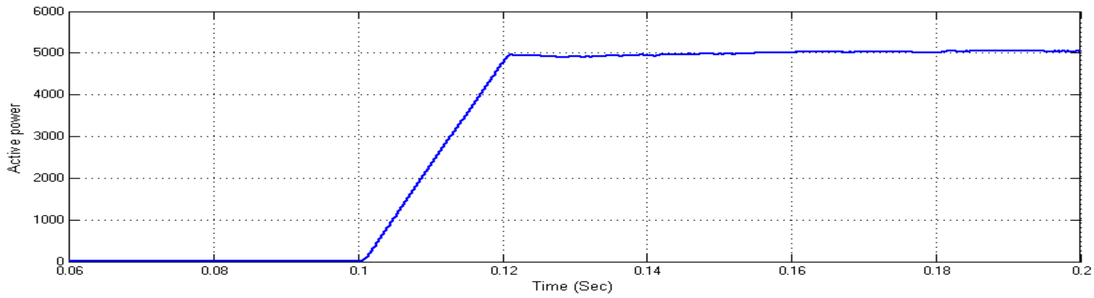

Figure 31. Injected active power into the grid

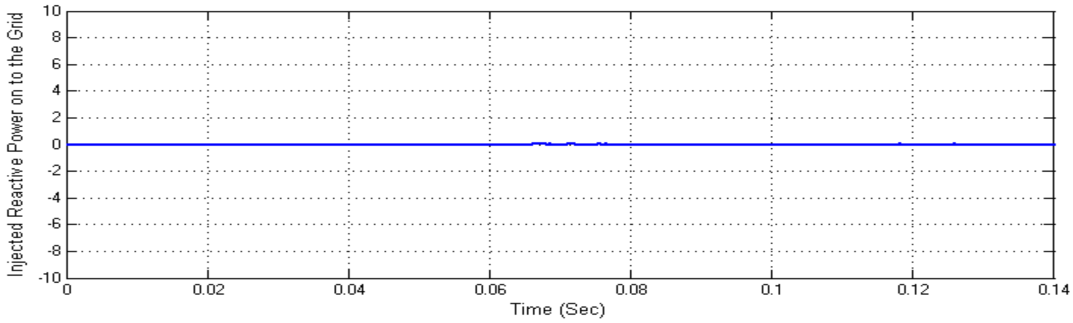

Figure 32. Injected reactive power into the grid

Active power fed from DG is shown in Figure 31 and reactive power from DG is shown in Figure 32. DG is switched in to power distribution system at instant 0.1 seconds. The active power from DG remains zero up to 0.1 sec and after switching of DG in to system; active power of 5KW is fed from DG to grid. Reactive power from DG is zero indicating no reactive power feeding to grid or absorption from grid.

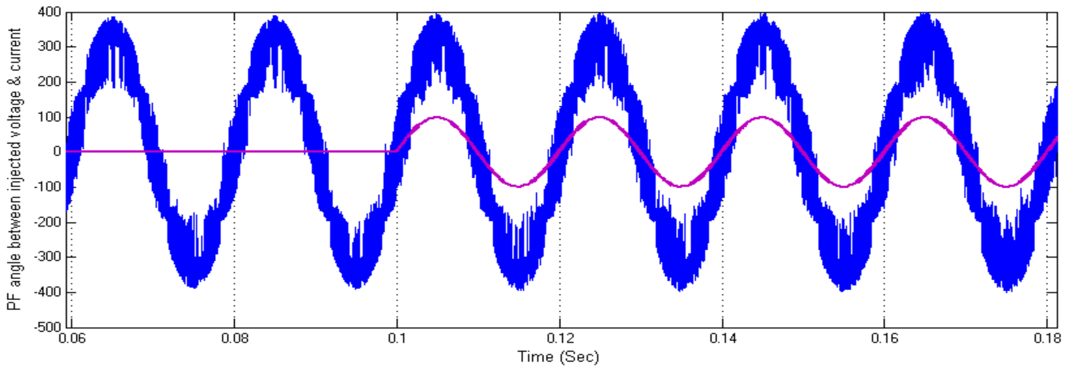

Figure 33. Power factor angle between injected voltage and current

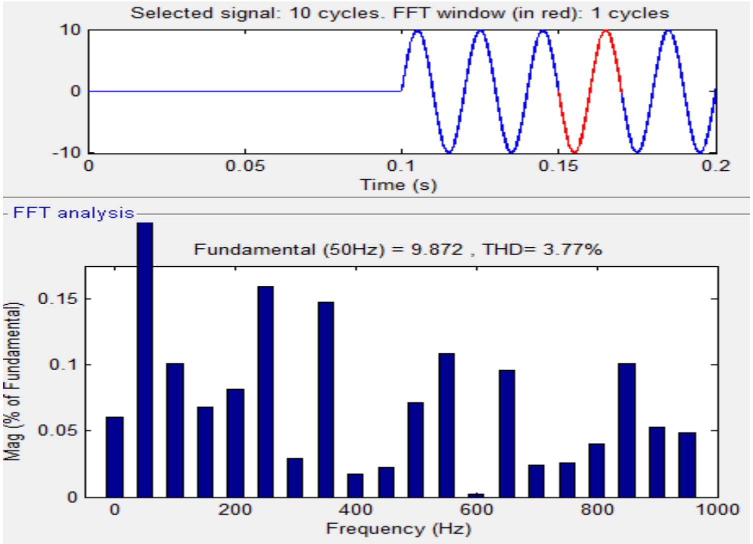

Figure 34. THD of injected grid current

Power angle between induced voltage and current from DG after switched ON to grid is shown in Figure 33. The phase angle is zero and hence power factor is maintained nearer unity while feeding power to grid from DG. Harmonic distortion in DG injected current is 3.77% as shown in Figure 34 and is maintained within nominal value of limit. Table 2 represents the THD analysis in source current, load current and injected currents from DG with balanced and unbalanced non-linear load conditions.

Table 2. THD Analysis

THD	Source Current	Load Current	Injected current from DG
Balanced non-linear load	4.9 %	27.22 %	3.77 %
Unbalanced non-linear load	3.18 %	17.68 %	3.77 %

5. Conclusion

This paper presents the power quality mitigation with power distribution system consisting of non-linear loads. Harmonic distortion mitigation was done using dual APF for balanced non-linear and unbalanced non-linear load conditions. Dual APF is two parallel APF's sharing compensating signals such that the stress on APF switches reduces and with less size APF. For the said system, DG integration scheme was also connected. While sending active power to grid from DG through DG inverter, harmonics in source components was mitigated using APF. System performance of mitigation harmonic distortion was depicted with THD analysis. Harmonic distortion is limited within nominal values as tabulated. Harmonic distortion in DG currents is also maintained within nominal limits.power factor of the system is maintained nearer to unity as shown in results in both balanced and unbalanced non-linear load conditions. Active power of 5KW is fed from DG to grid and when DG feeds grid, the main source current reduces as a result there will be reduction in conventional power.

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