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Voltage Sag and Swell Compensation using UPQC-S Technique

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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.

Index Terms—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. 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.

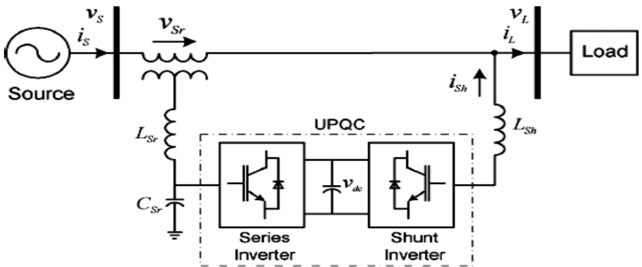

Fig. 1. Unified power quality conditioner (UPQC) system configuration.

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-VAmin is concentrated on the Optimal VA load of the series inverter ofUPQC 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-VAmin determined on the basis of voltage sag, may not be at optimal value. A detailed investigation on VA loading in UPQC-VAmin 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 swell 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). 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 availableVAloading is utilized to its maximum capacity during all the working conditions contrary to UPQC-VAmin 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.

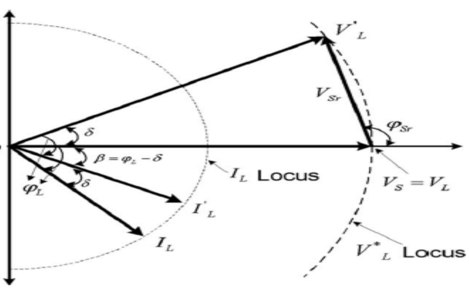

Fig. 2. Concept of PAC of UPQC.

II. FUNDAMENTALS OF PAC CONCEPT

AUPQCis one of the most suitable devices to control the voltage sag/swell on the system. The rating of a UPQC is governed by the percentage of maximum amount of voltage sag/swell need to be compensated [19]. However, the voltage variation (sag/swell) is a short duration power quality issue. Therefore, under normal operating condition, the series inverter of UPQC is not utilized up to its true capacity. The concept of PAC of UPQC suggests that with proper control of the power angle between the source and load voltages, the load reactive power demand can be shared by both shunt and series inverters without affecting the overall UPQC rating [15].

The phasor representation of the PAC approach under a rated steady-state condition is shown in Fig. 2 [15]. According to this theory, a vector _*V*Srwith proper magnitude *V*Sr and phase angle ϕSr when injected through series inverter gives a power angle δ boost between the source *VS* and resultant load *V _L* voltages maintaining the same voltage magnitudes. This power angle shift causes a relative phase advancement between the supply voltage and resultant load current *I_ L*, denoted as angle β. In other words, with PAC approach, the series inverter supports the load reactive power demand and thus, reducing the reactive power demand shared by the shunt inverter.
For a rated steady-state condition

$$|V_S| = |V_L| = |V_L^*| = |V_L'| = k. \qquad (1)$$

Using Fig. 2, phasor $\vec{V}_{\mathrm{Sr}}$ can be defined as [15]

$$\begin{aligned}\vec{V}_{\mathrm{Sr}} &= |V_{\mathrm{Sr}}| \angle \varphi_{\mathrm{Sr}} \\ &= \left(k.\sqrt{2}.\sqrt{1-\cos\delta}\right) \angle \left\{180^\circ - \tan^{-1}\left(\frac{\sin\delta}{1-\cos\delta}\right)\right\} \\ &= \left(k\cdot\sqrt{2}\cdot\sqrt{1-\cos\delta}\right) \angle \left(\frac{90^\circ+\delta}{2}\right) \qquad (2)\end{aligned}$$

where

$$\delta = \sin^{-1}\left(\frac{Q_{\mathrm{Sr}}}{P_L}\right). \qquad (3)$$

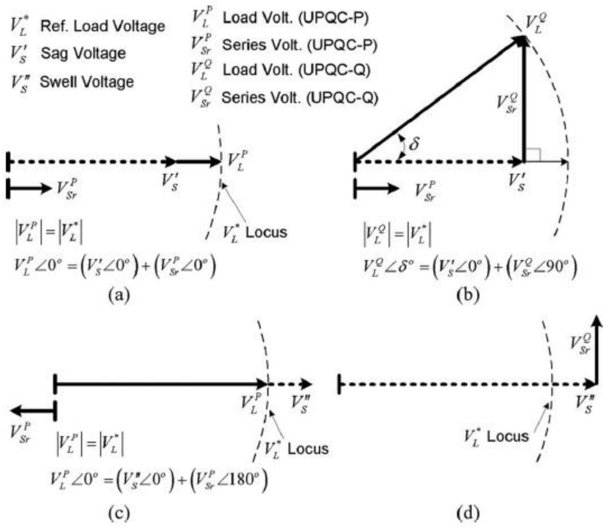

Fig. 3. Voltage sag and swell compensation using UPQC-P and UPQC-Q: phasor representation. (a) Voltage Sag (UPQC-P). (b) Voltage Sag (UPQC-Q). (c) Voltage Swell (UPQC-P). (d) Voltage Swell (UPQC-Q)

III. VOLTAGE SAG/SWELL COMPENSATION UTILIZING UPQC-P AND UPQC-Q

The voltage sag on a system can be compensated through active power control [16]–[22] and reactive power control [23], [24] methods. Fig. 3 shows the phasor representations for voltage sag compensation using active power control as in UPQC-P [see Fig. 3(a)] and reactive power control as in UPQC-Q [see Fig. 3(b)]. Fig. 3(c) and (d) shows the compensation capability of UPQC-P and UPQC-Q to compensate a swell on the system. For a voltage swell compensation using UPQC-Q [see Fig. 3(d)], the quadrature component injected by series inverter does not intersect with the rated voltage locus. Thus, the UPQC-Q approach is limited to compensate the sag on the system. However, the UPQC-P approach can effectively compensate both voltage sag and swell on the system. Furthermore, to compensate an equal percentage of sag, the UPQC-Q requires lager magnitude of series injection voltage than the UPQC-P (*V Q* Sr > *VP* Sr).

Interestingly, UPQC-Q also gives a power angle shift between resultant load and source voltages, but this shift is a function of amount of sag on the system. Thus, the phase shift in UPQCQ cannot be controlled to vary the load reactive power support. Additionally, the phase shift in UPQC-Q is valid only during the voltage sag condition. Therefore, in this paper, PAC concept is integrated with active power control approach to achieve simultaneous voltage sag/swell compensation and the load reactive power support utilizing the series inverter of UPQC. This new approach in which the series inverter of UPQC performs dual functionality is named as UPQC-S. The significant advantages of UPQC-S over other approaches are given as follows.

1) The series inverter of UPQC-S can support both active power (for voltage sag/swell compensation) and reactive power (for load reactive power compensation) simultaneously and hence the name UPQC-S (S for complex power).

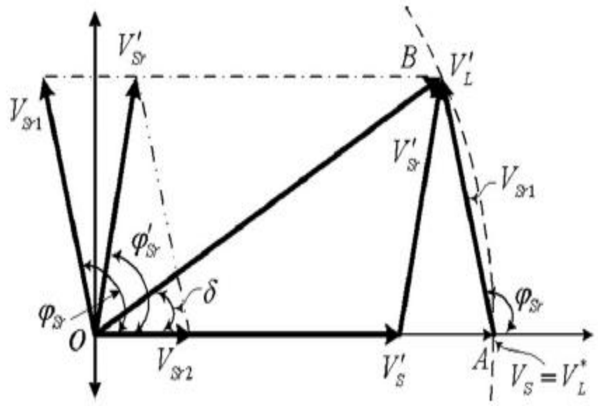

Fig. 4. Phasor representation of the proposed UPQC-S approach under voltage sag condition.

2) The available VA loading of UPQC is utilized to its maximum capacity and thus, compared to general UPQC operation for equal amount of sag compensation, the required rating of shunt inverter in UPQC-S will be smaller.

IV. 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 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

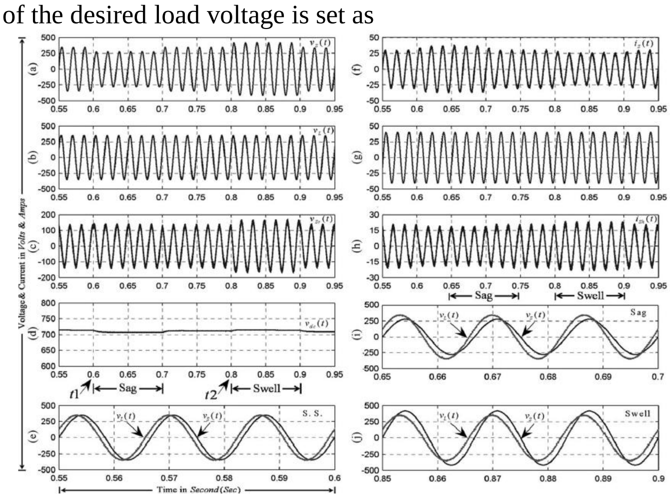

Fig. 5. Simulation results: performance of the proposed UPQC-S approach under voltage sag and swell conditions. (a) Supply voltage. (b) Load voltage. (c) Series inverter injected voltage. (d) Self-supporting dc bus voltage. (e) Enlarged power angle δ relation between supply and load voltages during steady-state 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.

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 vSra , vSr,b , vSr,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].

V. 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 are given in Fig. 11. Before time $t1$, the UPQC-S system is working under steadystate condition, compensating the load reactive power using both the inverters. A power angle δ of 21◦ is maintained between the resultant load and actual source voltages. The series inverter shares 1.96 kVAR per phase (or 5.8 kVAR out of 15 kVAR) demanded by the load. Thus, the reactive power support from the shunt inverter is reduced from 15 to 9.2 kVAR by utilizing the concept of PAC. In other words, the shunt inverter rating is reduced by 25% of the total load kilovoltampere rating. At time $t1$ = 0.6 s, a sag of 20% is introduced on the system (sag last till time t = 0.7 s). Between the time period t = 0.7 s and t = 0.8 s, the system is again in the steady state. A swell of 20% is imposed on the system for a duration of $t2$ = 0.8–0.9 s. The active and reactive power flows through the source, load, and UPQC are given in Fig. 12. The distinct features of the proposed UPQC-S approach are outlined as follows.

1) From Fig. 5(a) and (b), 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, as viewed from Fig. 5(f), to maintain the appropriate active power balance in the network, the source current increases 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 [see Fig. 5(e)], voltage sag [see Fig. 11(i)], and voltage swell [see Fig. 5(j)] is maintained at 21◦
3) The UPQC-S controller maintains a self-supporting dc link voltage between two inverters [see Fig. 5(d)].

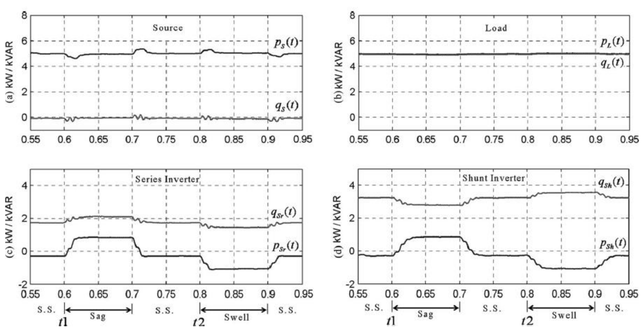

Fig. 6. Simulation results: active and reactive power flow through source, load, shunt, and series inverter utilizing proposed UPQC-S approach under voltage sag and swell conditions. (a) Source P and Q. (b) Load P and Q. (c) Series inverter P and Q. (d) Shunt inverter P and Q.

TABLE I
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 %

4) From Fig. 6(c) and (d), 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 Fig. 5(h), 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.

Thus, the aforementioned simulation study illustrates that with PAC of UPQC-S, the series inverter can compensate the load reactive power and voltage sag/swell simultaneously. The shunt inverter helps the series inverter to achieve the desired performance by maintaining a constant self-supporting dc bus.
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.

Table I 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. The rms values of current flowing through shunt and series inverters and series injection voltage are also given in Table I. Initially, it is considered that the shunt inverter alone supports the load reactive power and the series inverter is assumed to be in OFF condition. The series injection transformer is also short circuited. This operating condition gives the losses in the shunt part of UPQC, which are found as 0.74% of the rated load power. In the second condition, the series inverter is turned on as well. The percent power losses, when both the inverters of UPQC are in operation, are noticed as 1.7%. Under this condition when UPQC is controlled as UPQC-S to support the load reactive power using both shunt and series inverters, controlled by the PAC approach, losses are observed as 1.2%.

The power loss in the UPQC system with PAC approach thus is lower than the normal UPQC control. 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.

VI. 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) themultifunction ability of series inverter to compensate voltage variation (sag, swell, etc.) while supporting load reactive power; 2) better utilization of series inverter rating of UPQC; and 3) reduction in the shunt inverter rating due to the reactive power sharing by both the inverters.

VII. APPENDIX

The important parameters used for laboratory prototype of UPQC-S are as follows.
Source: Three-phase ac supply, 35 V (rms), *f* = 60 Hz; *Load*: 40-Ω resistance in parallel with 50-mH inductance giving 0.6 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 = 50 μs.

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