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Management of reactive power sharing & power quality improvement with SRF-PAC based UPQC under unbalanced source voltage condition

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ABSTRACT

This paper is proposed to establish a new control algorithm for UPQC (unified power quality conditioner) to improve power quality and manage effectively equal reactive power sharing between shunt and series inverter of UPQC under unbalanced source voltage condition. The extraction of instantaneous power angle for reactive power sharing faces difficulty with unbalanced source voltage condition. This paper presents a new SRF (synchronous reference frame) based PAC (power angle control) method using decoupled load current parameters for efficient utilization and coordination of UPQC inverters. The proposed controller contributes in improvement of source current and load voltage harmonic profile, provides efficient way of load reactive power compensation and load voltage compensation for sag, swell and unbalanced condition. Effect of source voltage variations in the form of sag, swell or unbalancing on variable power angle estimation and reactive power calculations are also validated through a mathematical analysis. SRF based PAC control approach and PAC based UVT (unit vector template) control approach is adapted for estimating the reference signals of shunt and series inverter respectively and thus reducing the need of extra computation. The simulation and experimental analysis is carried out using Matlab/Simulink software package for computer simulation and a dSPACE based experimental setup for real time verifications.

Introduction

In today's world with increasing demand of electricity, the quality of power being supplied is a factor which needs to be maintained at par with the quantity of power supplied. Nowadays, for proper controlling of equipments and mechanical devices, the controllers are entirely based on power electronic systems which undesirably introduce harmonics in the supply system [1]. All electrical and electronic equipment irrespective of its sensitivity might suffer due to degrading power quality [2]. Also, due to sudden load activation and load shedding, voltage unbalancing among the three phases occurs at the common coupling point. Maintaining a steady state voltage is a major factor that can affect the consumer loads [3]. These current and voltage related issues need to be taken care of along with important and vintage power related problem of reactive power compensation which always exerts an extra burden on the supply chain. Active filters (shunt or series) provide a good dynamic response to these disturbances with self management capability [4]. But, for addressing all these issues simultaneously, a unified power quality conditioner is an obvious choice of selection and due to its all round performance has been a topic for continued research in recent years [5,6]. Many interesting topologies and control mechanisms of UPQC have been in the limelight in these years and belong to a good area of research [6–24,28–36]. Source voltage variation (sag, swell or unbalance), is considered as one of the major power quality degrading factor. An active power control approach (UPQC-P) is adapted to mitigate the voltage sag by injecting in phase voltage component through series inverter [7,8]. Voltage sag can also be addressed by using reactive power control approach (UPQC-Q) where the series voltage is injected at quadrature with the source voltage [9,10]. With this control, the active power requirement to compensate voltage sag is eliminated but rating of series inverter increases as the magnitude of series injected voltage increases and this method is also not suitable for voltage swell conditions. For optimal minimum VA loading of UPQC system for voltage sag compensation, series voltage can also be injected at a certain optimum angle with respect to the source current as reported in [11–13] and this approach is termed as UPQC-VA_{min}. Unlike UPQC-VA_{min} approach, introduction of concept of power angle control for reactive power control [14], and its extended version known as complex power control (UPQC-S) [15] for simultaneous handling of reactive power and voltage related issues, has given a promising solution with maximum VA utilization of series and shunt inverter. PAC

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based UPQC finds its suitability in radial distribution networks [16–18] and for integration of PV modules with grid [19]. The UPQC-S approach as reported in [15] have been considered under balanced three phase supply system where as in most practical scenarios, voltage unbalancing among three phases is a common voltage phenomena and is not at all suitable for a three phase loading system, especially for industries with three phase loads. Also, voltage variation in the form of sag, swell or unbalancing affects power angle estimation with UPQC-S approach.

Among various control techniques used for shunt/series active power filter or UPQC system for determining the reference current and voltage signals, most popularly adapted methods are *pq* theory, synchronous reference frame (SRF) theory and unit vector template generation (UVTG) [14,15,19–33,35,36]. With unbalanced supply voltage condition SRF method always exhibits superior performance as it deals with only current component for shunt inverter independent of supply voltage [25,26]. For voltage and current compensation under unbalanced source voltage condition, SRF technique can be implemented for both shunt and series inverter, thus dealing with dc quantities of voltage and current [28–32]. SRF controller for UPQC with PAC concept is adapted in [35,36] but under a balanced supply voltage condition. A major issue with SRF method for series inverter is generation of reference load voltage signals with magnitude different from rated load voltage. Due to sag, swell or unbalancing on the source side, the magnitude of direct axis voltage derived from the source voltage might be less or more than the rated voltage of load.

With conventional approach of reactive power sharing between shunt and series inverter as discussed in [14] and [15], series inverter role of handling reactive power comes into picture only when the load reactive power demand exceeds a particular limit. This limit is fixed based on the maximum voltage that can be compensated by series inverter. If the reactive power demand is within the specified limit, it is handled by shunt inverter alone. Since the active power flow through both inverters remains constant, shunt inverter experiences more stress than the other one. Since both inverters share a common dc link capacitor with a common dc voltage maintained, two inverters with identical rating and IGBT modules would be a more obvious and practical choice. This idea motivates for application of two inverters with same rating and sharing an equal amount of compensating reactive power. As reported in [7], for any kind of source voltage disturbance, the active power flow through both inverters remains same and in normal working condition, active power flows only from source to load. Thus, reactive power sharing burden can be evaluated irrespective of source voltage disturbance and could be fixed depending on maximum load reactive power that can be compensated.

In this paper, a mathematical analysis is presented which indicates the effect of source voltage variation in estimation of variable instantaneous power angle. This prompts to calculate the power angle with an idea of known and fixed share of reactive power handled by each inverter especially under unbalanced source voltage condition. Therefore, in our analysis power angle estimation is based on equal reactive power sharing feature, thus performing a successful implementation of PAC concept under unbalanced supply with efficient utilization of both inverters. Here, power angle is derived from SRF based load current parameters i_{Ld} and i_{Lq} which are further utilized for controlling shunt inverter. The proposed controller based UPQC is evaluated for load voltage balancing, voltage sag and swell compensation, voltage and current harmonic compensation and efficient reactive power compensation with different loading condition such as linear, nonlinear or both. MATLAB/Simulink based rigorous simulative analysis for the UPQC system, assumed to be installed for an industrial setup with total active and reactive power consumption of 20 kW and 20 kVAR is carried out under different operating conditions. Also, an experimental prototype based on dSPACE DS1103 real time controller is used for experimental verification of the same.

Fig. 1 exhibits a 3 phase UPQC system for a composite load combination of linear and nonlinear load. Series and shunt inverter consist of three leg bridge circuit each connected to a common dc link. Shunt inverter is connected through coupling inductors with the main line where as series inverter is connected via LC filter and injection transformer to inject series compensating voltage. Linear load consist of a balanced load combination, with high active and reactive power demand and nonlinear load consist of a diode bridge rectifier with an RL load on its dc side.

Section 'Overview of PAC concept under voltage sag, swell and unbalanced condition' describes the PAC concept for different voltage varying conditions. Section 'SRF based estimation under unbalanced source voltage conditions' presents SRF based reference signal estimation for shunt inverter control and load active and reactive power calculations. Sections 'Proposed power angle calculation for unbalanced source voltage condition' and 'Active power flow through the UPQC system under unbalanced supply voltage' explains the proposed power angle calculation under unbalanced source voltage condition and active power flow analysis through UPQC, respectively. Section 'UPQC controller' describes the series inverter controller part of UPQC. Estimation of maximum injectable series compensating voltage is discussed in Section 'Maximum voltage injected by series inverter'. Sections 'Simulation results' and 'Experimental analysis' present simulation and experimental analysis respectively.

Overview of PAC concept under voltage sag, swell and unbalanced condition

Maximum power angle calculation under varying voltage condition

The power angle control approach is used to introduce a phase angle shift of load voltage with respect to the source voltage. As a result, load reactive power is being shared between shunt and series inverter depending on their maximum handling capabilities.

Fig. 2 shows the voltage phasor diagram for a single phase A. Here,

$|V_{Sa}| = k$ = rms value of phase A source voltage under normal condition.
$|V'_{Sa}| = k'$ = rms value of phase A source voltage under sag condition.
$|V_{La}| = k$ = rms value of desired phase A load voltage.
$|V_{Sra}|$ = rms value of compensating phase A series injected voltage under normal condition.
$|V'_{Sra}|$ = rms value of compensating phase A series injected voltage under sag condition.

From Fig. 2

$$x = k\sin\delta, \qquad y = k\cos\delta \tag{1}$$

$$z = |V'_{Sa}| - y = k' - k\cos\delta \tag{2}$$

Also,

$$|V'_{Sra}| = \sqrt{x^2 + z^2} \tag{3}$$

$$\therefore |V'_{Sra}| = \sqrt{k^2(\sin\delta)^2 + k'^2 + k^2(\cos\delta)^2 - 2kk'\cos\delta} \tag{4}$$

$$|V'_{Sra}| = \sqrt{k^2 + k'^2 - 2kk'\cos\delta} \tag{5}$$

Say, $k' = f_a k$ (f_a is the fraction of phase A voltage with respect to reference voltage due to sag, swell or unbalancing)

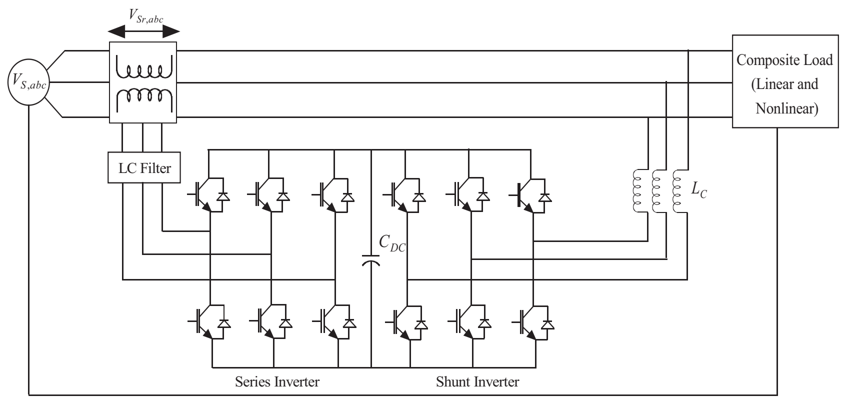

Fig. 1. A 3 phase UPQC system.

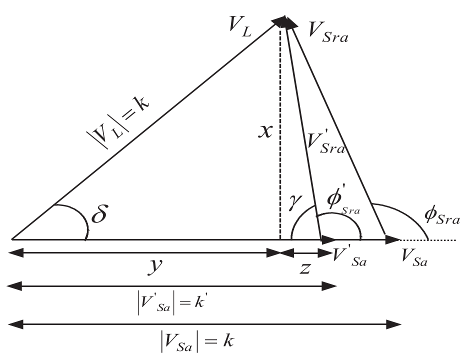

Fig. 2. Voltage phasor diagram for phase A.

$$|V'_{Sra}| = k \cdot \sqrt{1 + f_a^2 - 2f_a \cos\delta} \tag{6}$$

For varying values of f_a maximum series injection voltage $|V_{Sra\_max}|$ depends on δ_{max} and can be expressed as:

$$|V_{Sra\_max}| = k \cdot \sqrt{1 + f_a^2 - 2f_a \cos\delta_{max}} \tag{7}$$

Also, $|V_{Sra\_max}|$ is given by:

$$|V_{Sra\_max}| = f_{Sr\_max} k \tag{8}$$

From both the equations:

$$f_{Sr\_max} = \sqrt{1 + f_a^2 - 2f_a \cos\delta_{max}} \tag{9}$$

$$\therefore \delta_{max} = \cos^{-1}\left[\frac{1 + f_a^2 - f_{Sr\_max}^2}{2f_a}\right] \tag{10}$$

It can be seen from the above equation that variable maximum power angle not only depends on maximum series rms injected voltage but also on voltage variation. As observed in conventional approach [15], the instantaneous power angle (δ) is determined using maximum reactive power handling capacity of series and shunt inverter, which in turn is decided from the fixed maximum power angle (δ_{max}) without considering the effect of voltage variation. Also, the rating of shunt and series inverter cannot be defined on per phase basis under unbalanced voltage and distorted current condition. Hence to overcome these difficulties transformed direct and quadrature axis quantities of load current are utilized for calculation of load power and instantaneous power angle.

Comparison of voltage variation with respect to power angle and maximum reactive power

The maximum power angle is calculated for two different operating conditions i.e. including and excluding the effect of voltage variation. Voltage variation here is assumed in the form of sag, i.e. reduction in voltage magnitude.

Case I. Excluding effect of voltage variation

For a maximum series voltage injection capacity of 40% (K_{Sr}) by the series inverter, fixed maximum power angle can be expressed as [14]:

$$\delta_{max\_fix} = \cos^{-1}\left(1 - \frac{K_{Sr}^2}{2}\right) = 23.07^\circ \tag{11}$$

This maximum power angle value is a fixed quantity irrespective of variation in source voltage for a fixed maximum voltage injection capability.

Case II. Including effect of voltage variation

As derived in the Eq. (10), variable maximum power angle can be expressed as:

$$\delta_{max\_var} = \cos^{-1}\left[\frac{1 + f_a^2 - f_{Sr\_max}^2}{2f_a}\right] \tag{12}$$

Let $f_{Sr\_max} = 0.4$ and for a sag of say 35% in phase A voltage, $f_a = 0.65$.

$$\delta_{max\_var} = 13.79^\circ \tag{13}$$

Maximum reactive power handled by the series inverter (for single phase) is given by:

$$Q_{Sr\_max} = I_S \cdot k \cdot \sin\delta_{max} \tag{14}$$

Therefore, for two different maximum power angles maximum reactive power handled by series inverter are obtained as:

$$Q_{Sr\_max\_fix} = 0.392 \cdot I_S \cdot k \quad \text{and} \quad Q_{Sr\_max\_var} = 0.238 \cdot I_S \cdot k \tag{15}$$

$$\therefore Q_{Sr\_max\_var} = 0.607 Q_{Sr\_max\_fix} \tag{16}$$

Hence the maximum reactive power that can be handled by the series inverter with 35% voltage reduction reduces to around 60% of maximum reactive power handled by series inverter with no voltage variation. This further affects the maximum reactive power handled by shunt inverter, instantaneous reactive power handled by series inverter and lastly the instantaneous power angle.

For a maximum active and reactive loading condition of 20 kW and 20 kVAR respectively including both linear as well as nonlinear load and considering maximum voltage injection capacity of series inverter as 40% of reference load voltage, series injected voltage variation for different source voltage conditions for above two depicted cases is as illustrated in Table 1. Magnitude of series injected voltage is estimated by the following equation:

$$V_{Sr} = k \cdot \sqrt{1 + f^2 - 2f\cos\delta_{\max}} \tag{17}$$

Thus, it is clear from Table 1 that for variable maximum power angle, voltage magnitude of series injected voltage for different source voltage conditions remains more or less constant. Also, it is different and less than that calculated based on excluding the variation in the source voltage.

SRF based estimation under unbalanced source voltage conditions

Here, SRF based control algorithm is described for shunt inverter and the estimated parameter are utilized for proposed instantaneous power angle calculation under unbalanced voltage with sag and swell conditions effectively.

Shunt inverter reference signal estimation

An instantaneous active-reactive current control technique based on transformation techniques is used for controlling the 3 phase shunt inverter that incorporates reactive power and current harmonic compensation. In addition to this it is also used to calculate the load active and reactive power and instantaneous power angle under unbalanced voltage and distorted current conditions as described in the next section. Three phase unbalanced load currents are transformed to two phase active and reactive current components using abc-dq0 transformations:

$$\begin{bmatrix} i_{l0} \\ i_{ld} \\ i_{lq} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \sin\omega t & \sin\left(\omega t - \frac{2\pi}{3}\right) & \sin\left(\omega t + \frac{2\pi}{3}\right) \\ \cos\omega t & \cos\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} \tag{18}$$

The complete block diagram is as shown in Fig. 3. The *d* axis and *q* axis component represents the active and reactive component of load current respectively consisting of average and oscillating component. The average parts of both components are filtered using a modified high pass filter obtained from a tuned low pass filter. The oscillating active current is added to the loss component current of UPQC which is in the form of processed error of DC link capacitor voltage from a PI controller. Proper gain parameters are used to tune the controller. Tuning rules based on improved Ziegler–Nichols method is used to obtain these values. If the oscillating *q* axis current is only used to generate the compensating current, then shunt will not take any part in reactive power compensation

Table 1
Series injected voltage variation for fixed and variable power angle.

f (Source voltage in p.u)	$\delta_{\max\_fix}$	V_{Sr} (Conventional)	$\delta_{\max\_var}$	V_S (Actual)
0.65	23.07	109.46	13.79	92.00
0.7	23.07	103.37	18.19	91.98
0.75	23.07	98.25	20.77	92.00
0.8	23.07	94.27	22.33	92.00
0.85	23.07	91.56	23.20	92.00
0.9	23.07	90.26	23.55	92.00
0.95	23.07	90.40	23.49	92.00

Table 2
Series injected voltage variation for different power angles.

Source voltage in p.u	RMS value of magnitude of series injected voltage (volts)			
	Total load = 15 kW and 5 kVAr with δ = 9.59°	Total load = 20 kW and 10 kVAR with δ = 14.47°	Total load = 15 kW and 10 kVAR with δ = 19.47°	Total load = 20 kW and 20 kVAR with δ = 30°
0.65	83.95	93.17	102.32	125.98
0.7	76.14	84.44	95.16	121.18
0.75	66.46	76.45	88.93	118.06
0.8	57.45	69.45	83.81	116.00
0.85	49.49	63.78	80.04	115.06
0.9	43.15	59.8	77.79	115.27
0.95	39.23	57.86	77.21	116.62

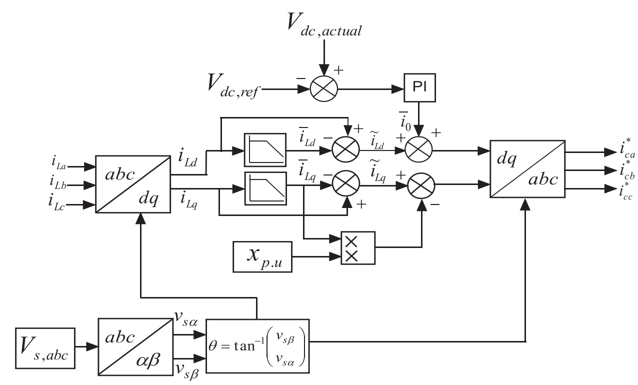

Fig. 3. Control block diagram for shunt inverter.

where as if the fundamental q axis current is also incorporated in a controlled manner for deducing compensating currents than reactive power compensation feature by shunt inverter can be made available. Thus, the $x_{p.u}$ value can be used to control the amount of reactive power being shared by shunt inverter. Here, as the inverters are designed to share equal load reactive power, this value is set at 50%. These compensating components are again transformed to three phase compensating currents using dq0-abc transformation as:

$$\begin{bmatrix} i^*_{ca} \\ i^*_{cb} \\ i^*_{cc} \end{bmatrix} = \begin{bmatrix} \cos\omega t & -\sin\omega t & 1 \\ \cos\left(\omega t - \frac{2\pi}{3}\right) & -\sin\left(\omega t - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\omega t + \frac{2\pi}{3}\right) & -\sin\left(\omega t + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} i_{cd} \\ i_{cq} \\ i_{c0} \end{bmatrix} \tag{19}$$

These reference compensating currents are compared with their actual compensating currents in a hysteresis controller to generate the required switching pulses for the shunt inverter.

Load active and reactive power calculation

As load voltage is balanced and distortion free after compensation, the resultant voltage in synchronous dq reference frame is given by:

$$V_{L,dq} = V_{Ld} = \sqrt{v_{L\alpha}^2 + v_{L\beta}^2} \tag{20}$$

If the balanced three phase load voltage signals are transformed to synchronous rotating reference frame, then the direct axis voltage component V_{Ld} is the same as the peak value of per phase load voltage V_{Lm} and can be treated as a fixed reference value for a particular rated system as $V_{d(ref)}$.

$$\text{i.e. } V_{L,dq} = V_{Ld} = V_{Lm} = V_{d(ref)} \tag{21}$$

Therefore, Fundamental Load Active Power,

$$P_L = \frac{3}{2} V_{L,dq} i_{Ld} = \frac{3}{2} V_{d(ref)} i_{Ld} \quad (22)$$

Here, the gain factor $\left(\frac{3}{2}\right)$ is used to maintain power invariance.

Fundamental Load Reactive Power,

$$Q_L = \frac{3}{2} V_{L,dq} i_{Lq} = \frac{3}{2} V_{d(ref)} i_{Lq} \quad (23)$$

Proposed power angle calculation for unbalanced source voltage condition

Power angle control approach as proposed in [14], is assumed to operate under balanced three phase mains voltage condition. But practically, an unbalanced magnitude among the three phases is quiet common phenomena to observe.

Also, since the active power flow through both series and shunt inverter of UPQC remains same, an equal reactive power sharing approach based on load current parameters can be implemented for application of inverters with equal rating. This approach simplifies the required estimation under unbalanced source voltage condition with effective utilization of parameters derived for shunt inverter controller.

Reactive power handled by series inverter for phase A from Fig. 2:

$$Q'_{Sr} = V'_{Sra} I'_S \sin \varnothing'_{Sra} \quad (24)$$
$$Q'_{Sr} = V'_{Sra} I'_S \sin(180^\circ - \gamma) \quad (25)$$
$$Q'_{Sr} = V'_{Sra} I'_S \sin \gamma \quad (26)$$
$$\sin \gamma = \frac{x}{V'_{Sra}} = \frac{k \cdot \sin \delta}{V'_{Sra}} \quad (27)$$
$$\therefore Q'_{Sr} = k \cdot I'_S \sin \delta \quad (28)$$

Total reactive power handled by series inverter for three phases:

$$Q_{Sr,T} = 3 \cdot k \cdot I'_S \sin \delta \quad (29)$$
$$\text{i.e. } \delta = \sin^{-1}\left[\frac{Q_{Sr,T}}{3 \cdot k \cdot I'_S}\right] \quad (30)$$

If both shunt and series inverters are designed for equal load reactive power sharing, then:

$$Q_{Sr,T} = 0.5 Q_{L,T} \quad (31)$$
$$\therefore \delta = \sin^{-1}\left[\frac{0.5 Q_{L,T}}{3 \cdot k \cdot I'_S}\right] \quad (32)$$

The total load reactive power in synchronous dq reference frame can be expressed as:

$$Q_{L,T} = \frac{3}{2} V_{d(ref)} \cdot i_{Lq} \quad (33)$$

Also, the rms value of reference load voltage, k can be expressed as:

$$k = \frac{V_{d(ref)}}{\sqrt{2}} \quad (34)$$

Source current after compensation will consist of only active component of load current and loss component of UPQC and its rms value can be expressed in synchronous dq reference frame as:

$$I'_S = \frac{(i_{Ld} + i_o)}{\sqrt{2}} \quad (35)$$

Substituting the values of $Q_{L,T}$, k and I'_S, instantaneous power angle can be finally expressed as:

$$\delta = \sin^{-1}\left[\frac{i_{Lq}}{2 \cdot (i_{Ld} + i_o)}\right] \quad (36)$$

Thus, for equal load reactive power sharing of both inverters, i.e. for inverters with equally designed rating power angle depends on active-reactive component of load current and loss component of UPQC.

Active power flow through the UPQC system under unbalanced supply voltage

Total active power supplied by the source is equal to the total active power consumed by the load and the power loss component occurring in the UPQC system, although its magnitude is very small as compared to load active power demand.

$$\therefore P_{Sa} + P_{Sb} + P_{Sc} = P_{La} + P_{Lb} + P_{Lc} + P_0 \quad (37)$$

After compensation the three phase supply voltage are in phase with the three phase balanced source current, therefore the input side power factor is unity and both side active power can be expressed as:

$$V_{Sa} I'_S + V_{Sb} I'_S + V_{Sc} I'_S = k I_{La} \cos \varphi_{La} + k I_{Lb} \cos \varphi_{Lb} + k I_{Lc} \cos \varphi_{Lc} + P_0 \quad (38)$$
$$k I'_S (f_a + f_b + f_c) = k(I_{La} \cos \varphi_{La} + I_{Lb} \cos \varphi_{Lb} + I_{Lc} \cos \varphi_{Lc}) + P_0 \quad (39)$$
$$I'_S = \frac{(I_{La} \cos \varphi_{La} + I_{Lb} \cos \varphi_{Lb} + I_{Lc} \cos \varphi_{Lc})}{(f_a + f_b + f_c)} + \frac{P_0}{k \cdot (f_a + f_b + f_c)} \quad (40)$$

The second term on the right hand side of the above equation is negligibly small as compared to the first and hence can be neglected.

$$\therefore I'_S = \frac{(I_{La} \cos \varphi_{La} + I_{Lb} \cos \varphi_{Lb} + I_{Lc} \cos \varphi_{Lc})}{(f_a + f_b + f_c)} \quad (41)$$

From Fig. 2 active power flow through series inverter for phase A can be expressed as:

$$P_{Sr,a} = V'_{Sra} I'_S \cos \varnothing'_{Sra} \quad (42)$$
$$P_{Sr,a} = V'_{Sra} I'_S \cos(180 - \gamma) \quad (43)$$
$$P_{Sr,a} = -V'_{Sra} I'_S \cos \gamma \quad (44)$$
$$\cos \gamma = \frac{V'_{Sa} - y}{V'_{Sra}} = \frac{V'_{Sa} - k \cos \delta}{V'_{Sra}} \quad (45)$$
$$\therefore P_{Sr,a} = -I'_S (V'_{Sa} - k \cos \delta) \quad (46)$$
$$\because V'_{Sa} = f_a k \quad (47)$$
$$\therefore P_{Sr,a} = -I'_S k (f_a - \cos \delta) \quad (48)$$

Similarly series active power flow for other two phases can be given as:

$$P_{Sr,b} = -I'_S k (f_b - \cos \delta) \quad \text{and} \quad P_{Sr,c} = -I'_S k (f_c - \cos \delta) \quad (49)$$

Hence, total series active power flow:

$$P_{Sr} = P_{Sr,a} + P_{Sr,b} + P_{Sr,c} \quad (50)$$

From Eqs. (48)–(50)

$$P_{Sr} = -I'_S \cdot k \cdot (f_a - \cos \delta + f_b - \cos \delta + f_c - \cos \delta) \quad (51)$$
$$P_{Sr} = -I'_S \cdot k \cdot (f_a + f_b + f_c - 3 \cos \delta) \quad (52)$$

Substituting value of I'_S from Eq. (41) in Eq. (52), we get:

$$P_{Sr} = \frac{3 P_L \cos \delta}{(f_a + f_b + f_c)} - P_L \quad (53)$$

where

$$P_L = k(I_{La} \cos \varphi_{La} + I_{Lb} \cos \varphi_{Lb} + I_{Lc} \cos \varphi_{Lc}) \quad (54)$$

Since the dc link capacitor is not responsible for any consumption of active power, the active power flowing through the series inverter is equal to the active power flowing through the shunt inverter.

$$P_{Sh} = P_{Sr} = \frac{3P_L \cos\delta}{(f_a + f_b + f_c)} - P_L \quad (55)$$

$$\therefore P_{Sh} = P_{Sr} = \frac{3}{2} V_{d(ref)} i_{Ld} \left[\frac{3\cos\delta}{(f_a + f_b + f_c)} - 1\right] \quad (56)$$

Suppose $V_{d(ref)}, i_{Ld}$ and $(f_a + f_b + f_c)$ are not varying than active power flow through UPQC is entirely dependent on the power angle and therefore with increase in δ, P_{Sh} and P_{Sr} reduces. Active power flow through the series and shunt inverter can be estimated from the above equation even under non ideal conditions of source voltage. Thus, rating of each inverter as well as of the UPQC system can be well defined for equal load reactive power sharing.

UPQC controller

The control mechanism for series inverter is based on unit vector generation method with an additional feature of accommodating instantaneous power angle for sharing of reactive power by series inverter as shown in Fig. 4. The shunt inverter controller is as described in Section 'SRF based estimation under unbalanced source voltage conditions'. The transformation angle is derived from the transformed source voltage parameters which offers better performance than conventional PLL under unbalanced and distorted condition and is utilized for both shunt and series inverter control algorithm.

Thus, the three phase reference load voltage signals for series inverter are given by:

$$V^*_{La} = V_{d(ref)} \sin(\omega t + \delta) \quad (57)$$

$$V^*_{Lb} = V_{d(ref)} \sin(\omega t - 120 + \delta) \quad (58)$$

$$V^*_{Lc} = V_{d(ref)} \sin(\omega t - 240 + \delta) \quad (59)$$

Maximum voltage injected by series inverter

For a maximum active and reactive loading condition of 20 kW and 20 kVAR, maximum reactive power that can be handled by series inverter is 10 kVAR as both inverters share equal reactive power and are designed for same power ratings.

For a fixed maximum load, maximum power angle can be calculated as:

$$\delta_{max} = \sin^{-1}\left[\frac{Q_{Sr\_max}}{P_S}\right] = \sin^{-1}\left[\frac{Q_{Sr\_max}}{P_L + P_o}\right] \quad (60)$$

Since the loss component of UPQC system is very small as compared to load active power, hence can be neglected.

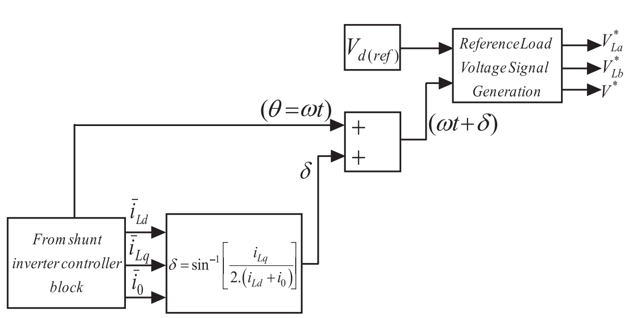

Fig. 4. Control block diagram for series inverter.

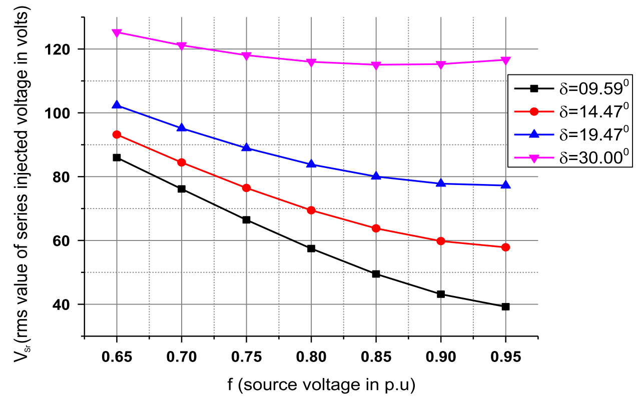

Fig. 5. Series injected voltage variation with respect to source voltage for different power angles.

$$\therefore \delta_{max} = \sin^{-1}\left[\frac{Q_{Sr\_max}}{P_L}\right] = \sin^{-1}\left[\frac{10}{20}\right] = 30^\circ \quad (61)$$

If maximum reduction in voltage of any phase (say phase A) is considered as 35%, then $f_{min\_a} = 0.65$ and maximum per phase voltage injection by series inverter is given by:

$$|V_{Sra\_max}| = k \cdot \sqrt{1 + f^2_{min\_a} - 2f_{min\_a}\cos\delta_{max}} \quad (62)$$

Here, k is the reference per phase rms load voltage and is equal to 230 V.

$$\therefore |V_{Sra\_max}| = 125.28\ \text{V (RMS value)} \quad (63)$$

With the above specified condition of load and voltage angle of series injected voltage can be found from Fig. 2 as:

$$\varnothing_{Sr\_a} = (180^\circ - \gamma_a) \quad (64)$$

where

$$\gamma_a = \sin^{-1}\left[\frac{k \cdot \sin\delta_{max}}{|V_{Sra\_max}|}\right] = 66.62^\circ \quad (65)$$

$$\therefore \varnothing_{Sr\_a} = 113.37^\circ \quad (66)$$

Variation of series injected voltage with respect to variation in source voltage for different loading conditions, i.e. for different power angles is clearly shown in Table 2. Therefore, considering a maximum voltage reduction of 35% and a maximum loading condition of 20 kW and 20 kVAR, the series inverter transformer can be rated to inject a maximum rms voltage of around 130 V. The variation is also presented in Fig. 5. It is clear from the figure that the magnitude of series injected voltage increases with increase in power angle and reduction in source voltage.

Simulation results

In order to analyze the performance of proposed UPQC controller under different voltage and load conditions, the entire system is simulated using MATLAB/SIMULINK. Simulation parameters are as listed in Table 3. A typical three phase industrial load is considered to be connected to a three phase unbalanced supply system. Load consists of both linear and nonlinear type. Total maximum active and reactive load is assumed to be 20 kW and 20 kVAR respectively. Two three phase IGBT based inverters, connected via a common dc link constitute the UPQC system. Load is assumed to be operating at rated voltage condition of 400 V (L–L). The system is analyzed for different operating conditions as discussed in the following cases.

Table 3
Simulation system parameters.

Source	Per phase steady state voltage	230 V (RMS)
	Frequency	50 Hz
Shunt inverter	Coupling inductor	3.5 mH
Series inverter	L, C filter	1.5 mH, 45 μF
	Transformer	100:200, 4 kVA
DC link	Capacitor	3000 μF
	Reference voltage	700 V
Load	3∅ linear load	10 kW, 10/20 kVAR
	3∅ non-linear load (rectifier with RL load)	R = 29 Ω, L = 10 mH
PI controller parameter	K_p and K_i	0.25 and 3.4

Case I

Considering unbalanced source voltage sag condition of 10%, 20% and 30% for phase A, B and C respectively, comparison of load voltage profile for complex power control approach, synchronous reference frame method and for proposed SRF-PAC-UVT based approach are as shown in Fig. 6. With the first method as the estimation of series injected voltage magnitude and phase angle are based on a balanced supply system and the calculation of maximum power angle and subsequently instantaneous power angle will alter with unbalanced voltage, hence load voltage will not be compensated properly and will remain unbalanced. With SRF based method, load voltage remains balanced under unbalanced condition of source voltage but as the direct axis voltage magnitude is different than the required reference value due to different source phase voltages, the reference voltage generated is of altered amplitude than the rated voltage required for load. This in turn will affect the load and it will operate at lower or higher voltage condition. With the proposed method, the three phase load voltage is balanced and also its amplitude is fixed at rated value as required for a particular load.

With the same source voltage condition simulation results of three phase source current before compensation, source current after compensation, compensating current and direct and quadrature axis load current (i_{Ld} and i_{Lq}) with the proposed controller are as shown in Fig. 7(a)–(d) respectively. Source current is unbalanced before compensation due to the unbalanced nature of the source voltage. Also, with the reactive load change at t = 0.5 s load demand increases as observed but the source current after compensation is maintained constant and balanced. THD of source current is reduced from 11.7% to 2.02%.

Direct and quadrature axis load current mainly decides the instantaneous power angle with equal reactive power sharing feature between shunt and series inverter as shown in Fig. 8(a). Equal reactive power sharing phenomena between shunt and series inverter for estimation of power angle can be observed in Fig. 8 (b). Here, source reactive power is almost negligible as compared to the total load reactive power. With increase in reactive load demand from 10 kVAR to 20 kVAR at 0.5 s, power angle δ increases up to 29.51° from 14.55° and active power flow (Fig. 8(c)) reduces as evident from Eq. (56). DC link voltage is maintained at set reference value as observed from Fig. 8(d).

Case II

UPQC system with the proposed controller is also analyzed for load voltage compensation under different source voltage conditions such as unbalanced sag, unbalanced swell and harmonics as depicted in Fig. 9. It also shows the series injected voltage by the series inverter under different conditions. It is clear from the figure that the load voltage is balanced and at its rated steady level under possible source voltage variations, thus justifying the effectiveness of the proposed controller.

Case III

For load transition from composite load (linear and nonlinear) to only nonlinear load at t = 0.5 s, the performance of the system is analyzed with simulation results as shown in Fig. 10. Source voltage is kept at unbalanced sag condition. As the phase A supply voltage is assumed to be at its rated value, with reactive load cut off at 0.5 s, the series injected voltage for phase A reduces to almost negligible amount while the series injected voltage for phase B and C accounts for only compensating the sag occurred in the respective phases. Similarly, the magnitude of compensating current reduces at 0.5 s since reactive power demand from the load side reduces to negligible amount and only current harmonic compensation is expected from the shunt inverter.

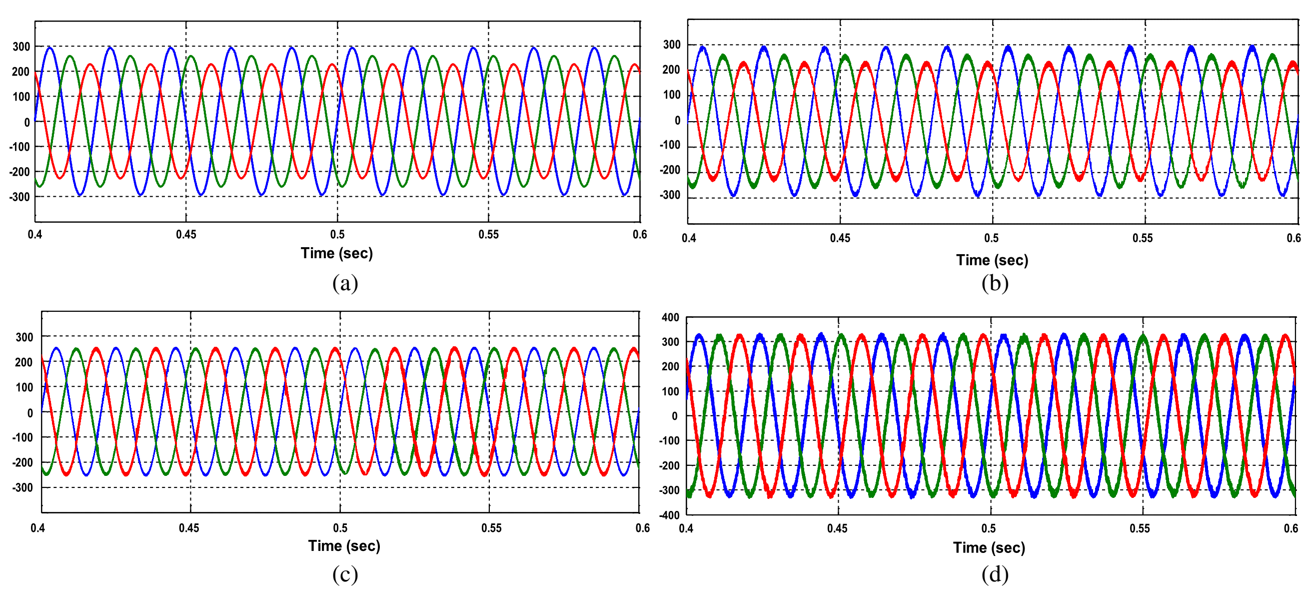

Fig. 6. Simulation results: (a) Three phase unbalanced supply voltage. (b) Load voltage with UPQC-S approach. (c) Load voltage with SRF approach. (d) Load voltage with proposed controller approach.

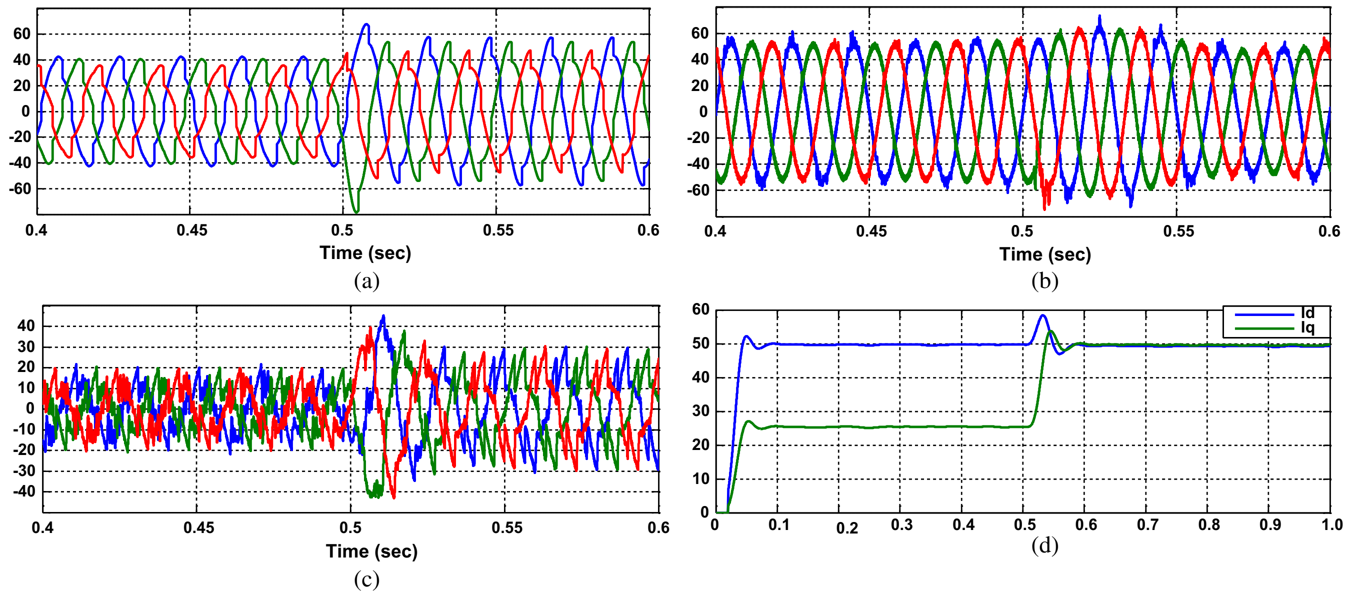

Fig. 7. Simulation results with proposed controller showing different current behaviour during sudden reactive load change: (a) Source current before compensation. (b) Source current after compensation. (c) Compensating current. (d) Direct and quadrature axis load current.

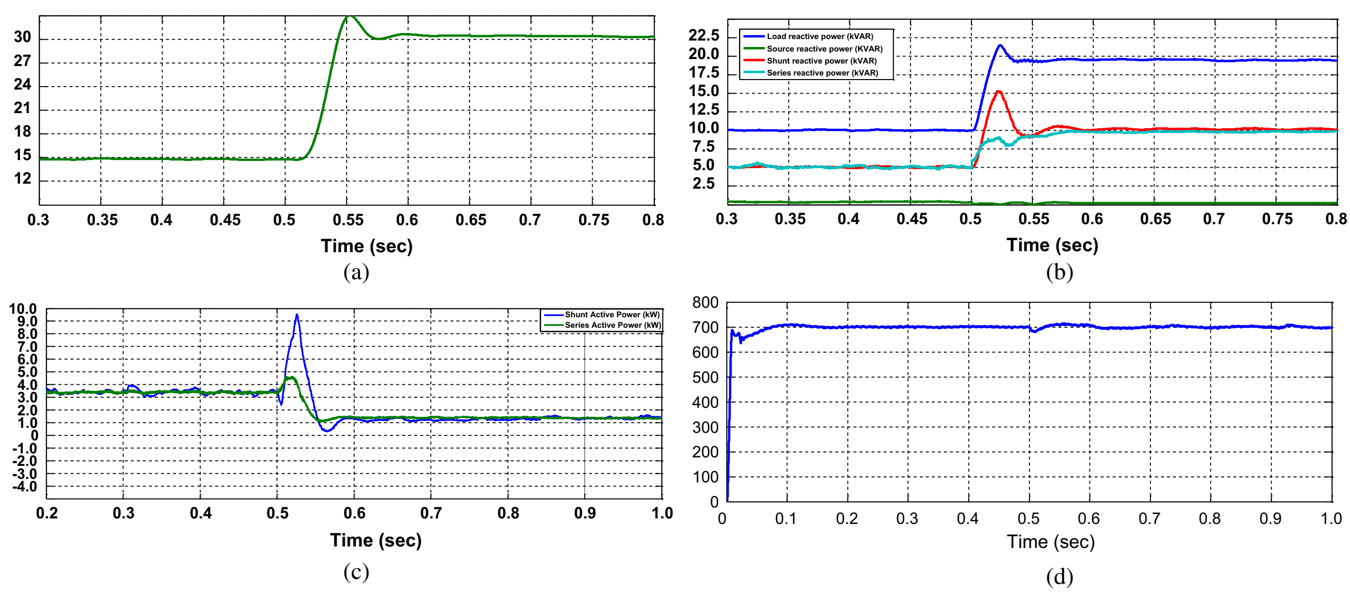

Fig. 8. Simulation results during sudden reactive load change: (a) Instantaneous power angle (δ degrees). (b) Reactive power in kVAR (source, load, shunt and series inverter). (c) Active power flow through shunt and series inverter. (d) DC link voltage.

Thus, from the above mentioned illustrations, it can be concluded that the UPQC system with proposed controller responds successfully under different operating conditions of supply and load. As the same active power flows through both inverters, two inverters of same rating can easily be adapted for such configuration by incorporating equal reactive power sharing feature.

Experimental analysis

The Experimental validation of the proposed controller for UPQC system for a particular loading condition is successfully performed. A dSPACE based experimental prototype is used for analysis as shown in Fig. 11. dSPACE module DS1103 is used for implementation of proposed control algorithm with connector panel module CP1103 for analog feedback signals.

For shunt and series inverter of UPQC system, two SEMIKRON built three phase IGBT based inverter stack are used as shown in Fig. 11. These inverters consist of IGBT modules SKM75GB123D and IGBT drivers as SKHI 22AR along with heat sink, fan and thermal trip. Driver is the interface unit between the power module and controller. Each driver drives two switches in a module. It amplified the logic signal ON/OFF and delivers high peak current for switching. Noise suppression of the input signal is necessary for reliable performance. This current is delivered through the gate resistors, which determines dynamic response of the IGBT. Driver provides short circuit protection and power supply under voltage protection when error condition is detected. The driver also helps in creating isolation between high potential of the power side and low potential side, yet allows the control signal to be transmitted between them. An auxiliary supply of 15 V dc is required for

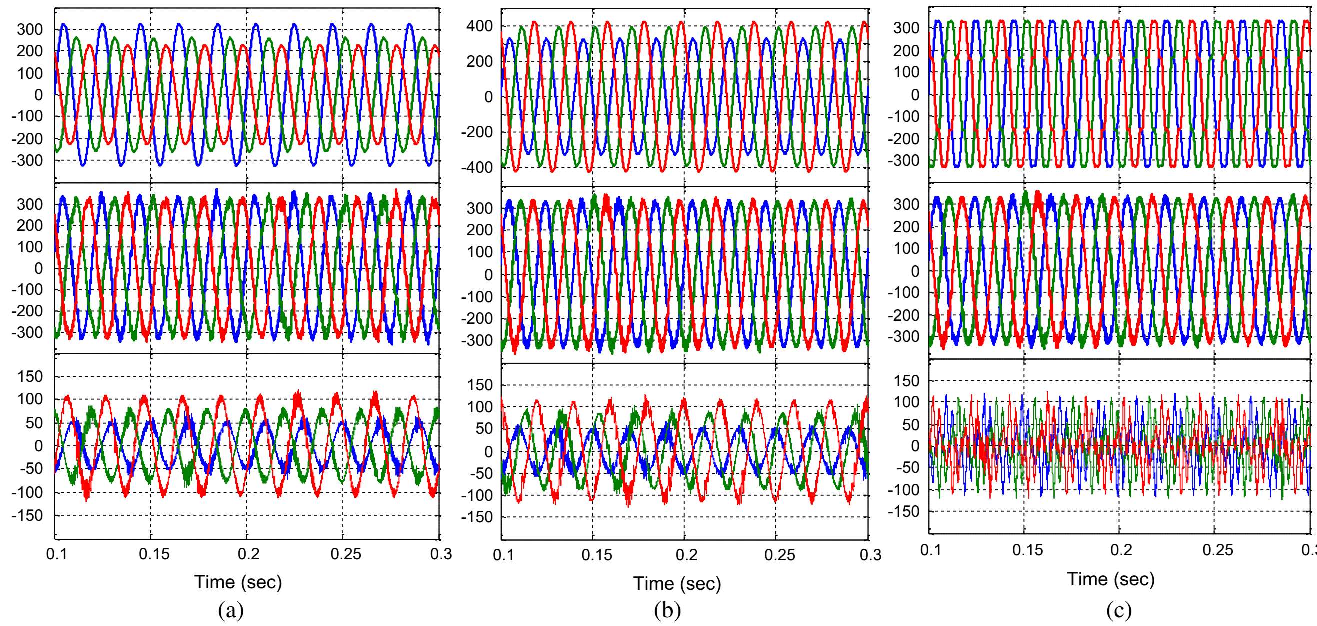

Fig. 9. Simulation results: Three phase source voltage, load voltage and injected voltage by series inverter from top to bottom for different source voltage condition in volts. (a) Unbalancing with sag. (b) Unbalancing with swell. (c) Balanced with harmonics.

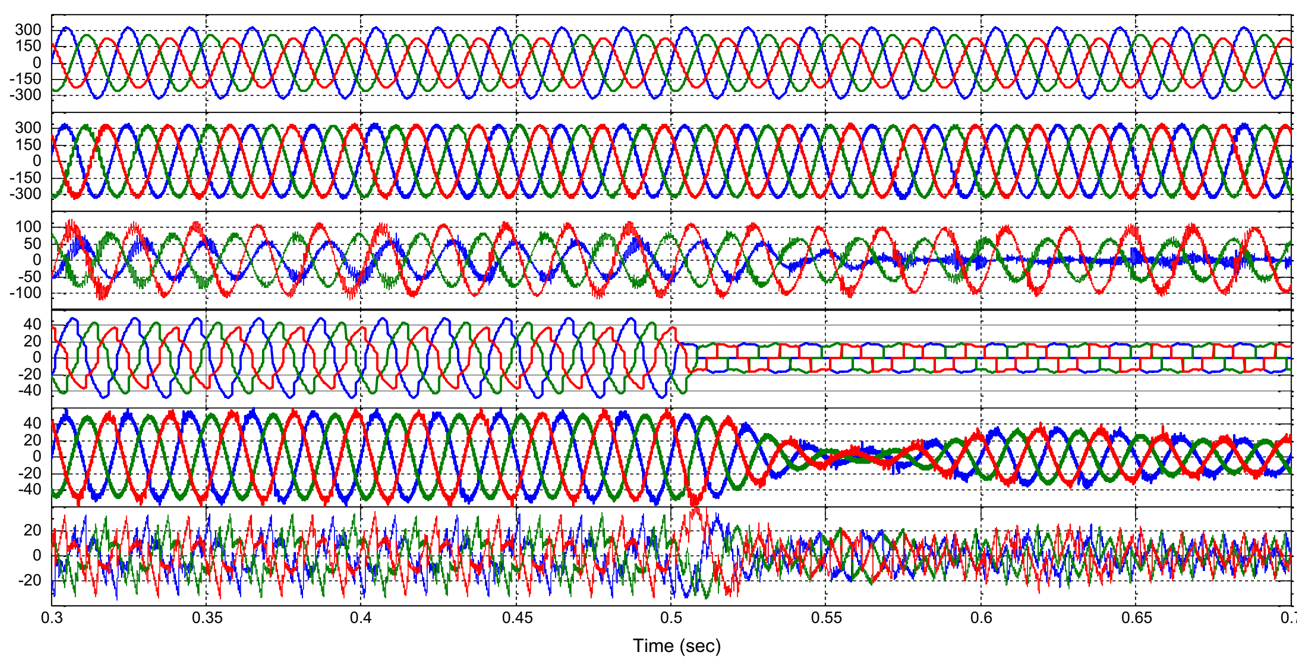

Fig. 10. Simulation results under unbalanced and sag voltage condition with load transition from composite (linear and nonlinear) to nonlinear only (top to bottom): Source voltage, load voltage, injected voltage, source current before compensation, source current after compensation and compensating current.

the inverter. All these components are encapsulated in acrylic case for protection from electrical shocks.

Hall effect voltage transducer LEM LV 25-P and current transducer LA 55-P are used for sensing voltage and current feedback signals respectively. For both current and voltage sensor, measurement resistance adapted is of value 150 Ω. Input resistance for voltage sensor is of value 56 kΩ. Both the sensors have excellent accuracy, good linearity, wide bandwidth and optimized response time. They are used in wide range of industrial applications. Their application in our system is depicted in the schematic diagram shown in Fig. 12. Current sensor is used for measurement of load current and compensating current whereas voltage sensor is used for measurement of source voltage, load voltage and dc link voltage. The switching signals being generated by the controller are communicated to the drivers of IGBT.

For series voltage injection three identical DE LORENZO built transformers are used of rating 1 kVA and turn's ratio of 1:1. The coupling inductor with shunt inverter are used to limit the rate of change of current. The LC filter used with series inverter is essential for elimination of high order switching harmonics. For generating three phase source voltage of unbalanced magnitude, three identical single phase autotransformers are used with

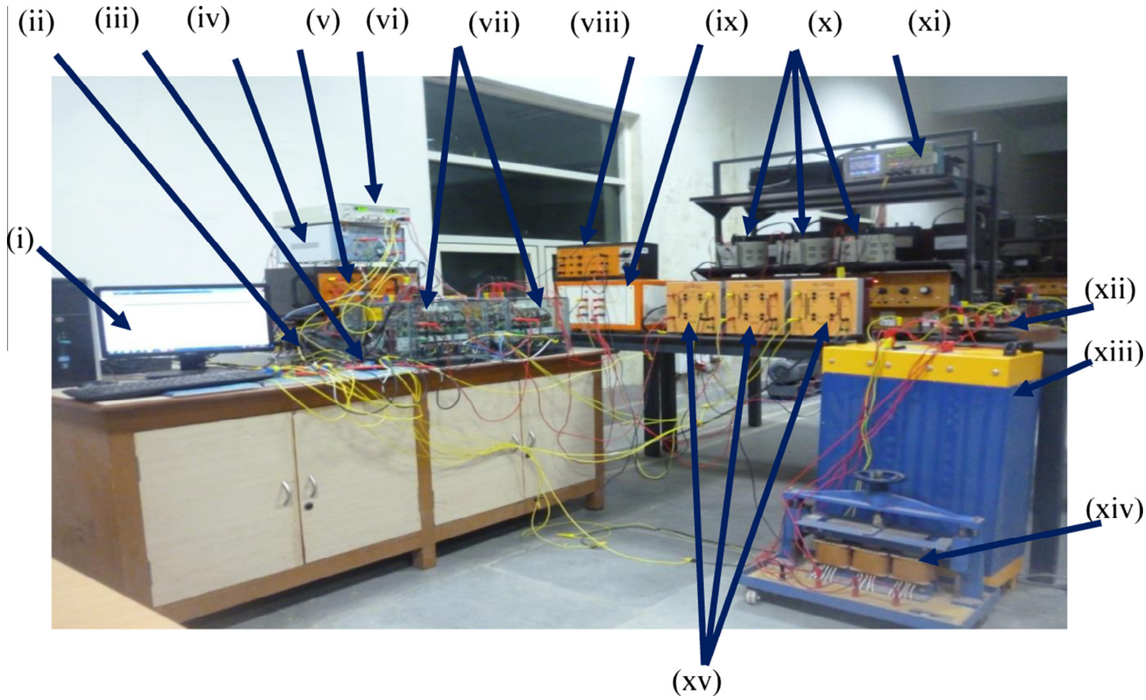

Fig. 11. Experimental set up (a) UPQC laboratory prototype: (i) Host PC with installed dSPACE setup, (ii) dSPACE connector panel, (iii) current sensing circuit, (iv) voltage sensing circuit, (v) filter inductor for series inverter, (vi) auxiliary dc supply for sensing circuit, (vii) semikron built IGBT based series and shunt inverter, (viii) filter capacitor for series inverter, (ix) coupling inductor for shunt inverter, (x) three single phase autotransformer for unbalanced supply voltage, (xi) digital storage oscilloscope, (xii) three phase diode bridge rectifier with RL load, (xiii) linear three phase resistive load, (xiv) linear three phase reactive load, (xv) three single phase series injection transformers.

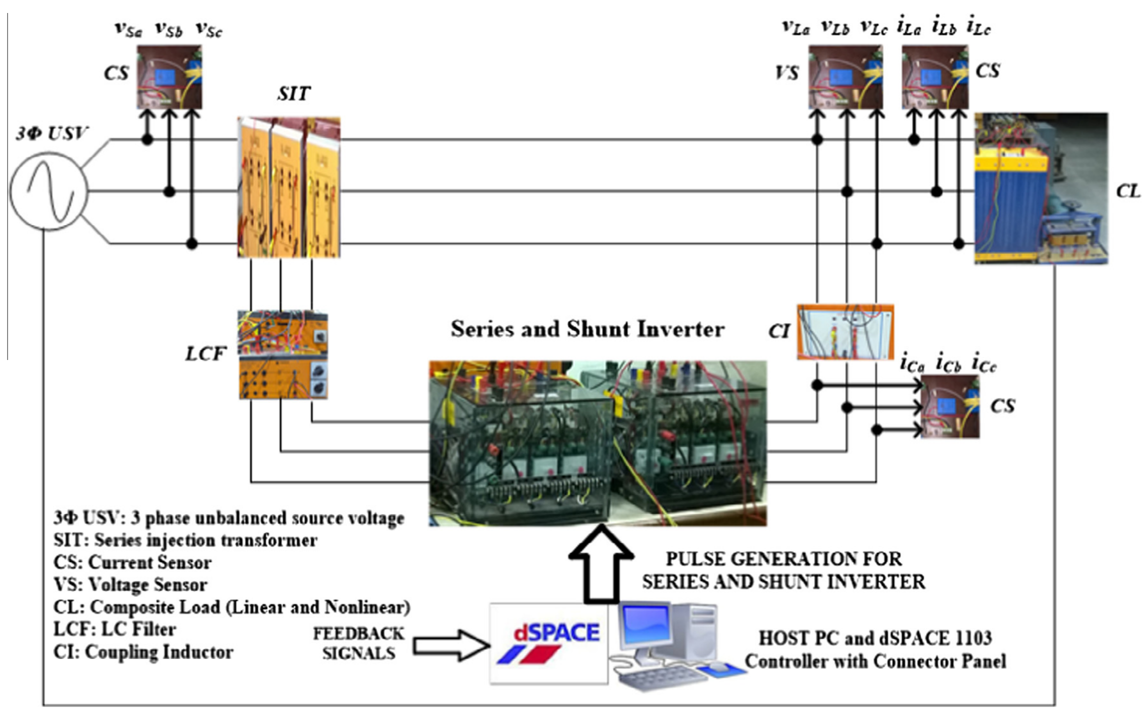

Fig. 12. Schematic diagram of experimental setup.

unequal settings. Steady state per phase nominal source voltage is considered to be 100 V (RMS). Load consist of a parallel combination of series connected three phase resistive-inductive load and a three phase diode bridge rectifier with an RL load on its dc side. The experimental parameters are as listed in Table 4.

UPQC system analysis with sag-unbalanced source voltage

The experimental results of the UPQC system with the proposed controller under sag-unbalanced source voltage condition are as shown in Fig. 13. Phase C is kept at rated reference voltage with

Table 4
Experimental parameters.

Source	Per phase steady state voltage	100 V (RMS)
	Frequency	50 Hz
Shunt inverter	Coupling inductor	2.2 mH
Series inverter	L, C filter	1.15 mH, 20 μF
	Transformer	1:1, 1 kVA
DC link	Capacitor	3300 μF
	Reference voltage	300 V
Load	3∅ linear load	Total P = 500 W &
	3∅ non-linear load (rectifier with RL load)	Q = 300 VAr

rms value as 100 V. Phase A and phase B are kept at 20% and 30% reduction as compared to reference value of phase C with rms values as 80 V and 70 V respectively (Fig. 13(a)). Load voltage is balanced and maintained at its set reference as can be seen from Fig. 13(b). The series injected voltage for the same can be observed from Fig. 13(c). Magnitude of each phase series injected voltage differs due to the reduction in voltage in their respective source voltages in order to maintain voltage across the load. Also, the source current before compensation, source current after compensation and the compensating current are shown in Fig. 13(d)–(f). Source current before compensation is unbalanced due to unbalanced source voltage while after compensation is balanced in nature. The THD of the source current without compensation is not very high as can be observed due to the presence of linear load but still is considerably reduced after compensation.

UPQC system analysis with swell-unbalanced source voltage

Fig. 14 illustrates the experimental performance analysis of UPQC system with proposed controller under swell-unbalanced condition. Here, phase C is again kept at rated reference voltage with its rms value as 100 V. Phase A and B are kept at 20% and 30% hike as compared to phase C with their respective rms values as 120 V and 130 V (Fig. 14(a)). With proper series and shunt compensation, load voltage (Fig. 14(b)) and source current is observed as balanced and maintained at its required value. The series injected voltage of the three phases can be observed in Fig. 14(c) with different magnitudes as per the compensation required for their respective phase source voltages. For swell-unbalanced condition, source current before compensation, source current after compensation and compensating current are shown in Fig. 14(d)–(f).

The compensation results for the UPQC system under both sag-unbalanced and swell-unbalanced condition are summarized in Table 5. Fig. 15 illustrates equal load reactive power sharing by shunt and series inverter, thus accommodating power angle control concept alongwith efficient utilization of both inverters under unbalanced source voltage condition.

Estimation of series injected voltage by series inverter

For steady state and rated per phase voltage of 100 V (RMS), the per phase (RMS) value of injected voltage by series inverter can be estimated from Eq. (6). Also, for the total active and reactive load demand with equal sharing phenomena, the instantaneous power angle is around 17.5°.

For sag-unbalanced condition

With voltage sag-unbalanced condition per phase rms value of source voltage for phase A, B and C are 80 V, 70 V and 100 V respectively. Therefore, the series injected voltage can be calculated as:

$$|V'_{Sra}| = k \cdot \sqrt{1 + f_a^2 - 2f_a \cos\delta}$$
$$\therefore |V'_{Sra}| = 33.7\ \mathrm{V}$$

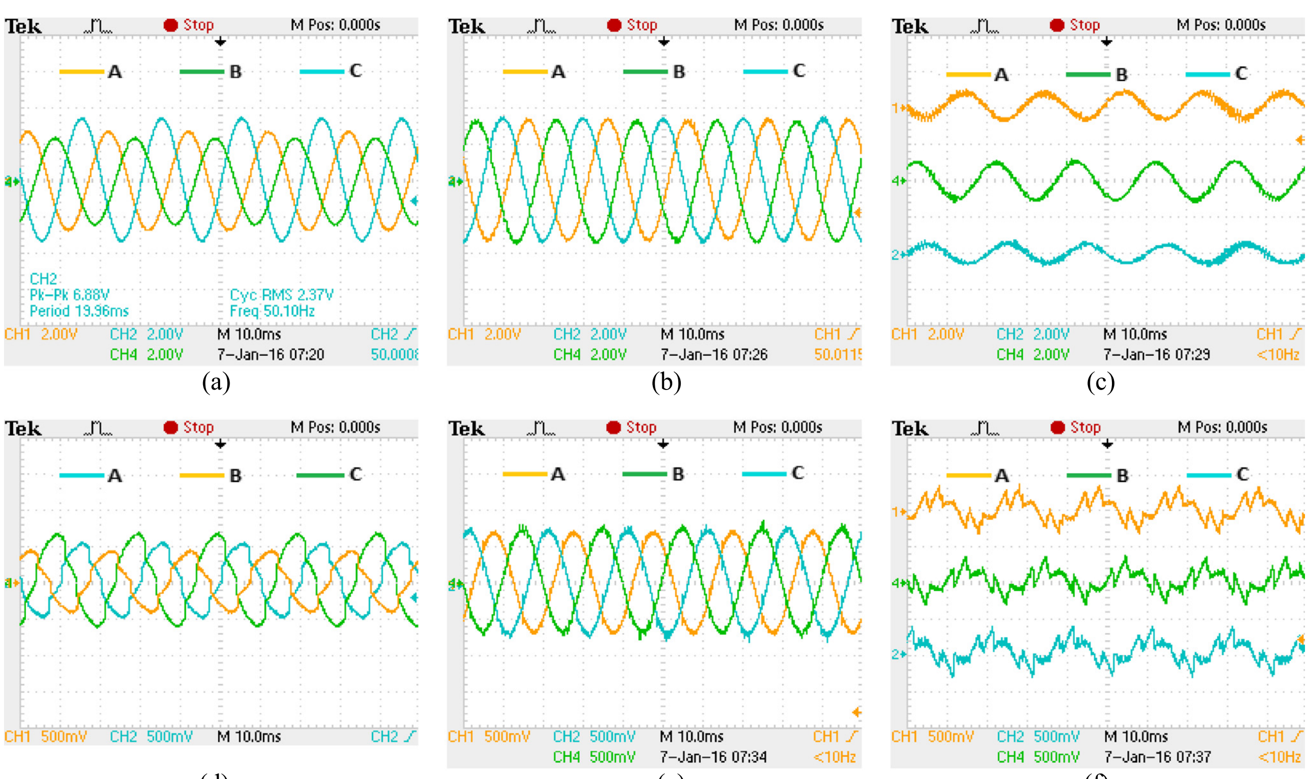

Fig. 13. Experimental results for sag-unbalanced condition: (a) Three phase source voltage. (b) Three phase load voltage with proposed PAC-SRF-UVT method. (c) Three phase series injected voltage. (d) Three phase source current before compensation. (e) Three phase source current after compensation. (f) Three phase compensating current.

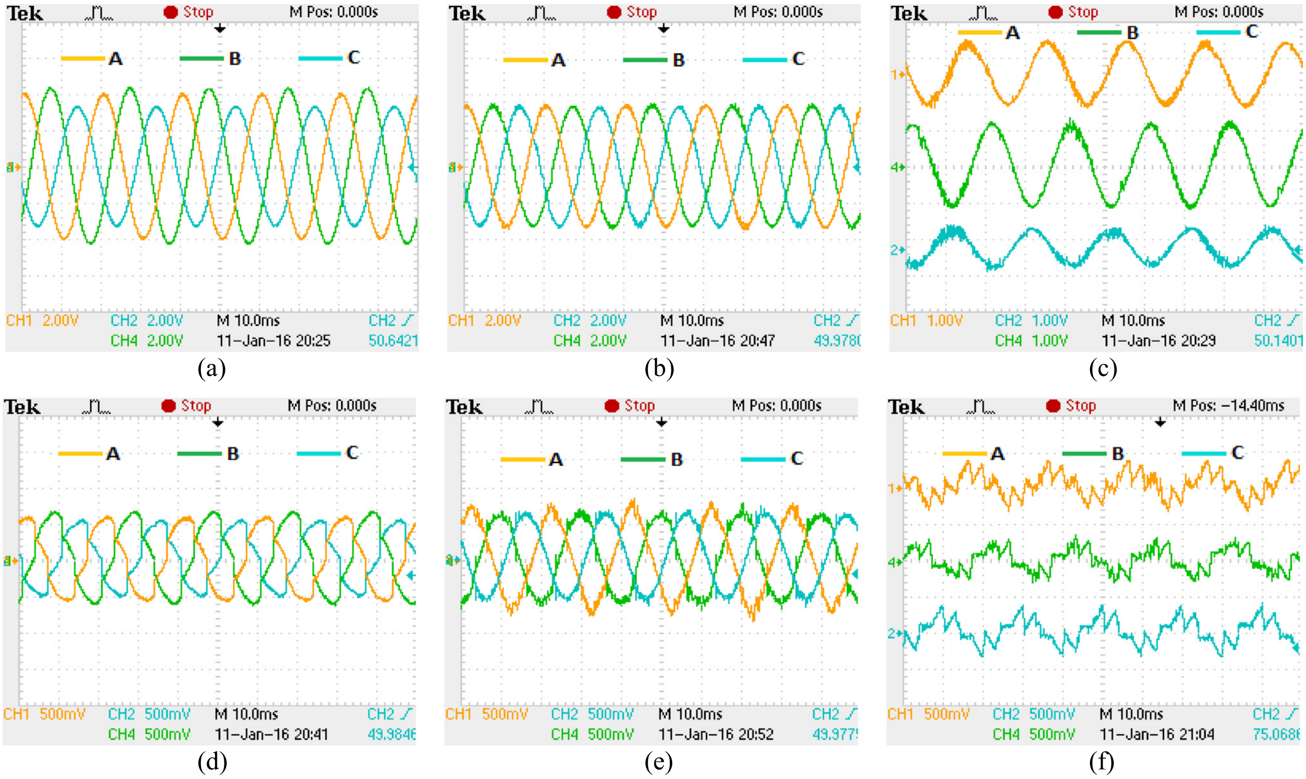

Fig. 14. Experimental results for swell-unbalanced condition: (a) Three phase source voltage. (b) Three phase load voltage with proposed PAC-SRF-UVT method. (c) Three phase series injected voltage. (d) Three phase source current before compensation. (e) Three phase source current after compensation. (f) Three phase compensating current.

Table 5
Summary of experimental verification.

Different voltage and current parameters	Sag-unbalanced (RMS value of each phase)			Swell-unbalanced (RMS value of each phase)		
	A	B	C	A	B	C
Source voltage (V)	82	71	101	122	133	104
Load voltage (V)	102	101.5	103	103.2	101.5	102
Series injected voltage (V)	33.7	39.29	30.34	38.65	45.37	31.25
Source current without compensation (A)	7.4	8.6	5.8	3.85	2.56	5.72
Source current after compensation (A)	5.64	5.72	5.54	5.3	5.9	5.6

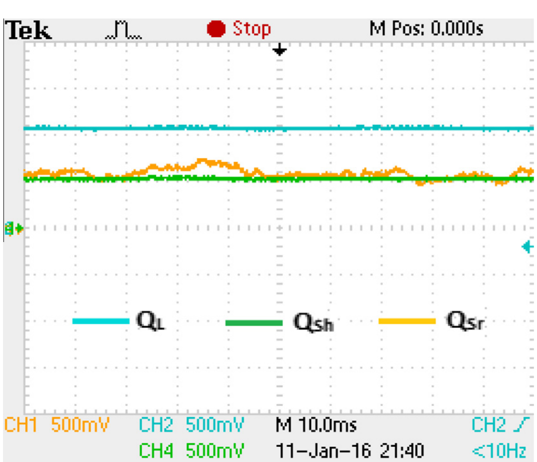

Fig. 15. Experimental result of load, shunt and series reactive power.

Similarly, $|V'_{Srb}| = 39.3$ V and $|V'_{Src}| = 30.4$ V

For swell-unbalanced condition

With voltage swell-unbalanced condition per phase rms value of source voltage for phase A, B and C are 120 V, 130 V and 100 V respectively. Therefore, the series injected voltage are obtained as:

$$|V'_{Sra}| = 38.8\ \text{V}, \quad |V'_{Srb}| = 45.7\ \text{V} \quad \text{and} \quad |V'_{Src}| = 30.4\ \text{V}$$

Thus, it can be concluded from experimental verification that an equal reactive power sharing algorithm based on load parameters can be successfully implemented for UPQC system under unbalanced source voltage condition. With desired results obtained for load voltage and source current in conjunction with equal reactive power sharing by shunt and series inverter, this UPQC system with proposed controller proves to be an effective and efficient power quality improving device.

Conclusion

This paper presents a new SRF based PAC approach for fixed and equal reactive power sharing between series and shunt inverter irrespective of the source voltage variations due to sag, swell or unbalancing. It also helps in application of two inverters with identical rating. A mathematical analysis is presented for maximum power angle estimation with and without inclusion of source voltage variation. Therefore, the estimated power angle is not in accordance with the rating of series inverter, if decided based on maximum injection capacity. The proposed power angle estimation approach utilizes the SRF based load current parameters which are also applicable for shunt inverter controller. The proposed controller based UPQC is evaluated for load voltage balancing, voltage sag and swell compensation, voltage and current harmonic compensation and efficient reactive power compensation with different loading condition such as linear, nonlinear or both. MATLAB/Simulink based rigorous simulative analysis for the UPQC system is carried out under different operating conditions. Also, an experimental prototype based on dSPACE DS1103 real time controller is used for experimental verification of the same.

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