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Modeling and Simulation of Three Phases 4-Wire Distribution System Utilizing Unified Power Quality Conditioner (UPQC)

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Abstract: **This paper presents a detail structure for a three phase Four-wire (3P4W) distribution system using unified Power quality conditioner (UPQC). The 3P4W system is realized from a three-phase 3-wire system. The neutral of series transformer used in the fourth wire for the 3P4W system. The neutral current that may flow toward transformer neutral point is compensated by using a four-leg voltage source inverter topology for shunt part. The series transformer neutral will be at virtual zero potential (Vn=0v) during all operating conditions. The Unified Power Quality Conditioner (UPQC) device combines a shunt active filter together with a series active filter in a back-to-back configuration, to simultaneously compensate the supply voltage and the load current. A new control strategy (unit vector template) to balance the unbalanced load currents and also presented in this paper. The control strategies are modeled using MATLAB/SIMULINK. The performance is also observed under influence of utility side disturbances.**

Keywords: **Active power filter (APF), four-leg voltage-source inverter (VSI) structure, three-phase four-wire (3P4W) system, p-q theory, unified power quality conditioner (UPQC).**

I. INTRODUCTION

Modern power system comprises of complex networks, where many generating stations and load centers are interconnected through long power transmission and distribution networks. Utility distribution networks, critical commercial operations and sensitive industrial loads all suffer from various types of outages and interruptions which can lead to significant financial loss, loss of production, idle work forces etc. Today due the changing trends and restructuring of power systems, the consumers are looking forward to the quality and reliability of power supply at the load centers. A power quality problem is an occurrence manifested as a nonstandard voltage, current or frequency that results in a failure or a miss-operation of end use equipments.

The power-electronics-based devices have been used to overcome the major power quality problems . To provide a balance, distortion-free, and constant magnitude power to sensitive load and, at the same time, to restrict the harmonic, unbalance, and reactive power demanded by the load and hence to make the overall power distribution system more healthy, the unified power quality conditioner (UPQC) is one of the best solutions.

A three-phase four-wire (3P4W) distribution system can be realized by providing the neutral conductor along with the three power lines from generation station or by utilizing a delta-star (Δ–Y) transformer at distribution level. The UPQC installed for 3P4W application generally considers 3P4W supply. This paper proposes a new topology/structure that can be realized in UPQC-based applications, in which the series transformer neutral used for series inverter can be used to realize a 3P4W system even if the power supplied by utility is three phase three-wire (3P3W). This new functionality using UPQC could be useful in future UPQC-based distribution systems. The unbalanced load currents are very common and yet an important problem in 3P4W distribution system. This paper deals with the unbalanced load current problem with a new control approach, in which the fundamental active powers demanded by each phase are computed first, and these active powers are then redistributed equally on each of the phases. Thus, the proposed control strategy makes the unbalanced load currents as perfectly balanced source currents using UPQC. The proposed 3P4W distribution system realized from existing 3P3W UPQC-based system.

II. PROPOSED 3P4W DISTRIBUTION USING UPQC

Generally, a 3P4W distribution system is realized by providing a neutral wire along with three phase three wire distribution line from generation station or by using a three-phase Δ–Y transformer at distribution level. Fig. 1 shows a 3P4W network in which the neutral wire is provided from the generating station itself, whereas in Fig. 2 shows a 3P4W distribution network considering a Δ–Y transformer at the distribution line. Assume a plant where three-phase three-wire UPQC is already installed to protect a sensitive loads and to restrict any entry of distortion from load side toward utility, as shown in Fig. 3. If we want to upgrade the system from 3P3W to 3P4W due to installation of single-phase loads and if the distribution transformer is close to the plant under consideration, we would easily provide the neutral conductor from this transformer without major investment. In certain cases, this may be an uneconomical because the distribution transformer may not be nearer to load centers.

Recently, the utility service providers are putting more restrictions on current total harmonic distortion (THD) limits, drawn by nonlinear loads (that maybe single phase or three phase loads), to control the power distribution system harmonic pollution. At the same time, the use of sensitive 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 necessary. Fig. 4 shows the proposed structure of 3P4W topology that can be realized from a 3P3W system. This proposed system has all the advantages of general UPQC and easy expansion of 3P3W system to 3P4W system. Thus, the proposed topology may play an vital role in the future 3P4W distribution system for more advanced UPQC based plants installation, where utilities would be having an additional option to realize a 3P4W system just by providing a 3P3W supply.

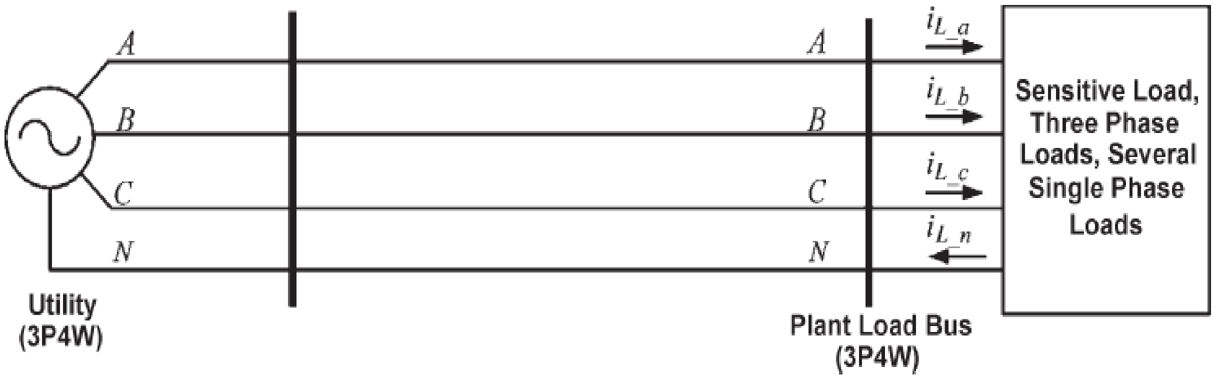

Fig: 1 3-phase four wire distribution system
(Neutral is provided by generating station)

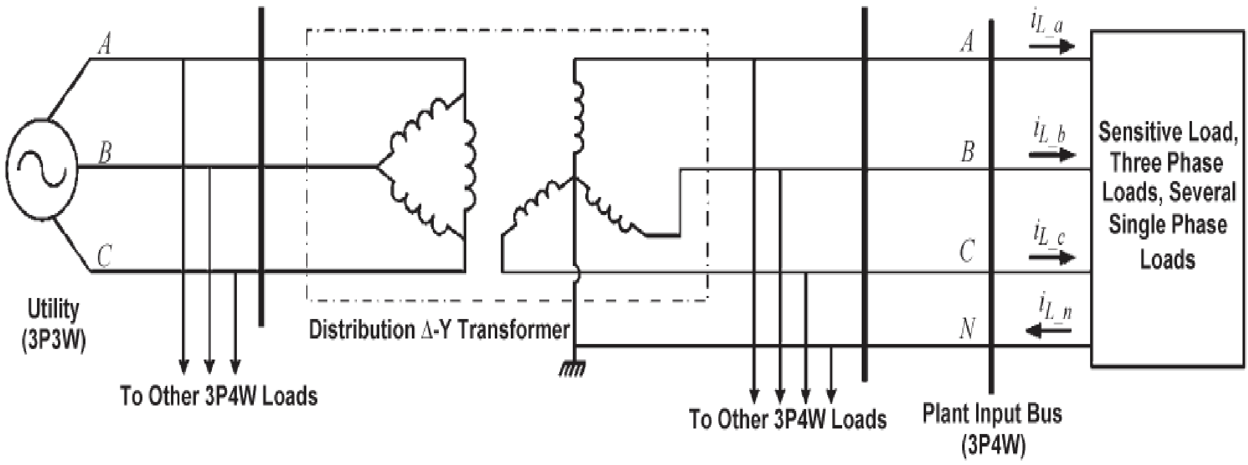

Fig: 2 3P4W distribution (neutral is provided by Δ–Y transformer)

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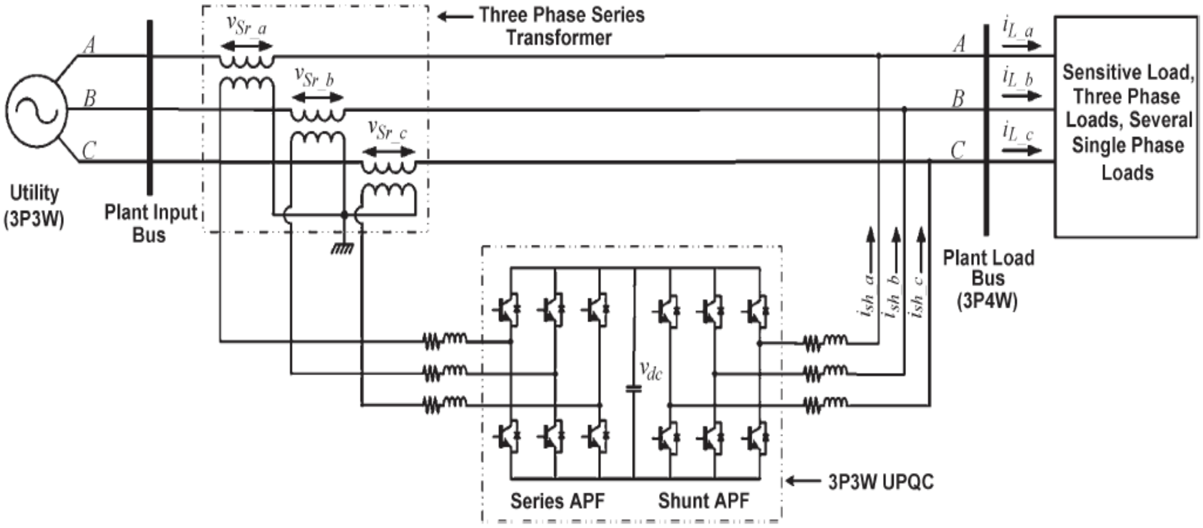


Fig: 3 3P3W distribution system with UPQC

As shown in Fig. 3, the UPQC should necessarily consist of 3-phase series transformer in order to connect one of the inverters in the series with the line to function as a controlled voltage source. If we could use the neutral of 3-phase series transformer to connect a neutral wire to realize the 3P4W system, then 3P4W system can easily be achieved from a 3P3W system (Fig. 4). The neutral current, present if any, would flow through this fourth wire toward transformer neutral point. This neutral current can be compensated by using a split capacitor topology or a four-leg voltage-source inverter (VSI) topology for a shunt inverter (in our project the neutral current is compensated by using 4-leg VSI). The 4-leg VSI topology requires one additional leg as compared to the split capacitor topology. The neutral current compensation in the 4-leg VSI structure is much easier than that of the split capacitor because the split capacitor topology essentially needs two capacitors and an extra control loop to maintain a zero voltage error difference between both the capacitor voltages, resulting in a more complex control loop to maintain the dc bus voltage at constant level.

In this paper, the four-leg VSI topology is considered to compensate the neutral current flowing toward the transformer neutral point. A fourth leg is added on the existing 3P3W UPQC, such that the transformer neutral point will be at virtual zero potential (i.e. Vn=0v). Thus, the proposed structure would help to realize a 3P4W system from a 3P3W system at distribution load end. This would be easily expansion from 3P3W to 3P4W systems. A new control strategy to generate balanced reference source currents under unbalanced load condition is also proposed in this paper.

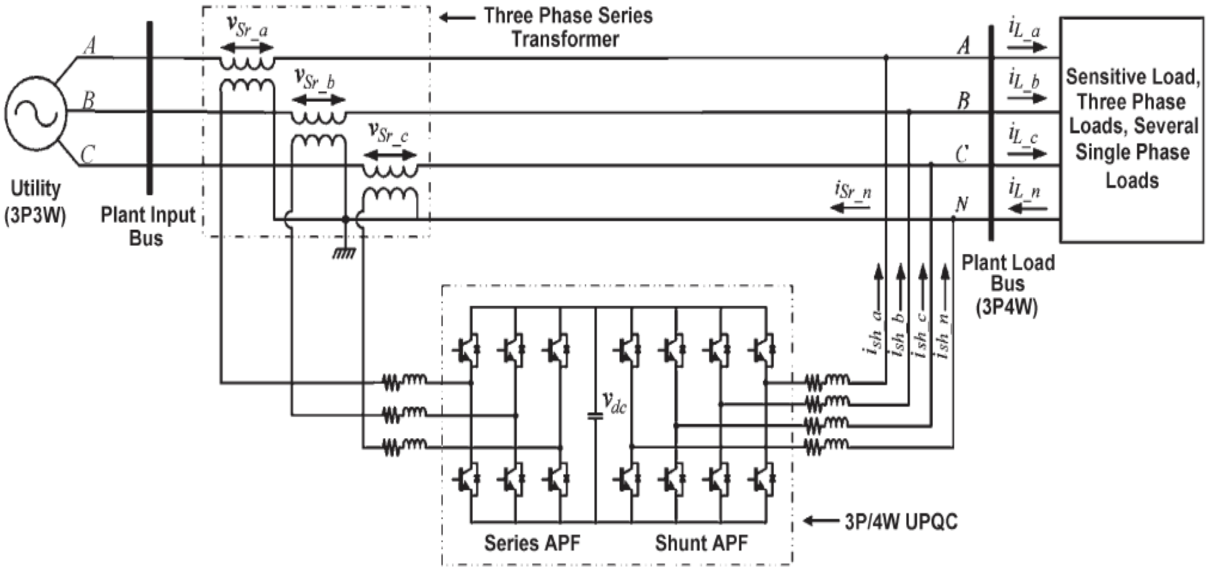


Fig: 4 3P4W distribution system with UPQC

III. MODELLING OF UPQC CONTOLLER

The control algorithm for series active power filter (APF) is based on unit vector template generation scheme (7), whereas 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. In this paper, a new control strategy is proposed to compensate the current unbalance present in the load currents by expanding the concept of single phase *p–q* theory (5),(6). According to this theory, a signal phase system can be defined as a pseudo two-phase system by giving $\pi/2$ lead or $\pi/2$ lag, i.e., each phase voltage and current of the original three-phase system can be considered as three independent two-phase systems. These resultant two phase systems can be represented in α–β coordinates, and thus, the *p–q theory* applied for balanced three-phase system(3) can also be used for each phase of unbalanced system independently. The actual load voltages and load currents are considered as α-axis quantities, whereas 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 (4),(5). 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 voltages.

For phase *a*, the load voltage and current in α–β coordinates can be represented by $\pi/2$ lead as where $v*La(\omega t)$ represents the reference load voltage and *VLm* 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

$$\begin{bmatrix} v_{La\_\alpha} \\ v_{La\_\beta} \end{bmatrix} = \begin{bmatrix} v^*_{La}(\omega t) \\ v^*_{La}(\omega t + \pi/2) \end{bmatrix} = \begin{bmatrix} V_{Lm}\sin(\omega t) \\ V_{Lm}\cos(\omega t) \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_{La\_\alpha} \\ i_{La\_\beta} \end{bmatrix} = \begin{bmatrix} i_{La}(\omega t + \varphi_L) \\ i_{La}\left[(\omega t + \varphi_L) + \pi/2\right] \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} v_{Lb\_\alpha} \\ v_{Lb\_\beta} \end{bmatrix} = \begin{bmatrix} v^*_{Lb}(\omega t) \\ v^*_{Lb}(\omega t + \pi/2) \end{bmatrix} = \begin{bmatrix} V_{Lm}\sin(\omega t - 120^\circ) \\ V_{Lm}\cos(\omega t - 120^\circ) \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} i_{Lb\_\alpha} \\ i_{Lb\_\beta} \end{bmatrix} = \begin{bmatrix} i_{Lb}(\omega t + \varphi_L) \\ i_{Lb}\left[(\omega t + \varphi_L) + \pi/2\right] \end{bmatrix} \quad (4)$$

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

$$\begin{bmatrix} v_{Lc\_\alpha} \\ v_{Lc\_\beta} \end{bmatrix} = \begin{bmatrix} v^*_{Lc}(\omega t) \\ v^*_{Lc}(\omega t + \pi/2) \end{bmatrix} = \begin{bmatrix} V_{Lm}\sin(\omega t + 120^\circ) \\ V_{Lm}\cos(\omega t + 120^\circ) \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} i_{Lc\_\alpha} \\ i_{Lc\_\beta} \end{bmatrix} = \begin{bmatrix} i_{Lc}(\omega t + \varphi_L) \\ i_{Lc}\left[(\omega t + \varphi_L) + \pi/2\right] \end{bmatrix} \quad (6)$$

By using the definition of three-phase *p–q* theory for balanced three-phase system [3], the instantaneous power components can be represented as

Instantaneous active power

$pL,abc = vL,abc\_\alpha \cdot iL,abc\_\alpha + vL,abc\_\beta \cdot iL,abc\_\beta$------ (7)

Instantaneous reactive power

$qL,abc = vL,abc\_\alpha \cdot iL,abc\_\beta - vL,abc\_\beta \cdot iL,abc\_\alpha$.------ (8)

Considering phase *a*, the phase-*a* instantaneous load active and instantaneous load reactive powers can be represented by

$$\begin{bmatrix} p_{La} \\ q_{La} \end{bmatrix} = \begin{bmatrix} v_{La\_\alpha} & v_{La\_\beta} \\ -v_{La\_\beta} & v_{La\_\alpha} \end{bmatrix} \cdot \begin{bmatrix} i_{La\_\alpha} \\ i_{La\_\beta} \end{bmatrix} \quad (9)$$

Where

$pLa = pLa + \tilde{}pLa$ –----- (10)

$qLa = qLa + \tilde{}qLa$----. (11)

In (10) and (11), pLa and qLa represent the dc components that are responsible for fundamental load active and reactive powers, whereas $\tilde{}pLa$ and $\tilde{}qLa$ 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 pLa and qLa, respectively, by using a low pass filter.

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

$pLa, 1 = pLa$ (12)

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

$qLa, 1 = qLa$. (13)

Similarly, the fundamental instantaneous load active and the fundamental instantaneous load reactive powers for phase's *b* and *c* can be calculated as

Instantaneous fundamental load active power for phase *b*

$pLb,1 = pLb$. (14)

Instantaneous fundamental load reactive power for phase *b*

$qLb, 1 = qLb$. (15)

Instantaneous fundamental load active power for phase *c*

$pLc,1 = pLc$. (16)

Instantaneous fundamental load reactive power for phase *c*

$qLc, 1 = qLc$. (17)

Since the load current drawn by each phase may be different due to different loads that may be present inside plant, therefore, the instantaneous fundamental load active power and instantaneous fundamental load reactive power demand for each phase may not be the same. In order to make 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 between 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 demands of all the three phases and redistributing it again on each utility phase, i.e., from (12), (14), and (16),

pL, total $= pLa,1 + pLb,1 + pLc,1$ (18)

$p*S/\text{ph} = (pL,\text{total})/\ 3$. (19)

Equation (19) gives the redistributed per-phase fundamental active power demand that each phase of utility should supply in order to achieve perfectly balanced source currents. From (19), it is evident that under all the conditions, the total fundamental active power demanded by the loads would be equal to the total power drawn from the utility but with perfectly balanced way 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 (9)

$$\begin{bmatrix} i^*_{Sa\_\alpha} \\ i^*_{Sa\_\beta} \end{bmatrix} = \begin{bmatrix} v_{La\_\alpha} & v_{La\_\beta} \\ -v_{La\_\beta} & v_{La\_\alpha} \end{bmatrix}^{-1} \cdot \begin{bmatrix} p^*_{S/\mathrm{ph}} + p_{\mathrm{dc/ph}} \\ 0 \end{bmatrix} \quad (20)$$

In (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 $\tilde{p}_{La}$ should be exchanged between the load and shunt APF. The reactive power term (q_{La}) in (20) 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 $\pi/2$ lead with respect to the original system.

Therefore,

$$i^*_{Sa}(t) = \frac{v_{La\_\alpha}(t)}{v^2_{La\_\alpha} + v^2_{La\_\beta}} \cdot \left[p^*_{S/\mathrm{ph}}(t) + p_{\mathrm{dc/ph}}(t)\right] \quad (21)$$

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

$$i^*_{Sb}(t) = \frac{v_{Lb\_\alpha}(t)}{v^2_{Lb\_\alpha} + v^2_{Lb\_\beta}} \cdot \left[p^*_{L/\mathrm{ph}}(t) + p_{\mathrm{dc/ph}}(t)\right] \quad (22)$$

$$i^*_{Sc}(t) = \frac{v_{Lc\_\alpha}(t)}{v^2_{Lc\_\alpha} + v^2_{Lc\_\beta}} \cdot \left[p^*_{L/\mathrm{ph}}(t) + p_{\mathrm{dc/ph}}(t)\right]. \quad (23)$$

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

$i_{L\_n}(t) = i_{La}(t) + i_{Lb}(t) + i_{Lc}(t)$ (24)
$i^*_{Sh\_n}(t) = -\, i_{L\_n}(t)$. (25)

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 (21)–(23), and the reference neutral current generation are shown in Fig. 5(a)–(d), respectively

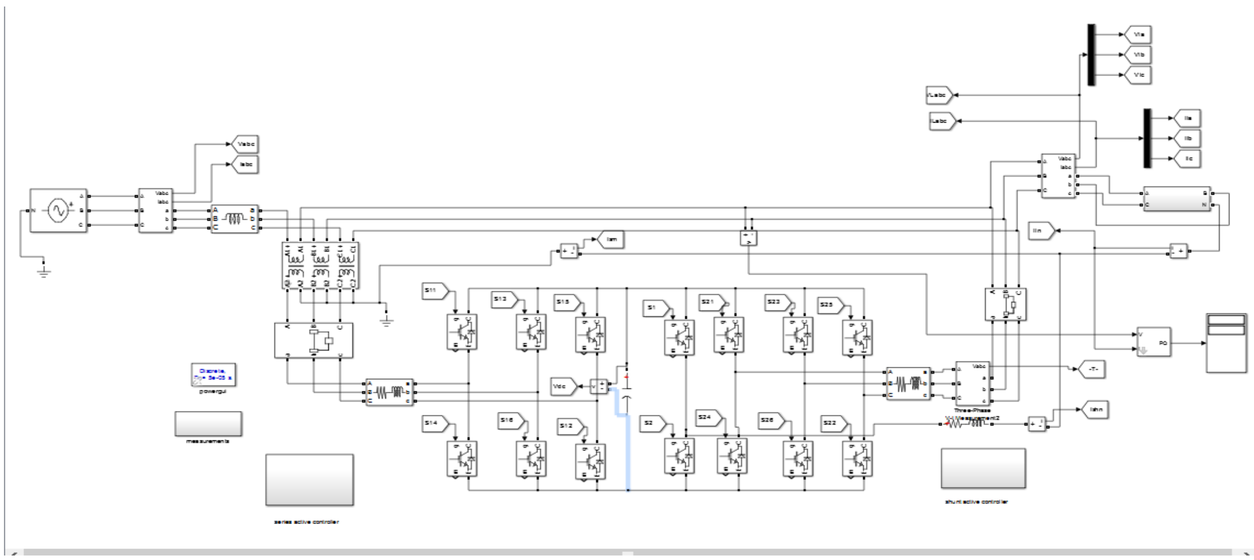


Fig: Matlab model of 3P4W Distribution system using UPQC

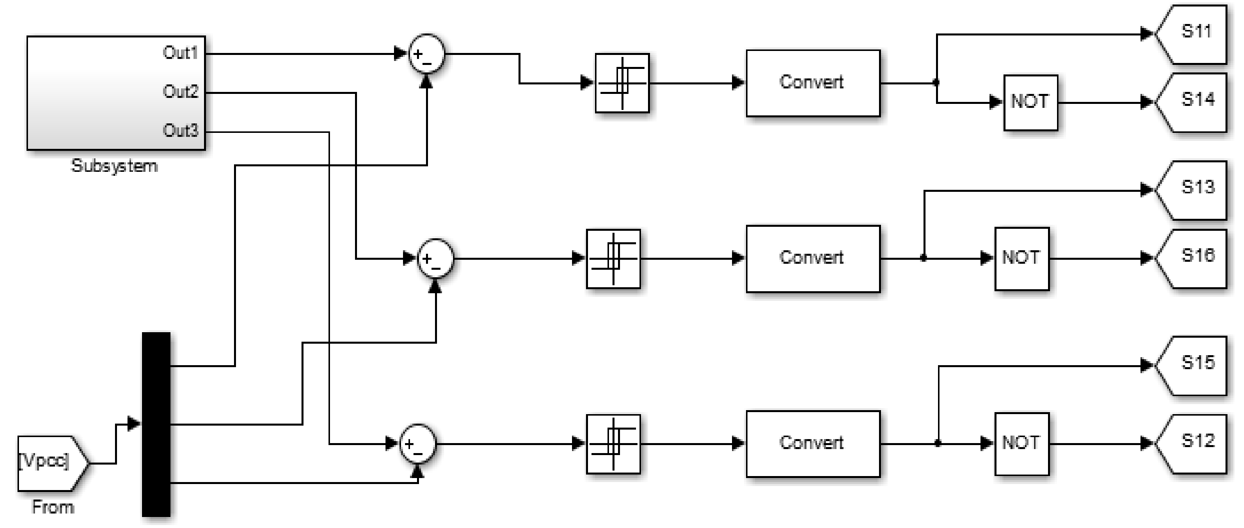


Fig: Matlab model of Series active power filter

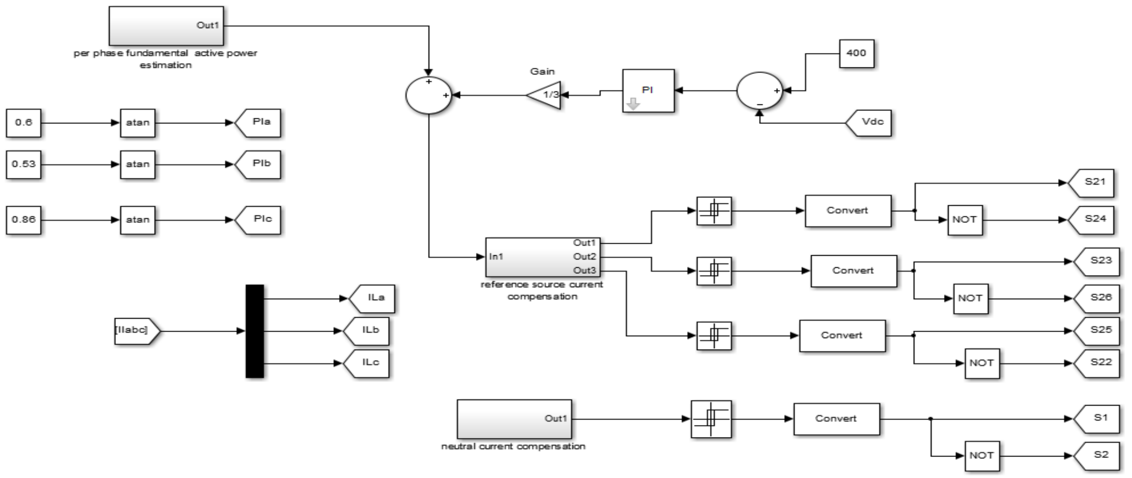


Fig: Matlab model of Shunt active power filter

4. SIMULATION RESULTS

An ideal three-phase sinusoidal supply voltage of 100v, 60Hz is applied to the non-linear load. Fig. B shows supply current and Fig. A shows the supply voltage. Shunt inverter is able to reduce the harmonics from entering into the system. The Total Harmonic Distortion (THD) in voltage at load end is 8.91% Fig. I before

Compensation was effectively reduced to 5.60 % Fig.J after compensation using PI controller. The compensating shunt currents generated contain harmonic content of the load current Fig.H but with opposite polarity such that when they are injected at the point of common coupling the harmonic content of supply current is effectively reduced. Fig.A and Fig.B shows the load voltage and load currents respectively. The distortion due to non linear *RL* load.

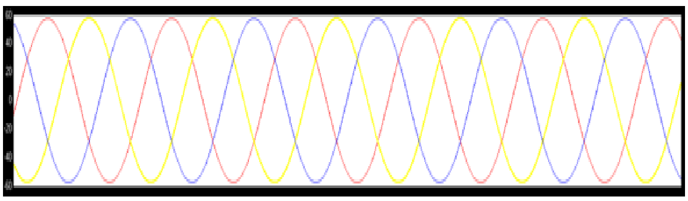


Fig : (A) Source voltage

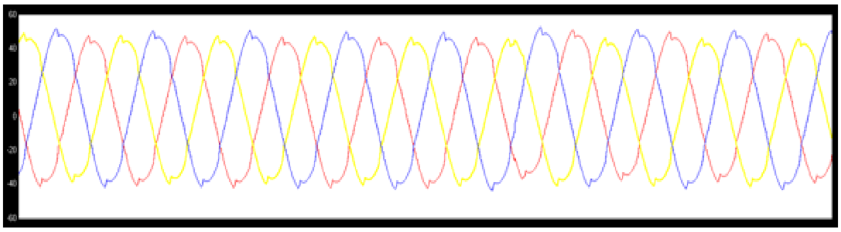


Fig : (B) Source current

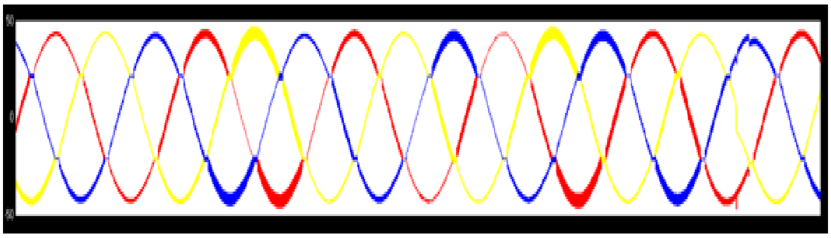


Fig : (C) Load voltage

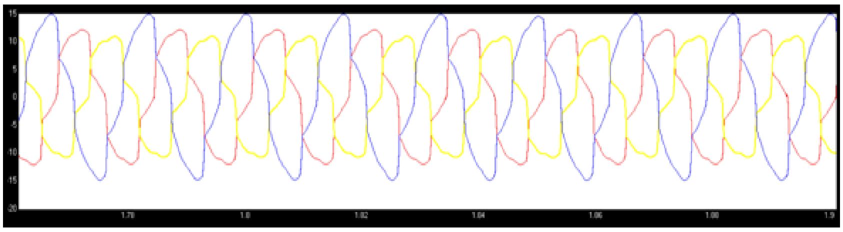


Fig : (D) Load current

Fig : (E) Voltage across capacitor

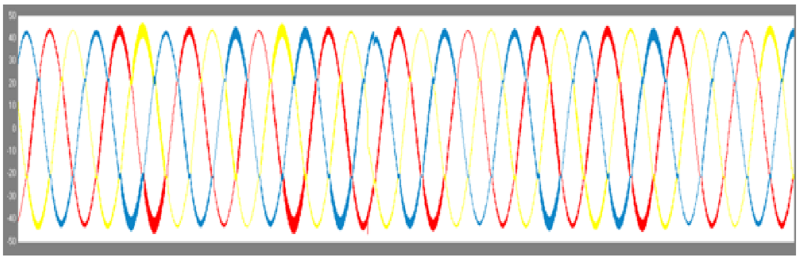


Fig : (F) Vinjected

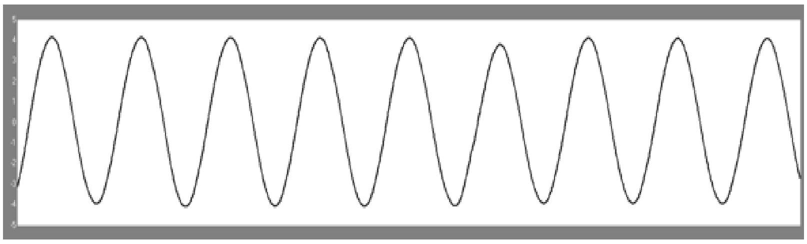


Fig : (G) Current through neutral line

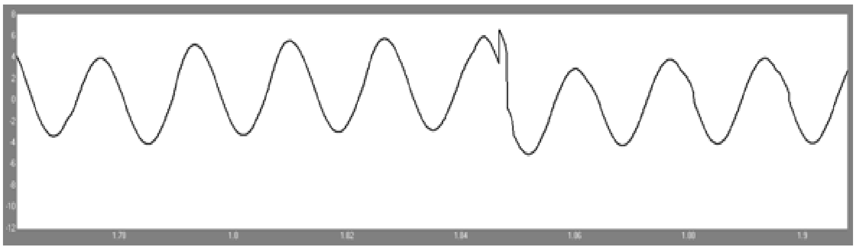


Fig : (H) Ism

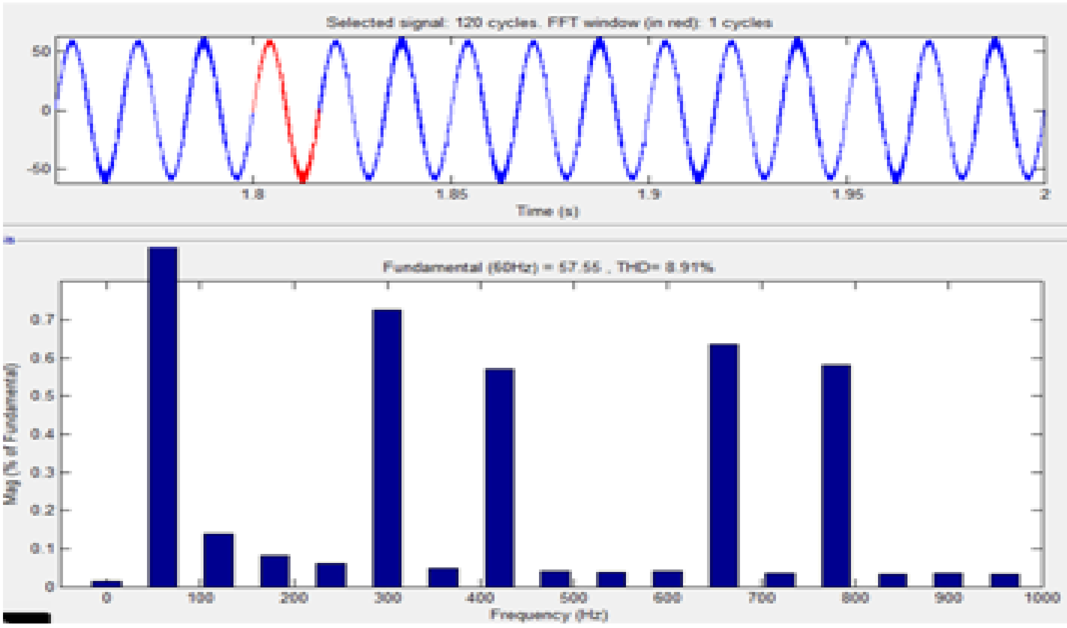


Fig: (I) Load voltage total harmonic distortion (THD) Without controller is 8.91%

THD response of the line current and line voltage in the Shunt APF side are found to be very low. Fig.C shows load voltage. Transmission capability of the existing transmission line is highly improved with the presence of UPQC. The difference between the sending-end voltage and receiving end voltage is high in the transmission line without UPQC.

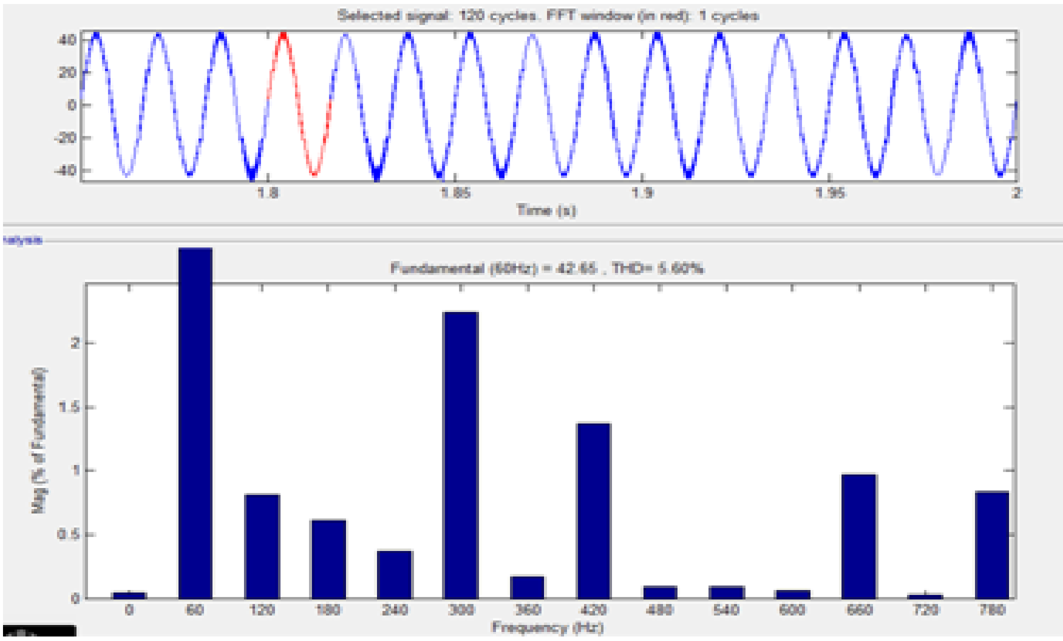
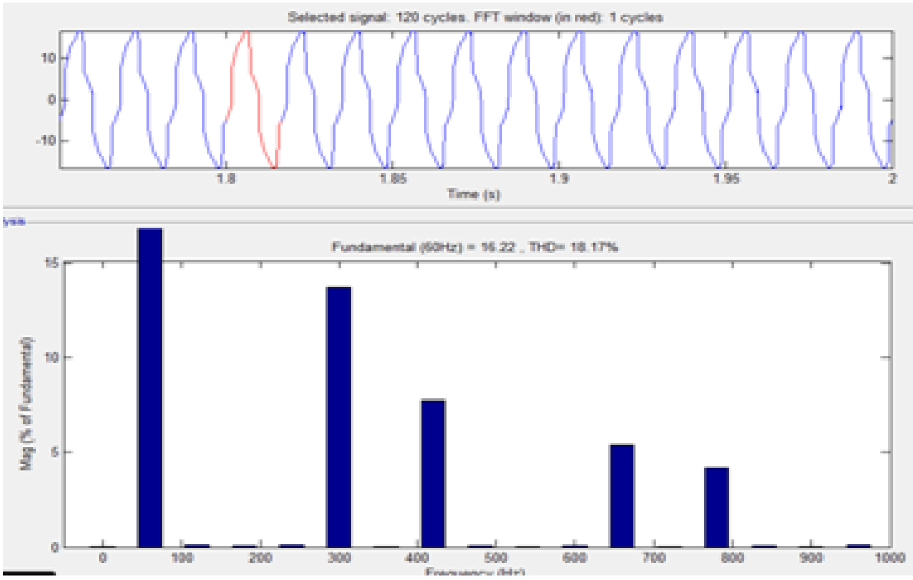
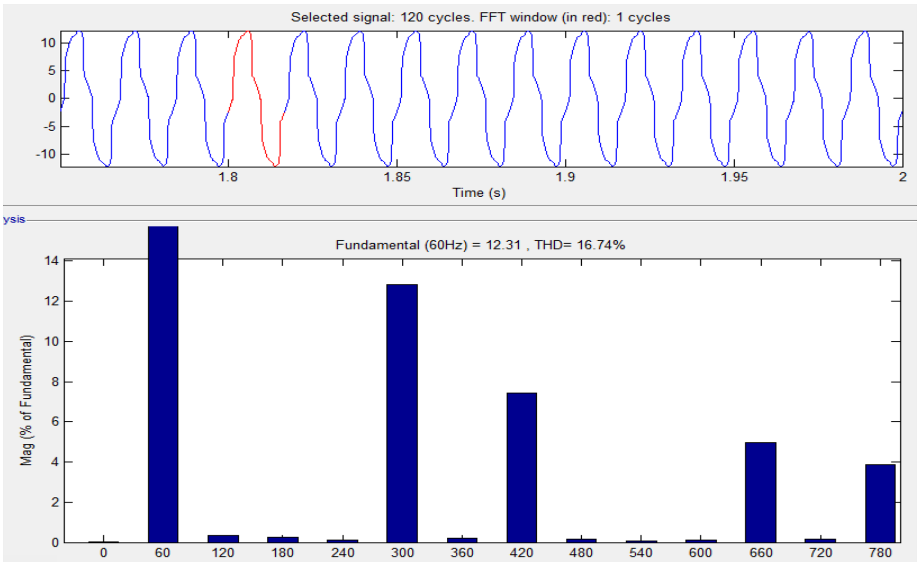


Fig: (j)Load voltage total harmonic distortion (THD) With controller is 5.60%

This is due to the increase in transmission losses, which are minimized with the help of UPQC. It also helps in improving power factor of the transmission line. The Load voltage and Load current with and without UPQC is shown in Fig.B & D. the raise in the transmission capability is noticed from the simulation results. The power transfer capability of long transmission lines is usually limited by their thermal capability. Utilizing the existing transmission line at its maximum thermal capability is possible with UPQC. The series 4 leg inverter injects voltage of variable magnitude and phase into the transmission line at the point of its connection, there by controlling real and reactive power flow through the line. The shunt inverter provides the required power to the series inverter through the dc link. UPQC performs active, reactive compensation and harmonic filtering. Hence UPQC performance tasted under normal as well as unbalanced condition.



Load current total harmonic distortion (THD) Without controller is 18.17***%***



Load current total harmonic distortion (THD) With controller is 16.74%

V. CONCULSION

This paper presents control and performance of UPQC in-tended for installation on a transmission line with the help of PI controller. A control system is simulated in switching and unbalanced condition with shunt inverter and series 4 leg inverter in vector template control mode. Simulation results show the effectiveness of UPQC in active filtering and controlling harmonics in voltage and current through the line.AC voltage regulation and power factor of the transmission line also improved. This chapter presents an reducing harmonics in voltage and current in the transmission line with UPQC using PI controller when compared to the system without UPQC.

VI. APPENDIX

The system parameters are given as follows

Vs=100v(peak and fundamental),F=60hz,Ls=0.1mH,Lsh=3mH,Rsh=0.1 Ω,Lsr=3mH,Rsr=0.1 Ω and Cdc=600μ F

Plant loads

1) 3-phase diode bridge rectifier followed by R-L load with R=10 Ω,L=5mH
2) 3 single phase loads with 1000W and 600Var,750W and 400Var and 1400W and 1200Var demand on phase a,b and c respectively

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