Three-Phase Four-Wire Distribution System Utilizing Unified Power Quality Conditioner

Sahar Aslanzadeh, Morteza Nasooti

Abstract— This paper presents a novel structure for a threephase four-wire (3P4W) distribution system utilizing unified power quality conditioner (UPQC). The 3P4W system is realized from a three-phase three-wire system where the neutral of series transformer used in series part UPQC is considered as the fourth wire for the 3P4W system. A new control strategy to balance the unbalanced load currents is also presented in this paper. The neutral current that may flow toward transformer neutral point is compensated by using a four-leg voltage source inverter topology for shunt part. Thus, the series transformer neutral will be at virtual zero potential during all operating conditions. The simulation results based on MATLAB/Simulink are presented to show the effectiveness of the proposed UPQC-based 3P4W distribution system.

Index Terms— Active power filter (APF), four-leg voltage-source inverter (VSI) structure, three-phase four-wire (3P4W) system, unified power quality conditioner (UPQC).

I. INTRODUCTION

With the advancement of power electronics and digital control technology, the renewable energy sources are increasingly being connected to the distribution systems. On the other hand, with the proliferation of the power lectronics devices, nonlinear loads and unbalanced loads have degraded the power quality (PQ) in the power distribution network [1]. Custom power devices have been proposed for enhancing the quality and reliability of electrical power. Unified PQ conditioner (UPQC) is a versatile custom power device which consists of two inverters connected back-to-back and deals with both load current and supply voltage imperfections. UPQC can simultaneously act as shunt and series active power filters. The series part of the UPQC is known as dynamic voltage restorer (DVR). It is used to maintain balanced, distortion free nominal voltage at the load. The shunt part of the UPQC is known as distribution static compensator (DSTATCOM), and it is used to compensate load reactive power, harmonics and balance the load currents thereby making the source current balanced and distortion free with unity power factor. Voltage rating of dc-link capacitor largely influences the compensation performance of an active filter [2]. In general, the dc-link voltage for the shunt active filter has much higher value than the peak value of the line-to-neutral voltage.

This is done in order to ensure a proper compensation at the peak of the source voltage. In [3], the authors mentioned about the current distortion limit and loss of control limit, which states that the dc-link voltage should be greater than or equal to $\sqrt{6}$ times the phase voltage of the system for distortionfree compensation. When the dc-link voltage is less than this limit, there is insufficient resultant voltage to drive the currents through the inductances so as to track the reference currents. The primary condition for reactive power compensation is that the magnitude of reference dc-bus capacitor voltage should be higher than the peak voltage at the point of common coupling (PCC) [4]. Due to the aforementioned criteria, many researchers have used a higher value of dc capacitor voltage based on applications [5]–[13]. Similarly, for series active filter, the dc-link voltage is maintained at a value equal to the peak of the line-to-line voltage of the system for proper compensation [14]–[18]. In case of the UPQC, the dc-link voltage requirement for the shunt and series active filters is not the same. Thus, it is challenging task to have a common dc-link of appropriate rating in order to achieve satisfactory shunt and series compensation. The shunt active filter requires higher dc-link voltage when compared to the series active filter for proper compensation. In order to have a proper compensation for both series and shunt active filter, the researchers are left with no choice rather than to select common dc-link voltage based on shunt active filter requirement. This will result in over rating of the series active filter as it requires less dc-link voltage compared to shunt active filter. Due to this criterion, in literature, a higher dclink voltage based on the UPQC topology has been suggested [19]–[22]. With the high value of dc-link capacitor, the voltage source inverters (VSIs) become bulky, and the switches used in the VSI also need to be rated for higher value of voltage and current. This in turn increases the entire cost and size of the VSI. To reduce the dc-link voltage storage capacity, few attempts were made in literature. In [23], [24], a hybrid filter has been discussed for motor drive applications. The filter is connected in parallel with diode rectifier and tuned at seventh harmonic frequency. Although an elegant work, the design is specific to the motor drive application, and the reactive power compensation is not considered, which is an important aspect

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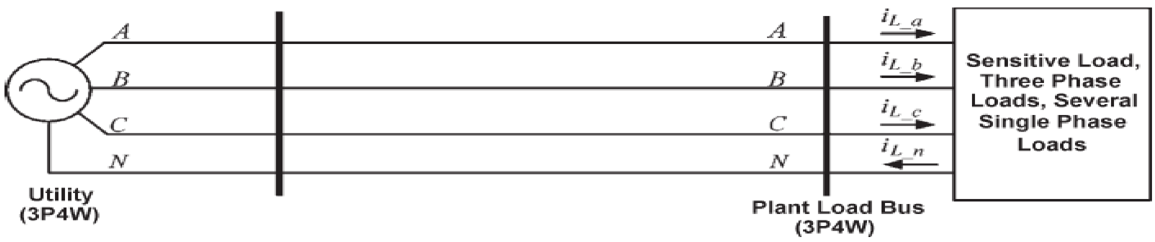

Fig. 1. 3P4W distribution system: neutral provided from generation station

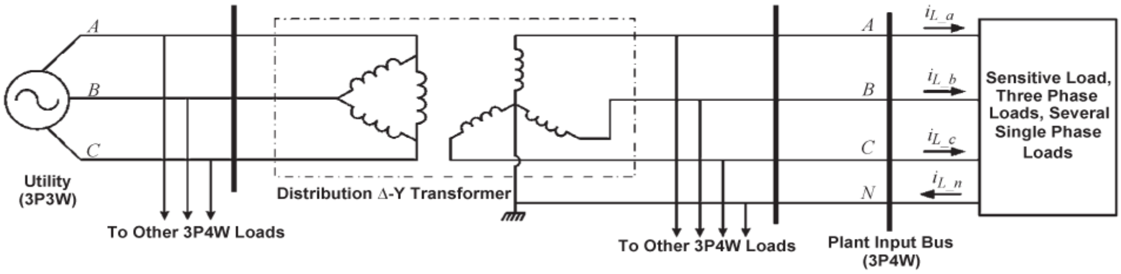

Fig. 2. 3P4W distribution system: neutral provided from Δ–Y transformer

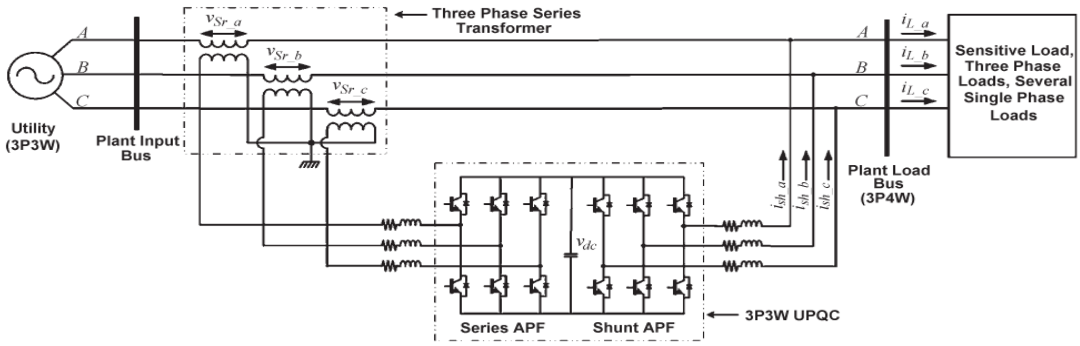

Fig. 3. 3P3W UPQC structure

in UPQC applications. In case of the three-phase four-wire system, neutral-clamped topology is used for UPQC [25], [26]. This topology enables the independent control of each leg of both the shunt and series inverters, but it requires capacitor voltage balancing [27]. In [21], four-leg VSI topology for shunt active filter has been proposed for three-phase four-wire system. This topology avoids the voltage balancing of the capacitor, but the independent control of the inverter legs is not possible. To overcome the problems associated with the four-leg topology, in [28], [29], the authors proposed a T-connected transformer and three-phase VSCbased DSTATCOM. However, this topology increases the cost and bulkiness of the UPQC because of the presence of extra transformer.

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 is discussed in Section II. The proposed control strategy for balancing the unbalanced load currents is explained in Section III. The simulation results are given in Section IV, and finally, Section V concludes this paper.

II. PROPOSED 3P4W DISTRIBUTION SYSTEM UTILIZING UPQC

Generally, a 3P4W distribution system is realized by pro-viding a neutral conductor along with three power conductors from generation station or by utilizing a three-phase Δ–Y trans- former at distribution level. Fig. 1 shows a 3P4W network in which the neutral conductor is provided from the generating station itself, whereas Fig. 2 shows a 3P4W distribution network considering a Δ–Y transformer. Assume a plant site where three-phase three-wire 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. 3. 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

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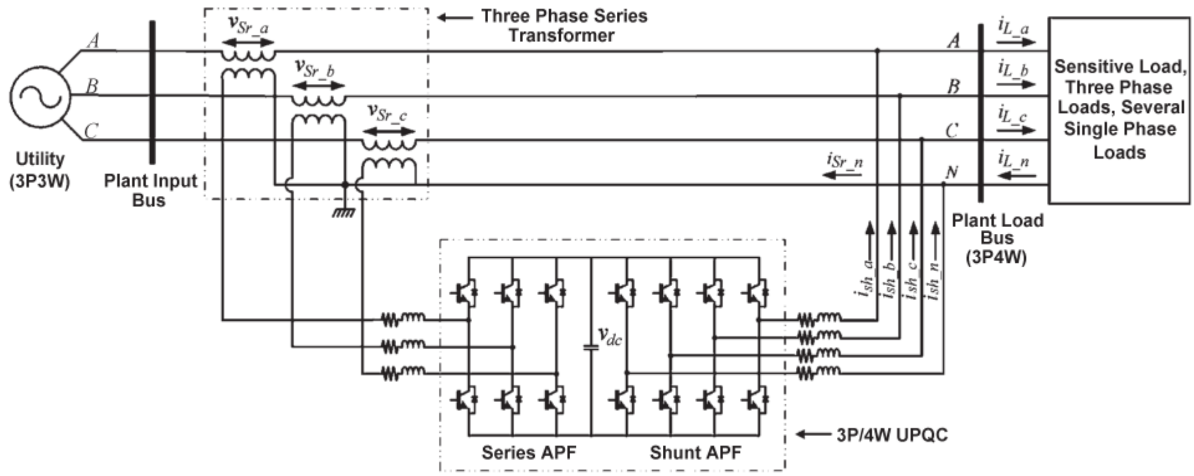


Fig. 4. Proposed 3P4W system realized from a 3P3W system utilizing UPQC

neutral conductor from this transformer without major 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) 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.

As shown in Fig. 3, the UPQC should necessarily consist of three-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 three-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 [2], [9], [10] or a four-leg voltage-source inverter (VSI) topology for a shunt inverter [2], [11]. The four-leg VSI topology requires one additional leg as compared to the split capacitor topology. The neutral current compensation in the four-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. Thus, the proposed structure would help to realize a 3P4W system from a 3P3W system at distribution load end. This would eventually result in easy 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 and is explained in the next section.

III. UPQC CONTROLLER

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 con- trol 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 in- dependently. 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. 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 [4], [5]. 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

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

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

where $v^*_{La}(\omega t)$ 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 *π*/2 lead as

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

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

In addition, for phase *c*, the load voltage and current in *α–β* coordinates can be represented by *π*/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

$$p_{L,abc} = v_{L,abc\_\alpha} \cdot i_{L,abc\_\alpha} + v_{L,abc\_\beta} \cdot i_{L,abc\_\beta}. \quad (7)$$

Instantaneous reactive power

$$q_{L,abc} = v_{L,abc\_\alpha} \cdot i_{L,abc\_\beta} - v_{L,abc\_\beta} \cdot i_{L,abc\_\alpha}. \quad (8)$$

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

$$p_{La} = \bar{p}_{La} + \tilde{p}_{La} \quad (10)$$

$$q_{La} = \bar{q}_{La} + \tilde{q}_{La}. \quad (11)$$

In (10) and (11), *pLa* and *qLa* represent the dc components that are responsible for fundamental load active and reactive powers, whereas $\tilde{p}_{La}$ and $\tilde{q}_{La}$ 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

$$p_{La,1} = \bar{p}_{La} \quad (12)$$

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

$$q_{La,1} = \bar{q}_{La}. \quad (13)$$

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

$$p_{Lb,1} = \bar{p}_{Lb}. \quad (14)$$

Instantaneous fundamental load reactive power for phase *b*

$$p_{Lc,1} = \bar{p}_{Lc}. \quad (16)$$

Instantaneous fundamental load active power for phase *c*

$$q_{Lc,1} = \bar{q}_{Lc}. \quad (17)$$

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),

$$p_{L,\text{total}} = p_{La,1} + p_{Lb,1} + p_{Lc,1} \quad (18)$$

$$p^*_{S/\text{ph}} = \frac{p_{L,\text{total}}}{3}. \quad (19)$$

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)

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

In (20), $p_{\text{dc/ph}}$ 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 *π*/2 lead with respect to the original system.

Therefore,

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

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

$$i_{L\_n}(t) = i_{La}(t) + i_{Lb}(t) + i_{Lc}(t) \quad (24)$$

$$i^*_{\mathrm{Sh}\_n}(t) = -\, i_{L\_n}(t). \quad (25)$$

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.

IV. SIMULATION RESULTS

Simulation results for the proposed UPQC-based 3P4W topology are shown in Fig. 6(a)–(j).MATLAB/Simulink is used as a simulation tool. Utility voltages are assumed to be distorted with voltage THD of 9.5%. The distorted voltage profile is shown in Fig. 6(a). The UPQC should maintain the voltage at load bus at a desired value and free from distortion. 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. The resulting load current profile shown in Fig. 6(g) has THD of 12.15%.

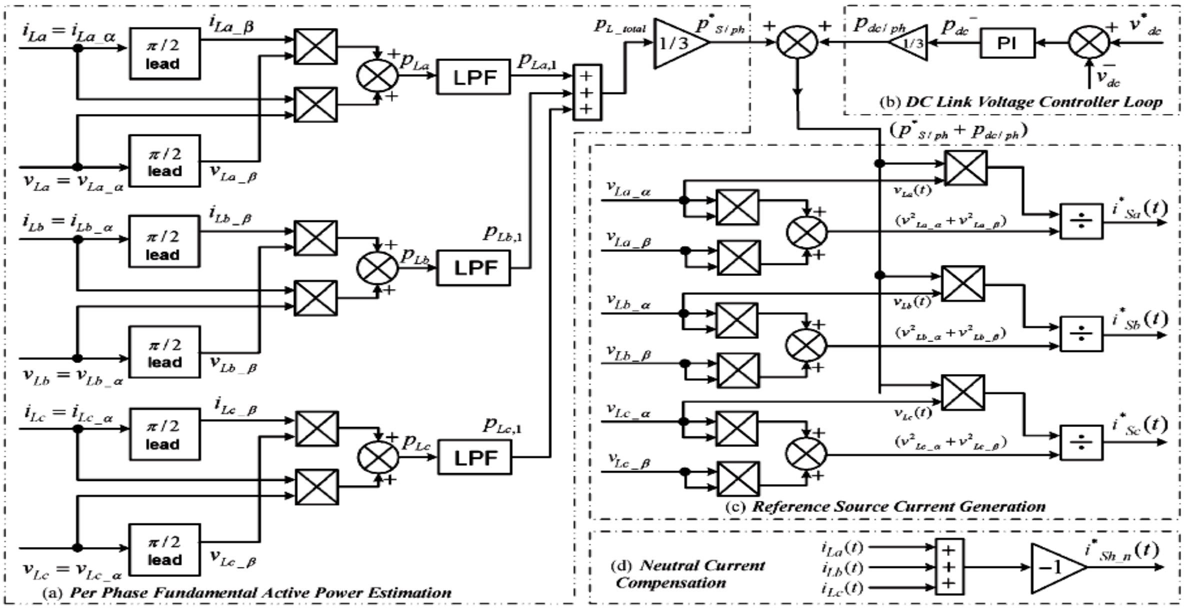
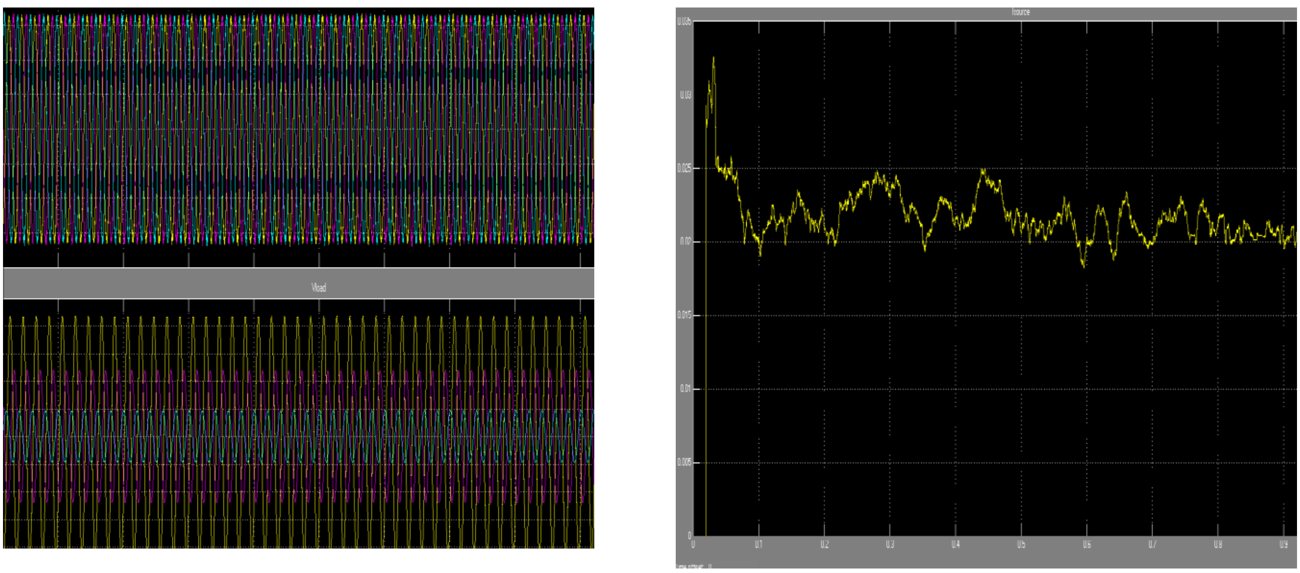


Fig. 5. Shunt active filter control block diagram. (a) Proposed balanced per-phase fundamental active power estimation. (b) DC-link voltage control loop. (c) Reference source current generation. (d) Neutral current compensation



(a) Load voltage (v_{L_abc}) and THD with out UPQC

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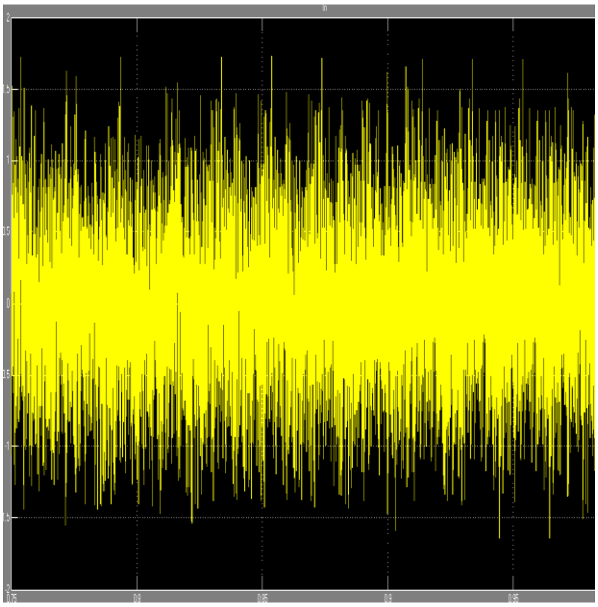
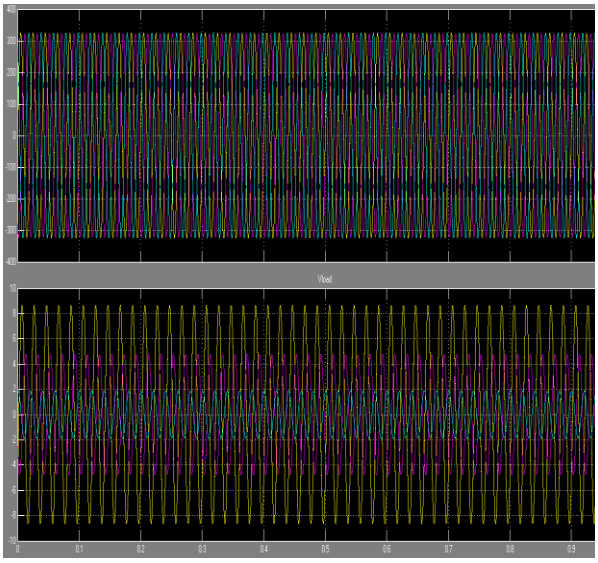
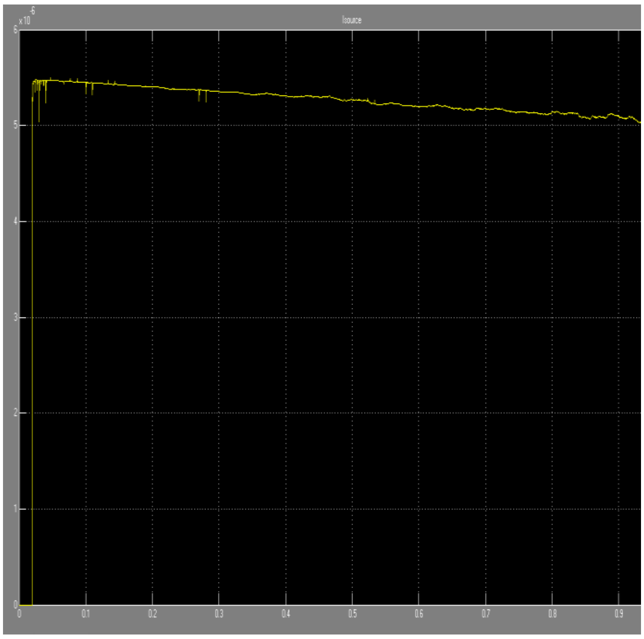
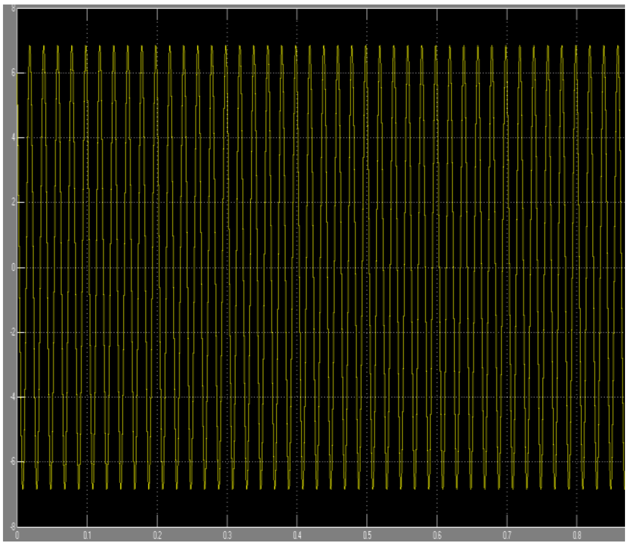


(b) null current without UPQC





(c) Load voltage and THD with UPQC



(d) Null Currnet with UPQC

Fig. 6. Simulation result—proposed 3P4W UPQC structure. (a) Load voltage (v_{L_abc}) and THD. (b) Null current. (c) Load voltage and THD with UPQC. (d) Null Currnet with UPQC.

Simulation result—proposed 3P4W with out/with UPQC structure are shown in Fig. 6. Fig. 6(a) shows Load voltage (v_{L_abc}) and THD with out UPQC and it is clear that THD in load side is high. Fig. 6(b) show null current which it is too vaiable and too noisy. Fig. 6(c) the UPQC switched on and the THD and voltage in load site has better condition. Fig 6.(d) show null current witch is sinousial and has not noise.

V. CONCLUSION

A new 3P4W topology for distribution system utilizing UPQC has been proposed in this paper. This proposed topology would be very useful to expand the existing 3P3W system to 3P4W system where UPQC is installed to compensate the different power quality problems, which may play an important role in future UPQC-based distribution system. A new control strategy to generate the balanced reference source current un- der unbalanced load condition is also presented in this paper. The MATLAB/Simulink-based simulation results show that the distorted and unbalanced load currents seen from the utility side act as perfectly balanced source currents and are free from distortion. 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.

APPENDIX

The system parameters are given as follows: VS = 100 V (peak, fundamental), f = 60 Hz, LS = 0.1 mH, LSh =3 mH, RSh = 0.1 Ω, LSr =3 mH, RSr = 0.1 Ω, and Cdc = 5000 μF.

Plant loads: 1) three-phase diode bridge rectifier followed by R–L load with R = 10 Ω and L =5 mH.

2) three single-phase loads with 1000 W and 600 Var, 750 W and 400 Var, and 1400 W and 1200 Var demand on phases a, b, and c, respectively. on phases a, b, and c, respectively.

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