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OPTIMAL CONTROL STRATEGY OF UPQC FOR MINIMUM OPERATIONAL LOSSES

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ABSTRACT

The paper deals with a new control technique for a Unified Power Quality Conditioner (UPQC), which is the most comprehensive of FACTS devices. The problems of power quality continue to gain in significance because of the proliferation of sensitive and harmonic producing loads in electrical networks. Greater awareness among customers with regard to supply integrity and a desire by suppliers to be able to guarantee a certain degree of power quality to customers is being reflected in the development of innovative power quality solutions. The UPQC, which is a combination of shunt and series compensation, is designed to cater for multiple power quality problems. The shunt compensator provides VAR compensation to the load. It also provides harmonic isolation between the load and the utility supply. The series compensator regulates the incoming voltage quality from the supply side, and keeps the load end voltage insensitive to the supply voltage problems like sag/swell or unbalance. All these quality controls are achieved simultaneously. A comprehensive control technique has been designed based on the VA loading of the two compensators, such that minimum VA loading of the two compensators is ensured. This has been achieved by pre-calculating a suitable angle of injection voltage for the series compensator. This also minimises the operational losses of the UPQC. The design details are elaborated and verified with appropriate simulation results.

Keywords: Control, Power Quality, UPQC

INTRODUCTION

Over the last decades there has been increasing interest among electric utility operators and customers in the issue of power quality for several reasons, including [1-3]:

- Increased sophistication of industrial and commercial loads in the system, which are highly sensitive to poor voltage and current quality;
- Proliferation of power semiconductor switching devices in the network (UPS, PC, converters etc), which can cause significant harmonic distortion;
- Mal-operation of electronic control equipment, leading to problems including harmonics injection.

Although equipment design standards have become more stringent, general solutions to problems of power quality in distribution system are still required. FACTS devices, based on active filtering techniques, have proved promising in this regard. Among these custom power devices, the Unified Power Quality Conditioner (UPQC) [4-8] provides the most comprehensive solution to power quality (PQ) issues as it can improve both the voltage and current quality.

The UPQC, typically installed at the service entry point [8,9] of a sensitive load, can maintain the load end voltage at the desired level, and prevent incoming sags/swells in voltages. The UPQC can efficiently support the reactive power requirement of the load, and suppress the generated harmonic currents from the loads, so that they do not propagate back to the utility, which can cause voltage and current distortion to other consumers.

The UPQC is required to operate in a reliable and efficient manner. The present paper presents a control technique for coordinated control of the equipment to ensure that minimum VA loading of the UPQC is achieved, operational losses are minimised and the UPQC operates at maximum efficiency.

POWER CIRCUIT CONFIGURATION

The UPQC is a combination of a shunt and a series compensator connected in cascade via a common dc link capacitor, as shown in Fig. 1. Each compensator consists of a IGBT based full bridge inverter (single or three phase, according to the application), which may be operated in a voltage or a controlled mode depending on the control scheme. Inverter I (Series Compensator, SC) is connected in series with the supply voltage through a low pass RLC filter and transformer. Inverter II (Synchronous Link Converter VAR Compensator, SLCVC) is connected in parallel to the load (which may be linear or non-linear) through a synchronous link inductor, L_{SLC}. The SC operates in a PWM voltage controlled mode and compensates appropriately for the deficiency of the incoming voltage, such that load end voltage remains unaffected by any voltage disturbance.

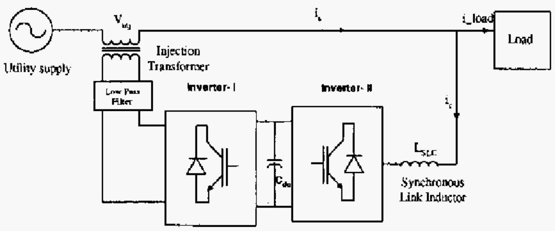

Fig. 1 Schematic diagram of UPQC

The main objectives of the SLCVC are to compensate for the reactive power demanded by the load; to eliminate the harmonics from the supply current and to regulate the common dc link voltage. The SLCVC can compensate load current unbalance, so that the load always appears balanced to the utility. The SLCVC operates with a hysteresis current controlled mode to ensure that the supply current is in phase with the supply voltage. The two inverters operate in a coordinated manner with a distinct hierarchy and the control strategy is described later in the paper.

FUNDAMENTAL PHASOR CONFIGURATION

Fig. 2 shows a fundamental phasor description of the UPQC, where the SC has been modelled as an ideal voltage source and the SLCVC has been modelled as an ideal current source. The source voltage (V_S) is taken as the reference and is given by:

$$V_S \angle 0 = V_{inj} \angle \gamma + V_L \angle \alpha \tag{1}$$

where V_L is the load voltage and V_{inj} is the injected voltage from the SC of the UPQC. It should be noted that for a given load power factor and voltage sag the requirement is to determine the magnitude and phase angle of V_{inj} to maintain the load voltage constant at its rated value. There are an infinite number of solutions for V_{inj}. The novel control strategy proposed in this paper pre-calculates this angle of injection γ to optimise the loading of the UPQC. The load current is given by:

$$I_L \angle \alpha - \phi = I_S \angle \delta + I_c \angle \beta \tag{2}$$

The angle ϕ represents the lagging angle of the load current (I_L) with respect to V_L. As the source is assumed to supply only the active component of the load current, δ=0. The SLCVC current I_C is ideally the reactive current component of the load.

Fig. 3 explains the operation of the UPQC by means of a phasor diagram. The suffix L denotes the load terms, and S denotes the supply terms. The suffixes 1 and 2 denote two states in time, with different supply voltage condition for which the UPQC takes action. Initially in State 1, the supply voltage has no deficiency,

$$V_S = V_{L1} = V_{S1} = \text{Constant} = V_0$$

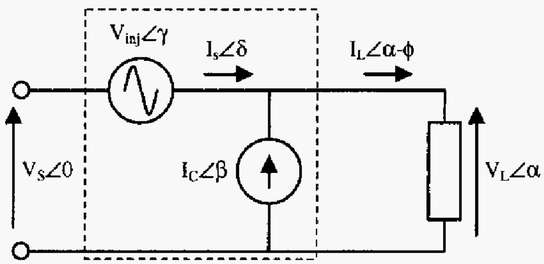

Fig. 2 Fundamental Frequency Representation of

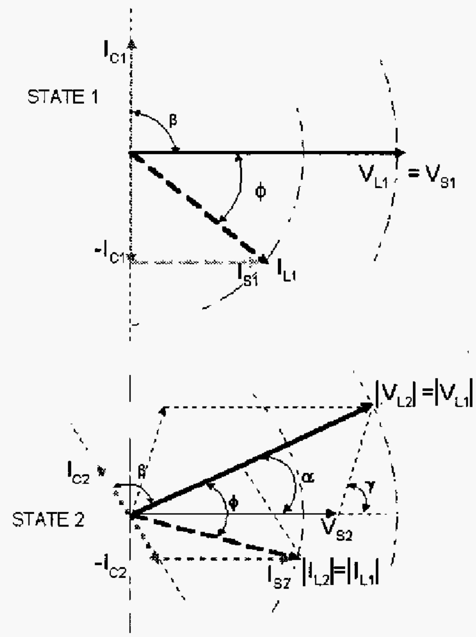

Fig. 3 Phasor diagram of UPQC for States 1 and 2

Corresponding to that situation, the SLCVC current is given by I_{C1}, where angle β = +90, in advance of the supply voltage, as the load power factor is assumed to be lagging.

In State 2, the supply voltage magnitude has reduced to V_{S2}, which requires the UPQC to take action such that V_{L2} is restored to its original magnitude ($|V_{L1}| = |V_{L2}|$). This is achieved by injecting the series voltage $V_{inj}\angle\gamma$. As seen from Fig. 3, the solution is not unique as the restoration of the load voltage can be achieved by selecting γ in a range from 0 to 90^0, together with the appropriate magnitude of V_{inj}. In State 2, according to Fig. 3,

$$I_{S2} \cos\alpha = I_{L2} \cos\phi \tag{3}$$

$$I_{C2} = \frac{I_{L2} \sin(\phi - \alpha)}{\cos\alpha} \tag{4}$$

If $\alpha<\phi$, the two compensators share the load inductive VAR. It is interesting to observe that if a supply voltage sag is such that for a given load power factor, the angle α becomes equal to ϕ, then from (3), it can be inferred that $I_{S2} = I_{L2}$. Thus I_{C2} is zero and this represents zero VA loading of the shunt compensator. The load current is assumed to be constant:

$$I_{L1} = I_{L2} = I_0 \quad (5)$$

with a fundamental lagging power factor of $\cos\phi$. The active power demand in the load remains constant and is equal to that drawn from the source.

$$V_S I_S = V_L I_L \cos\phi = \text{Constant} \quad (6)$$

In the case of a sag, where $|V_{S2}| < |V_{S1}|$ and x is the per unit voltage sag:

$$V_{S2} = (1-x)V_{S1} = (1-x)V_0 \quad (7)$$

To maintain constant active power under voltage sag conditions, $V_{S1}I_{S1} = V_{S2}I_{S2}$ and:

$$I_{S2} = \frac{V_0 I_L \cos\phi}{V_0(1-x)} = I_0 \frac{\cos\phi}{(1-x)} \quad (8)$$

Referring to Fig. 3,

$$V_{L2}\sin\alpha = V_{inj}\sin\gamma \quad (9)$$

$$V_{L2}\cos\alpha = V_{s2} + V_{inj}\cos\gamma \quad (10)$$

or

$$\sin\gamma = \frac{V_{L2}}{V_{inj}}\sin\alpha; \quad \cos\gamma = \frac{\sqrt{\left(V_{inj}^2 - V_{L2}^2\sin^2\alpha\right)}}{V_{inj}} \quad (11)$$

From (6) and (11)

$$V_{L2}\cos\alpha = V_0\cos\alpha = V_0(1-x) + \sqrt{\left(V_{inj}^2 - V_{L2}^2\sin^2\alpha\right)}$$
$$V_{inj}^2 = V_0^2 x^2 + 2V_0^2(1-x)(1-\cos\alpha) \quad (12)$$

The VA rating of the series compensator is given by:

$$|V_{inj}||I_{S2}| = V_0 I_0 \cos\phi \frac{\sqrt{x^2 + 2(1-x)(1-\cos\alpha)}}{(1-x)} \quad (13)$$

Referring to Fig. 3 again, the SLCVC current is given by:

$$I_{C2}\cos\alpha = I_{L2}\sin(\phi-\alpha) \quad (14)$$

Therefore, the VA rating of the SLCVC is given by:

$$I_{C2}V_{L2} + I_{C2}^2 Z_{SLC} = I_{L2}\left(V_0\frac{\sin(\phi-\alpha)}{\cos\alpha} + I_{L2}\left(\frac{\sin(\phi-\alpha)}{\cos\alpha}\right)^2 Z_{SLC} \right) \quad (15)$$

where Z_{SLC} is the p.u. impedance of the synchronous link converter inductor (L_{SLC}). Adding (13) and (15), the total VA rating of the UPQC can be written as:

$$VA\text{-}UPQC = V_0 I_0 \left(F_1(\phi,x,\alpha) + F_2(\phi,\alpha)\right) + I_0^2 F_2^2(\phi,\alpha) Z_{SLC} \quad (16)$$

$$F_1(\phi,x,\alpha) = \cos\phi \frac{\sqrt{x^2 + 2(1-x)(1-\cos\alpha)}}{(1-x)}$$

$$F_2(\phi,\alpha) = \frac{\sin(\phi-\alpha)}{\cos\alpha}$$

Therefore, for a given load power factor angle ϕ and voltage sag x p.u., the VA loading will be a function of the advance angle α of V_L. The minimum VA loading will occur when ϕ=α, so that $I_{S2} = I_{L2}$ and $I_{C2} = 0$. Under these conditions, the optimal injected voltage is given by:

$$V_{inj} = V_0\sqrt{x^2 + 2(1-x)(1-\cos\phi)} \quad (17)$$

and the voltage advance angle for the SC is given by:

$$\sin\gamma = \frac{\sqrt{1-\cos^2\phi}}{\sqrt{x^2 + 2(1-x)(1-\cos\phi)}} \quad (18)$$

Therefore, (17) and (18) are the key equations which will determine the optimum angle of voltage injection by the SC, such that minimum VA loading of the UPQC could be obtained.

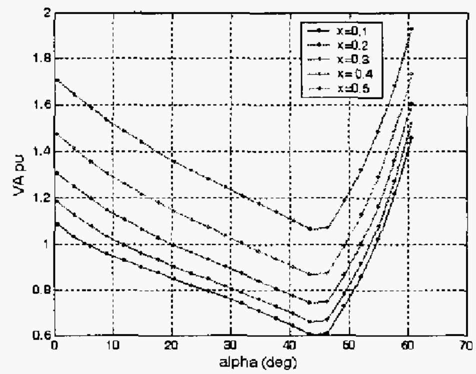

Fig. 4 UPQC Loading Curve

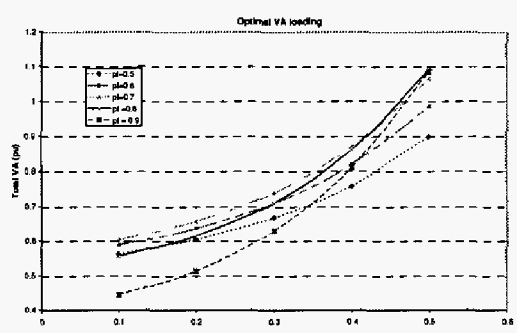

Fig. 5 Optimal Loading Curve for UPQC

Fig. 4 gives the results for the application of the above analysis for a load power factor of 0.6 and a variation in voltage sag between 10% and 60%. The SLCVC is assumed to be 0.7 p.u. in this case. The minimum VA loading condition angle α has been identified as the angle that equals the load power factor angle ϕ.

Fig. 5 gives graphical representation of the optimal VA loading locus of UPQC under different power factor and voltage sag conditions. This figure readily yields information of the UPQC VA loading under different contingencies.

UPQC AND ITS FUNCTIONALITY

Based on the analysis above, a suitable control technique has been designed for the UPQC. Fig. 6 shows the closed loop control circuit for both the SC and SLCVC. The control scheme can be divided into 4 modules:

- Current controller for SLCVC
- Controller for maintaining dc link voltage
- SC controller
- PWM voltage controller

With only 2 signals sensed (i_s and V_{dc}) the SLCVC controller generates the appropriate switching signals for the SLCVC. The dc link voltage reference V^*_{dc} is selected depending upon the maximum VAR to be compensated at the load end and the % sag to be mitigated at the supply end. The difference between the two voltages (V^*_{dc} - V_{dc}) is processed through a PI controller (PI_1) and gives a direct measurement, $I_{ref(mag)}$, of the active power requirement of the load and the UPQC from the supply. This signal, multiplied by a synchronised sinusoidal template with the supply voltage, generates the reference current (i_s*) for the hysteresis controller. The harmonic current suppression in the utility current is performed through a hysteresis controller, where the hysteresis band determines the quality of the supply current spectra. A narrow band will yield less THD, but the switching frequency of the converter may be very high. Then, based on minimum THD guidelines, a suitable trade-off can be designed.

Because of the fast acting current controller of the SLCVC, the SC would always find the load as linear in nature and with unity power factor. Therefore, for all load conditions the phasor diagram analysis in Fig. 3 would hold good for optimal voltage injection analysis for SC.

The supply voltage (V_S), injected voltage (V_{inj}) and the load current (I_L) are to be sensed. After processing V_S through a peak detector, a sag detector would determine the percentage of voltage sag occurring in the supply. The load current is filtered through a narrow band-pass filter and conditioner to extract the fundamental current and power factor. All this information is processed based on (17) and (18), and the magnitude and phase angle of V_{inj}* is calculated.

With a suitable attenuation factor, the primary modulating signal m_1 is determined and is incorporated through a feed-forward control loop. The actual V_{inj} is compared with Vinj* and the error is processed through a second PI controller (PI2) to form m_2, which dynamically modulates the modulating signal. The feed-forward and the feedback signals are then added to form the final modulating signal (m_3). This goes to the PWM generator to generate appropriate switching signal for the SC.

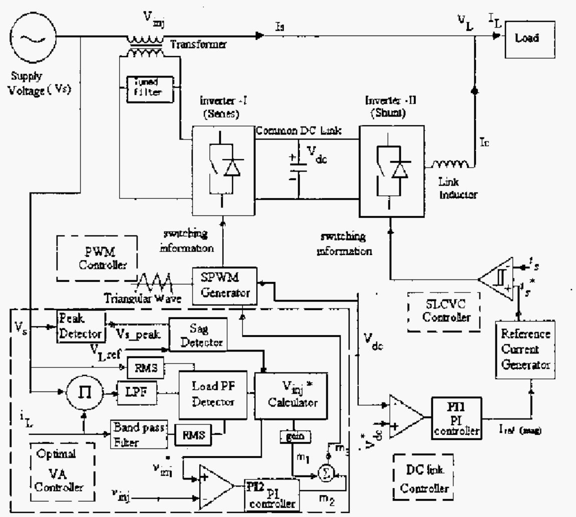

Fig. 6 Control Block Diagram of UPQC for Optimal VA Loading

SIMULATED PERFORMANCE OF UPQC

The proposed control scheme has been verified with extensive circuit simulation with the SABER simulation tool. The simulation model closely reflects the actual system and includes the details of control circuits. A few typical results are provided here to justify the efficacy of the control scheme.

A single-phase case has been considered. The system parameters of the load and UPQC are given in Table 1.

Table 1: System Parameters

Supply	230V, 50 Hz
Synchronous link inductance	6mH
dc link capacitor	2200 μF (600V)
Load current	11.5A (rms)
THD	15.5%
LPF parameter s	4.4 mH, 60μF

The load consists of a rectifier feeding a dc load of R=20Ω and L=60mH, with a source inductance of 16mH on the ac side.

UPQC and voltage quality problem

Fig. 7 shows the compensated load voltage under 11% supply voltage sag. The load power factor was found to be

0.7 lagging. From the earlier analysis (equations 17 and 18), the magnitude and phase angle of the injected voltage were calculated to be 0.74 p.u. and 74.8° in advance of the supply voltage. The load voltage THD measures 2.4%, which is well within accepted limits. The simulation using the SABER model of the system in Fig. 7 confirmed these values.

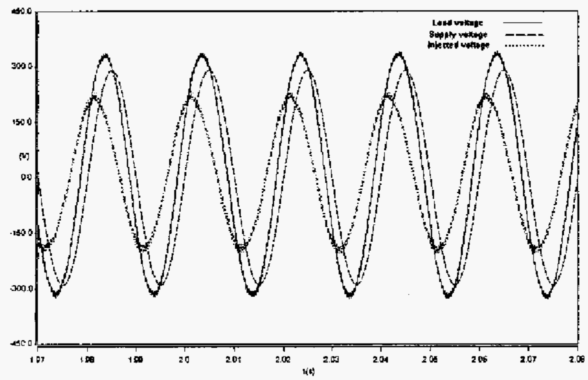

Fig. 7 Load, Supply and Injected Voltage at SC

UPQC and current quality problems

Fig. 8 shows the non-linear load current, SLCVC current and the reshaped supply current with the operation of UPQC for the load described in Table 1.

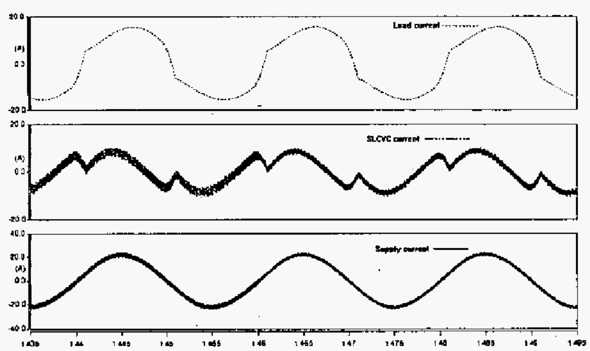

Fig. 8 System Currents

From FFT analysis, the load current THD is 15.5%. With a 4% hysteresis band on the supply current the supply current THD is reduced to 4.13% with an average switching frequency 18.5 kHz. The SLCVC current not only provides the higher order load harmonic requirements, but when the SC consumes some active power, it is supplied via the DC link of the UPQC from the supply. It also replenishes all the converter losses and the loss in the DC link capacitor. The active current consumption of the SC in the present case is 4.2 A, whereas the fundamental current drawn by the SLCVC is 5.5 A (from the FFT analysis). The input power factor is almost unity.

CONCLUSION

An optimal control design for minimum VA loading of a UPQC has been described in the present paper. The detailed simulation is supported by phasor analysis. Extensive simulation results are carried out in SABER implementing the coordinated control scheme to justify the performance of the UPQC. The experimental results await and would be presented in forthcoming papers.

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