A Comparison of Single-Phase p-q Theory and UVT Based Control Algorithms for Single-Phase UPQC

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Abstract— **This paper employs a single-phase unified quality conditioner (UPQC), an integration of shunt and series active filters (APF), to perform voltage and supply current harmonics mitigation and power factor correction. Both the shunt and series APFs are realized using a single-phase, two leg voltage source inverter (VSI). For the series APF the control strategy is based on Unit Vector Template (UVT), while a comparison is made for the two control strategies namely UVT and single–phase p-q theory for shunt APF. In both of the control strategies the control is made over the fundamental supply current and fundamental supply voltage instead of the fast changing AFs current and voltage, thereby reducing the computational delay and number of required sensors. A dynamic model of the UPQC is developed in the MATLAB/SIMULINK enviournment and the simulation results demonstrating the power quality improvement in the system are presented for distorted supply and a combination of linear and non-linear load.**

Keywords— **Power Quality, UPQC, Harmonics, Power Factor Correction, voltage and current harmonic mitigation.**

I. INTRODUCTION

With the increasing application of nonlinear loads, the appearance of power quality problems is inevitable. On the other hand, modern industrial equipments become more sensitive to power quality. Generally speaking, the UPQC can be classified in two categories, namely single phase and three phases UPQC [1]. However, there are no many applications of UPQC in single-phase systems. This paper presents a modified single-phase p-q Theory, which is easy to implement and suitable to obtain the references for the shunt APF of single-phase UPQC.

For the control of three-phase UPQC, many control strategies have been proposed [3]-[7]. Some of these control techniques are instantaneous reactive power theory (pq-theory) [5], [6] extended pq theory [7], SRF control strategy [4] and Unit Vector template techniques [3]. However, for single-phase systems, the p-q Theory cannot be applied directly, and some transformation needs to be done, before implementation. The p-q theory first proposed for multi-phase systems [6] and it needs to be adaptive for single–phase systems [8].In this paper the single-phase p-q theory is further modified to get the reference over the fundamental supply current, instead of the fast changing APF current, thereby reducing the computational delay and number of required sensors. In this paper a comparison is made between two control strategies namely single-phase p-q theory and UVT technique for the control of shunt APF of single-phase UPQC, while UVT is applied for the control of series APF. The performance of the proposed system is demonstrated through simulated waveforms and the harmonic spectra of supply currents and load voltage with and without UPQC.

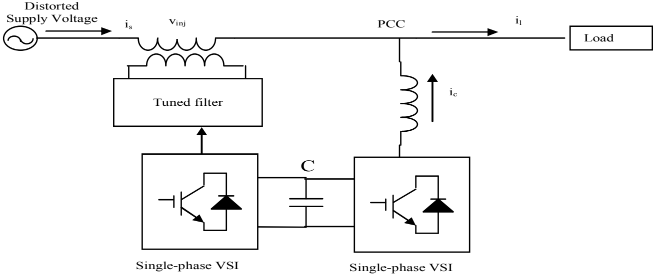

Fig.1Detailed configuration of UPQC

Fig.1 shows the proposed 1-phase, 2-wire UPQC connected to a power system feeding a combination of linear and non-linear unbalanced load. It consists of single-phase voltage controlled VSI used as a series active filter and a single-phase current controlled VSI used as a shunt active filter. The dc link of both active filters is connected to a common dc link capacitor. The series filter is connected between the supply and load terminals using a single phase transformers with turn's ratio of 2:1. In addition to injecting the voltage, this transformer is used to filter the switching ripple content in the series active filter. A small capacity rated R-C filter is connected in parallel with the secondary of the series transformer to eliminate the high switching ripple content in the series active filter injected voltage. The voltage source inverter for both the active filter are implemented with IGBTs (Insulated gate Bipolar Transistors).The two-leg VSI based

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shunt active filter is capable of suppressing the harmonics in the source currents and power-factor correction. The implemented control algorithm consists mainly of the computation of reference of fundamental source current (i^*_s) and load voltage (v_s^*) respectively. The values of the circuit parameters and load under consideration are given in Appendix.

II. CONTROL SCHEME OF SERIES APF

The proposed control strategy is aimed to generate reference signals for the voltage at PCC. The series AF filter is controlled such that it injects required voltages, which cancel out the distortions present in the supply voltage, thus making the voltage at PCC perfectly sinusoidal with the desired amplitude. In other words, the sum of supply voltage and the injected series filter voltage makes the desired voltage at the load terminals. The control strategy for the series AF is shown in Fig. 2. The distorted supply voltages are sensed and given to single-phase PLL which generates two quadrature unit vectors (sin*wt,*coswt).The in-phase sine output from the PLL is multiplied with desired peak value of the PCC voltage(V^*_{lm}) using eqn.(1) as:

$$\left[v_s^*\right] = V_{lm}^*\left[1\sin wt\right] \tag{1}$$

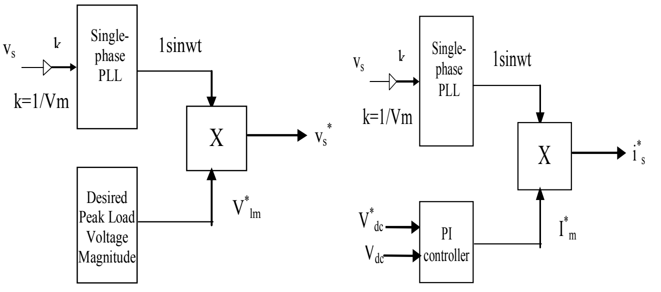

Fig.2 Control Scheme of Series and Shunt APF of UPQC

III. CONTROL SCHEME OF SHUNT APF

The control algorithm for shunt APF is desired to make the source current sinusoidal and in phase with the voltage at PCC. In both the single-phase p-q theory and UVT control scheme, the current control is applied over the fundamental supply current.

A. Single-phase p-q theory

Let v(t) and i(t) stand for instantaneous single-phase utility voltage and load current, respectively. Using the instantaneous space vector concept, it is possible to represent v(t) in space vector form as follows:

$$\bar{v}(t) = Ve^{j(\beta(t))} = V\left[\cos(\beta(t)) + j\sin(\beta(t))\right] \tag{2}$$
$$= V_r(t) + jV_i(t)$$

where, V_r(t) and V_i(t) stand for the amplitude real part and imaginary part of $\bar{v}(t)$ respectively.

Similarly current can be written as follows:

$$\bar{i}(t) = I_r(t) + jI_i(t) \tag{3}$$

Defining the $\bar{v}'(t)$ and $\bar{i}'(t)$ as space vectors which are Π/2 phase lead in respect with $\bar{v}(t)$ and $\bar{i}(t)$ respectively, results in (4) and (5), easily.

$$\bar{v}'(t) = -V_i(t) + jV_r(t) \tag{4}$$

$$\bar{i}'(t) = -I_i(t) + jI_r(t) \tag{5}$$

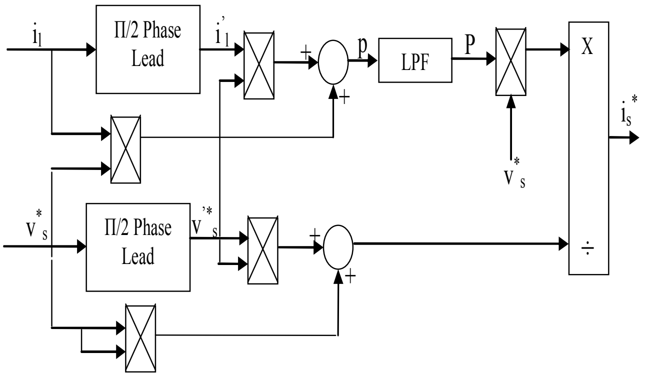

Fig.4Control Scheme of Shunt APF using Single-phase p-q Theory

The single phase instantaneous complex power $S_{1\varphi}(t)$ as follows:

$$S_{1\varphi}(t) = \bar{v}(t)\bar{i}^*(t) \tag{6}$$

where $\bar{i}^*(t)$ is called the conjugate space vector of $\bar{i}(t)$.

The single phase instantaneous active power $p_{1\varphi}(t)$ and the instantaneous reactive power $q_{1\varphi}(t)$, results in (8) and (9) as follows:

$$p_{1\varphi}(t) = \left[V_r(t)I_r(t) + V_i(t)I_i(t)\right] \tag{7}$$

$$q_{1\varphi}(t) = \left[V_r(t)I_i(t) - V_i(t)I_r(t)\right] \tag{8}$$

It is possible writing these equations in the matrix form as follows:

$$\begin{bmatrix} p_{1\varphi}(t) \\ q_{1\varphi}(t) \end{bmatrix} = \begin{bmatrix} V_r(t) & V_i(t) \\ -V_i(t) & V_r(t) \end{bmatrix} \cdot \begin{bmatrix} I_r(t) \\ I_i(t) \end{bmatrix} \tag{9}$$

Based on the original p-q theory and considering the above mentioned subjects shows that $p_{1\varphi}(t)$ and $q_{1\varphi}(t)$, are the instantaneous real power and imaginary power in their single-phase scheme. Now, it is possible to write eqn. (9) in every part of the system. Writing this equation on the source side and rearranging it results in eqn.(10)as follows:

$$\begin{bmatrix} i_{sr-ref}(t) \\ i_{si\_ref}(t) \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} V_r(t) & -V_i(t) \\ V_i(t) & V_r(t) \end{bmatrix} \cdot \begin{bmatrix} P_{1\varphi r} \\ 0 \end{bmatrix} \tag{10}$$

where $\Delta = \left[V_r^2(t) + V_i^2(t)\right]$

In eqn.(10), $i_{sr\_ref}(t)$ and $i_{si\_ref}(t)$ are the reference of real and imaginary part of the source current and $P_{1\varphi}$ is the dc component of the instantaneous real power.

B. Control scheme of Shunt APF using single-phase p-q theory

Fig 3 shows the control scheme to generate reference source current using single-phase p-q theory. In this figure of v_s^* (t) and i(t) stands for the desired reference load voltage and load current respectively. The notations of $v_s^{'*}$ (t) and $i^{'}$(t) show Π/2 phase leaded waveform of v_s^* (t) and i(t) respectively.

In the implementation of the single-phase p-q theory to get the reference of source current i^*_s , the reference load voltage v_s^* (t) is used in stead of the utility voltage v(t)and the is the dc component of the instantaneous real power $P_{1\varphi}$ is obtained by passing the total instantaneous real power $p_{1\varphi}(t)$ through a Low Pass Filter. Finally, the real component of $i_{sr\_ref}(t)$ is calculated as per eqn.(10). In this way, the compensator compensates for the entire reactive of the load and oscillating component of the real power.

C. Control scheme of Series APF using UVT technique

The control algorithm using UVT technique for shunt AF consists of the generation of reference supply current and it is depicted in Fig.2.This algorithm uses supply in-phase vector 1sinwt.The amplitude of the reference supply current (I^*_m) is computed from the comparison of average and the reference value of the dc bus voltage of the common dc link voltage. The voltage error is fed to a proportional integral (PI) controller and the out put of the PI controller is taken as the reference amplitude (I^*_m) of the supply currents. The reference supply currents are computed by multiplying their amplitude (I^*_m) and 1sinwt as:

$$\left[i_s^*\right] = I_m^*\left[1\sin wt\right] \tag{11}$$

The computed supply reference current is compared with the sensed supply current and are given to a hysteresis current controller to generate the switching signals to the switches of the shunt APF, while computed reference load voltage is compared with the sensed load voltage and are given to a hysteresis voltage controller to generate the switching signals to the switches of the series APF.

IV. RESULTS AND DISCUSSION

The model of UPQC system is developed in the MATLAB/SIMULINK environment. The distortion in utility voltage is introduced deliberately by injecting 5th, 7th, 11th, 13th, 17th and 19th order voltage harmonics along with the fundamental. The combination of linear and non-linear load is considered to verify the effectiveness of UPQC for power-factor correction and current harmonic mitigation. An R-L load is considered as a linear load and a single-phase diode bridge rectifier drawing constant dc current is considered as the non-linear load. The series transformer, ripple filters and active filters are developed using the Power System Blockset toolbox.

Fig.6 and Fig.7 shows the dynamic performance of the proposed UPQC system. As already mentioned the control algorithm for the series APF is common in both the scheme, while the control algorithm for the shunt APF is based on UVT technique and single phase p-q theory. The distorted supply voltage is feeding a combination of linear R-L and single-phase diode bridge rectifier. The shunt and series APF is put into operation at t=0.10 sec. From the Fig. 6 and Fig.7, we find that the shunt APF currents compensates for the reactive-power and current harmonics effectively in both of the control scheme used and the series APF injects the required voltage in series with the supply voltage to make the voltages at PCC sinusoidal and maintained at the desired value. Fig.8 shows the harmonic spectrum source current and load voltage before compensation. The Fig.9 shows the harmonic spectrum of the source current and load voltage after compensation using UVT. The supply current harmonic spectrum after compensation using Single-phase p-q Theory is shown in Fig.10. From the simulation results we find that both the control schemes are effective for power-factor correction, current harmonic mitigation and voltage harmonic mitigation. In addition to this, in all the dynamic conditions, the dc link voltage is effectively maintained at its desired value by the shunt APF. The comparative performance for Single-phase p-q theory and UVT scheme is tabulated in terms of THD and RMS values of currents and voltages with and without compensation in Table1.

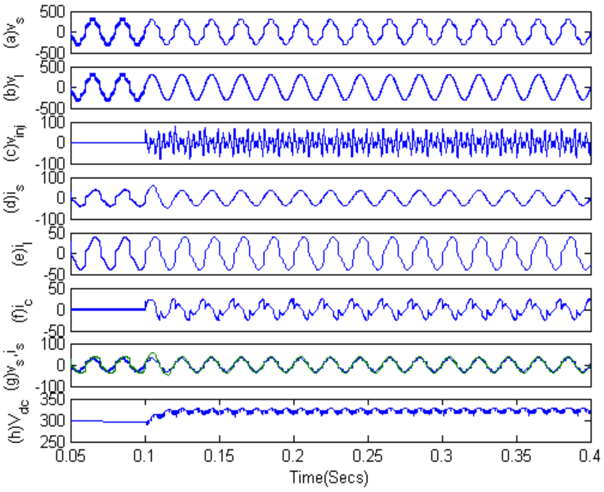

Fig.6 Dynamic response of UPQC under distorted supply voltage and non-linear load using UVT technique

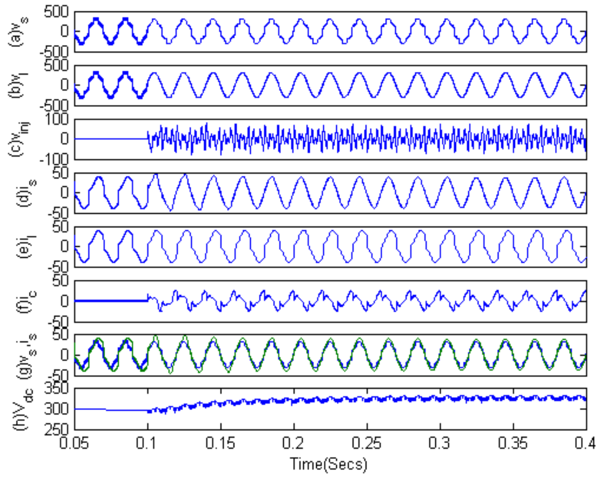

Fig7 Dynamic response of UPQC under distorted supply voltage and non-linear load using single-phase p-q Theory

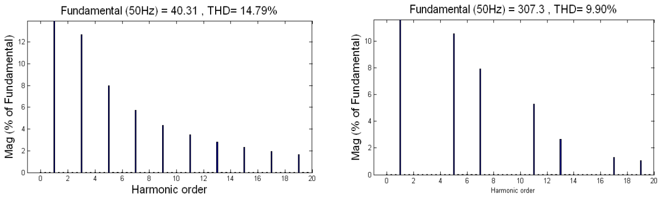

Fig.8 Source Current and Load voltage harmonic spectrum before compensation

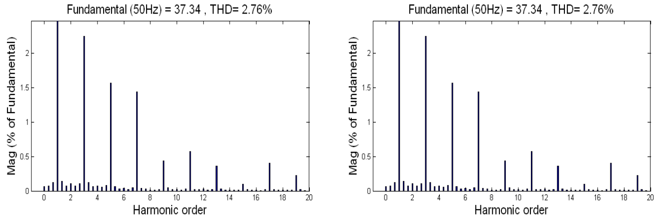

Fig.9 Source current harmonic spectrum after compensation using UVT technique and single phase p-q theory

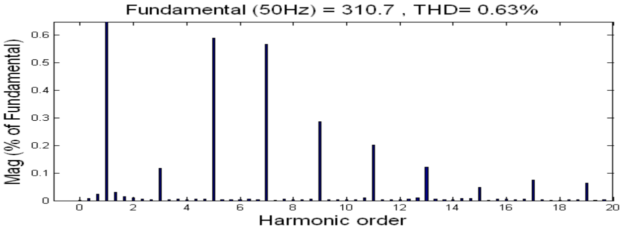

Fig.10 Load voltage harmonic spectrum after compensation using UVT technique

TABLE I
RMS VALUES AND %THD OF SOURCE CURRENT AND LOAD VOLTAGE WITH AND WITHOUT COMPENSATION

	Source current		**Load voltage**	
	RMS (A)	**THD (%)**	**RMS (A)**	**THD (%)**
Without compensation	28.5	14.79	217. 3	9. 90
Compensation using UVT Technique	26.4	2.76	219.7	0.63
Compensation using Single-phase p-q Theory	26.4	2.76	-	-

V. CONCLUSION

The effectiveness of two control schemes namely Single-phase p-q theory and UVT for the shunt APF of single phase UPQC has been compared for power-factor correction and current harmonic mitigation. On the other has the UVT technique is exploited for the compensation of voltage harmonics by series APF. From the simulation results it is found that both the control schemes of shunt APF are equally effective for current harmonic mitigation and power factor correction. For voltage harmonic mitigation UVT technique is equally effective in both the cases. Supply currents and load voltage harmonics levels are maintained below IEEE-519 standards in both of the scheme applied. In single-phase p-q theory, the dc voltage is maintained without using PI controller; hence the number of sensors required is less as compared to UVT technique. One the other hand single-phase p-q theory is complicated as compared to UVT.

VI. APPENDIX

Supply voltage: 220 V RMS, 50Hz.
Supply impedance: 50μH, 0.01Ω.
DC link capacitance value: 4700μF.
DC link voltage: 300 V (for UVT).
Ripple filter parameter: 0.01Ω, 0.5m H, 0.1Ω, 0.5mH.
Transformer: 250MVA, 58KV/12KV.
Linear load: 15 Ω, 50mH.
Non-linear load: Single-Phase Rectifier Load on dc side R=10Ω and L_a=25mH.

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