P-Q Theory Based Power Quality Improvement in Three Phase Four Wire Distribution System

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Abstract: **This work addresses a special requirement of the control strategy for grid interfacing inverter in three-phase four wire distribution systems to deal with power quality problems. A controller based on instantaneous real and reactive power (p-q) theory is proposed for improving harmonic patterns of all the three phases. Total harmonic distortion (THD) of voltage and current for all the three phases is found remarkably low when system is observed with the proposed controller. The harmonic patterns are studied while system is having major varieties of non-linear loads. Effectiveness of control scheme is verified through responses obtained at source side and load side. MATLAB / SIMULINK implementation of a three-phase four wire inverter is presented.**

Keywords: **Power quality, p-q theory, Grid, Shunt active filter, Inverter, Non-linear load.**

1. INTRODUCTION

The trend of connecting loads in distribution system through power electronic devices is escalating exponentially. The performance of installation is stricken by harmonic distortion and uncompensated neutral currents in a power system. Voltage unbalance and harmonic distortions are quite common and often. The possible cause of this is the presence of nonlinearity in loads and lack of proper compensation in the power network. Voltage unbalance & harmonics affect the controllability of power system and power devices. Thus power quality of the signals received at distribution end is a crucial issue to deal with. Non-linear loads provide end-user benefits of improved efficiency but they degrade the overall power quality [1-2]. This process cause pollution in electrical power system & often causes interference with neighbouring loads, and further increases the reactive power demand & harmonics in power system.

Shunt active filter with three-phase four wire system supplying non-linear load and a controller, used to generate compensating reference current in accordance to instantaneous reactive power theory. In view of same, a hysteresis current controller is proposed in [3]. All the approaches have the aim to improve the power quality of the signals. Further the literature survey gives new direction on the highlighted issue of power quality. Johan H.R. Enslin et.al. mentioned phenomenon of harmonic interference on distributed power inverters. The interaction between house hold capacitance and distributed power inverters has been presented with experimental measurement. They found the topology of the inverter has a large influence on distortion [4]. Johan.et.al proposed a new Digital Phase Lock Loop (DPLL) method for single phase grid connected power conversion system. This DPLL method is based on trigonometric function transformation and p-q theory. Many research addresses potential problem related with current harmonic. Prassad.an.enjeti.et.al. proposed a new active power filter scheme to cancel neutral current harmonic. They employed star/delta transformer along with two switch PWM control active filter [5].

However many extensions of the p-q theory are developed and presented by Akagi et.al. [1], but the major deficiencies in these approaches were identified by J.L Willems [6-7] as system was seen from physical point of view. Muktihar Singh et.al. presented a novel control strategy for grid interfacing multitasking inverter which performs two major functions (a) compensation of current unbalance (b) load current harmonic reduction and as a neutral current compensator [8-12].

This paper presents instantaneous real and reactive power (p-q) theory based controller for three- phase four wire systems. It is studied through simulations that controller based on p-q theory performs following important functions: a) harmonic compensation at load side of all the three phases for voltage & current profile; b) harmonic compensation at source side of all the three phases for voltage & current profile; c) Maintain DC voltage of the inverter. Moreover, with adequate control of inverter three objectives can be accomplished either individually or simultaneously.

To exhibit the effectiveness of the proposed control scheme Total Harmonic Distortion (THD) is calculated on both sides (source and load side) for all the three phases.

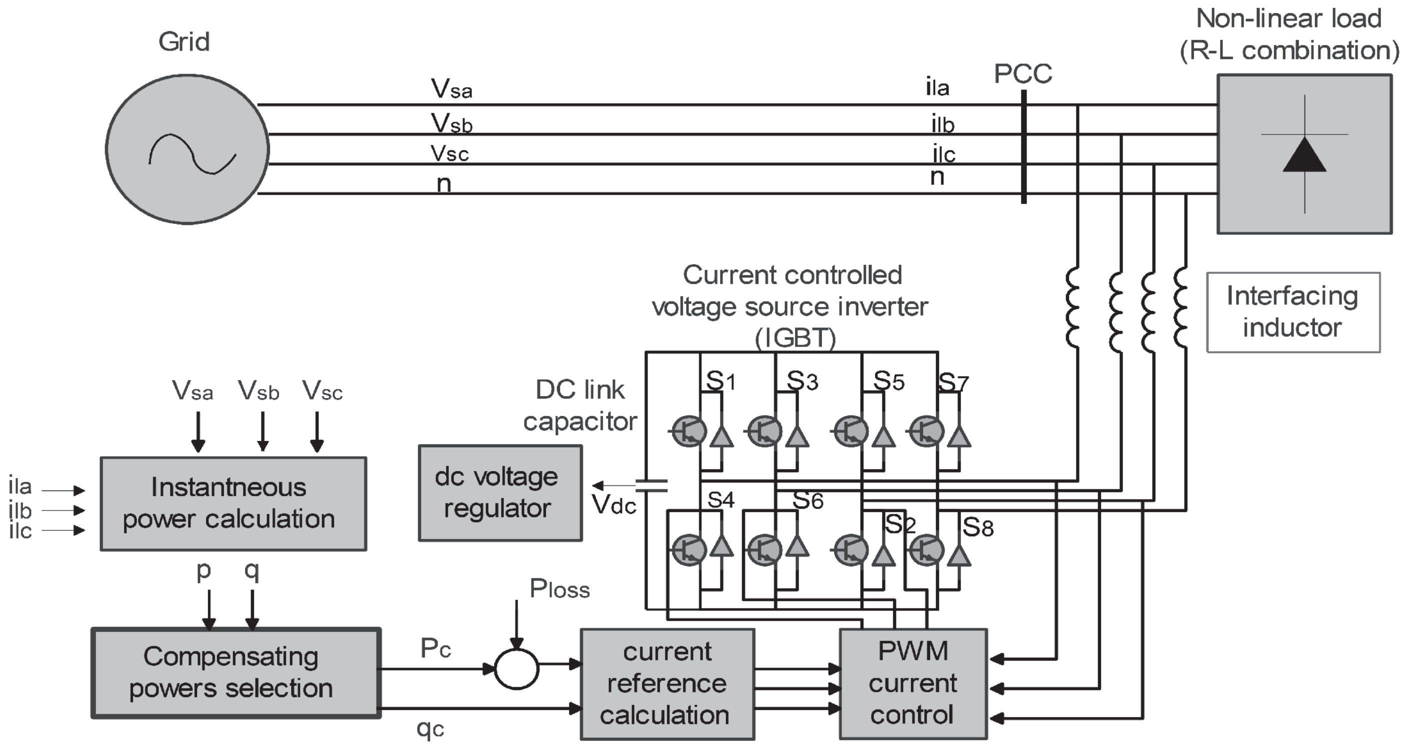

Fig. 1: Three-Phase Four-Wire Connected Shunt Active Filter

The organization of the paper is as follows: System details are given in section 2. Section 3 presents mathematical representation of the proposed controller. Section 4 includes the analysis and evaluation of the simulation results. The conclusion of the work and suggestions for the future scope are given in section 5.

2. SYSTEM DESCRIPTION

Figure 1 shows the three phase four wire shunt active filter. The proposed system consists of four leg grid interfacing voltage source inverter. This inverter consists of three legs, one for each phase and one leg for neutral compensation. PWM technique is used to control the switching of eight IGBT switches. DC voltage is used for the proper operation of the inverter. The system parameters are given in appendices A & B in section 5. The active filter reference current is generated by using instantaneous p-q theory. This reference current and actual filter current is compared to produce the error. To make the error steady, it is passed through PI controller and to enable the inverter to work efficiently, a DC link capacitor of higher value is used. To make the study more pragmatic and close to the real operation, a non linear RL branch with different loading combinations is used. An interfacing inductor is used to connect the grid supply to the inverter.

3. CONTROL PHILOSOPHY

This section presents the details of the control methodology.

1. Concept of p-q theory:

The block diagrammatic presentation of the control [1] methodology is shown in figure 1. Both, the sensed PCC voltage and load currents are converted in α-β-0 coordinate system using the Clarke's transformation. In the α-β-0 transformation the three-phase instantaneous voltages in a-b-c phases (v_a,v_b and v_c) are transformed into the instantaneous voltages on the α-β-0 axes (v_α,v_β and v_0). The Clarke's transformation of voltages are given by equation (1)

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (1)$$

Three-phase (generic load) instantaneous line currents transformed on the α-β-0 axes are given by equation (2).

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2)$$

One advantage of applying the α-β-o transformation is to separate zero-sequence components from a-b-c- phase components. The α and β axis makes no contribution to the existence of zero sequence currents in a three-phase three-wire system. Even if the three-phase voltages are balanced in a four-wire system, no zero sequence voltage is present so v_0 can be neglected.

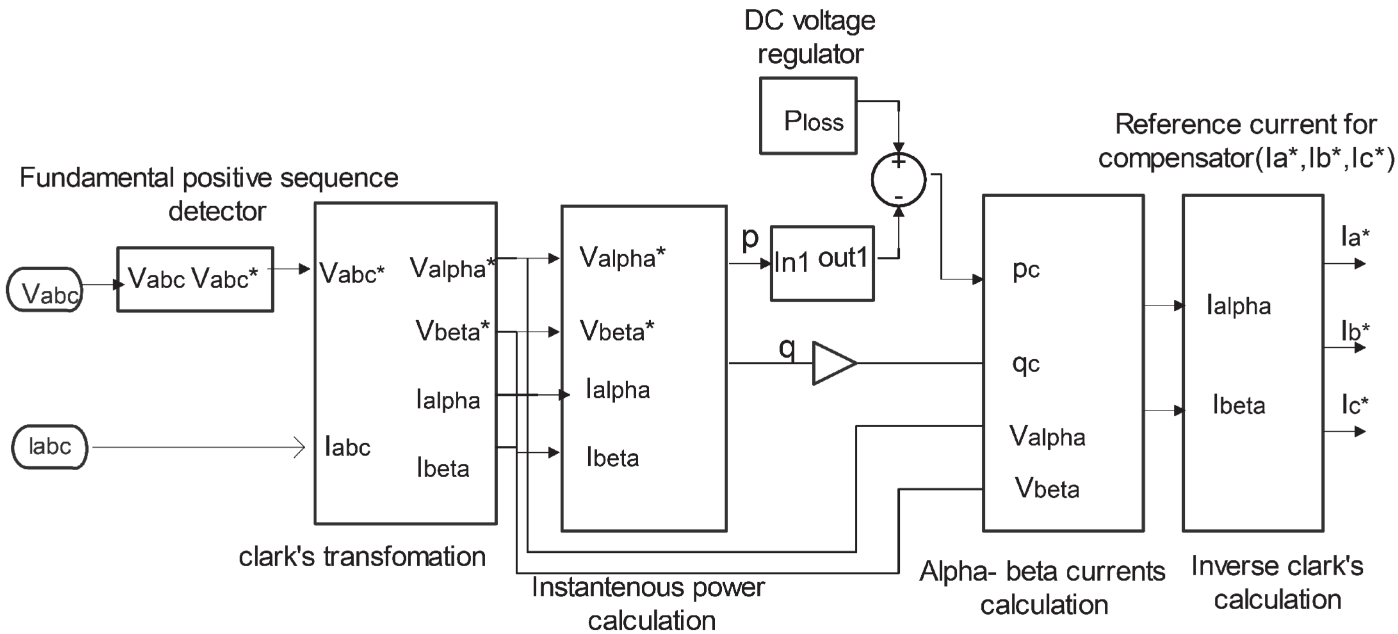

Fig. 2: Schematic Diagram of Controller Circuit

However, when zero-sequence voltage and current components are present, the complete transformation has to be considered. Figure 2 shows the schematic diagram of controller circuit. Here, instantaneous values of voltages and currents referred to the a-b-c stationery axis are transformed into the α-β stationery axes and a, b and c axes are spatially shifted by 2π/3 radians from each other while the α and β axes are orthogonal and the α axis is parallel to a axis. The direction of the β axis was so chosen that if a voltage or current spatial vector on the a-b-c coordinates rotate in a-b-c sequence, they would rotate in α- β sequence in a α- β coordinate system.

The p-q theory can be applied to a three-phase system with or without a neutral conductor. Three instantaneous powers: the instantaneous real power p, the instantaneous reactive power q, the zero-sequence power p_0 are derived from the instantaneous phase voltage and line current on the α-β-0 axes and is given by equation (3).

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (3)$$

Only instantaneous powers defined on the α-β axes exist because the product $v_0\, i_0$ is always zero. Since zero sequence power in three phases is always zero then equation (3) modifies to equation (4) as given below;

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (4)$$

Therefore, real power (p) is defined as.

$$p = v_\alpha i_\alpha + v_\beta i_\beta \quad (5)$$

and reactive power (q) is defined as

$$q = v_\alpha i_\beta - v_\beta i_\alpha \quad (6)$$

In general, when the load is nonlinear the real and imaginary powers can be divided in average and oscillating components as given by equations (7) & (8):-

$$\text{Real power } (p) = \bar{p} + \tilde{p} \quad (7)$$

$$\text{Reactive power } (q) = \bar{q} + \tilde{q} \quad (8)$$

Where

$\bar{p}$= The average value of the instantaneous real power and is transferred from the power source to the load.

$\tilde{p}$= Alternating value (oscillating component) of the instantaneous real power exchanged between the power source and the load through the a-b-c coordinates.

$\bar{q}$= Average value of the instantaneous imaginary power, exchanged between system phases.

$\tilde{q}$= Alternating value of the instantaneous imaginary power exchanged between system phases.

Instantaneous reactive power supplied by the compensator is given by equation (9).

$$q_c = -q \quad (9)$$

Instantaneous active power supplied by the compensator is given by equation (10).

$$p_c = -\tilde{p} \quad (10)$$

The power converter of the shunt active filter is a boost-type converter. It means that dc voltage must be kept higher than the peak value of the ac bus voltage, in order to guarantee the true controllability of the current control. So equation (10) will transform into equation (11):-

$$p_c = -\tilde{p} + \bar{p}_{\text{loss}} \tag{11}$$

The compensator reference currents in α-β domain are calculated by equations (12) and (13):-

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p_c \\ q_c \end{bmatrix} \tag{12}$$

$$\Delta = {v_\alpha}^2 + {v_\beta}^2 \tag{13}$$

In a-b-c domain compensator reference currents will become:-

$$\begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} \tag{14}$$

The reference currents (generated by instantaneous p-q theory) and actual currents are compared and passed through PI controller to produce gating pulses for IGBT inverter (VSI). These gating pulses are given to the inverter for switching purposes.

4. SIMULATION RESULTS & ANALYSIS

The p-q theory based control approach is applied to achieve multi-objectives for grid interfaced inverter connected to a three-phase four wire network. MATLAB/SIMULINK is used for simulation purpose. Current controlled voltage source inverter is operated to achieve balanced sinusoidal grid current despite of unbalanced load. An unbalanced three-phase four-wire non-linear load is connected to the grid at PCC. For study, two different types of load combinations are considered. (a) Three phase non-linear load (b) Three phase and single phase (linear & non-linear) load.

a. Three-phase non-linear load

In this case a three phase non-linear load is considered. After connecting the non-linear load to circuit, the voltage and current profile becomes distorted and unbalanced (see figure 3). Figure 4 shows that after connecting controller in the circuit, waveforms of both voltage and current become balanced and sinusoidal.

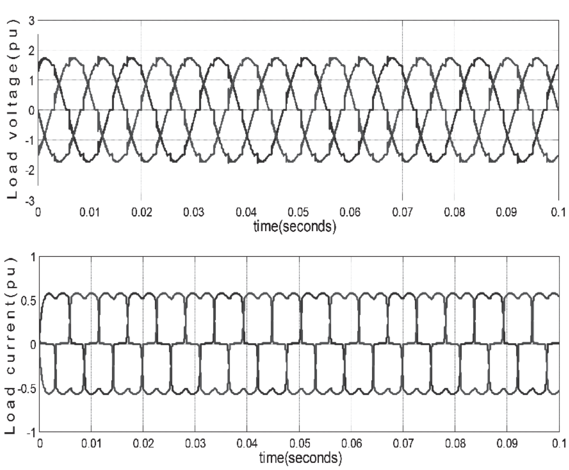

Fig 3: (A) Load Voltage (B) Load Current (Without Compensation)

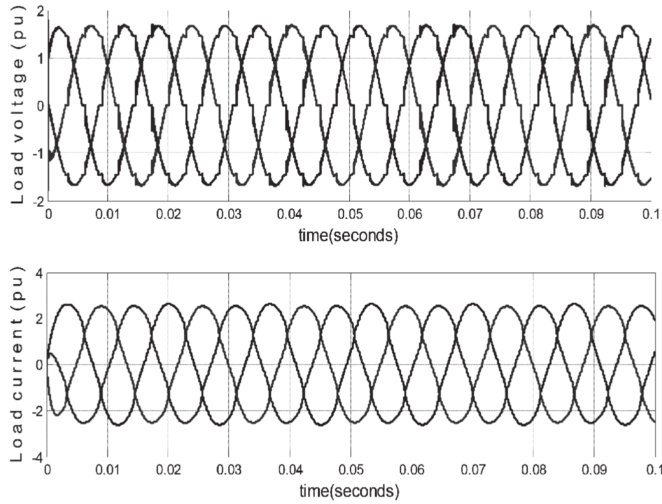

Fig 4: (A) Load Voltage (B) Load Current (With Compensation)

Figure 4 shows load side current with compensation. This is the sum of load current and compensator current. Load current and compensator current are shown in figures 5 and 6 respectively.

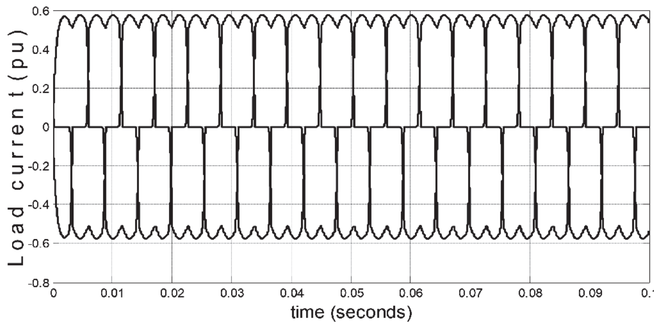

Fig 5: Load Current

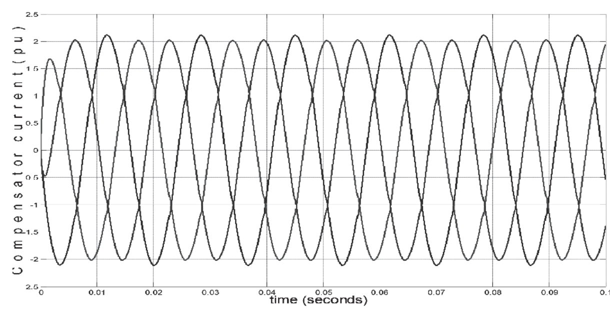

Fig 6: Compensator Current

When controller is connected to the circuit, inverter improves the voltage profile and current profile. Thus from unbalance condition it has achieved balanced and sinusoidal condition. Controller not only compensates the unbalance condition but it also fulfils the distortion factor in the circuit. For further analysis THD calculations are carried out.

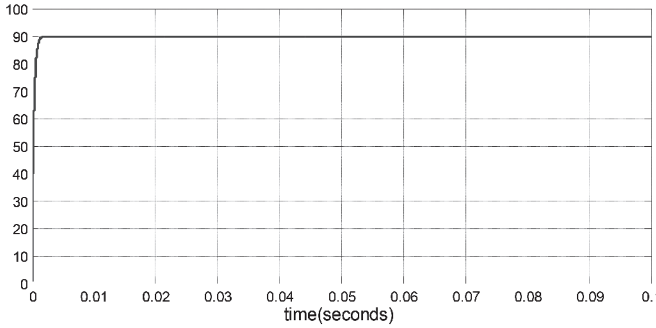

Fig 7: DC Voltage

Figure 7 shows the DC voltage which is maintained at 90 V. The effect of non-linear load on the system is to make THD to increase exponentially.

Figures 8, 9 and 10 shows THD of current in phases a, b, c respectively on load side without compensation and figures 11, 12 and 13 shows THD with compensation.

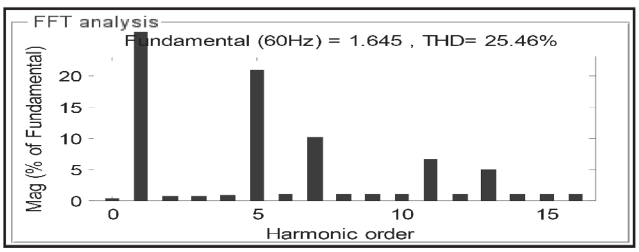

Fig 8: THD of Phase a (Without Compensation)

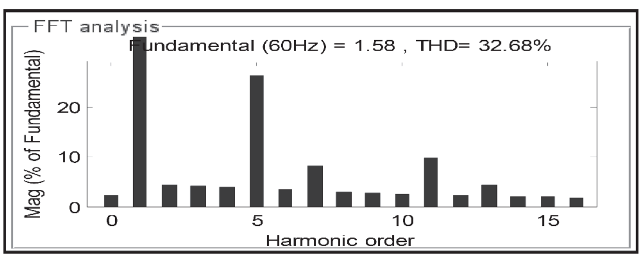

Fig 9: THD of Phase b (Without Compensation)

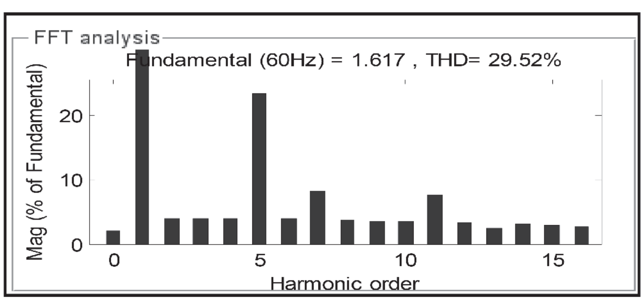

Fig 10: THD of Phase c (Without Compensation)

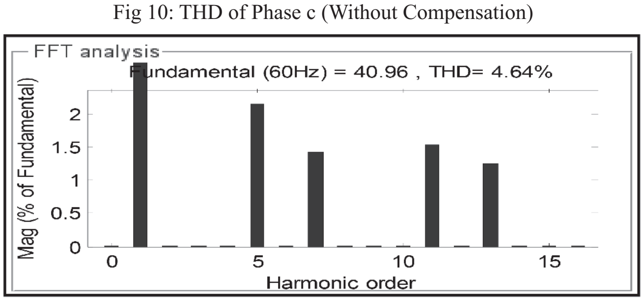

Fig 11: THD of Phase a (With Compensation)

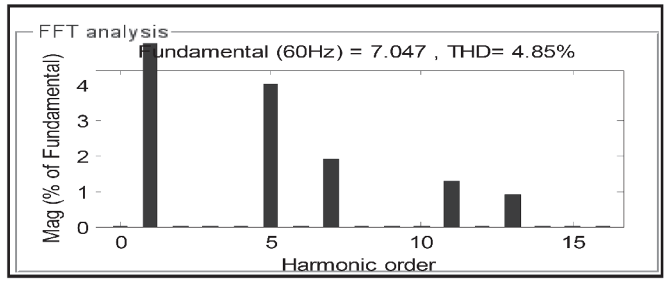

Fig 12: THD of Phase b (With Compensation)

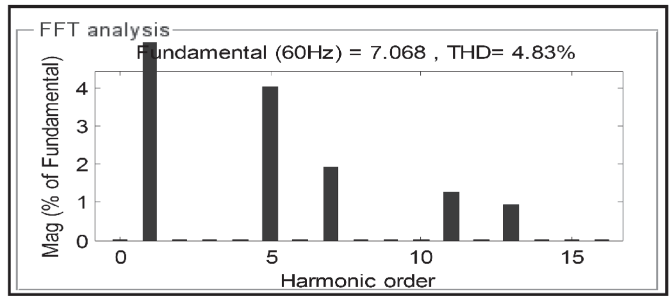

Fig 13: THD of Phase c (With Compensation)

Table 1: THD of Load Current

THD of load Current	Without compensation	With compensation
Phase a	25.46%	4.64%
Phase b	32.68%	4.85%
Phase c	29.52%	4.83%

Table 2: THD of Load Voltage

THD of load voltage	Without compensation	With compensation
Phase a	7.84 %	4.64 %
Phase b	7.88 %	4.67 %
Phase c	4.72 %	4.62 %

b. Set of three-phase (non-linear) load and single phase (linear & non-linear) load

Similarly, set of three-phase non-linear load and single phase linear and non-linear loads is considered. The 3-phase non-linear load is having values as R=26.66 Ω & L=10 mH. Second load is a 1-phase non-linear load with values R=26.66 Ω & L=10 mH and third load is 1-phase linear load with values as R=36.66 & L=10 mH.THD of load currents of phases a, b & c before and after compensation is shown in figures 14-19.

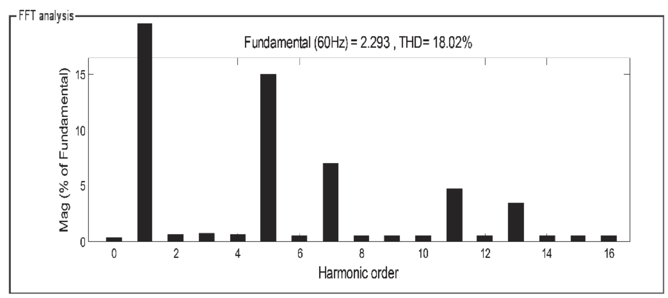

Fig 14: THD of Phase a (Without Compensation)

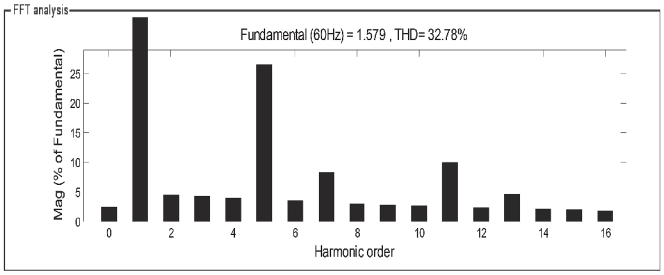

Fig 15: THD of Phase a (Without Compensation)

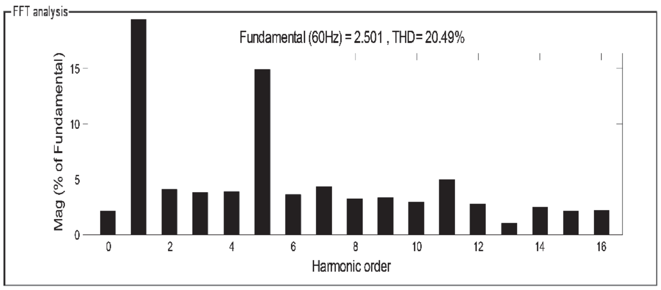

Fig 16: THD of Phase c (Without Compensation)

Thus, after connecting filter in the circuit the THD has reduced drastically from 18.02%, 32.78 %, 20.49 % to 4.35%, 4.86%, 4.18%.

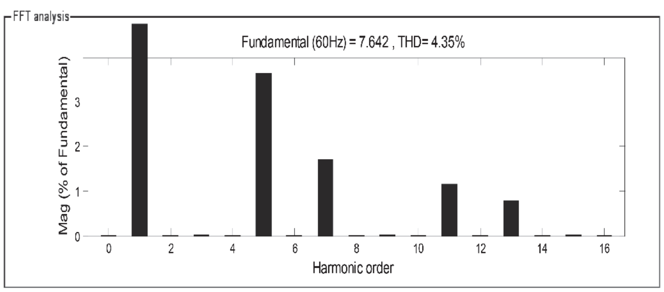

Fig 17: THD of Phase a (With Compensation)

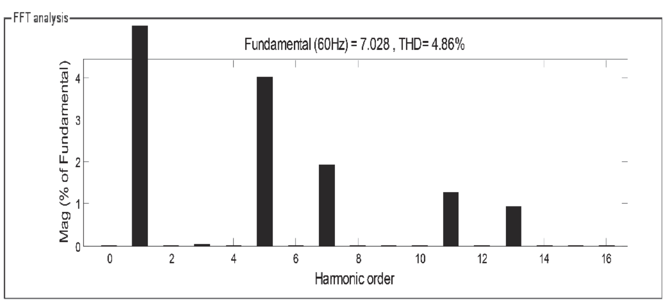

Fig 18: THD of Phase b (With Compensation)

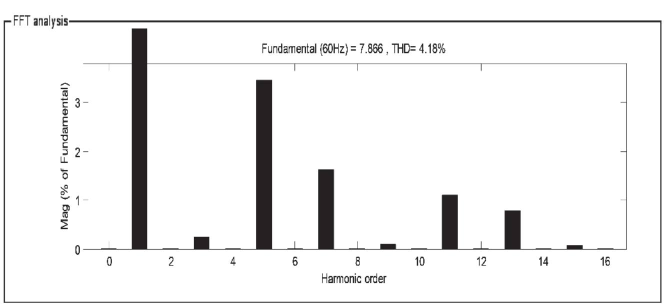

Fig 19: THD of Phase c (With Compensation)

THD of load currents is shown in Table 3.

Table 3: THD of load Current

THD (load Current)	Without compensation	With compensation
Phase a	18.02 %	4.35%
Phase b	32.78 %	4.86 %
Phase c	20.49%	4.18 %

Similarly THD of load voltage is shown in Table 4.

Table 4: THD of load voltage

THD (Source Current)	Without compensation	With compensation
Phase a	6.39 %	2.88 %
Phase b	6.22 %	2.88 %
Phase c	3.31 %	2.85 %

APPENDIX-A
SYSTEM PARAMETERS

3-phase supply (r.m.s)	v =30V, 60 Hz
3-phase non-linear load	R=26.66 Ω , L=10mH
DC-link capacitance	C_{dc}=3000μF
DC-link voltage	V_{dc} = 90 V
Coupling Inductance	L_{sh} =2.0 mH

APPENDIX-B
SYSTEM PARAMETERS

3-phase supply (r.m.s)	V=30 V, 60 Hz
3-phase non-linear load	R=26.66 Ω , L=10mH
1-phase non-linear load	R=26.66 Ω , L=10mH
1-phase linear load	R=36.66 Ω , L=10mH
DC-link capacitance	C_{dc} =3000 μF
DC-link voltage	V_{dc} = 90 V
Coupling Inductance	L_{sh} =2.0 mH

5. CONCLUSION

This paper presents a controller based on p-q theory consisting of four leg eight IGBT inverter configuration. It deals with the power quality issue in the grid and load. The simulations reveal that controller is able to mitigate all small disturbances, harmonic injections and voltage unbalances. Significant reduction in THD levels validates the effectiveness of the controller. By taking combination of linear and nonlinear loads, an effort is made to study the performance of proposed controller when applied to a real time distribution system. The proposed approach may be further applied to a hybrid or an integrated system consisting of conventional and renewable energy systems

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