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Distributed Generation Inverter as APF in Dual APF DG Interfacing Scheme

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ABSTRACT

Power quality issues are the most concerned area for electrical engineers in these modern days due to indusrtrialization and advancements in electronics. Harmonics are one of the power quality issues that deteriorated the quality of source components delivered to load. Active power filters (APF) are the compensating devices used to mitigate harmonics. Distributed generation (DG) became a trendline due to economical, technical and environmental reasons. This paper presents the harmonic compensation using dual APF sharing compensating signals while active power is fed from distributed generation to grid. DG inverter acts as an interface between DG system and grid to feed active power from DG to grid. In this context, the DG inverter acts both as inverter and APF, used as inverter to invert supply from DG and feeds grid for specified time and also as APF for harmonic compensation there after along with dual APF. The proposed system is developed and results are obtained using MATLAB/SIMULINK software. Results are shown for DG inverter feeding active power to grid and also acting as APF. Dual APF characteristics are also shown.

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1. INTRODUCTION

Distributed generation (DG) plays a vital role due to advancements in power system like smart grids and shifting electrical power generation from conventional energies to sustainable energies. The name distributed generation suggests that electrical power generation is distributed. DG can be defined as small scale electrical power generation at load centers in conjunction with power grid [1-2]. While DG is feeding grid, the power generation from the main power source is reduced and the demand power is met from both main power source and DG. DG can be operated in two modes of operation-standalone mode of operation and grid connected mode of operation. In grid connected mode of operation, the power from DG is fed to grid reducing the amount of power from main power source. In standalone mode of DG operation, power from DG is fed directly to loads. DG can be more of a back-up type of power to improve the reliability of the power system. DG reduces the investment to generate electrical power than compared to that of conventional power stations. Since DG is installed at load points, transmission losses are gradually reduces and provisions for power transmission and distribution is eliminated [3]. Also DG operates with renewable sources of energy which are freely available and while generating electrical power, zero pollution is achieved which is lauded by global bodies. The major reason for penetration of distributed generation in power system is due to economic, environmental and technical reasons. Many researchers have worked towards DG's and the sizing of a particular DG is very important factor to be considered while installing DG in power system.

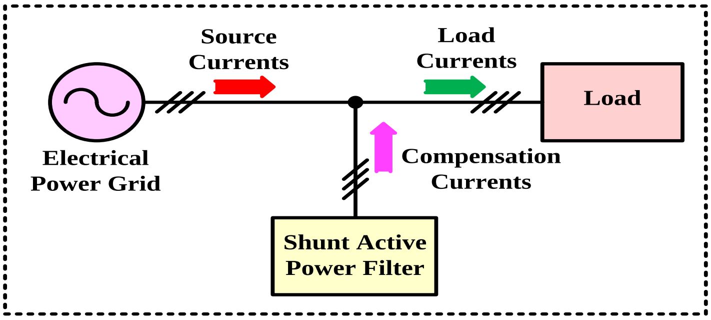

Figure 1. Schematic diagram of APF in power system

Non-linear loads are commonly present in industrial facilities, service facilities, office buildings, and even in our homes. They are the source of several Power Quality problems such as harmonics, reactive power, flicker and resonance [4-5]. Therefore, it can be observed an increasing deterioration of the electrical power grid voltage and current waveforms, mainly due to the contamination of the system currents with harmonics of various orders, including inter-harmonics [6]. Harmonic currents circulating through the line impedance produces distortion in the system voltages. To compensate the harmonics, FACTS controllers are developed. Shunt APF is a device developed to nullify the harmonic distortion in source components. The Shunt Active Power Filter behaves as a controlled current-source draining the undesired components from the load currents, such that the currents in the electrical power grid become sinusoidal, balanced, and in phase with fundamental positive sequence component of the system voltages [7-11]. The schematic diagram of APF in power system is shown in figure 1. In this context, dual APF is employed for harmonic suppression. Dual APF is the concept of having two parallel APF’s for harmonic suppression in power system source components.

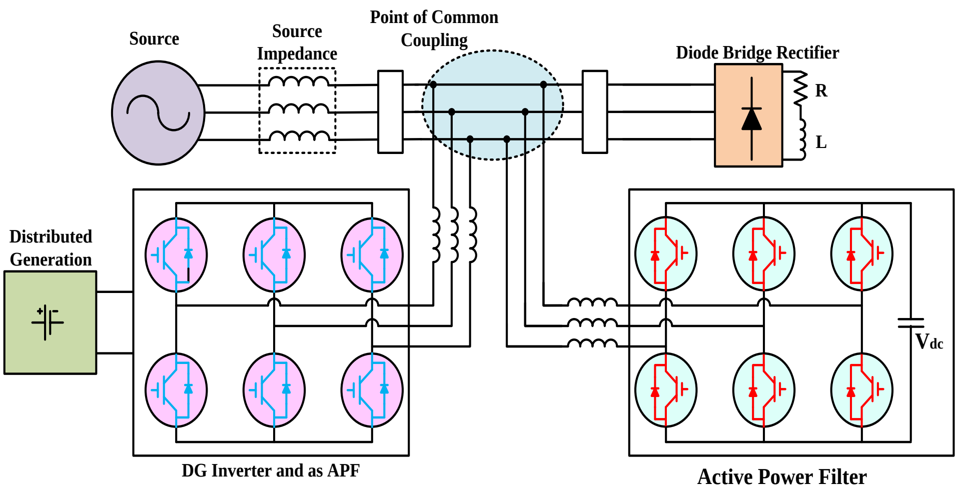

Figure 2. Schematic system with dual APF and DG integrating scheme

This paper presents the harmonic compensation using dual APF sharing compensating signals while active power is fed from distributed generation to grid. Dual APF is the concept of having two parallel APF’s for harmonic suppression in power system source components. DG inverter acts as an interface between DG system and grid to feed active power from DG to grid. In this context, the DG inverter acts both as inverter and APF, used as inverter to invert supply from DG and feeds grid for specified time and also as APF for harmonic compensation thereafter along with dual APF. The proposed system is developed and results are obtained using MATLAB/SIMULINK software. Results are shown for DG inverter feeding active power to grid and also acting as APF. Dual APF characteristics are also shown. Dual APF is controlled using instantaneous PQ theory and DG inverter is controlled using simple control strategy to feed 5KW power to grid.

2. PROPOSED DISTRIBUTION SYSTEM WITH DUAL APF AND DG INTEGRATING SCHEME

Figure 2 shows the schematic system of power distribution system with dual APF and DG integration scheme. Dual APF is meant for harmonic elimination and DG integrating inverter acts as an interfacing inverter to invert the type of DG supply. In this context, for a prescribed time when the DG is switched in to the power distribution system, DG inverter acts as an interfacing inverter to invert the type of DG supply from DC to AC. After prescribed time, DG inverter acts as an APF for harmonic elimination along with APF. DG inverter is controlled with simple control strategy to feed power of 5KW to grid. DG inverter consists of solid-state switches in three legs for three-phase output. The output of DG inverter is filtered out to give smooth sinusoidal output using filter circuit. Initially the DG is switched in to the power system at the instant of 0.1 seconds. From 0.1 sec, the DG inverter just acts as an inverter converting DC type from DG to AC type to feed power of 5KW to grid. At 0.2 seconds, the DG inverter is switched to act as APF to feed compensating signals to point of common coupling.

Dual APF is the concept of having two parallel APF's for harmonic elimination. Each individual APF shares the compensating current load such that the stress and capacity of the individual APF reduces and as a result losses get reduced. Each individual APF of dual APF consists of power switches with a small DC source. The two parallel APF's individually sends compensating signals to point of common coupling such that harmonics in source components are reduced. Apart from DG inverter acting as APF, APF works individually to reduce the harmonic distortion in source currents.

3. CONTROL OF DG INVERTER AND DUAL APF

3.1. Control of DG Inverter

Initially the DG is switched in to the power system at the instant of 0.1 seconds. From 0.1 sec, the DG inverter just acts as an inverter converting DC type from DG to AC type to feed power of 5KW to grid. At 0.2 seconds, the DG inverter is switched to act as APF to feed compensating signals to point of common coupling.

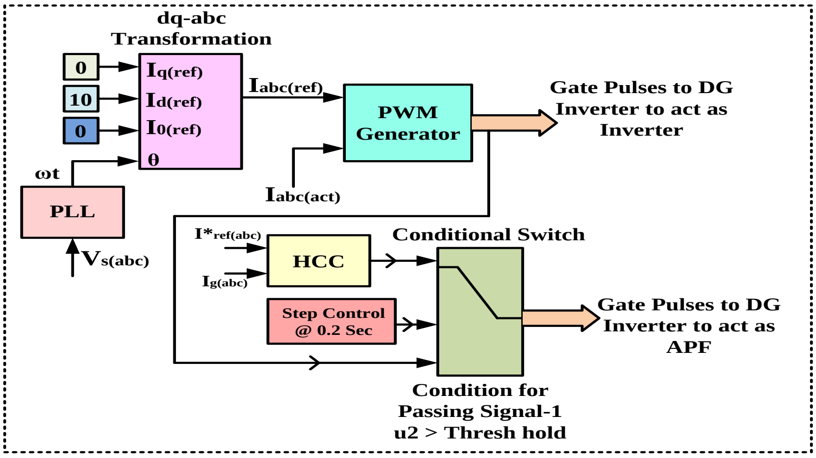

Figure 3. Control strategy for DG inverter

Control strategy for controlling DG inverter placed after DG to invert power from DC type to AC type is shown in Figure 3. While DG inverter acting as inverter to invert the DG supply, source voltage is sent to PLL to obtain the information regarding phase angle. 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 to invert the Dg supply type to AC.

3.1. Control of Dual APF

At 0.2 seconds, the DG inverter is switched to act as APF to feed compensating signals to point of common coupling. Instantaneous active-reactive power theory is used to control dual APF. Instantaneous active and reactive power is 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.

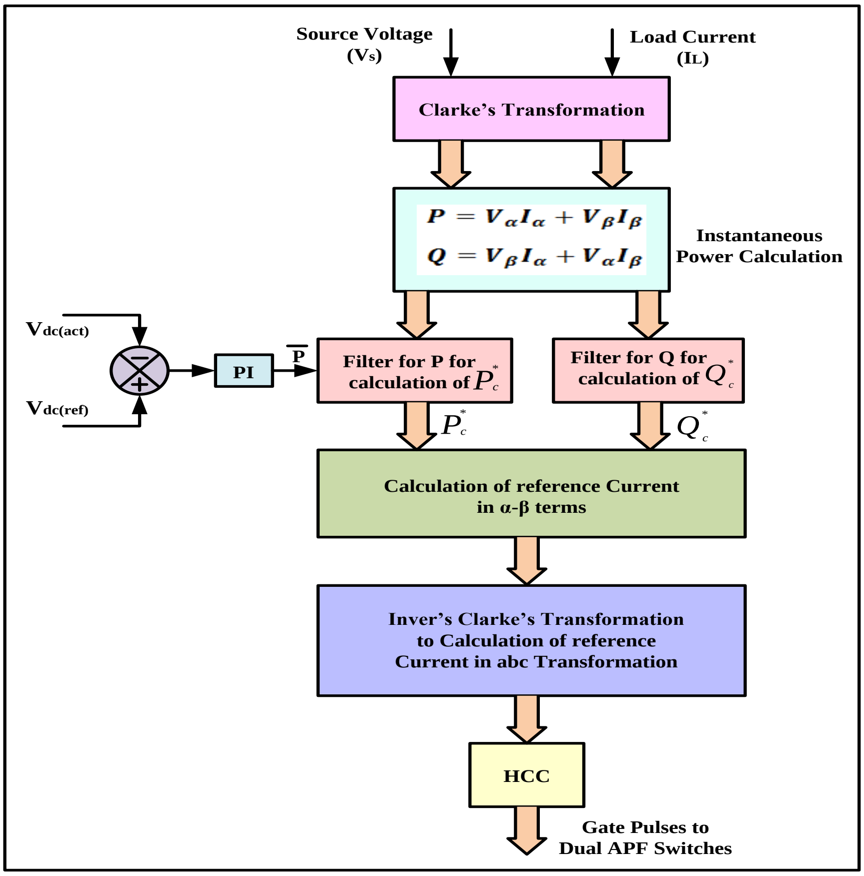

Figure 4. Control algorithm of P-Q theory

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.

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

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

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

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

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

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

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).

$$P = V_\alpha I_\alpha + V_\beta I_\beta \tag{7}$$

$$Q = V_\beta I_\alpha - V_\alpha I_\beta \tag{8}$$

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

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).

$$P_C^* = \tilde{P} - \bar{P} \tag{10}$$

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).

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

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

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 two parallel voltage source converters (APF's) sends compensating signals to point of common coupling to reduce the harmonic distortion in power distribution source components. 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 5.

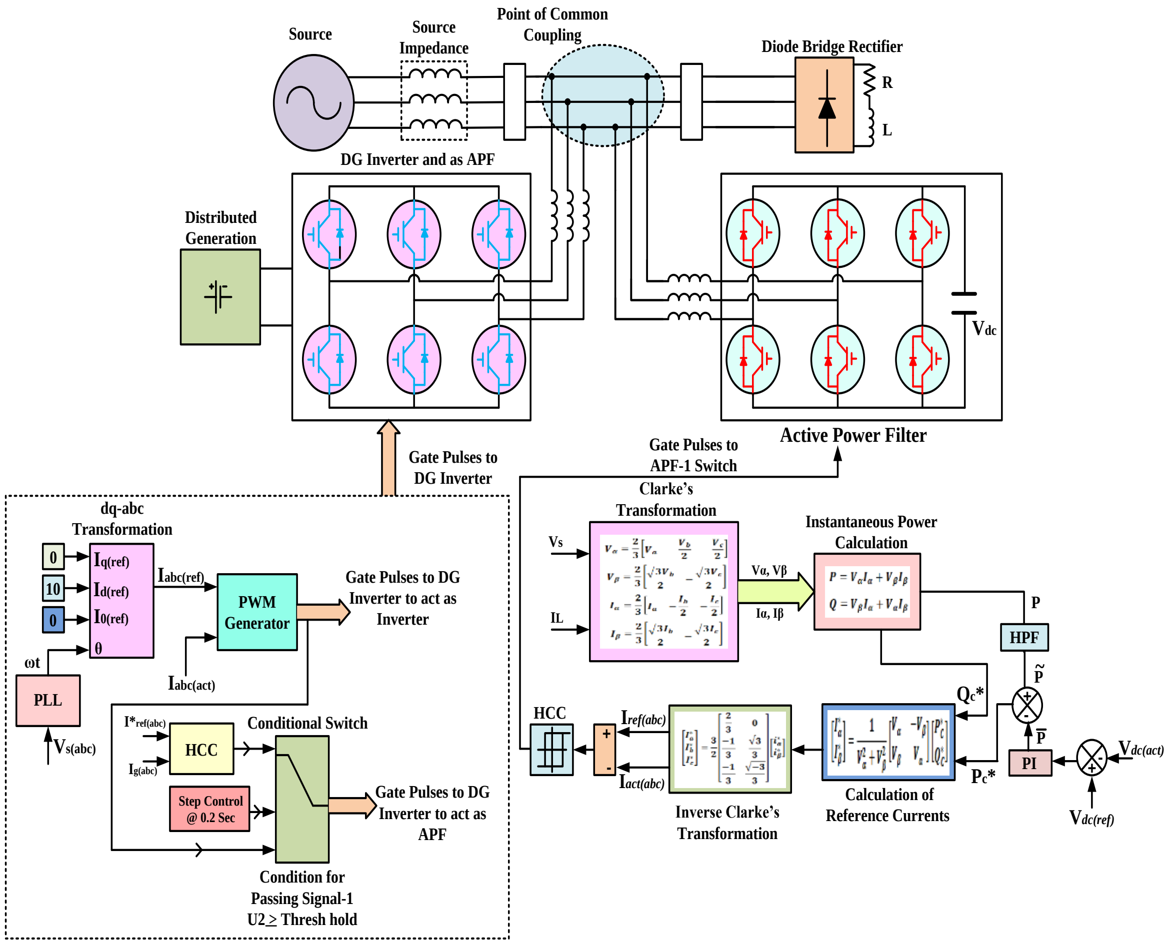

Figure 5. The complete schematic arrangement of DG integration to grid with two parallel inverters for harmonic suppression with their respective control strategies

4. RESULTS AND ANALYSIS

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

4.1. DG Inverter without Interchange, DG Inverter Acts as Inverter to Feed Active Power to Grid

Three-phase source voltage and source currents are shown in Figure 6 and Figure 7 respectively for Distribution system. 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 8 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. Three-phase compensating signals from two parallel APF's are shown in Figure 9. Figure 9 represents the compensating signals induced from APF. Power factor angle between source voltage and current is represented in Figure 10. The phase angle difference between source voltage and current is zero and thus power factor is maintained nearer unity.

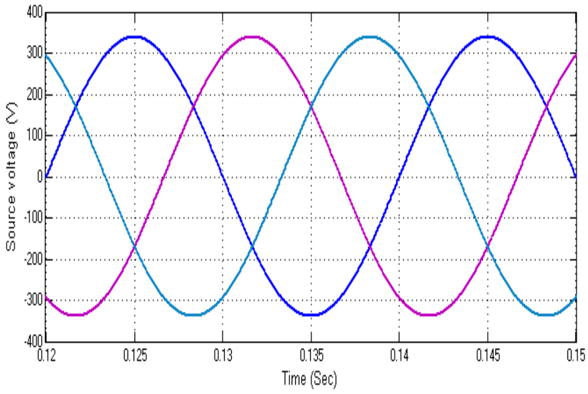

Figure 6. Three-phase source voltage

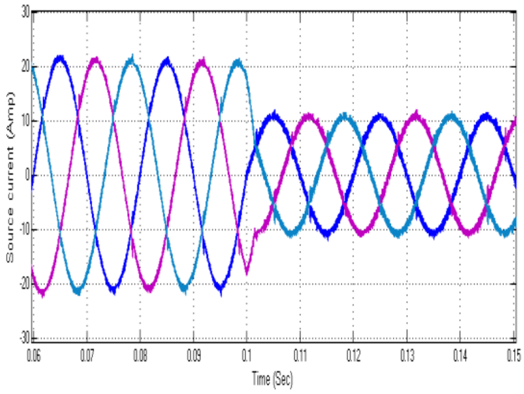

Figure 7. Three-phase source current

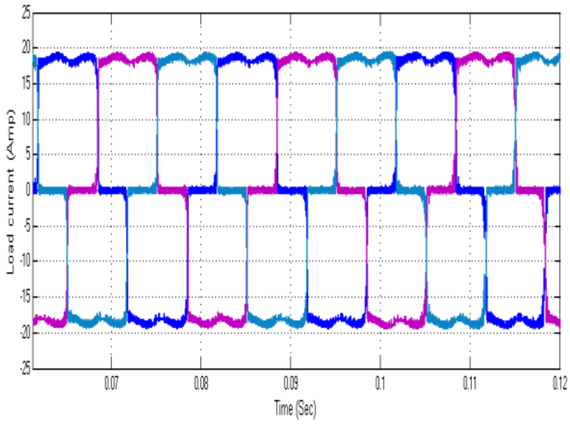

Figure 8. Three-phase Load current

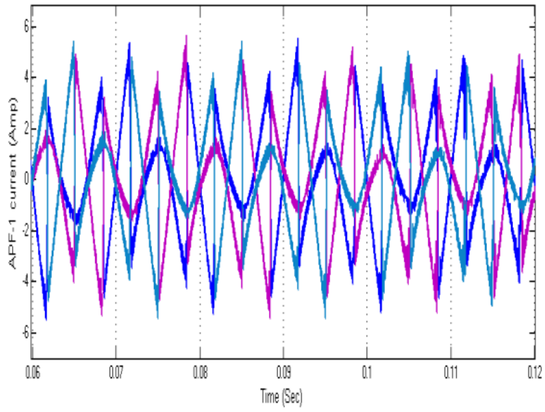

Figure 9. APF Compensation current

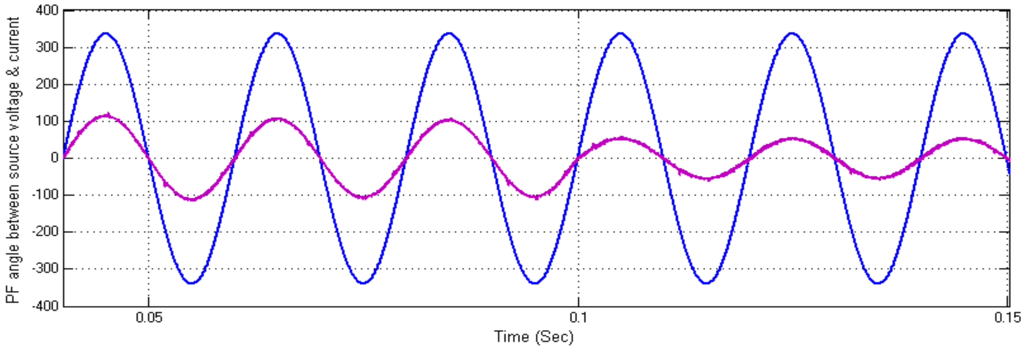

Figure 10. Power factor angle between source voltage and current

Harmonic distortion in source current is shown in Figure 11 and distortion in load current is shown in Figure 12. Harmonic distortion in load current is 27.97% and distortion in source current is maintained at 4.96% which is within nominal limit.

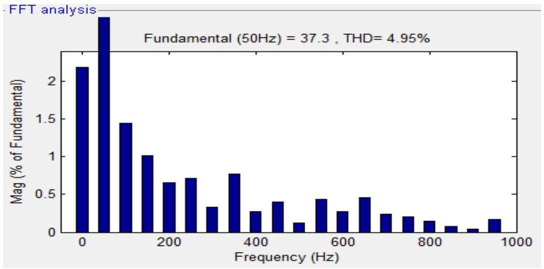

Figure 11. Source current THD

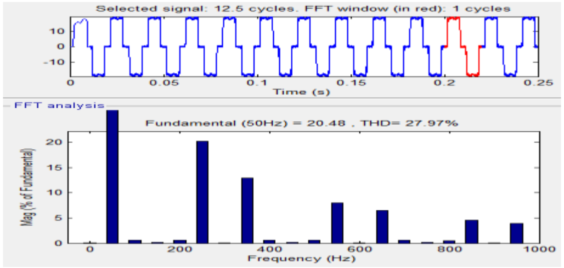

Figure 12. Load current THD

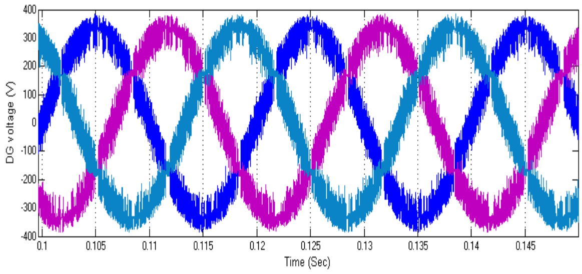

Figure 13. DG generated voltage after filtering

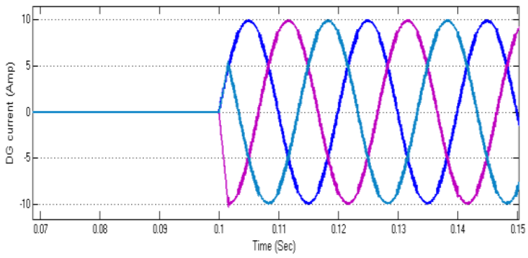

Figure 14. DG generated current after filtering

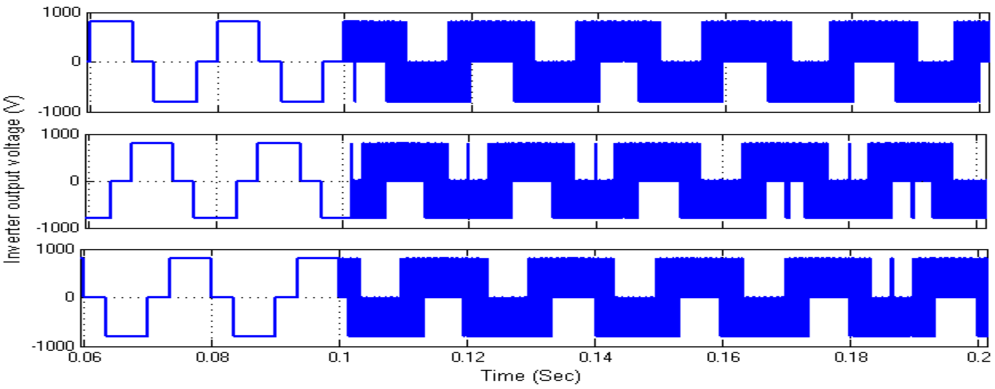

Figure 15. DG generated voltage before filtering

Output voltage of inverter of distributed generation after filtering is shown in Figure 13. Currents fed to distribution system from DG are shown in Figure 14. 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 15.

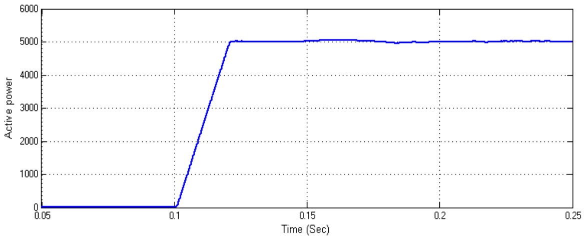

Figure 16. Injected active power into the grid

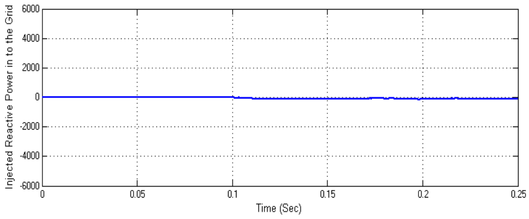

Figure 17. Injected Reactive power into the grid

Active power fed from DG is shown in Figure 16 and reactive power from DG is shown in Figure 17. 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.

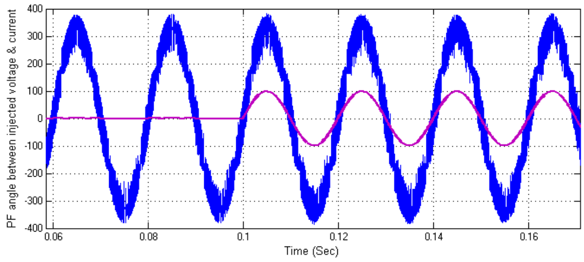

Figure 18. Power factor angle between injected voltage and current

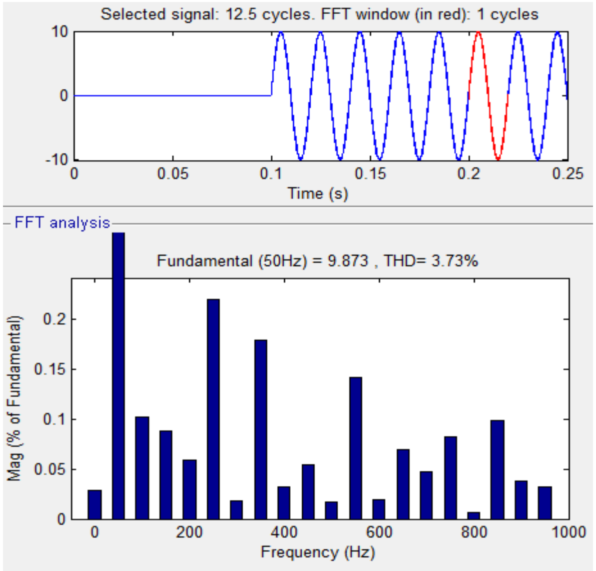

Figure 19. THD of injected current to grid

Power angle between induced voltage and current from DG after switched ON to grid is shown in Figure 18. 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 3.73% as shown in Figure 19 and is maintained within nominal value of limit.

4.2. DG Inverter with Interchange, DG Inverter Acts as APF to Feed Compensating Signals

Three-phase source voltage and source currents are shown in Figure 20 and Figure 21 respectively for distribution system after DG inverter is interchanged to act as APF. 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. At 0.2 sec, the DG invert is interchanged to act as APF and thus the current signal after 0.2 sec rises agin to original waveform as like instant before 0.1 sec since DG is disconnected and feeds no power to grid. Load current of balanced 20A is shown in Figure 22 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.

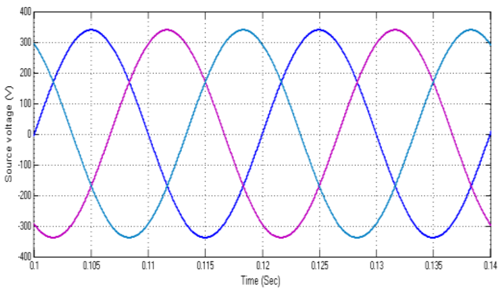

Figure 20. Three-phase source voltage

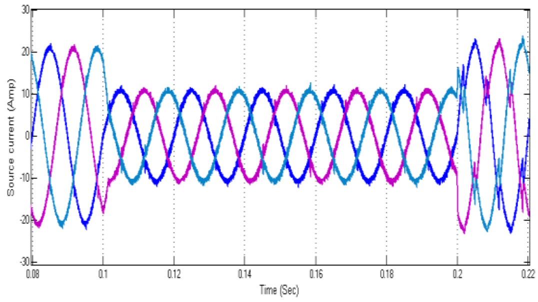

Figure 21. Three-phase source current

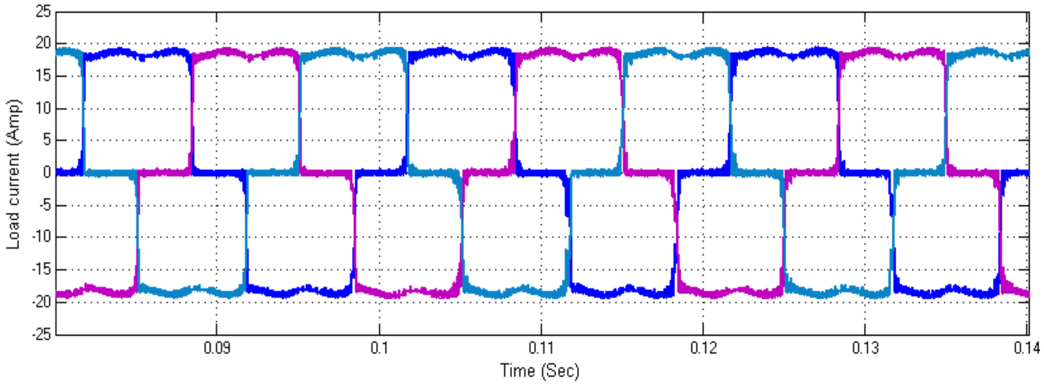

Figure 22. Three-phase load current

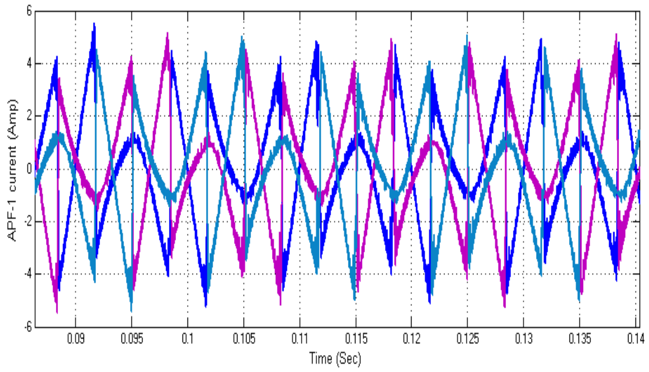

Figure 23. APF Compensation current

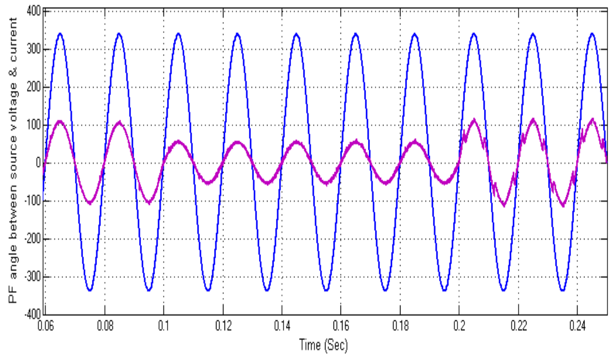

Figure 24. Power factor angle between source voltage and current

Three-phase compensating signals from parallel APF are shown in Figure 23. Figure 23 represents the compensating signals induced from APF Power factor angle between source voltage and current is represented in Figure 24. The phase angle difference between source voltage and current is zero and thus power factor is maintained nearer unity. Harmonic distortion in source current is shown in Figure 25 and distortion in load current is shown in Figure 26. Harmonic distortion in load current is 28.12% and distortion in source current is maintained at 4.9 % which is close to nominal limit.

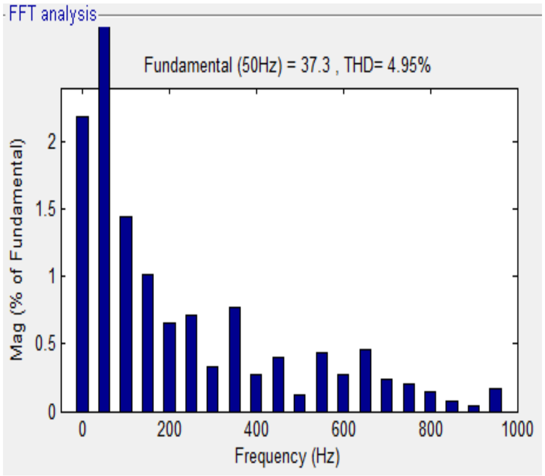

Figure 25. Source current THD after interchange

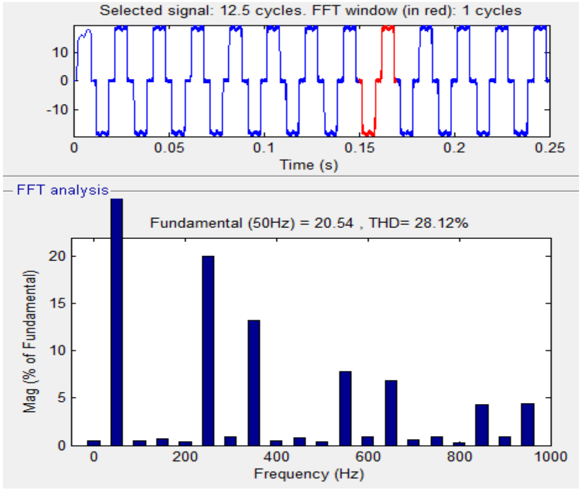

Figure 26. Load current THD

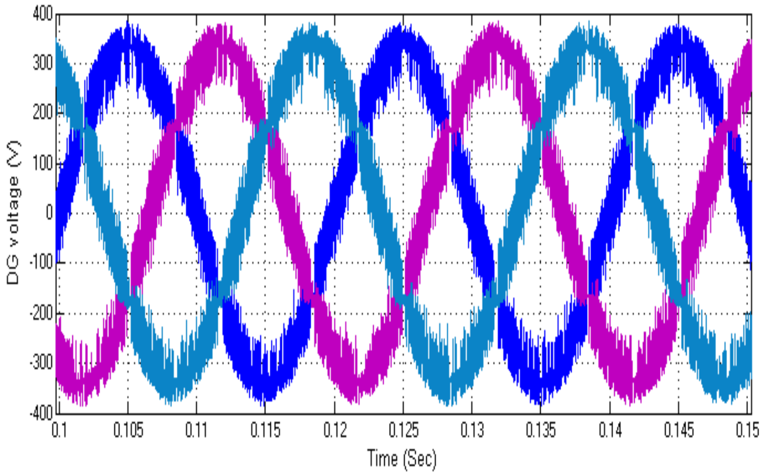

Figure 27. DG generated voltage after filtering

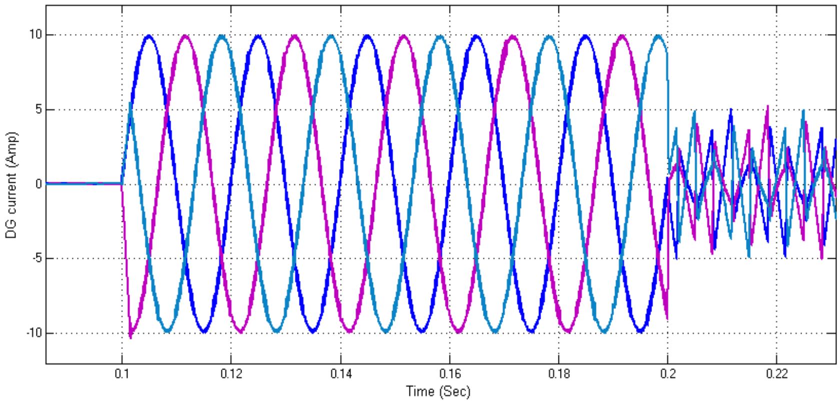

Figure 28. DG generated current after filtering

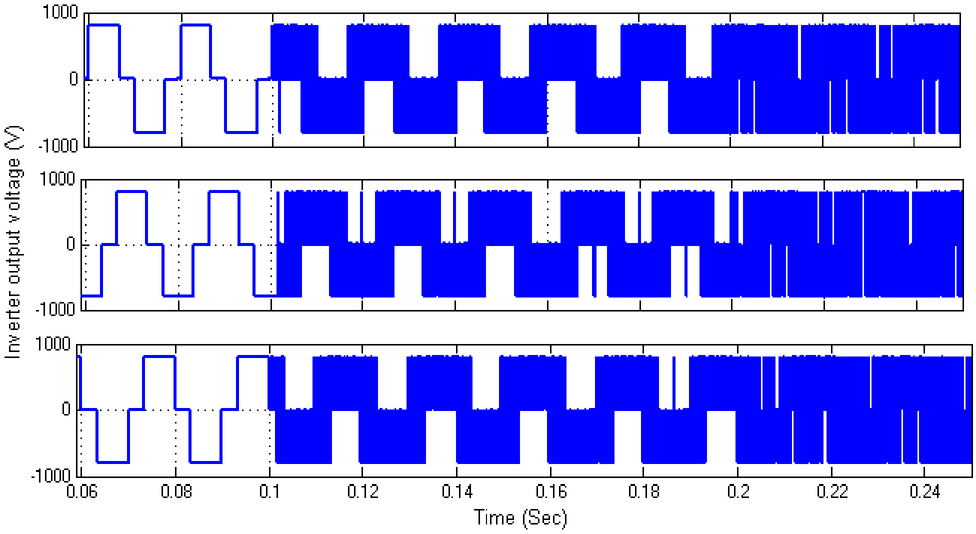

Figure 29. DG generated voltage before filtering

Output voltage of inverter of distributed generation after filtering is shown in Figure 27. Currents fed to distribution system from DG are shown in Figure 28. 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. When DG is interchanged to act as APF at 0.2 sec, DG inverter sends compensating signals. DG inverter output voltage in three phases before filtering is shown in Figure 29.

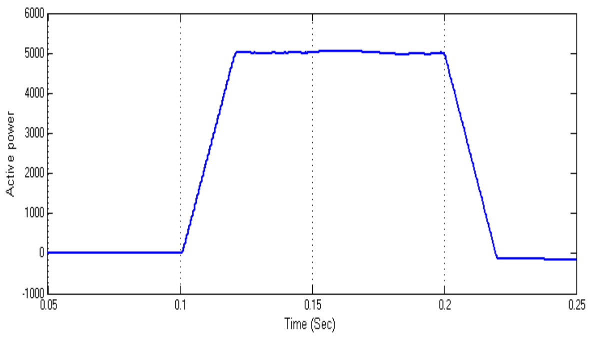

Figure 30. Injected active power into the grid

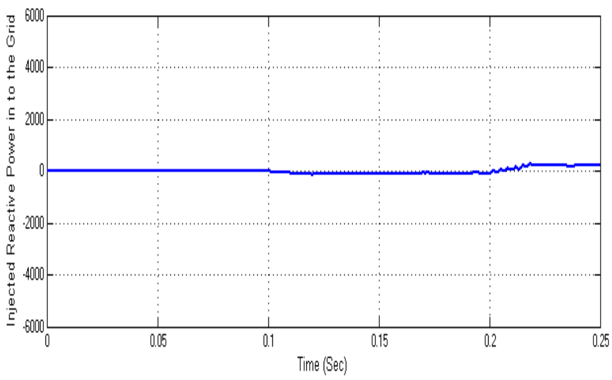

Figure 31. Injected Reactive power into the grid

Active power fed from DG is shown in Figure 30 and reactive power from DG is shown in Figure 31. 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. After 0.2 sec, DG inverter is interchanged to act as APF and thus no active power is fed to grid and thus active power to grid from DG falls back to zero. Reactive power from DG is zero indicating no reactive power feeding to grid or absorption from grid.

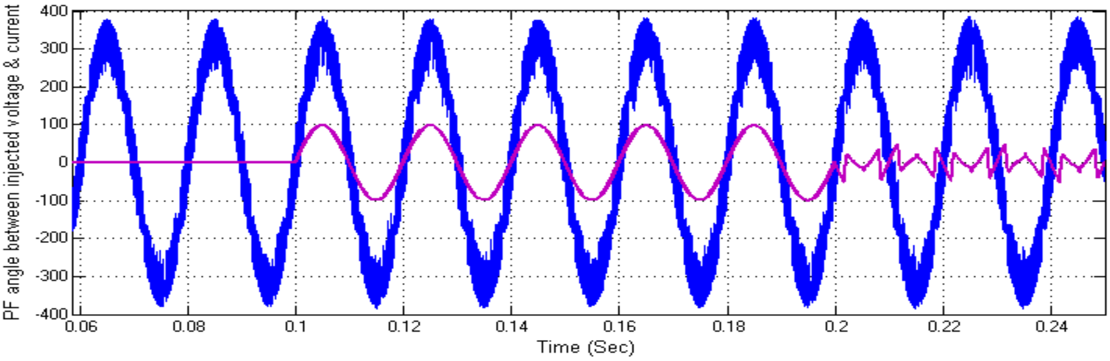

Figure 32. Power factor angle between injected voltage and current

Power angle between induced voltage and current from DG after switched ON to grid and after interchanging to act as APF is shown in Figure 32.

5. CONCLUSION

This paper presents the scheme of harmonic elimination using dual APF and DG integration scheme in power distribution system. DG integration scheme involves power converter to invert power of DC type from DG to AC to feed power to grid. This paper presents the scheme of interchanging the power converter in DG interfacing scheme to act as both inverter to convert the type of supply and APF to nullify harmonics. Results are shown for power converter interchanging scheme. DG is switched to power system at 0.1 sec and from 0.1 sec to 0.2 sec, converter in DG interfacing scheme acts as inverter to invert the type of supply. After 0.2 sec, the converter acts as APF and feeds compensating signals to point of common coupling to nullify harmonics. Characteristics of DG interfacing scheme and dual APF are shown. While DG converter acting as inverter feeding power to grid, the source current decreases indicating the amount of power consumed from main source is reduced. Then after, when DG converter is interchanged to act as APF, the source current again rises but DG converter feeds compensating currents to point of common coupling.harmonic distortion in both the cases and power factor is shown.

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