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A Structure for Three-Phase Four-Wire Distribution System Utilizing Unified Power Quality Conditioner (UPQC)

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Abstract
This paper presents a novel structure for a three- phase 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

The Use OF sophisticated equipment/loads at transmission and distribution level has increased considerably in recent years due to the development in the semiconductor device technology. The equipment needs clean power in order to function properly. At the same time, the switching operation of these devices generates current harmonics resulting in a polluted distribution system. The power-electronics-based devices have been used to overcome the major power quality problems [1]. 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 [6]–[11]. 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 [9]–[11]. This paper proposes a new topology/structure that can be realized in UPQC-based applications, in which the series trans- former 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 transformer 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 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)

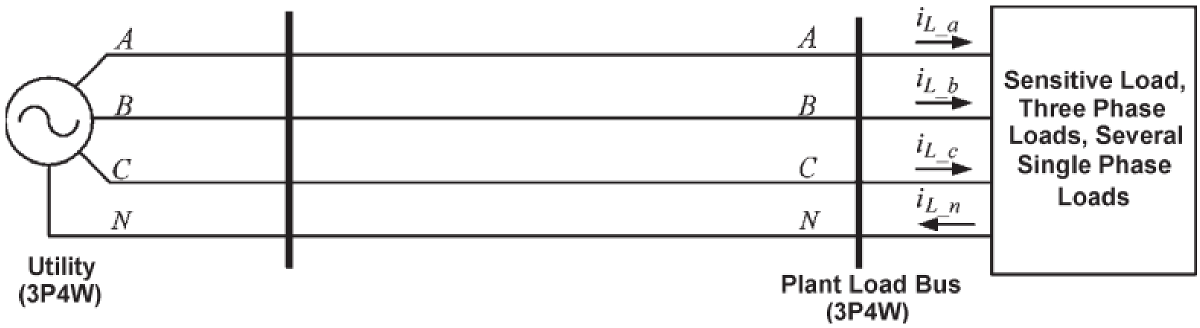

Fig.1.3P4Wdistributionsystem:neutral provided from generation station.

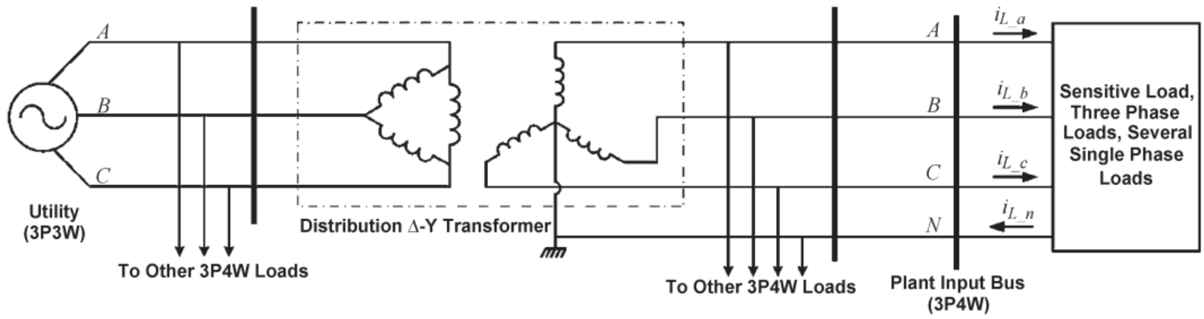

Fig.2.3P4Wdistributionsystem: neutral provided from Δ–Y transformer

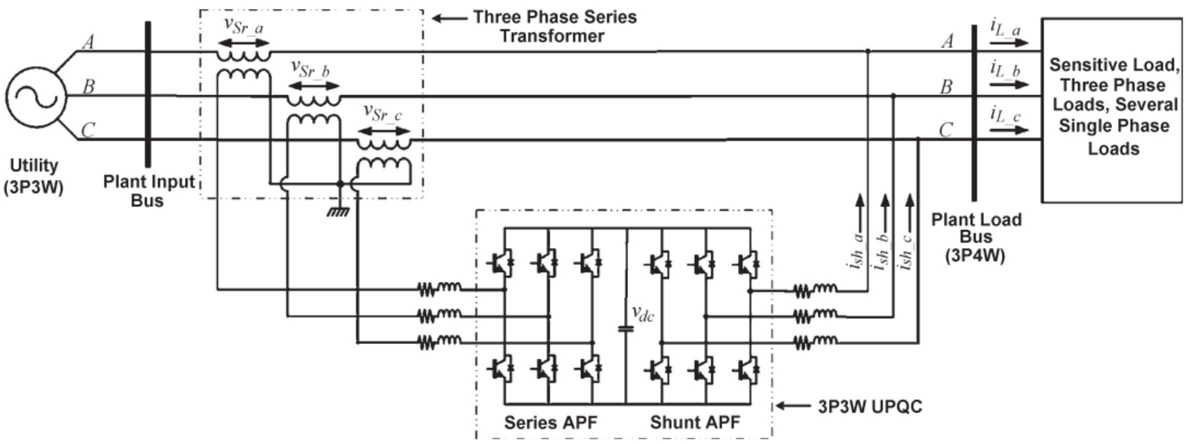

Fig.3.3P3WUPQCstructure

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

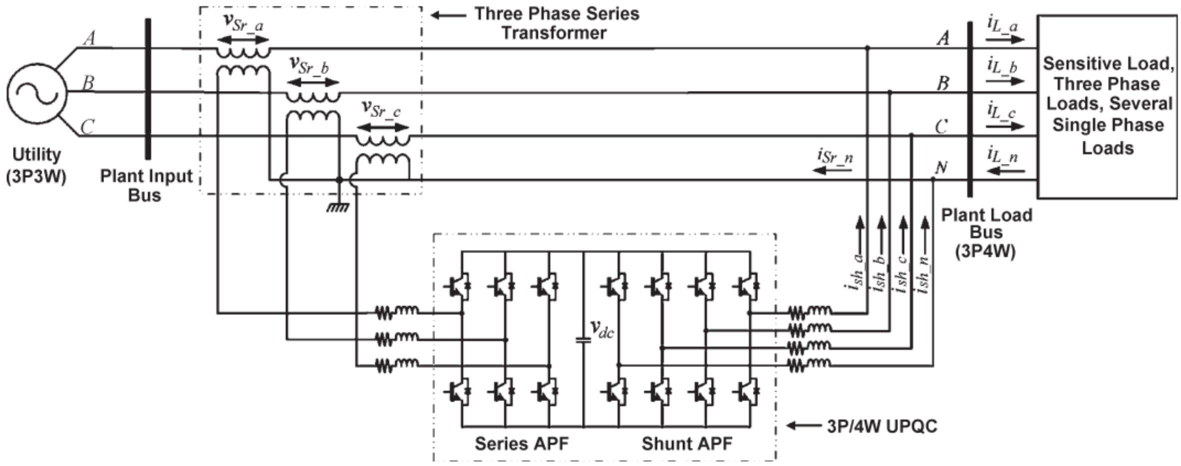

Fig.4.Proposed3P4W systemrealizedfroma3P3Wsystemutilizing UPQC

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 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. 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

$\pi/2$ lead as

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

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

In addition, for phase *c*, the load voltage and current

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

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

in α–β coordinates can be represented by $\pi/2$ lead as

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), $p_{L\bar{a}}$ and q_{La} *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 pLa and q pLa, 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 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

$$q_{Lb,1} = \bar{q}_{Lb}. \quad (15)$$

Instantaneous fundamental load active power for phase c

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

Instantaneous fundamental load reactive 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), pdc/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 ˜p should be exchanged between the load and shunt APF. The reactive power term (qLa) in (20) is considered as zero, since the utility should not supply load reactive power demand. In the above matrix, the a-axis reference compensating current represents the instantaneous fundamental source current, since a-axis quantities belong to the original system under consideration and the ß-axis reference compensating current represents the current that is at p/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

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

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

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

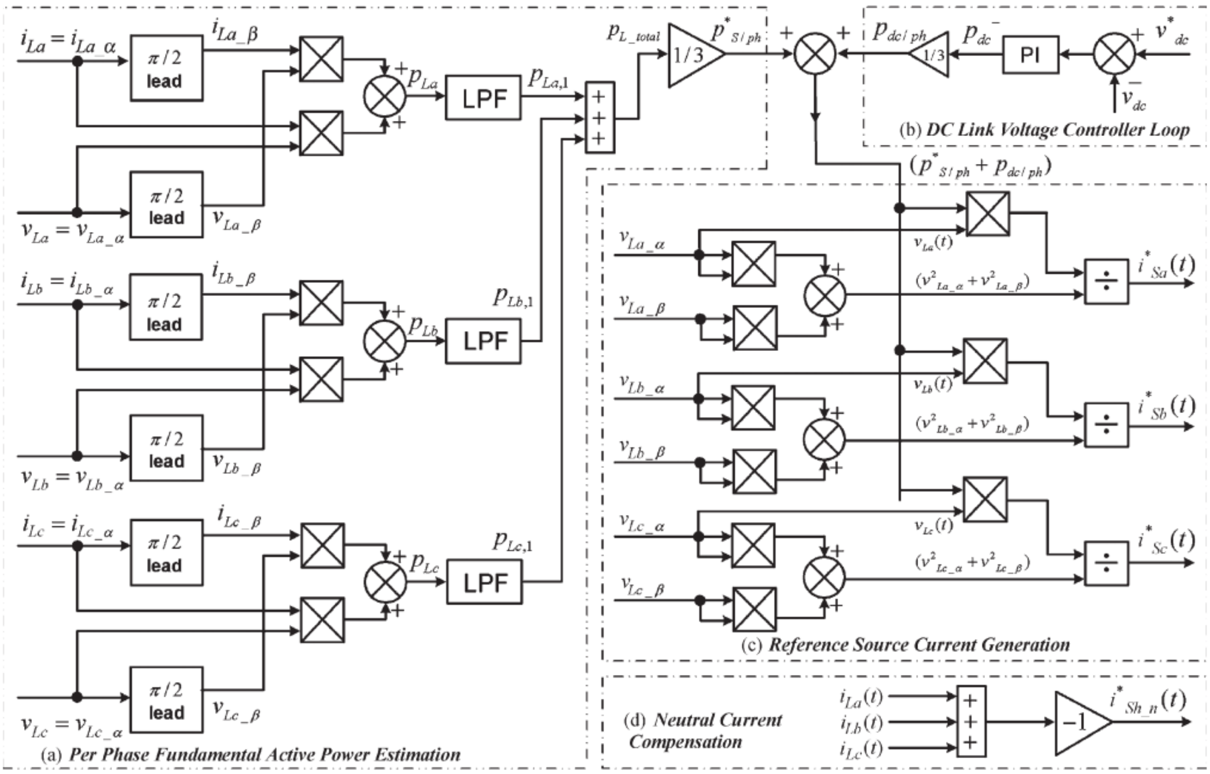

Fig. 5. Shunt active filter control block diagram. (a) Proposed balanced per-phase fundamental active power estimation. (b) DC-link voltage control loop.(c) Reference source current generation. (d) Neutral current compensation.

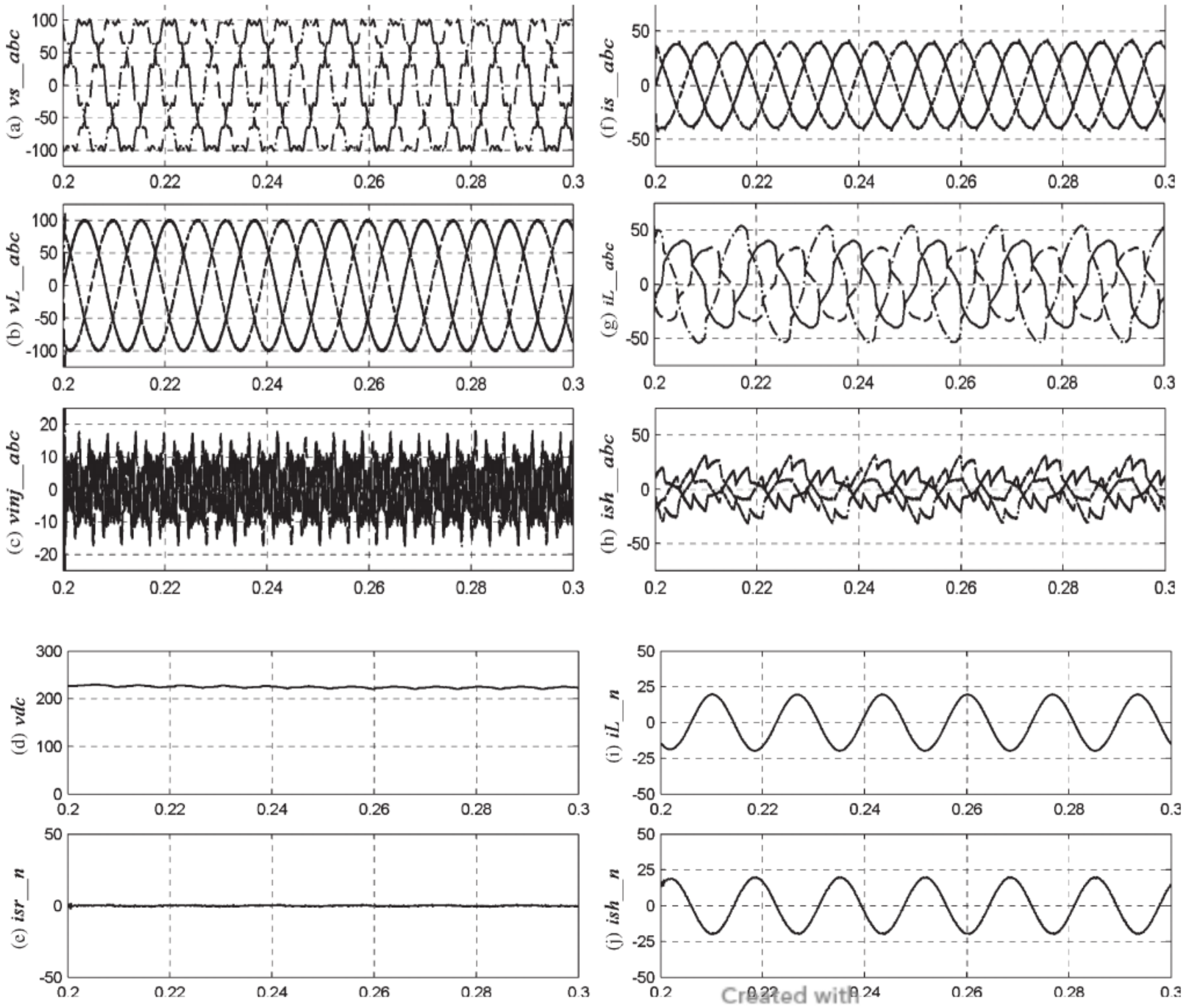

Fig. 6. Simulation result—proposed 3P4W UPQC structure. (a) Utility voltage (vS_abc). (b) Load voltage (vL_abc). (c) Injected voltage (v inj_abc) (d) DC-link voltage (vdc). (e) Neutral current flowing toward series transformer (iSr_n). (f) Source current (iS_abc). (g) Load current (i). (h) Shunt L_abc compensating current (iSh_abc). (i) Current flowing through load neutral wire (iL_n). (j) Shunt neutral compensating current (iSh_n).

power demands. The resulting load current profile shown in Fig. 6(g) has THD of 12.15%.

The shunt APF is turned ON first at time t =0.1 s (not shown in Fig. 6) such that it maintains the dc-link voltage at a set reference value, here 220 V. At time t =0.2 s, the series APF is put into operation. The series APF injects the required compensating voltages through series transformer, making the load voltage free from distortion (THD=1.5%) and at a desired level as shown in Fig. 6(b). The series-APF-injected voltage profile is shown in Fig. 6(c). Simultaneously, the shunt APF injects the compensating currents to achieve the balanced source current, free from distortion, as discussed in the previous section. The compensated source currents shown in Fig. 6(f) are perfectly balanced with the THD of 2.3%. The currents injected by the shunt APF are shown in Fig. 6(g). Since the load on the network is unbalanced in nature, the neutral current may flow through neutral conductor toward the series transformer neutral point. The load neutral current profile is shown in Fig. 6(i). As shown in Fig. 6(e), 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. The compensating current injected through the fourth leg of the shunt APF is shown in Fig. 6(j).

V. C ONCLUSION

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 under 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.

VI. APPENDIX

The system parameters are given as follows: $V_S = 100$ V (peak, fundamental), $f = 60$ Hz, $L_S = 0.1$ mH, $L_{Sh} = 3$ mH, $R_{Sh} = 0.1$ Ω, $L_{Sr} = 3$ mH, $R_{Sr} = 0.1$ Ω, and $C_{dc} = 5000\,\mu$F.
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.

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