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Application For Major Power Quality And Extend Pac For Upqc-S

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ABSTRACT

This paper introduces a new concept of optimal utilization of a unified power quality conditioner (UPQC). The series inverter of UPQC is controlled to perform simultaneous 1) voltage sag/swell compensation and 2) load reactive power sharing with the shunt inverter. The active power control approach is used to compensate voltage sag/swell and is integrated with theory of power angle control (PAC) of UPQC to coordinate the load reactive power between the two inverters. Since the series inverter simultaneously delivers active and reactive powers, this concept is named as UPQC-S (S for complex power). A detailed mathematical analysis, to extend the PAC approach for UPQC-S, is presented in this paper. MATLAB/ SIMULINK -based simulation results are discussed to support the developed concept. Finally, the proposed concept is validated with a digital signal processor-based experimental study.

Keywords - **Active power filter (APF), power angle control (PAC), power quality, reactive power compensation, unified power quality conditioner (UPQC), voltage sag and swell compensation.**

I. INTRODUCTION

The modern power distribution system is becoming highly vulnerable to the different power quality problems [1], [2]. The extensive use of nonlinear loads is further contributing to increased current and voltage harmonics issues. Furthermore, the penetration level of small/large-scale renewable energy systems based on wind energy, solar energy, fuel cell, etc., installed at distribution as well as transmission levels is increasing significantly. This integration of renewable energy sources in a power system is further imposing new challenges to the electrical power industry to accommodate these newly emerging distributed generation systems [3]. To maintain the controlled power quality regulations, some kind of compensation at all the power levels is becoming a common practice [5]–[9]. At the distribution level, UPQC is a most attractive solution to compensate several major power quality problems [7]–[9], [14]–[28]. The general block diagram representation of a UPQC-based system is shown in Fig. 1. It basically consists of two voltage source inverters connected back to back using a common dc bus capacitor. This paper deals with a novel concept of optimal utilization of a UPQC.

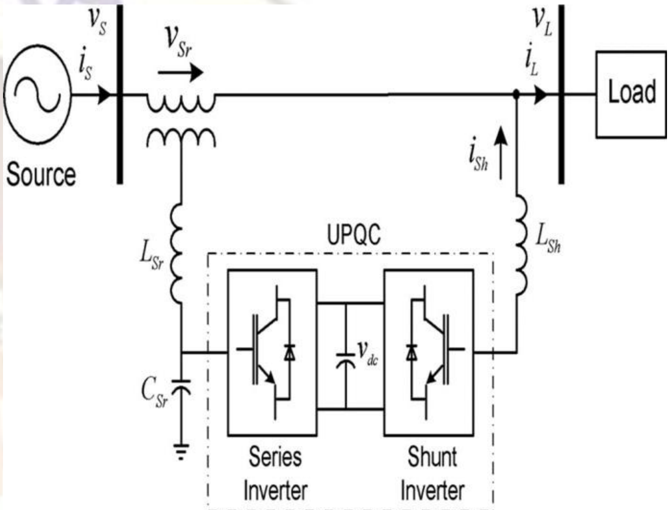


Fig. 1. Unified power quality conditioner (UPQC) system configuration.

The voltage sag/swell on the system is one of the most important power quality problems [1], [2]. The voltage sag/swell can be effectively compensated using a dynamic voltage restorer, series active filter, UPQC, etc. [7]–[28]. Among the available power quality enhancement devices, the UPQC has better sag/swell compensation capability. Three significant control approaches for UPQC can be found to control the sag on the system: 1) active power control approach in which an in-phase voltage is injected through series inverter [16]–[22], popularly known as UPQC-P; 2) reactive power control approach in which a quadrature voltage is injected [23], [24], known as UPQC-Q; and 3) a minimum VA loading approach in which a series voltage is injected at a certain angle, [25]–[28], in this paper called as UPQC-VA min. Among the aforementioned three approaches, the quadrature voltage injection requires a maximum series injection voltage, whereas the in-phase voltage injection requires the minimum voltage injection magnitude. In a minimum VA loading approach, the series inverter voltage is injected at an optimal angle with respect to the source current. Besides the series inverter injection, the current drawn by the shunt inverter, to maintain the dc link voltage and the overall power balance in the network, plays an important role in determining the overall UPQC VA loading. The reported paper on UPQC-VA min is concentrated on the optimal VA load of the series inverter of UPQC especially during voltage sag condition [25]–[28]. Since an out of phase component is required to be injected for voltage swell compensation, the suggested VA loading in UPQC-VA min determined on the basis of voltage sag, may not be at optimal value. A detailed investigation on VA loading in UPQC-VA min considering both voltage sag and swell scenarios is essential. In the paper [15], the authors have proposed a concept of power angle control (PAC) of UPQC. The PAC concept suggests that with proper control of series inverter voltage the series inverter successfully supports part of the load reactive power demand, and thus reduces the required VA rating of the shunt inverter. Most importantly, this coordinated reactive power sharing feature is achieved during normal steady-state condition without affecting the resultant load voltage magnitude. The optimal angle of series voltage injection in UPQC-VAmin is computed using lookup table [26], [27] or particle swarm optimization technique [28]. These iterative methods mostly rely on the online load power factor angle estimation, and thus may result into tedious and slower estimation of optimal angle. On the other hand, the PAC of UPQC concept determines the series injection angle by estimating the power angle δ. The angle δ is computed in adaptive way by computing the instantaneous load active/reactive power and thus, ensures fast and accurate estimation.

Similar to PAC of UPQC, the reactive power flow control utilizing shunt and series inverters is also done in a unified power flow controller (UPFC) [4], [5]. A UPFC is utilized in a power transmission system whereas a UPQC is employed in a power distribution system to perform the shunt and series compensation simultaneously. The power transmission systems are generally operated in balanced and distortion-free environment, contrary to power distribution systems that may contain dc component, distortion, and unbalance. The primary objective of a UPFC is to control the flow of power at fundamental frequency. Also, while performing this power flow control in UPFC the transmission network voltage may not be maintained at the rated value. However, in PAC of UPQC the load side voltage is strictly regulated at rated value while performing load reactive power sharing by shunt and series inverters. In this paper, the concept of PAC of UPQC is further expanded for voltage sag and swells conditions. This modified approach is utilized to compensate voltage sag/swell while sharing the load reactive power between two inverters.

Since the series inverter of UPQC in this case delivers both active and reactive powers, it is given the name UPQCS (S for complex power).

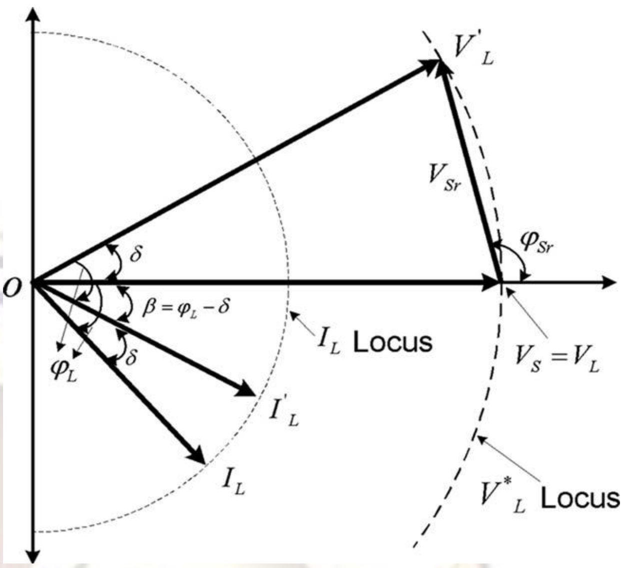


Fig. 2. Concept of PAC of UPQC.

The key contributions of this paper are outlined as follows.

1) The series inverter of UPQC-S is utilized for simultaneous voltage sag/swell compensation and load reactive power compensation in coordination with shunt inverter.
2) In UPQC-S, the available VA loading is utilized to its maximum capacity during all the working conditions contrary to UPQC-VA min where prime focus is to minimize the VA loading of UPQC during voltage sag condition.
3) The concept of UPQC-S covers voltage sag as well as swell scenario.

In this paper, a detailed mathematical formulation of PAC for UPQC-S is carried out. The feasibility and effectiveness of the proposed UPQC-S approach are validated by simulation as well as experimental results.

II. ACTIVE POWER FILTERS

The proliferation of microelectronics processors in a wide range of equipments, from home VCRs and digital clocks to automated industrial assembly lines and hospital diagnostics systems has increased the vulnerability of such equipment to power quality problems. These problems include a variety of electrical disturbances, which may originate in several ways and have different effects on various kinds of sensitive loads. What were once considered minor variations in power, usually unnoticed in the operation of conventional equipment, may now bring whole factories to standstill. As a result of this vulnerability, increasing numbers of industrial and commercial facilities are trying to protect themselves by investing in more sophisticate equipment to improve power quality. Moreover, the proliferation of nonlinear loads with large rated power has increased the contamination level in voltages and currents waveforms, forcing to improve the compensation characteristics required to satisfy more stringent harmonics standard. Between the different technical options available to improve power quality, active power filters have proved to be an important alternative to compensate for current and voltage disturbances in power distribution systems. Different active power filters topologies have been presented in the technical literature many of them are already available in the market. This paper will focus in the analysis of which to use with their compensation characteristics. Shunt active power filters, series active topologies, will be presented

III. POWER QUALITY IN POWER DISTRIBUTION SYSTEMS

Most of the more important international standards define power quality as the physical characteristics of the electrical supply provided under normal operating conditions that do not disrupt or disturb the customer's processes. Therefore, a power quality problem exists if any voltage, current or frequency deviation results in a failure or in a bad operation of customer's equipment. However, it is important to notice that the quality of power supply implies basically voltage quality and supply reliability. A voltage quality problem relates to any failure of equipment due to deviations of the line voltage from its nominal characteristics, and the supply reliability is characterized by its adequacy (ability to supply the load), security (ability to withstand sudden disturbances such as system faults) and availability (focusing especially on long interruptions). Power quality problems are common in most of commercial, industrial and utility networks. Natural phenomena, such as lightning are the most frequent cause of power quality problems. Switching phenomena resulting in oscillatory transients in the electrical supply, for example when capacitors are switched, also contribute substantially to power quality disturbances. Also, the connection of high power non-linear loads contributes to the generation of current and voltage harmonic components. Between the different voltage disturbances that can be produced, the most significant and critical power quality problems are voltage sags due to the high economical losses that can be generated. Short-term voltage drops (sags) can trip electrical drives or more sensitive equipment, leading to costly interruptions of production. For all these reasons, from the consumer point of view, power quality issues will become an increasingly important factor to consider in order satisfying good productivity. To address the needs of energy consumers trying to improve productivity through the reduction of power quality related process stoppages and energy suppliers trying to maximize operating profits while keeping customers satisfied with supply quality, innovative technology provides the key to cost-effective power quality enhancements solutions. However, with the various power quality solutions available, the obvious question for a consumer or utility facing a particular power quality problem is which equipment provides the better solution.

IV. SOLUTIONS TO POWER QUALITY PROBLEMS

There are two approaches to the mitigation of power quality problems. The first approach is called load conditioning, which ensures that the equipment is less sensitive to power disturbances, allowing the operation even under significant voltage distortion. The other solution is to install line conditioning systems that suppress or counteracts the power system disturbances. A flexible and versatile solution to voltage quality problems is offered by active power filters. Currently they are based on PWM converters and connect to low and medium voltage distribution system in shunt or in series. Series active power filters must operate in conjunction\ with shunt passive filters in order to compensate load current harmonics. Shunt active power filters operate as a controllable current source and series active power filters operates as a controllable voltage source. Both schemes are implemented preferable with voltage source PWM inverters, with a dc bus having a reactive element such as a capacitor. Active power filters can perform one or more of the functions required to compensate power systems and improving power quality. As it will be illustrated in this paper, their performance depends on the power rating and the speed of response.

The selection of the type of active power filter to improve power quality depends on the source of the problem as can be seen in Table 1.

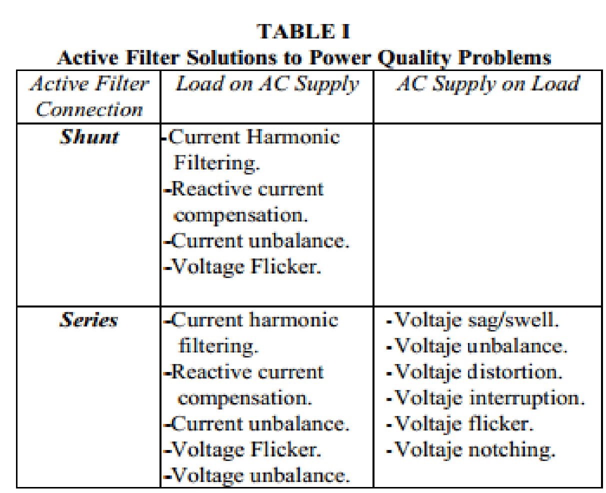


TABLE I
Active Filter Solutions to Power Quality Problems

Active Filter Connection	*Load on AC Supply*	*AC Supply on Load*
Shunt	-Current Harmonic Filtering. -Reactive current compensation. -Current unbalance. -Voltage Flicker.	
Series	-Current harmonic filtering. -Reactive current compensation. -Current unbalance. -Voltage Flicker. -Voltage unbalance.	-Voltaje sag/swell. -Voltaje unbalance. -Voltaje distortion. -Voltaje interruption. -Voltaje flicker. -Voltaje notching.

V. SHUNT ACTIVE POWER FILTERS

Shunt active power filter compensate current harmonics by injecting equal-but-opposite harmonic Compensating current. In this case the shunt active power filter operates as a current source injecting the harmonic components generated by the load but phase shifted by180 deg. This principle is applicable to any type of load considered a harmonic source. Moreover, with an appropriate control scheme, the active power filter can also compensate the load power factor. In this way, the power distribution system sees the non linear load and the active power filter as an ideal resistor. The current compensation characteristic of the shunt active power filter is shown in fig

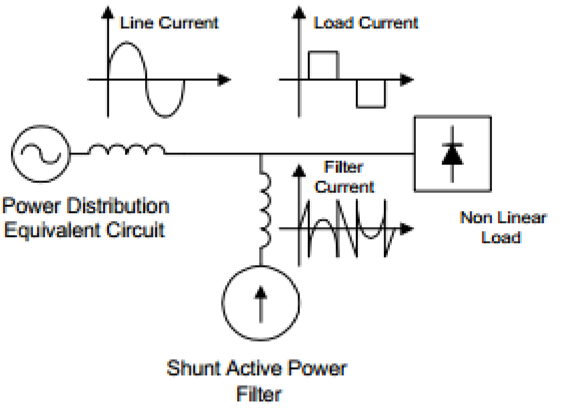


Fig.3. SHUNT ACTIVE POWER FILTERS

SERIES ACTIVE POWER FILTERS

It is well known that series active power filters compensate current system distortion caused by non-linear loads by imposing a high impedance path to the current harmonics which forces the high frequency currents to flow through the LC passive filter connected in parallel to the load. The high impedance imposed by the series active power filter is created by generating a voltage of the same frequency that the current harmonic component that needs to be eliminated. Voltage unbalance is corrected by compensating the fundamental frequency negative and zero sequence voltage components of the system.

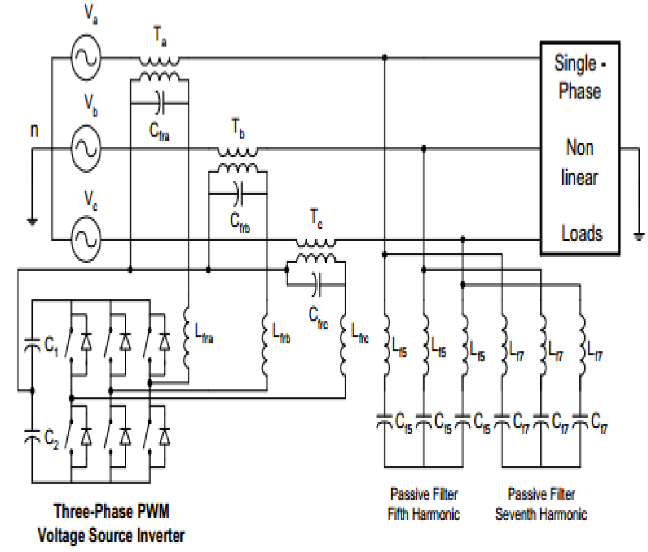


Fig.4. SERIES ACTIVE POWER FILTERS

Unified Power Quality Conditioner

The provision of both DSTATCOM and DVR can control the power quality of the source current and the load bus voltage. In addition, if the DVR and STATCOM are connected on the DC side, the DC bus voltage can be regulated by the shunt connected DSTATCOM while the DVR supplies the required energy to the load in case of the transient disturbances in source voltage. The configuration of such a device (termed as Unified Power Quality Conditioner (UPQC)) is shown in Fig. 14.15. This is a versatile device similar to a UPFC. However, the control objectives of a UPQC are quite different from that of a UPFC.

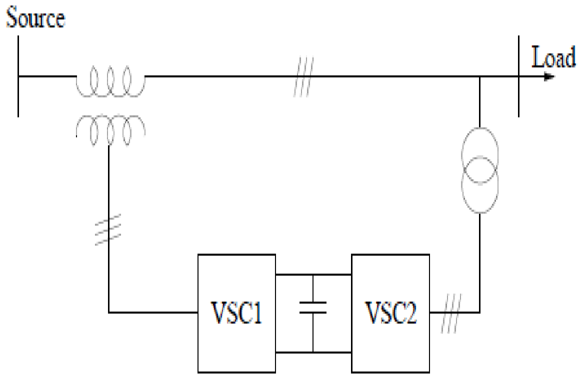


Fig.5. Unified Power Quality Conditioner.

VI. CONTROL OBJECTIVES OF UPQC

The shunt connected converter has the following control objectives

1. To balance the source currents by injecting negative and zero sequence components required by the load

2. The compensate for the harmonics in the load current by injecting the required harmonic currents

3. To control the power factor by injecting the required reactive current (at fundamental frequency)
4. To regulate the DC bus voltage.

Operation of UPQC

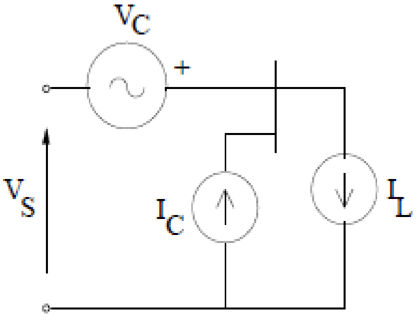


Fig.6.Operation of UPQC

The operation of a UPQC can be explained from the analysis of the idealized equivalent circuit shown in Fig. 14.16. Here, the series converter is represented by a voltage source VC and the shunt converter is represented by a current source IC. Note that all the currents and voltages are 3 dimensional vectors with phase coordinates. Unlike in the case of a UPFC (discussed in chapter 8), the voltages and currents may contain negative and zero sequence components in addition to harmonics. Neglecting losses in the converters, we get the relation

$$\langle V_L, I_C \rangle + \langle V_C, I_S \rangle = 0 \qquad (1)$$

Where X, Y denote the inner product of two vectors, defined by

$$\langle X, Y \rangle = \frac{1}{T} \int_0^T X^t(\tau) Y(\tau) d\tau. \qquad (2)$$

Let the load current IL and the source voltage VS be decomposed into two. Components given by

$$I_L = I_L^{1p} + I_L^r$$

$$V_S = V_S^{1p} + V_S^r \qquad (3)$$

Where I1p L contains only positive sequence, fundamental frequency components. Similar comments apply to V 1pS . IrL and V rS contain rest of the load current and the source voltage including harmonics. I1pL is not unique and depends on the power factor at the load bus. However, the following relation applies for I1p L .

$$P_L = \langle V_L, I_L \rangle = \langle V_L, I_L^{1p} \rangle \qquad (4)$$

This implies that hIrL ; VLi = 0. Thus, the fundamental frequency, positive sequence component in IrL does not contribute to the active power in the load. To meet the control objectives, the desired load voltages and source currents must contain only positive sequence, fundamental frequency components and

$$P_L = |V_L^* \, I_S^*| \cos\phi_l = |V_S^{1p} I_S^*| \cos\phi_s \qquad (5)$$

where V ¤ L and I¤S are the reference quantities for the load bus voltage and the source current respectively. Ál is the power factor angle at the load bus while Ás is the power factor angle at the source bus (input port of UPQC). Note that V ¤ L(t) and I¤S (t) are sinusoidal and balanced. If the reference current (I¤C) of the shunt converter and the reference voltage (V ¤ C) of the series converter are chosen as

$$I_C^* = I_L^*, \quad V_C^* = -V_S^r + V_C^{1p} \qquad (6)$$

with the constraint

$$\langle V_C^{1p}, I_S^* \rangle = 0 \qquad (7)$$

we have,

$$I_S^* = I_L^{1p}, \quad V_L^* = V_S^{1p} + V_C^{1p} \qquad (8)$$

Note that the constraint (14.30) implies that V 1p C is the reactive voltage in quadrature with the desired source current, I¤S. It is easy to derive that

$$\langle V_C^*, I_S^* \rangle = 0 = \langle I_C^*, V_L^* \rangle$$

The above equation shows that for the operating conditions assumed, a UPQC can be viewed as a inaction of a DVR and a STATCOM with no active power °ow through the DC link.

However, if the magnitude of V ¤ L is to be controlled, it may not be feasible to achieve this by injecting only reactive voltage. The situation gets complicated if V 1p S is not constant, but changes due to system disturbances or fault. To ensure the regulation of the load bus voltage it may be necessary to inject variable active voltage (in Phase with the source current). If we express

$$V_C = V_C^* + \Delta V_C, I_C = I_C^* + \Delta I_C \qquad (9)$$

$$I_S = I_S^* - \Delta I_C, V_L = V_S^{1p} + V_C^{1p} + \Delta V_C$$

$$\langle I_S, \Delta V_C \rangle + \langle V_L, \Delta I_C \rangle = 0 \qquad (10)$$

In deriving the above, we assume that

$$\langle I_S, V_C^* \rangle = 0 = \langle V_L, I_C^* \rangle \qquad (11)$$

This implies that both ¢VC and ¢IC are perturbations involving positive sequence, fundamental frequency quantities (say, resulting from symmetric voltage sags). the power balance on the DC side of the shunt and series converter. The perturbation in VC is initiated to ensure that

$$|V_C^* + \Delta V_C + V_S| = |V_L| = \text{constant}.$$

Thus, the objective of the voltage regulation at the load bus may require exchange of power between the shunt and series converters.

Remarks

1. The unbalance and harmonics in the source voltage can arise due to uncompensated nonlinear and unbalanced loads in the upstream of the UPQC.

2. The injection of capacitive reactive voltage by the series converter has the advantage of raising the source voltage magnitude.

UPQC-S CONTROLLER

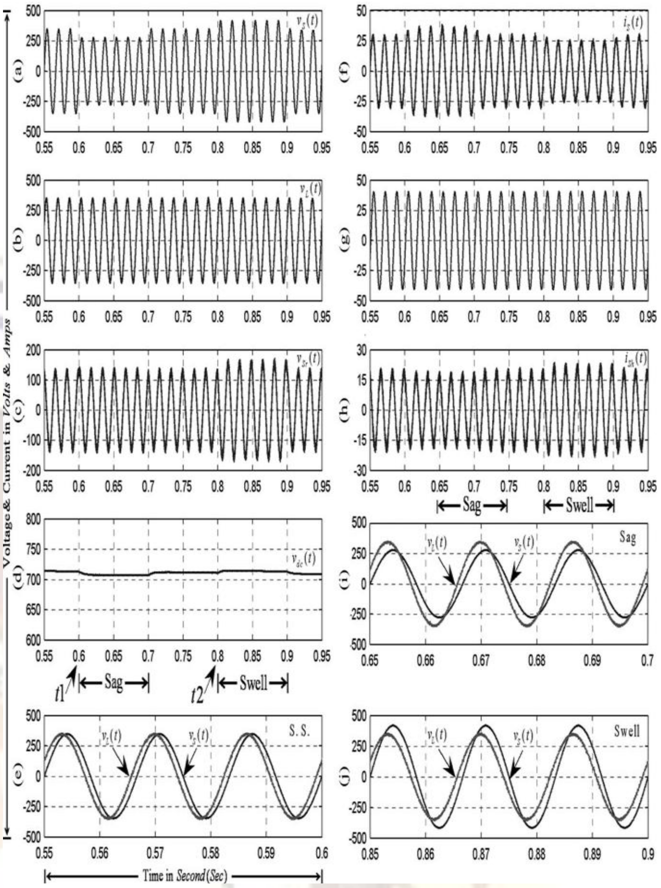
A detailed controller for UPQC based on PAC approach is described in [15]. In this paper, the generation of reference signals for series inverter is discussed. Note that, as the series inverter maintains the load voltage at desired level, the reactive power demanded by the load remains unchanged (assuming load on the system is constant) irrespective of changes in the source voltage magnitude. Furthermore, the power angle δ is maintained at constant value under different operating conditions. Therefore, the reactive power shared by the series inverter and hence by the shunt inverter changes as given by (47) and (54). The reactive power shared by the series and shunt inverters can be fixed at constant values by allowing the power angle δ to vary under voltage sag/swell condition.

The control block diagram for series inverter operation is shown in Fig. 10. The instantaneous power angle δ is determined using the procedure give in [15]. Based on the system rated specifications, the value of the desired load voltage is set as reference load voltage k. The instantaneous value of factors kf and nO is computed by measuring the peak value of the supply voltage in real time. The magnitudes of series injected voltage VSr and its phase angle ϕSr are then determined using (15) and (17). A phase locked loop is used to synchronize and to generate

Instantaneous time variable reference signals $v*$ Sr,a , $v*$ Sr,b , $v*$ Sr,c .

The reference signals thus generated give the necessary series injection voltages that will share the load reactive power and compensate for voltage sag/swell as formulated using the proposed approach. The error signal of actual and reference series voltage is utilized to perform the switching operation of series inverter of UPQC-S. The control diagram for the shunt inverter is as given in [15].

Fig.7. Simulation results: Performances of the proposed UPQC-S approach under voltage sags and swell conditions. (a) Supply voltage. (b) Load voltage. (c) Series inverter injected voltage. (d) Self-supporting dc bus voltage. (e) Enlarged power angle δ relation between supply and load voltages during steady-state condition. (f) Supply current. (g) Load current. (h) Shunt inverter injected current. (i) Enlarged power angle δ during voltage sag condition. (j) Enlarged power angle δ during voltage swell condition.



VII. SIMULATION RESULTS

The performance of the proposed concept of simultaneous load reactive power and voltage sag/swell compensation has been evaluated by simulation. To analyze the performance of UPQC-S, the source is assumed to be pure sinusoidal. Furthermore, for better visualization of results the load is considered as highly inductive. The supply voltage which is available at UPQC terminal is considered as three phase, 60 Hz, 600 V (line to line) with the maximum load power demand of 15 kW + j 15 kVAR (load power factor angle of 0.707 lagging). The simulation results for the proposed UPQC-S approach under voltage sag and swell conditions. The distinct features of the proposed UPQC-S approach are outlined as follows.

1) From Figure the load voltage profile is maintained at a desired level irrespective of voltage sag (decrease) or swell (increase) in the source voltage magnitudes. During the sag/swell compensation, to maintain the appropriate active power balance in the network, the source current increase during the voltage sag and reduces during swell condition.

2) As illustrated by enlarged results, the power angle δ between the source and load voltages during the steady state, voltage sag and voltage swell is maintained at 21◦.

3) The UPQC-S controller maintains a self-supporting dc link voltage between two inverters

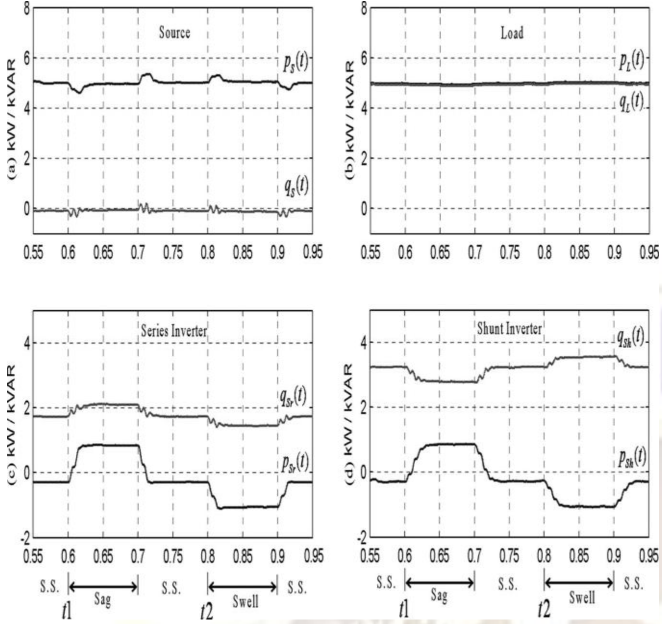


Fig.8. Simulation results: active and reactive power flow through source, load, shunt, and series inverter utilizing proposed UPQC-S approach under voltage sag and swell conditions. (a) Source P and Q. (b) Load P and Q. (c) Series inverter P and Q. (d) Shunt inverter P and Q.

TABLE II

LOSSES ASSOCIATED WITH UPQC UNDER DIFFERENT SCENARIOS

	Condition	I_{Sh} (rms)	I_{Sr} (rms)	V_{Sr} (rms)	$\frac{P_{loss}}{P_{load}}$
Steady-State	(*i*) Without PAC approach and Series transformer SC	20.20 A	-	-	0.74 %
	(*ii*) Without PAC and Series inverter in operation	20.20 A	20.80 A	4.00 V	1.70 %
	(*iii*) With PAC approach	13.18 A	19.95 A	92.3 V	1.20 %
Voltage Sag	(*i*) Without PAC approach	20.90 A	26.05 A	48.4 V	2.60 %
	(*ii*) With PAC approach	11.90 A	25.05 A	89.4 V	1.82 %
Voltage Swell	(*i*) Without PAC approach	20.60 A	17.45 A	48.5 V	1.58 %
	(*ii*) With PAC approach	14.94 A	16.62 A	110.5 V	1.39 %

The reactive power supplied by the series inverter during the voltage sag condition increases due to the increased source current. As load reactive power demand is constant, the reactive power supplied by the shunt inverter reduces accordingly. On the other hand, during the voltage swell condition, the reactive power shared by the series inverter reduces and the shunt inverter increases. The reduction and increment in the shunt compensating current magnitude, as seen from Figure, also confirm the aforementioned fact. Although the reactive power shared by the series and shunt inverters is varied, the sum of their reactive powers always equals the reactive power demanded by the load.

Table II gives the power losses associated with UPQC with and without PAC approach under different scenarios. The power loss is computed as the ratio of losses associated with UPQC to the total load power. This is an interesting outcome of the PAC approach even when the series inverter deals with both active and reactive powers due to δ shift between source and load voltages. One may expect to increase the power loss with the UPQC-S system. The reduction in the power loss is mainly due to the reduction in the shunt inverter rms current from 20.20 A (without PAC approach) to 13.18 A (with PAC approach). Second, the current through the series inverter (which is almost equal to the source current) remains unchanged. Similarly from the Table I, the power losses utilizing the PAC approach, during voltage sag and swell conditions, are observed lower than those without PAC approach. This study thus suggests that the PAC approach may also help to reduce the power loss associated with UPQC system in addition to the previously discussed advantages. The significant advantage of UPQC-S over general UPQC applications is that the shunt inverter rating can be reduced due to reactive power sharing of both the inverters.

VIII. CONCLUSION

In this paper, a new concept of controlling complex power (simultaneous active and reactive powers) through series inverter of UPQC is introduced and named as UPQC-S. The proposed concept of the UPQC-S approach is mathematically formulated and analyzed for voltage sag and swell conditions. The developed comprehensive equations for UPQC-S can be utilized to estimate the required series injection voltage and the shunt compensating current profiles (magnitude and phase angle), and the overall VA loading both under voltage sag and swell conditions. The simulation and experimental studies demonstrate the effectiveness of the proposed concept of simultaneous voltage sag/swell and load reactive power sharing feature of series part of UPQC-S. The significant advantages of UPQC-S over general UPQC applications are: 1) the multifunction ability of series inverter to compensate voltage variation (sag, swell, etc.) while lagging power factor; *DC bus*: dc bus capacitor = 1100 μF/220 V, reference dc bus voltage = 150 V; UPQC: shunt inverter coupling inductance = 5 mH, shunt inverter switching type = analog hysteresis current controller with average switching frequency between 5 and 7 kHz, series inverter coupling inductance = 2 mH, series inverter ripple filter capacitance = 40 μF, series inverter switching type = analog triangular carrier pulse width modulation with a fixed frequency of 5 kHz, series voltage injection transformer turn ratio = 1:3, DSP sampling time = 0 μs.

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