Implementation of Unified Power Quality Conditioner in 3-ϕ 4-wire distribution system by using instantaneous power theory

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---**ABSTRACT**---
This paper presents the design of Unified Power Quality Conditioner connected to three phase four wire system by using p-q theory to improve the power quality. The UPQC is the integration of series and shunt active filters. The p-q theory is applied to the control algorithm for series and shunt active filters and it consists of an algebraic transformation (Clarke transformation) of the three-phase voltages and currents in the a-b-c coordinates to the α-β-0 coordinates followed by the calculation of the p-q theory instantaneous power components. The implementation of active filters based on the p-q theory are cost-effective solutions, allowing the use of a large number of low-power active filters in the same facility, close to each problematic load (or group of loads),avoiding the circulation of current harmonics, reactive currents and neutral currents through the facility power lines. The 3P4W distribution system is realized from a three phase three wire system where the neutral of series transformer used in the fourth wire for the 3P4W system, the neutral current that may flow toward transformer neutral point. This neutral current can be compensated by using a four leg voltage source inverter. The simulation results based on MATLAB/SIMULINK are also presented.

Index Term: Active Power Filter (APF), Four-leg Voltage-Source Inverter (VSI) structure, Three-Phase Four-Wire (3P4W) system, Unified Power Quality Conditioner (UPQC).

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I. INTRODUCTION

In the present scenario, the power electronic converters and non-linear loads are increasing intensively in industry and by the customers. In general, it can be observed as an increase in deterioration of the power systems voltage and current waveforms. The presence of harmonics in the power lines results in greater power losses in distribution, interference problems in communication systems and mal operation of sensitive electronic equipments, which are operating under low voltage levels. Because of these problems, the issue of the power quality delivered to the end users is of great concern. A 3P4W distribution system can be realized by providing the neutral conductor along with the three power lines from generation station, where the neutral of series transformer of series APF of the Unified Power Quality Conditioner used in the fourth wire for the 3P4W system. The unbalanced load currents are very common and a severe problem in 3P4W distribution system. The power quality is improved by connecting the series APF and shunt APF .The p-q theory is applied to the control algorithm for series and shunt active filters .In 1983, Akagi et.al.[14] introduced the concept of instantaneous reactive power. This concept gives an effective method to compensate the instantaneous components of reactive power for three-phase systems without energy storage. Instantaneous real and imaginary powers have first been defined in the time domain. The three phase voltages are sensed at the PCC and denoted as e_a, e_b and e_c. The resultant load side line currents are sensed and denoted as i_{aL}, i_{bL} and i_{cL}. The three phase voltage and current space-vectors can be transformed into the corresponding 0-α-β co-ordinates.

II. 3P4W DISTRIBUTION SYSTEM UTILIZING UPQC

Generally, a 3P4W distribution system is realized by providing a neutral conductor along with three power conductors from generation station or by utilizing a three-phase Δ−Y transformer at distribution level. Assume a plant site where 3P3W UPQC is already installed to protect a sensitive load and to restrict any entry of distortion from load side toward utility, as shown in Fig. 1.

If we want to upgrade the system now from 3P3W to 3P4W due to installation of some single-phase loads and if the distribution transformer is close to the plant under consideration, utility would provide the

neutral conductor from this transformer without much cost involvement. In certain cases, this may be a costly solution because the distribution transformer may not be situated in close vicinity. Recently, the utility service providers are putting more and more restrictions on current Total Harmonic Distortion (THD).
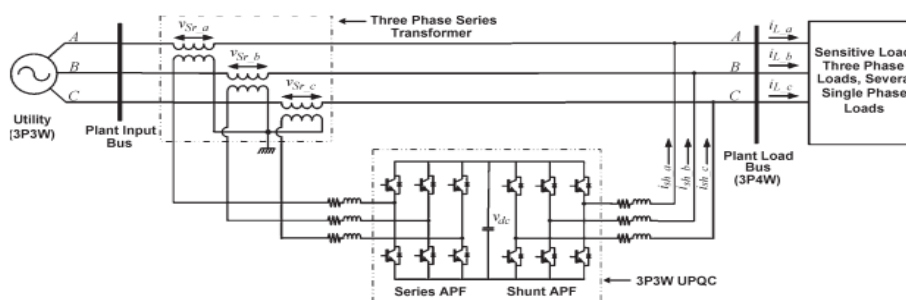

Fig 1: 3P3W UPQC structure

Fig.2 shows the scheme of a series active filter for a three-phase power system. It is the dual of the shunt APF, and is able to compensate for distortion in the power line voltages, making the voltages applied to the load sinusoidal (compensating for voltage harmonics). The filter consists of a voltage-source inverter (behaving as a controlled voltage source) and requires three single-phase transformers to interface with the power system. The series active filter does not compensate for load current harmonics but it acts as high-impedance to the current harmonics coming from the power source side. Therefore, it guarantees that passive filters eventually placed at the load terminals will not drain harmonic currents from the rest of the power system. Another solution to solve the load current harmonics is to use a shunt active filter together with the series active filter , so that both load voltages and the supplied currents are guaranteed to have sinusoidal waveforms.
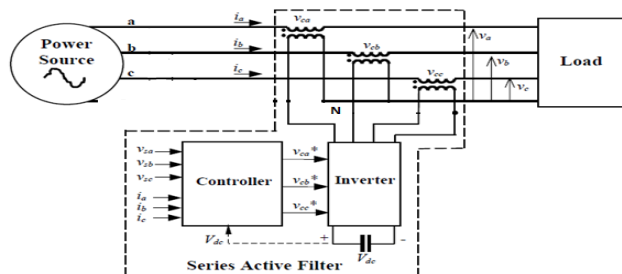

Fig 2: Series Active Filter

Fig 3.shows Shunt converter it is a voltage-source converter connected in shunt with the same AC line and acts as a current source to cancel current distortions, to compensate reactive current of the load and to improve the power factor. It also performs the DC-link voltage regulation, resulting in a significant reduction of the DC capacitor rating. The output current of the shunt converter is adjusted (e.g., using a dynamic hysteresis band) by controlling the status of semiconductor switches such that output current follows the reference signal and remains in a predetermined hysteresis band.
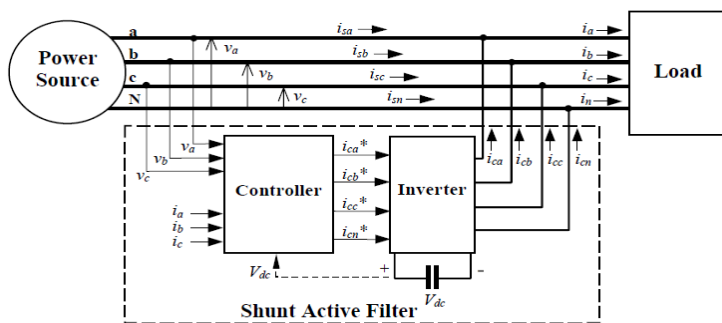

Fig 3: Shunt Active Filter

Recently, the utility service providers are putting more and more restrictions on current Total Harmonic Distortion (THD) limits drawn by nonlinear loads, to control the power distribution system harmonic pollution. At the same time, the use of sophisticated equipment/load has increased significantly, and it needs clean power

for its proper operation. Therefore, in future distribution systems and the plant/load centers, application of UPQC would be common. Fig. 4 shows the proposed novel 3P4W topology that can be realized from a 3P3W system. This proposed system has all the advantages of general UPQC, in addition to easy expansion of 3P3W system to 3P4W system. Thus, the proposed topology may play an important role in the future 3P4W distribution system for more advanced UPQC based plant/load center installation, where utilities would be having an additional option to realize a 3P4W system just by providing a 3P3W supply.
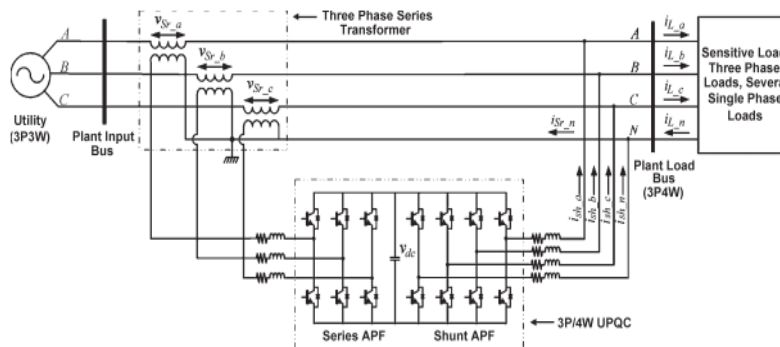

Fig .4. Proposed 3P4W System Realized From A 3P3W System Utilizing UPQC

III. DESIGN OF UPQC BY USING PQ THOERY

In 1983, *Akagi et al.* [14, 15] have proposed the "The Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits", also known as instantaneous power theory , or simply p-q theory. It is based on instantaneous values in three-phase power systems with or without neutral wire, and is valid for steady-state or transitory operations, as well as for generic voltage and current waveforms. The p-q theory consists of an algebraic transformation (Clarke transformation) of the three-phase voltages and currents in the *a-b-c* coordinates to the α-β-*0* coordinates, followed by the calculation of the p-q theory instantaneous power components:

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad and \quad \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$
(1)

$P_0 = v_0 . i_0$ Instantaneous zero-sequence power . (2)

$p = v_\alpha . i_\alpha + v_\beta . i_\beta$ Instantaneous real power . (3)

$q = v_\alpha . i_\beta - v_\beta . i_\alpha$ Instantaneous imaginary power (by definition) . (4)

The power components *p* and *q* are related to the same α-β voltages and currents, and can be written together

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$
(5)

These quantities are illustrated in Fig. 5 for an electrical system represented in *a-b-c* coordinates and have the following physical meaning:

$\bar{p}_0$ = Mean value of the instantaneous zero-sequence power – corresponds to the energy per time unity which is transferred from the power supply to the load through the zero-sequence components of voltage and current.

$\tilde{p}_0$ = Alternated value of the instantaneous zero-sequence power – it means the energy per time unity that is exchanged between the power supply and the load through the zero-sequence components. The zero-sequence power only exists in three-phase systems with neutral wire. Furthermore, the systems must have unbalanced voltages and currents and/or 3rd harmonics in both voltage and current of at least one phase.

$\bar{p}$ = Mean value of the instantaneous real power – corresponds to the energy per time unity which is transferred from the power supply to the load, through the *a-b-c* coordinates in a balanced way (it is the desired power component).

$\tilde{p}$ = Alternated value of the instantaneous real power – It is the energy per time unity that is exchanged between the power supply and the load, through the *a-b-c* coordinates.

q = Instantaneous imaginary power – corresponds to the power that is exchanged between the phases of the load.

This component does not imply any transference or exchange of energy between the power supply and the load, but is responsible for the existence of undesirable currents, which circulate between the system phases. In the case of a balanced sinusoidal voltage supply and a balanced load, with or without harmonics, $\tilde{q}$ (the mean value of the instantaneous imaginary power) is equal to the conventional reactive power ($\tilde{p}$= 3.$V.I.sin_{\varphi 1}$).
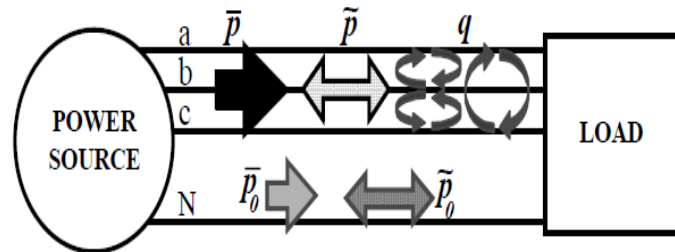
Fig: Power components of the p-q theory in *a-b-c* co-ordinates

IV. DESIGN OF UPQC CONTROLLER

The control algorithm for series APF is based on unit vector template generation scheme .Where as the control strategy for shunt APF is discussed in this section. Based on the load on the 3P4W system, the current drawn from the utility can be unbalanced. According to this theory, a single phase system can be defined as a pseudo two-phase system by giving $\pi/2$ lead or $\pi/2$ lag that is each phase voltage and current of the original three phase systems.

These resultant two phase systems can be represented in α-β coordinates, and thus p-q theory applied for balanced three phase system can also be used for each phase of unbalanced system independently. The actual load voltages and load currents are considered as α-axis quantities, where as the $\pi/2$ lead load or $\pi/2$ lag voltages and $\pi/2$ lead or $\pi/2$ lag load currents are considered as β-axis quantities. In this paper, $\pi/2$ lead is considered to achieve a two-phase system for each phase. The major disadvantage of p–q theory is that it gives poor results under distorted and/or unbalanced input/utility voltages. In order to eliminate these limitations, the reference load voltage signals extracted for series APF are used instead of actual load voltage.

For phase a, the load voltage and current in α–β coordinates can be represented by $\pi/2$ lead as

$$\begin{bmatrix} v_{La-\alpha} \\ v_{La-\beta} \end{bmatrix} = \begin{bmatrix} v_{La}^{\bullet}(\omega t) \\ v_{La}^{\bullet}(\omega t + {}^{\pi}/_2) \end{bmatrix} = \begin{bmatrix} V_{Lm}\sin(\omega t) \\ V_{Lm}\cos(\omega t) \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} i_{La-\alpha} \\ i_{La-\beta} \end{bmatrix} = \begin{bmatrix} i_{La}(\omega t + \varphi_L) \\ i_{La}[(\omega t + \varphi_L) + {}^{\pi}/_2] \end{bmatrix} \tag{7}$$

Where $v_{La}^{\bullet}(\omega t)$ represents the reference load voltage and V_{Lm} represents the desired load voltage magnitude. Similarly, for phase b, the load voltage and current in α–β coordinates can be represented by $\pi/2$ lead as

$$\begin{bmatrix} v_{Lb-\alpha} \\ v_{Lb-\beta} \end{bmatrix} = \begin{bmatrix} v_{Lb}^{\bullet}(\omega t) \\ v_{Lb}^{\bullet}(\omega t + {}^{\pi}/_2) \end{bmatrix} = \begin{bmatrix} V_{Lm}\sin(\omega t - 120^\circ) \\ V_{Lm}\cos(\omega t - 120^\circ) \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} i_{Lb-\alpha} \\ i_{Lb-\beta} \end{bmatrix} = \begin{bmatrix} i_{Lb}(\omega t + \varphi_L) \\ i_{Lb}[(\omega t + \varphi_L) + {}^{\pi}/_2] \end{bmatrix} \tag{9}$$

In addition, for phase c, the load voltage and current in α–β coordinates can be represented by $\pi/2$ lead as

$$\begin{bmatrix} v_{Lc-\alpha} \\ v_{Lc-\beta} \end{bmatrix} = \begin{bmatrix} v_{Lc}^{\bullet}(\omega t) \\ v_{Lc}^{\bullet}(\omega t + {}^{\pi}/_2) \end{bmatrix} = \begin{bmatrix} V_{Lm}\sin(\omega t + 120^\circ) \\ V_{Lm}\cos(\omega t + 120^\circ) \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} i_{Lc-\alpha} \\ i_{Lc-\beta} \end{bmatrix} = \begin{bmatrix} i_{Lc}(\omega t + \varphi_L) \\ i_{Lc}[(\omega t + \varphi_L) + {}^{\pi}/_2] \end{bmatrix} \tag{11}$$

By using the definition of three-phase p–q theory for balanced three-phase system, the instantaneous power components can be represented as Instantaneous active power

$$p_{L,abc} = v_{L,abc-\alpha} \cdot i_{L,abc-\alpha} + v_{L,abc-\beta} \cdot i_{L,abc-\beta} \tag{12}$$

Instantaneous reactive power

$$q_{L,abc} = v_{L,abc-\alpha} \cdot i_{L,abc-\beta} - v_{L,abc-\beta} \cdot i_{L,abc-\alpha} \tag{13}$$

The phase-a instantaneous load active and instantaneous load reactive powers can be represented by

$$\begin{bmatrix} p_{La} \\ q_{La} \end{bmatrix} = \begin{bmatrix} v_{La-\alpha} & v_{La-\beta} \\ -v_{La-\beta} & v_{La-\alpha} \end{bmatrix} \cdot \begin{bmatrix} i_{La-\alpha} \\ i_{La-\beta} \end{bmatrix} \tag{14}$$

Where

$$p_{La} = \overline{p_{La}} + \widetilde{p_{La}} \tag{15}$$
$$q_{La} = \overline{q_{La}} + \widetilde{q_{La}} \tag{16}$$

In eq. (15) and (16), $\overline{p_{La}}$ and $\overline{q_{La}}$ represent the dc components that are responsible for fundamental load active and reactive powers, whereas $\widetilde{p_{La}}$ and $\widetilde{q_{La}}$ represent the ac components that are responsible for harmonic powers. The phase-a fundamental instantaneous load active and reactive power components can be extracted from p_{La} and q_{La}, respectively, by using a low pass filter.

Therefore, the instantaneous fundamental load active power for phase a is given by

$$p_{La,1} = \overline{p_{La}} \tag{17}$$

and the instantaneous fundamental load reactive power for phase a is given by

$$q_{La,1} = \overline{q_{La}} \tag{18}$$

Similarly, the fundamental instantaneous load active and reactive powers for phases b and c can be calculated as
 Instantaneous fundamental load active power for phase b

$$p_{Lb,1} = \overline{p_{Lb}} \tag{19}$$

Instantaneous fundamental load reactive power for phase b

$$q_{Lb,1} = \overline{q_{Lb}} \tag{20}$$

Instantaneous fundamental load active power for phase c

$$p_{Lc,1} = \overline{p_{Lc}} \tag{21}$$

Instantaneous fundamental load reactive power for phase c

$$q_{Lc,1} = \overline{q_{Lc}} \tag{22}$$

Since the load current drawn by each phase is different due to different loads present inside plant, therefore, the instantaneous fundamental load active power and reactive power demand for each phase may not be the same. In order to meet this load unbalanced power demand, seen from the utility side, as a perfectly balanced fundamental three-phase active power the unbalanced load power should be properly redistributed among utility, UPQC, and load, such that the total load seen by the utility would be linear and balanced load. The unbalanced or balanced reactive power demanded by the load should be handled by a shunt APF. The aforementioned task can be achieved by summing instantaneous fundamental load active power demand of all the three phases and redistributing it again on each utility phase, i.e., from equations (19), (20), and (21),

$$p_{L,total} = p_{La,1} + p_{Lb,1} + p_{Lc,1} \tag{23}$$
$$p^{*}_{S/ph} = \frac{p_{L,total}}{3} \tag{24}$$

Equation (24) gives the redistributed per-phase fundamental active power demand that each phase of utility should supply in order to have balanced source currents. From equation (24), it is evident that under all the conditions, the total fundamental power drawn from the utility is perfectly balanced even though the load currents are unbalanced. Thus, the reference compensating currents representing a perfectly balanced three-phase system can be extracted by taking the inverse of eq. (14)

$$\begin{bmatrix} i^{*}_{sa-\alpha} \\ i^{*}_{sa-\beta} \end{bmatrix} = \begin{bmatrix} v_{La-\alpha} & v_{La-\beta} \\ -v_{La-\beta} & v_{La-\alpha} \end{bmatrix}^{-1} \cdot \begin{bmatrix} p^{*}_{S/ph} + p_{dc/ph} \\ 0 \end{bmatrix} \tag{25}$$

In equation (20), $p_{dc/ph}$ is the precise amount of per-phase active power that should be taken from the source in order to maintain the dc-link voltage at a constant level and to overcome the losses associated with UPQC. The oscillating instantaneous active power should be exchanged between the load and shunt APF. The reactive power term (q_{La}) in equation (25) is considered as zero, since the utility should not supply load reactive power demand. In the above matrix, the α- axis reference compensating current represents the instantaneous fundamental source current, since α-axis quantities belong to the original system under consideration and the β-axis reference compensating current represents the current that is at π/2 lead with respect to the original system.

Therefore,

$$i^{*}_{sa}(t) = \frac{v_{La-\alpha}(t)}{v^{2}_{La-\alpha} + v^{2}_{La-\beta}} \cdot [p^{*}_{S/ph}(t) + p_{dc/ph}(t)] \tag{26}$$

Similarly, the reference source current for phases b and c can be estimated as

$$i^{*}_{sb}(t) = \frac{v_{Lb-\alpha}(t)}{v^{2}_{Lb-\alpha} + v^{2}_{Lb-\beta}} \cdot [p^{*}_{l/ph}(t) + p_{dc/ph}(t)] \tag{27}$$
$$i^{*}_{sc}(t) = \frac{v_{Lc-\alpha}(t)}{v^{2}_{Lc-\alpha} + v^{2}_{Lc-\beta}} \cdot [p^{*}_{l/ph}(t) + p_{dc/ph}(t)] \tag{28}$$

The reference neutral current signal can be extracted by simply adding all the sensed load currents, without actual neutral current sensing, as

$$i_{L-n}(t) = i_{La}(t) + i_{Lb}(t) + i_{Lc}(t) \tag{29}$$
$$i_{sh-n}(t) = -i_{L-n}(t) \tag{30}$$

The proposed balanced per-phase fundamental active power estimation, dc-link voltage control loop based on PI regulator, the reference source current generation as given by equations (26)–(28),

V. SIMULATION BLOCK DIAGRAMS

The simulation block diagram of 3P4W system realized from a 3P3W system utilizing UPQC is shown in figure.7.The combination of series APF and shunt APF is connected common a dc-link. The plant load is assumed to be the combination of a balanced three-phase diode bridge rectifier followed by an R-L load, which acts as a harmonic generating load, and three different single phase loads on each phase, with different load active and reactive power demands. By using equations (6), (8) and (10) to design the unit vector template of series APF is and figure.5 is Series active power filter controller shown in below figures. And also shunt APF is Design by using all above equations is shown in below figure 6.
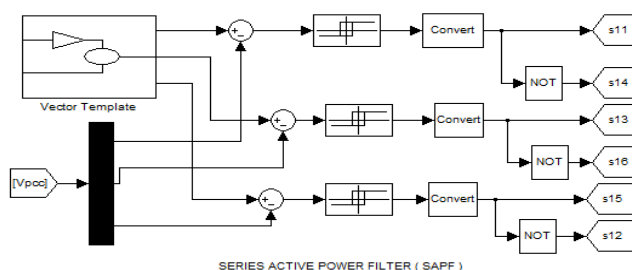
Figure.5: Simulation block of Series active power filter controller
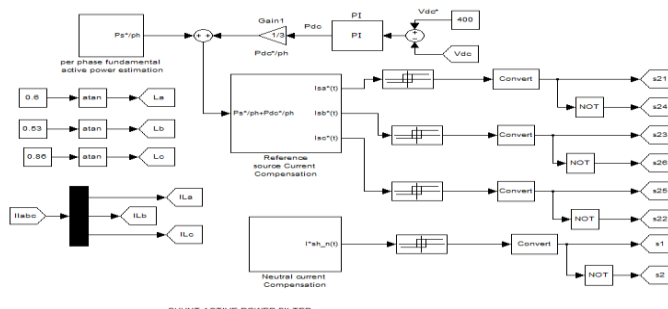
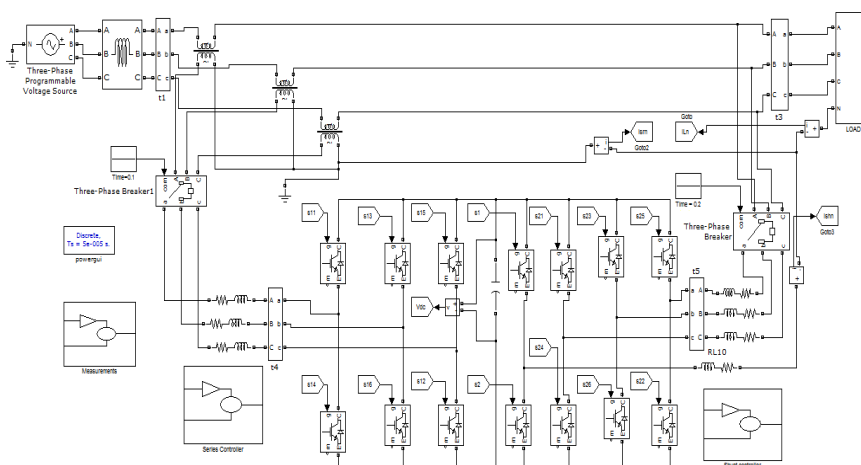**Figure.6: Simulation block of Shunt Active Power Filter.**

Figure.7: Simulation Block Diagram of 3P4W system realized from a 3P3W system utilizing UPQC

The simulation results for the proposed 3P4W system realized from a 3P3W system utilizing UPQC are shown in below figures 8 to 12.Utility voltage is assumed to be distorted with voltage THD of 27.0 %. The distorted voltage profile is shown in figure.8 (A). The UPQC should maintain the voltage at load bus at a desired

value and free from distortion. The shunt APF is turned on first at time t=0.1sec, such that it maintains the dc-link voltage at a set reference value, here V=220V.At time t=0.2sec .The series active power filter injects the required compensating voltages through series transformer, making the load voltage free from distortion (THD = 1.46%) and at a desired level as shown in figure.8 (B) in load voltage. The series active power filter injected voltage profile is shown in figure.8(C). The compensated source currents shown in figure.9(A) are perfectly balanced with the THD of 2.26% .The compensating current injected through the fourth leg of the shunt APF is shown in figure.9(C).The load neutral current profile is shown in figure.11 and figure.12. In figure.10, the shunt APF effectively compensates the current flowing toward the transformer neutral point. Thus, the series transformer neutral point is maintained at virtual zero potential is shown in figure 10(B).
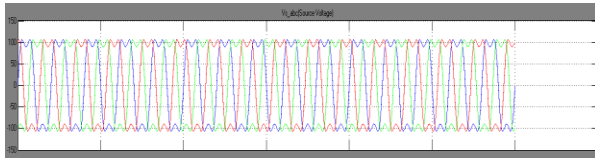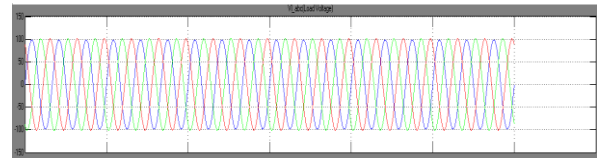

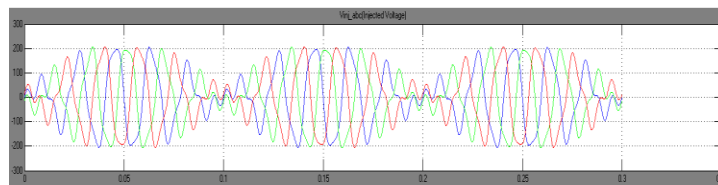**Figure 8(A): Utility Voltage.**

Figure 8(B): Load Voltage

Figure 8(C): Injected Voltage.

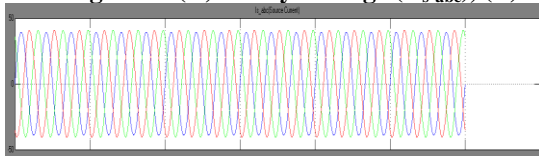**Figure.8: (A) Utility Voltage (V_{s-abc}), (B) Load Voltage (V_{l-abc}) and (C) Injected Voltage ($V_{ini-abc}$).**
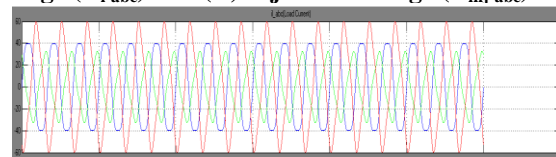

Figure.9(A): Source Current

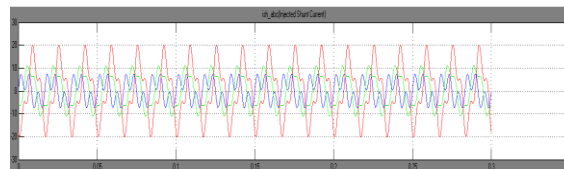**Figure 9(B): Load Current.**

Figure.9(C): shunt compensating current.

Figure.9:(A) Source Current (I_{s-abc}), (B) Load Current (I_{l-abc}) and (C) Shunt Compensating Current (I_{sh-abc}).
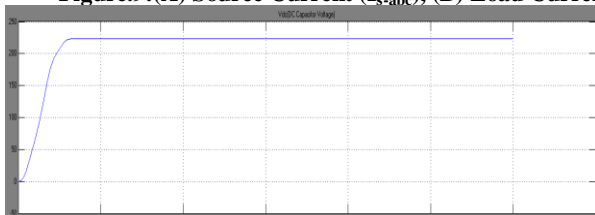

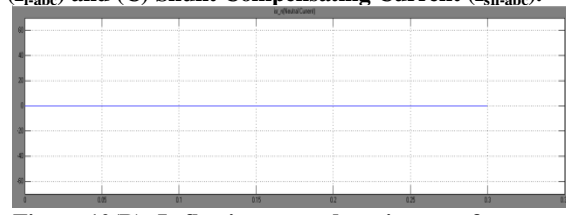**Figure.10 (A): Dc-link voltage**

Figure.10(B): I_N flowing towards series transformer.

Figure.10 :(A) Dc-link voltage (v_{dc}), and (B) neutral current flowing towards series transformer (i_{Sr-n}).
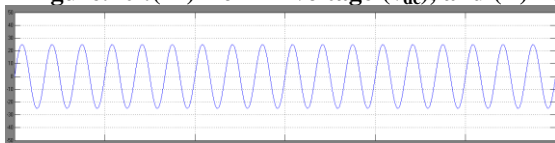

Figure.11: Shunt neutral compensating current (i_{Sh-n}).
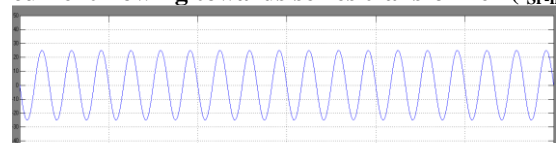

Figure.12: Current flowing through load neutral wire (i_{L-n})

V. CONCLUSION

The implementation of Unified Power Quality Conditioner (UPQC) connected to 3P4W distribution system has been presented. Where UPQC is installed to compensate the different power quality problems, which may play an important role in future UPQC- based distribution system. The simulation results shows that the distorted and unbalanced load currents seen from the utility side act as perfectly balanced source currents and are free from distortion. From the above observations the power quality problems like voltage and current unbalanced and reduced the Total Harmonic Distortion (THD) of 3P4W system utilizing 3P3W system to connect the UPQC. The neutral current that may flow toward the transformer neutral point is effectively compensated such that the transformer neutral point is always at virtual zero potential.

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