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Load Reactive power compensation using UPQC with Power angle control

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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 simultaneously voltage sag/swell compensation as well as 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. UPQC is a Custom Power Device and consists of combined series active power filter that compensates voltage harmonics, voltage unbalance, voltage flicker, voltage sag/swell and shunt active power filter that compensates current harmonics, current unbalance and reactive current. 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.

Keywords: power angle control (PAC), power quality, reactive power compensation, unified power quality conditioner (UPQC), voltage sag and swell compensation.

INTRODUCTION

Power quality issues are becoming more and more significant in these days because of the increasing number of power electronic devices that behave as nonlinear loads. The term “power quality” (PQ) has gained significant attention in the past few years. The advancement in the semi conductor device technology has made it possible to realize most of the power electronics based devices/prototypes at commercial platform. As a rule of thumb in all areas of engineering, the proper utilization of the resources that we have in the most efficient way has lead to great development and is the major concern for most engineers in their respective fields. Reactive power compensation is one of the common yet very important issues for power system engineers at transmission as well as at distribution level. It is a well-known fact that a typical distribution network consist of distribution transformer, motor loads, etc., demands reactive power. This load-reactive power demand level is mainly affected by the type of loads present on the network. The capacitor banks have been used to compensate the load-reactive power demand. It is the simplest and under certain conditions, is a very effective way to compensate the load-reactive power demand. This traditional way has certain major disadvantages, such as fixed compensation, possible occurrence of resonance condition with nearby loads, switching transient, bulky size, aging effect, etc. The powers processing at source, load, and for reactive and harmonic compensation by means of power electronic devices is becoming more prevalent due to the vast advantages offered by them.

Unified Power Quality Conditioner is also known as universal power quality conditioning system, the universal active power line conditioner and universal active filter. UPQC system can be divided into two sections: The control unit and the power circuit. Control unit includes disturbance detection, reference signal generation, gate signal generation and voltage/current measurements. Power circuit consists of two Voltage source converters, standby and system protection system, harmonic filters and injection transformers.

The voltage sag/swell on the system is one of the most important power quality problems. The voltage sag/swell can be effectively compensated using a dynamic voltage restorer, series active filter, Unified power quality conditioner etc among the available power quality enhancement devices, the Unified power quality conditioner has better sag/swell compensation capability. Three significant control approaches for Unified power quality conditioner 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, popularly known as UPQC-P

2) reactive power control approach in which a quadrature voltage is injected known as UPQC-Q and 3) a minimum VA loading approach in which a series voltage is injected at a certain angle, in this paper called as UPQC-VA_{min}.

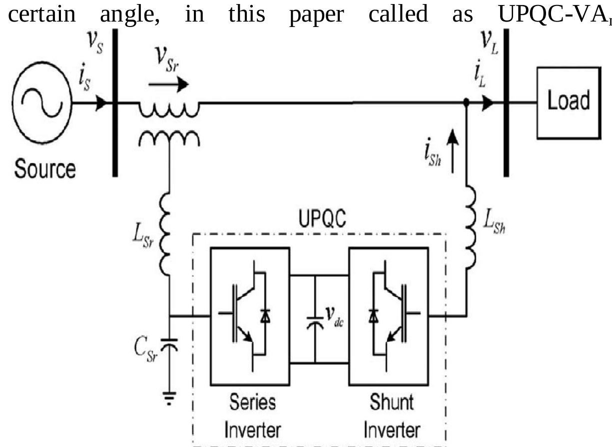

Fig. 1 Unified Power Quality Conditioner (UPQC) system configuration.

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UPQC

A UPQC is 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. 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.

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). 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). 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.

The phasor representation of the PAC approach under a rated steady-state condition is shown in Fig2. According to this theory, a vector $\vec{V}_{Sr}$ with proper magnitude VSr and phase angle Φ_{Sr} when injected through series inverter gives a power angle δ boost between the source V_S and resultant load V_L' voltages maintaining the same voltage magnitudes. This power angle shift causes 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.

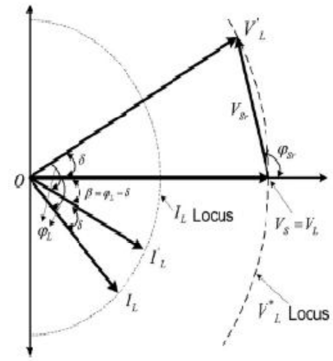

Fig: 2 Concept of PAC of UPQC.

For a rated steady-state condition

$$|V_S| = |V_L| = |V_L^*| = |V_L'| = K$$

Using Fig.4.1, phasor VSr can be defined as

Where $\vec{V}_{Sr} = V_{Sr}\angle\varphi_{Sr}$

$$= \left(k.\sqrt{2}.\sqrt{1-\cos\delta}\right)\angle\left\{180^{\theta} - \tan^{-1}\left(\frac{\sin\delta}{1-\cos\delta}\right)\right\}$$

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

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

The voltage sag on a system can be compensated through active power control and reactive power control methods.

Fig. 2 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 ($V^Q_{Sr} > V^P_{Sr}$).

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 UPQC-Q 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

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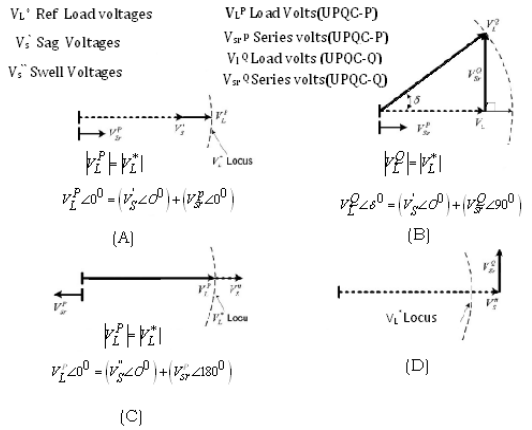

Fig. 3 Voltage sag and swell compensation using UPQC-P and UPQC-Q: phasor representation.(a) Voltage Sag (UPQC-P). (b) Voltage Sag (UPQC-Q) (c) Voltage Swell (UPQC-P). (d) Voltage Swell (UPQC-Q).

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).

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.

ACTIVE–REACTIVE POWER FLOW THROUGH UPQC-S

The per-phase active and reactive powers flow through the UPQC-S during the voltage sag/swell is determined in this section. As the performance equations for series and shunt inverters are identical for both sag and swell conditions, only sag condition is considered to determine the equations for active and reactive power.

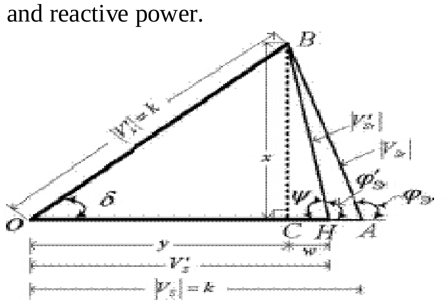

Fig.4 Detailed phasor diagram to estimate the series inverter parameters for the proposed UPQC-S approach under voltage sag condition

A. Series Inverter of UPQC-S

For active power

$$P'_{Sr} = V'_{Sr}.I'_S.\cos\varphi'_{Sr}$$

From Fig. 4

$$P'_{Sr} = V'_{Sr}.I'_S.\cos(180^o - \psi) \ldots\ldots\ldots\ldots\ldots(4.37)$$

$$P'_{Sr} = V'_{Sr}.I'_S.(-\cos\psi) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.38)$$

$$P'_{Sr} = -V'_{Sr}.I'_S.\left(\frac{\omega}{V'_{Sr}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.39)$$

$$P'_{Sr} = -I'_S.k.(\eta_O - \cos\delta) \ldots\ldots\ldots\ldots\ldots (4.40)$$

The increase I'_S or decrease I''_S in the source current magnitudes during the voltage sag or swell condition, respectively, is represented as $I'_S = I''_S = k_O.I_L.\cos\varphi_L$ ………….. ……… (4.41)

Therefore,

$$P_{Sr.PAC} = P'_{Sr} = -k_O.(\eta_O - \cos\delta).(P_L) \ldots\ldots(4.42)$$

$$\{Q\ P_L = k.I_L.\cos\varphi_L\}$$

For reactive power

$$Q'_{Sr} = V'_{Sr}.I'_S.\sin\varphi'_{Sr} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.43)$$

From Fig. 4

$$Q'_{Sr} = V'_{Sr}.I'_S.(180^0 - \psi) \ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.44)$$

$$Q'_{Sr} = V'_{Sr}.I'_S.\psi \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.45)$$

$$Q'_{Sr} = V'_{Sr}.I'_S.\left(\frac{x}{V'_{Sr}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.46)$$

Therefore,

$$Q_{Sr,PAC} = Q'_{Sr} = k_0.(\sin\delta).(P_L) \ldots\ldots\ldots\ldots(4.47)$$

Using (4.42) and (4.45), the active and reactive power flow through series inverter of UPQC-S during voltage sag/swell condition can be calculated.

B. Shunt Inverter of UPQC-S

The active and reactive power handled by the shunt inverter as seen from the source side is determined as follows.

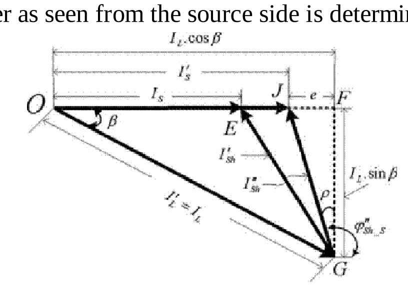

Fig.5 detailed phasor diagram to estimate the shunt inverter parameters for the proposed UPQC- S approach under voltage sag condition

For active power

$$P'_{Sh} = V'_S.I_{Sh}^{\cos\varphi\_(Sh-S)^\wedge} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.48)$$

From Fig.5

$$P_1Sh^{\dagger\prime} = -n_1 0.k.I_1Sh^{\dagger-}.(-\sin\rho) \ldots\ldots\ldots\ldots(4.49)$$

$$[\![P]\!]_1Sh^{\dagger\prime} = -n_1 0.k.I_1Sh^{\dagger-}.(e/(I_1Sh^{\dagger-})) \ldots\ldots(4.50)$$

$$P_{SH.PAC} = -\frac{(kI_L)(\cos\beta - K_0\cos\psi_L)}{K_O} \ldots\ldots\ldots\ldots(4.51)$$

For reactive power

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$$Q'_{sh} = v'_S \cdot I''_{sh} \cdot \sin \psi''_{sh\_s} \quad \text{.........................(4.52)}$$

From Fig 5

$$Q^{/}_{Sh} = \eta_O k.I^{//}_{Sh}.\cos(\rho) \quad \text{......................(4.53)}$$

$$Q_{Sh.PAC} = \frac{(k.I_L).(\sin\beta)}{k_O} \quad \text{................(4.54)}$$

Using (4.51) and (4.54), the active and reactive power flow through shunt inverter of UPQC-S during voltage sag/swell condition can be calculated and utilized to determine the overall UPQC-S VA loading.

C. UPQC-S CONTROLLER

A detailed controller for UPQC based on PAC approach is described. 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.

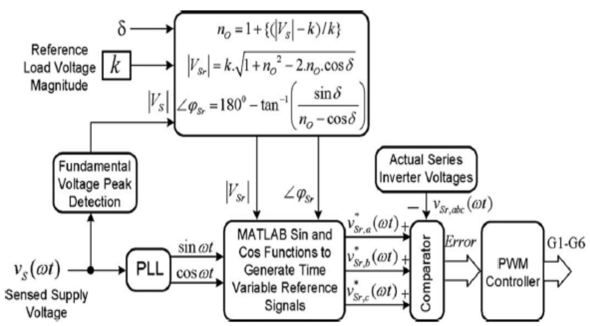

Fig. 6 Reference Voltage Signal generation for the series inverter of the Proposed UPQC-S approach

Therefore, the reactive power shared by the series inverter and hence by the shunt inverter changes as given by (4.47) and (4.44). 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. 4.8. 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 k_f and n_O is computed by measuring the peak value of the supply voltage in real time. The magnitudes of series injected voltage V_{Sr} and its phase angle ϕ_{Sr} are then determined using (4.15) and (4.17).

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.

SIMULATION AND RESULTS

The performance of the proposed concept of simultaneous load reactive power and voltage sag/swell compensation has been evaluated by simulation. To analyses 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 14 kW + *j* 14 kVAR (load power factor angle of 0.505 lagging).

The simulation results for the proposed UPQC-S approach under voltage sag and swell conditions are given before time t_1, the UPQC-S system is working under steady state 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 4.8 kVAR out of 14 kVAR) demanded by the load. Thus, the reactive power support from the shunt inverter is reduced from 14 to 9.2 kVAR by utilizing the concept of PAC.

In other words, the shunt inverter rating is reduced by 24% of the total load kVA rating. At time $t_1 = 0.6$ s, a sag of 20% is introduced on the system (sag last till time $t = 0.5$ s). Between the time period $t = 0.5$ 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 $t_2 = 0.8$–0.9 s.

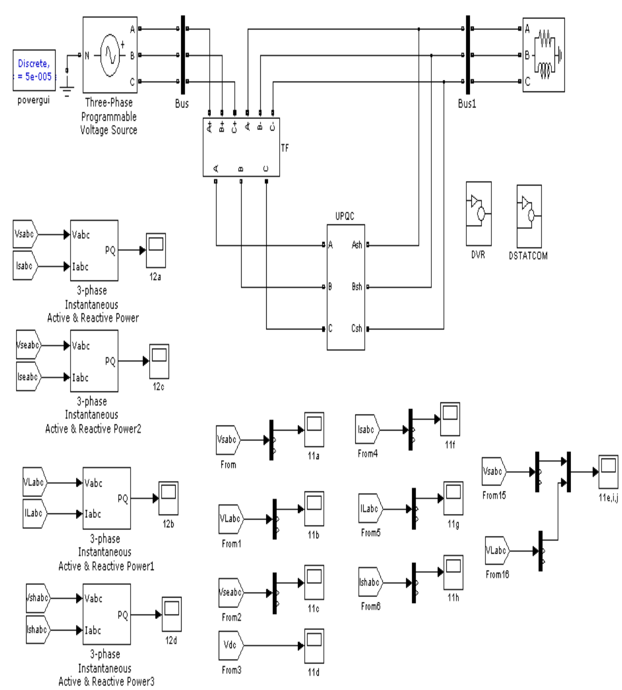

Fig. 7 Simulation Block Diagram

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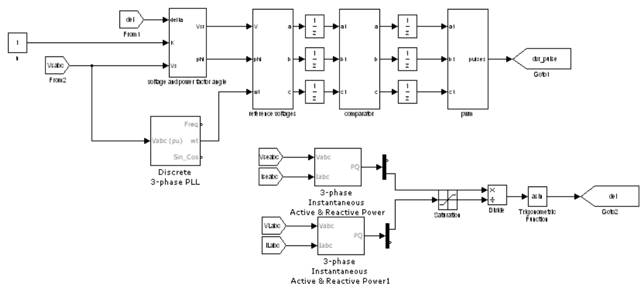

Fig.8 DVR sub circuit

It acts as controlled voltage source and can compensate all voltage related problems, such as voltage harmonics, voltage sag, voltage swell, flicker, etc.

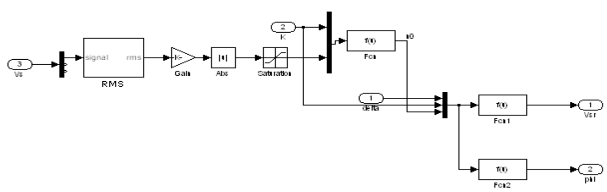

Fig.9 voltage and power factor angle sub circuit

RESULTS

Simulation time period is 0.95sec.

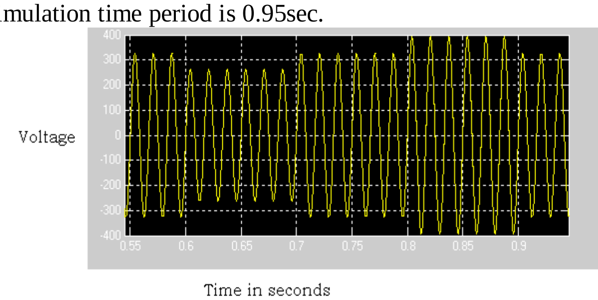

Fig. 10 Supply voltage

In the above Supply Voltage, sag occurs in the time period of 0.6ssec to 0.7sec and 07.sec to 0.8sec steady state occurs. 0.8sec to 0.9sec the swell occurs. Here voltage decreases current increases.

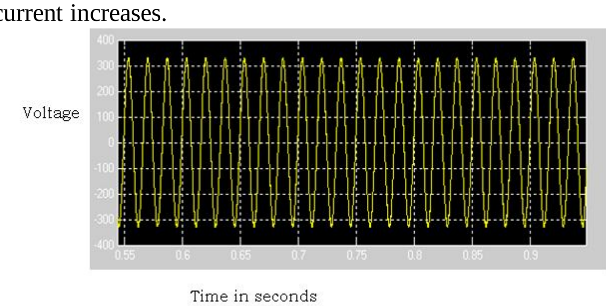

Fig. 11 Load voltage

In the above simulation of Load voltage, pure sinusoidal wave form occurs because any faults occurs in the Load side the UPQC compensate the faults.

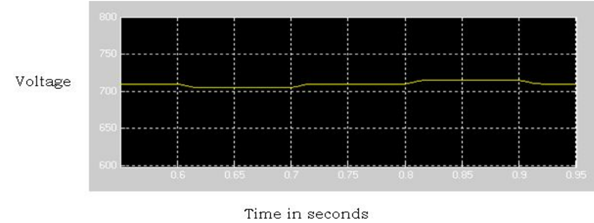

Fig.12 Self supporting dc bus voltage

In the above dc bus voltage sag occurs 0.6sec to 0.7sec and swell occurs 0.8sec to 0.9sec.

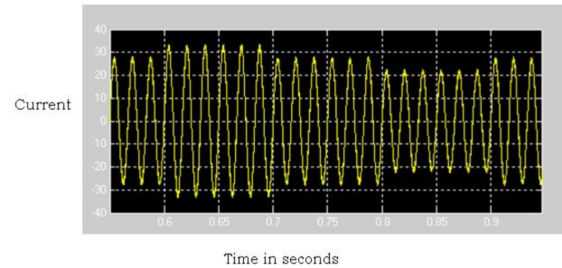

Fig.13 Supply current

In the supply current swell occurs 0.6sec to 0.7sec.here first swell occurs because voltage decreases.

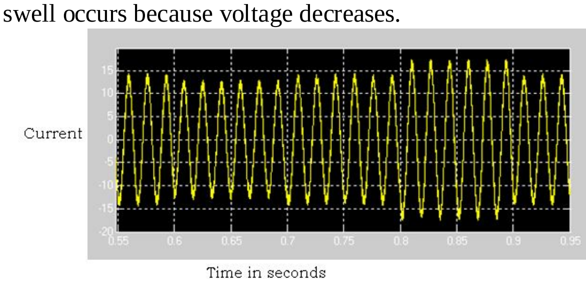

Fig. 14 Shunt inverter injected current

In shunt inverter injected current faults are occurred. Sag occurred in time period of 0.6sec to 0.7sec. Swell occurred 0.8sec to 0.9sec.

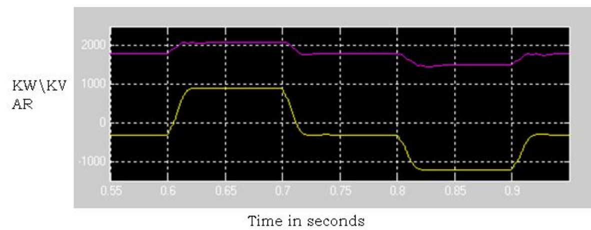

Fig. 15 Series inverter P and Q

In series inverter active and reactive powers increases in 0.6sec to 0.7sec due to increase of the load current, active and reactive powers are decreased in time period 0.8 sec to 0.9 sec.

In the below figure shunt inverter, active and reactive powers are shown. In shunt inverter reactive power is decreased at that time active power is increased.

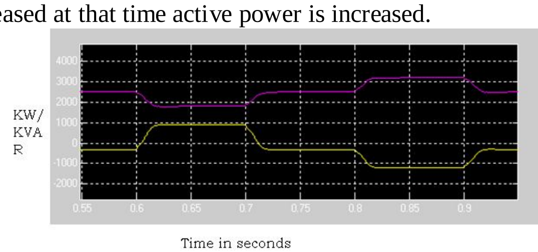

Fig. 16 Shunt Inverter P and Q

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With Vdc controller Simulation results:

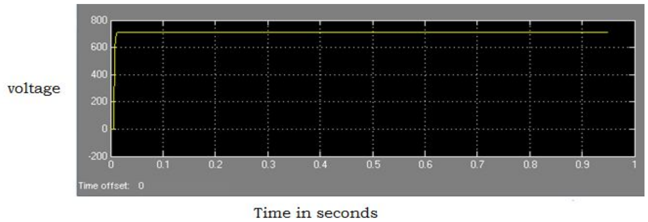

Fig.17 Self supporting dc bus voltage

In self supporting dc bus voltage using dc regulator transient response is decreased and system dynamic performance increased.

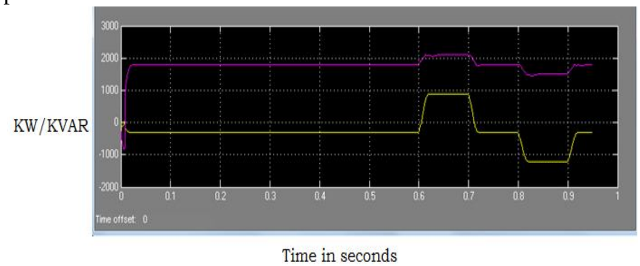

Fig.18 series inverter P and Q

Using the dc regulator of series active and reactive powers transient response is decreased. System starting period also decreased.

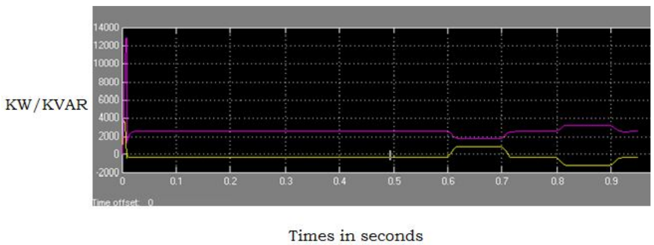

Fig.19 shunt inverter P and Q

In shunt inverter active and reactive power increased and series active power decreased. System dynamic performance increases.

CONCLUSION

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 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.

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