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VOLTAGE AND CURRENT REFERENCE GENERATION FOR UPQC CONTROL SYSTEM IN FREQUENCY VARYING CONDITIONS[*]

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Abstract– This paper proposes a new control technique for Unified Power Quality Conditioner (UPQC) control system, which can generate voltage and current reference components quickly and without sensitivity to the power frequency variation. Therefore, the stability of the compensation procedure will be improved greatly. The proposed technique uses wavelet transform decomposition and Multi-Resolution Analysis to extract the fundamental component of distorted waveform and The Least Square error method for estimating frequency, amplitude and phase angle of the fundamental component. In this case, Least Square method is used for estimating the amplitude and phase angle of a sine waveform, so the proposed control technique can extract compensating components quickly and accurately. Analyzing the proposed technique for series and shunt active power filter control, as well as simulation results are presented. Results confirm that the proposed method can extract voltage and current references not only more accurately and faster than other well-known control techniques, but also without sensitivity to the frequency variation.

Keywords– Power quality, Unified Power Quality Conditioner (UPQC), wavelet transform decomposition, Least Square method, harmonic compensation

1. INTRODUCTION

The development of power electronic technology makes it possible to realize many kinds of custom power devices to obtain high quality electric energy and enhance the control over power systems. One class of such devices is the UPQC [1] which is aimed at the integration of series and shunt active power filters [2]. Fig. 1 shows the basic configuration of a general UPQC system.

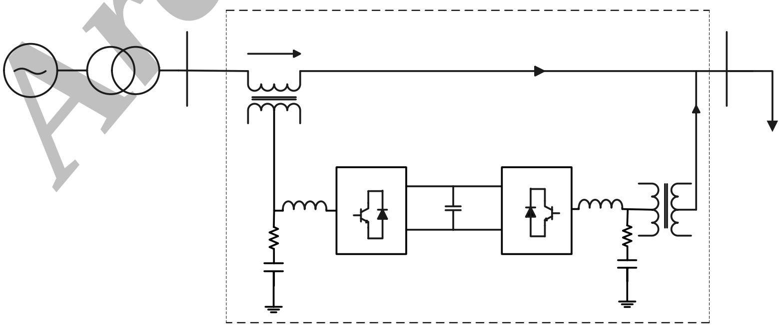

Fig. 1. General configuration of UPQC

The main purpose of a series active power filter (APF) is harmonic isolation between the subtransmission system and the distribution system. In addition, the series active power filter has the capability of voltage flicker/imbalance compensation as well as voltage regulation and harmonic compensation at the utility

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customer point of common coupling [3-5]. The main purpose of the shunt active power filter is to absorb current harmonics, compensate for reactive power and negative-sequence current, and regulate the dc link voltage between both active filters [1].

The UPQC control system extracts the aforementioned distortions of voltage and current for compensation by active power filters. In recent years, many control strategies have been proposed in order to achieve a comprehensive control strategy [5-18]. Some of these groups of control techniques such as instantaneous power theory (pq Theory) [5-7], vector control method [8], symmetrical component strategy [9], constant source instantaneous power strategy [10] and sinusoidal source current strategy [10] can not extract the actual compensating component if the amplitude and phase angle of harmonic components of each phase are not identical to the amplitude and phase angle of harmonics of other phases. Moreover, if the current amplitude increases (or decreases), these methods estimate the exact value of current amplitude at least after one period [11]. Similarly, the FFT (Fast Fourier Transform) control strategy [12] can be imposed on one period time delay to extract current amplitude. If the harmonic components of three phases are not identical, it can extract the distortions of three-phase currents and voltages. Other control techniques such as sliding mode [13], deadbeat control techniques [14-15] and state space control strategy [16] are extremely complicated and time consuming, so they can not be used for real-time applications unless powerful microprocessors with high costs are used. Predictive control algorithms [17-18] do not provide a comprehensive control system because they are mainly proposed for special kinds of distortions. Moreover, they are complicated as well.

A comprehensive control strategy should be capable of extracting unsymmetrical components and other custom distortions of three-phase currents and voltages, as well as unsymmetrical harmonics of three phases. Furthermore, the extraction should be fast and accurate. The aforementioned control strategies depend on the fundamental frequency of the system and frequency variations may produce significant errors in the responses. Therefore, they should be synchronized with the power frequency, however, it may last a few periods in the presence of harmonics. During this interval, the voltage and current distortion can not be compensated effectively.

This paper proposes a new control algorithm, together with a new control strategy to overcome the drawbacks of previous control strategy and achieve a comprehensive control strategy, which can be used for compensating most distortions of current and voltage. The proposed control technique not only extracts voltage and current references quickly and accurately, but can also be quickly synchronized with the power frequency. Thus it can estimate the distortions of voltage and current accurately in frequency varying conditions.

The subsequent section discusses the principle concept of the proposed technique. Section III introduces a new control strategy for the UPQC control system using the proposed estimation technique. Simulation results are presented in section IV. Section V concludes this paper.

2. REFERENCE GENERATION STRUCTURE

The proposed control technique uses Discrete Wavelet Transform (DWT) decomposition and Multi-Resolution Analysis (MRA) [19-20] to extract the fundamental component of distorted current and voltage. Then amplitude, phase angle and frequency of the fundamental component will be estimated using the Least Square technique [21-23]. Compensating components extraction using these values will be discussed in section III.

a) Fundamental component extraction

Wavelets have been applied with success in a wide variety of research areas such as signal analysis. A wavelet transform maps the time domain voltage and current signals in a real-valued time-frequency domain, where the signals are described by the wavelet coefficients [24]

$$i(t)=\sum_{k=0}^{2^{j_0-1}} c_{j_0,k}\phi_{j_0,k}(t)+\sum_{j\geq j_0}^{N-1}\sum_{k=0}^{2^{j-1}} d_{j,k}\psi_{j,k}(t) \tag{1}$$

$$v(t)=\sum_{k=0}^{2^{j_0-1}} c'_{j_0,k}\phi_{j_0,k}(t)+\sum_{j\geq j_0}^{N-1}\sum_{k=0}^{2^{j-1}} d'_{j,k}\psi_{j,k}(t) \tag{2}$$

with

$$c_{j_0,k}=\left\langle i(t),\phi_{j_0,k}(t)\right\rangle \quad \text{and} \quad d_{j,k}=\left\langle i(t),\psi_{j,k}(t)\right\rangle \tag{3}$$

$$c'_{j_0,k}=\left\langle v(t),\phi_{j_0,k}(t)\right\rangle \quad \text{and} \quad d'_{j,k}=\left\langle v(t),\psi_{j,k}(t)\right\rangle \tag{4}$$

where j and k are wavelet frequency scale and wavelet time scale, respectively and c and d are wavelet coefficients.

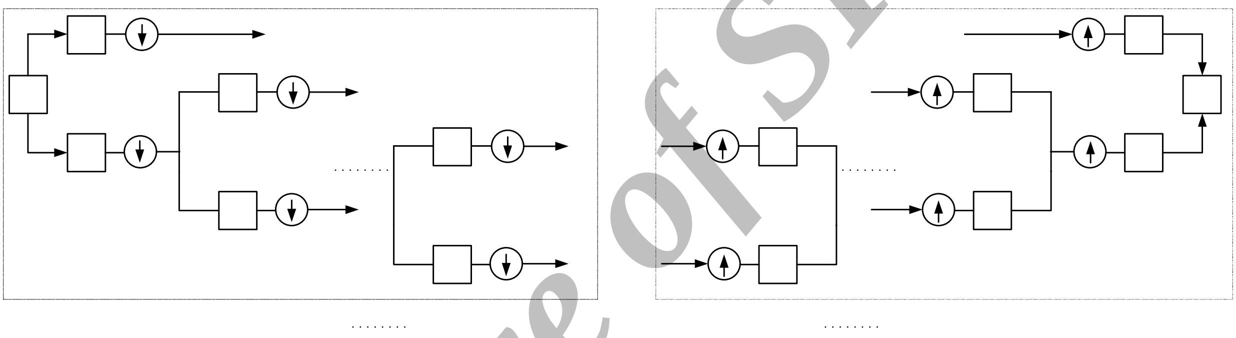

Fig. 2. 8-stage multi-resolution analysis

A time-varying signal can be represented in terms of its frequency components using MRA. The goal of MRA is to develop representations of a complicated signal $f(t)$ in terms of its basis, which are the scaling and the wavelet function. Figure 2 shows an 8-stage MRA used for extracting the fundamental component of the source waveform consisting of 1000 sampled points.

There is an enormous degree of freedom, namely the choice of the wavelet basis determined by the mother wavelets. Each of the mother wavelet has a special property that makes it suitable for special kinds of signals. Wavelet transform is inherently more appropriate for non-stationary and non-periodic wide-band signals [25-27]. Nevertheless, in this research, we want to use the wavelets to analyze power system harmonics, which are stationary signals. Thus a flat pass filter characteristic and cut-off as sharp as possible are required [28-29]. Wavelet transform decomposition can be used for periodic signals as will be discussed later. Indeed, for real-time applications, the periodic signal converts to an appropriate form to reduce the bad effect of wavelet transform on non-periodic signals. This is done in order to use the benefits of wavelet transform in eliminating harmonics from a periodic distorted signal. One of these unique benefits is the insensitivity of wavelet transform to frequency variation. The other is the capability of using fast estimation techniques together with wavelet transform decomposition.

For extracting the fundamental component of a waveform by using MRA, the sampling rate of the signal should be defined accurately. Thus, the number of MRA steps and the fundamental power frequency waveform can be obtained easily.

In real-time applications, using MRA for extracting the fundamental component of a distorted waveform produces an extraction error shown in Fig. 3. A great error is produced for extracting the fundamental component at present time (end of the signal in Fig. 3) because the mother wavelet, which is correlated with the sine waveform, is not stationary and periodic. For solving the problem, a synthetic waveform constructed from two separated parts is used as source signal (S) in Fig. 2. The first part is the original distorted signal up to present time and the second part is the prediction of distorted signal in future time. Using the second part of synthetic waveform aims to eliminate the error shown in Fig. 3. Originally, this part is selected to be similar to the last period of the original distorted signal.

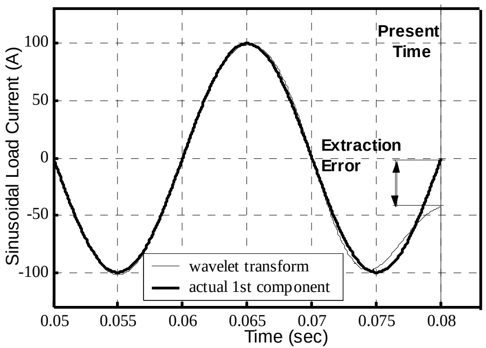

Fig. 3. Fundamental component of load current

If the amplitude of distorted waveform increases (or decreases), the exact value of the fundamental component will be obtained at least a half cycle later using the proposed method. For increasing the speed of extracting, the Best Fit method (or Curve Fitting) is used to extract the new amplitude of the distorted waveform and then the future waveform used for producing the synthetic waveform is multiplied to the proportion of the amplitude of the fundamental component extracted using the Best Fit method for the last cycle to the amplitude of the fundamental component of the previous cycle, so

$$f'(t) = f(t) \times \frac{\left| f_1^{0}(t) \right|}{\left| f_1^{-1}(t) \right|} \tag{5}$$

where $f(t)$ is the last period of original waveform, which is used for future time, and $f'(t)$ is its modification. $\left| f_1^{0}(t) \right|$ and $\left| f_1^{-1}(t) \right|$ are the amplitudes of the fundamental component of the waveform in the last and previous periods, respectively. Assume that the proportion of harmonic distortion amplitudes to the fundamental component amplitude remains relatively constant in each half cycle, so $\left| f_1^{0}(t) \right| / \left| f_1^{-1}(t) \right|$ can be found as follows

$$\frac{\left| f_1^{0}(t) \right|}{\left| f_1^{-1}(t) \right|} = \frac{\left| \sum_{i=1}^{k} f^{\,0,i}(t) \right|}{\left| \sum_{i=1}^{k} f^{\,-1,i}(t) \right|} \tag{6}$$

where i is the sample number in each half cycle, and k is the max sample number in the last half cycle, $f^{\,0}(t)$ and $f^{\,-1}(t)$ are the distorted waveform in the last two half cycles. The synthetic waveform can be extracted from Eqs. (5) and (6). Figure 4 shows the synthetic source waveform. It is assumed that the waveform is periodic and this assumption may cause inaccurate responses in some special conditions.

b) Amplitude and phase angle extraction

Finally, MRA produces a sine waveform, which is the estimation of the fundamental component of the distorted waveform. The sine waveform can be expressed as:

$$f(t) = F\sin(\omega t + \phi) \tag{7}$$

where F, ω and ϕ are amplitude, angular frequency and phase angle of the fundamental component. Equation (7) will be solved by using the Least Square error technique for estimating the mentioned variables of $f(t)$. The successive samples used for solving Eq. (7) are obtained by making a trade off for speed and accuracy. The number of samples used in Least Square algorithm for sine waveform can be decreased without significantly decreasing accuracy, but the accuracy of the results will decrease significantly by decreasing samples if the distorted signal is used in the Least Square algorithm. So, the proposed technique can extract the amplitude, phase angle and frequency rapidly using a sine waveform as a source signal for estimating amplitude and phase angle. Figure 5 shows a typical distorted waveform in which the fundamental and harmonic amplitudes increase sharply at 0.08 seconds from 1pu to 1.5pu. Also, the frequency of the waveform increases at 0.06 seconds from 49.5Hz to 50.5Hz. Fig. 6 shows the estimated amplitude and frequency of the waveform using the proposed method. The fast response of this technique is due to a relatively short observation window which is selected for the Least Square method to estimate a sine waveform amplitude and frequency.

The most important advantage of the proposed method are the fast operation and accurate results obtained using wavelet transform decomposition and Least Square algorithm. Figure 7 shows the proposed algorithm block diagram for obtaining the amplitude and phase angle of the source waveform.

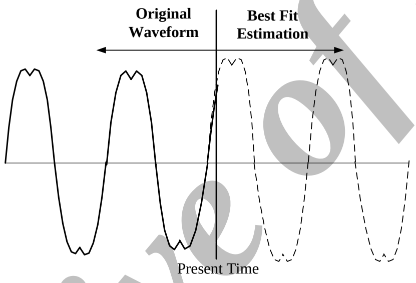

Fig. 4. Synthetic waveform obtained using best fit algorithm

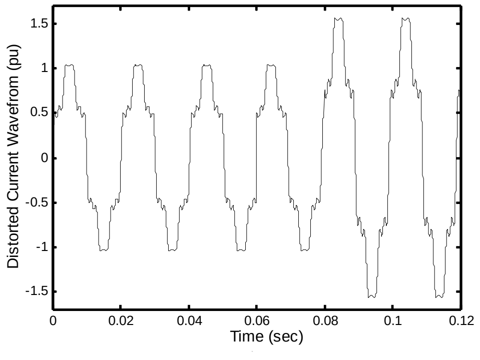

Fig. 5. Typical distorted waveform with frequency and amplitude variation

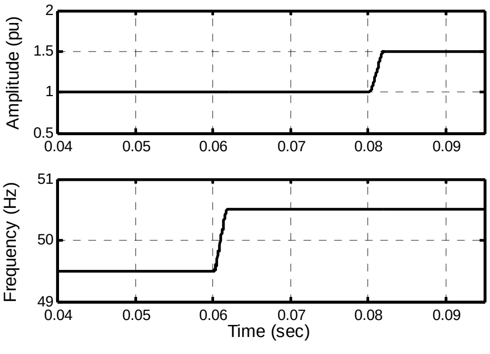

Fig. 6. Frequency and amplitude of the distorted waveform

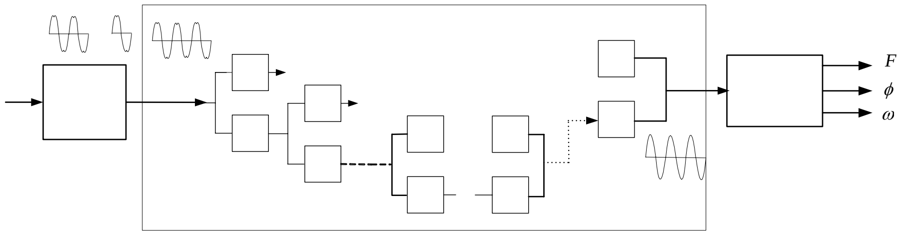

Fig. 7. Block diagram of proposed control strategy

3. UPQC CONTROL STRATEGY

The UPQC control system extracts the voltage and current references using the proposed technique and then compensating components will be obtained by subtracting these reference values from three-phase voltages and currents in the previous section.

a) Shunt active power filter control

Figure 8 shows the block diagram of the proposed control strategy for shunt active power filter of UPQC. The fundamental amplitude and phase angle of the load currents are extracted using the proposed estimation technique illustrated in the previous section. For eliminating unsymmetrical components of the three-phase load currents, the positive sequence of load currents is calculated and then the reference sine load current is obtained by multiplying the amplitude of positive sequence of load currents to a sine waveform with unit amplitude and the phase angle of the fundamental component of load voltages. The frequency of this sine waveform is synchronized with the estimated frequency obtained using the proposed estimation technique. The power frequency is obtained from system voltages and estimated by a series active power filter control system. Therefore, reactive components of load currents will be eliminated using the phase angle of the load voltages as the reference phase angle of the source current. Compensating components of the load currents will be extracted by subtracting the load currents from the reference source currents.

For compensating active power losses and the active power injected by the series active filter to the power system, which causes DC link voltage reduction, some active power must be absorbed by the shunt active power filter. For this purpose, the total DC link capacitor voltages are compared with the reference total value of DC link voltages and the active power that must be absorbed from the power system will be obtained using a PI (Proportional-Integrator) module [6].

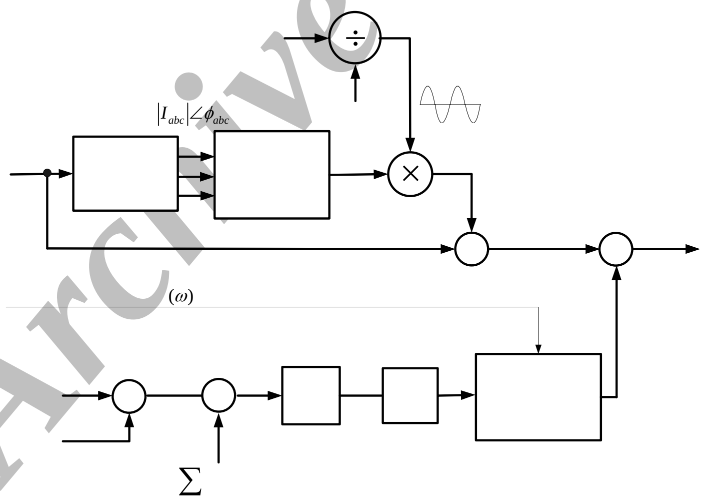

Fig. 8. Block diagram of shunt active power filter control system

b) Series active power filter control

The same as shunt active power filter control strategy, the phase angle and amplitude of three-phase source voltages can be obtained using the proposed estimation technique. Again, for eliminating unsymmetrical components of source voltages, the positive sequence components of the source voltages is extracted and then the reference load voltages are obtained by producing new sine waveforms with the reference amplitude of load voltages and the estimated phase angle of positive sequence voltage. The frequency of this waveform tracks the power frequency, so frequency oscillation does not cause errors in the results. Although, fast frequency estimation, achieved using the proposed estimation method makes this new control strategy insensitive to power frequency oscillation, the proposed control strategy is designed to not be sensitive to the power frequency significantly. For both the series and the shunt active power filters, the estimation technique produces the phase angles or amplitudes of the measured values and the frequency of the reference current and voltage can be obtained consequently.

The compensating voltages are obtained by subtracting the load voltages from these reference sine waveforms. In this case, unsymmetrical components are compensated by using the phase angle of the positive sequence of three-phase voltages, and voltage sag, swell, harmonic and flicker are compensated using the reference amplitude of load voltages. Figure 9 shows the block diagram of the proposed control strategy for a series active power filter.

Both a series and shunt active power filter control technique should be implemented to each phase of the system current or voltage to compensate unsymmetrical and harmonic components of the load current and source voltage of each phase independently.

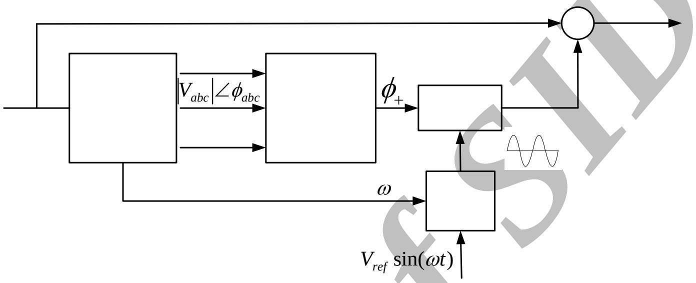

Fig. 9. Block diagram of series active power filter control system

4. SIMULATION RESULTS

In this section, the results of UPQC operation simulation, together with the proposed control strategy using MATLAB/SIMULINK software are presented. Figure 10 shows the power distribution system used in this simulation. A nonlinear load, which produces an unsymmetrical harmonic component in source voltages, was connected to bus 3. An unsymmetrical load with different impedance in three phases is connected to bus 4 to produce an unsymmetrical component in three-phase source voltages. The UPQC system is connected between bus 5 and 6 and it should make the voltage of bus 6 and current of bus 5 sinusoidal with an equal phase angle. The sensitive nonlinear load produces harmonic current component, however, it should be fed by sinusoidal voltages. This sensitive nonlinear load consists of a twelve-pulse thyristor rectifier and one and two single phase diode rectifiers are connected in series with phases (a) and (c) (which produce unsymmetrical components in load currents) respectively.

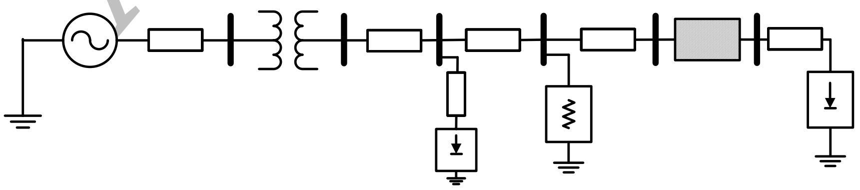

Fig. 10. Distribution system used for simulating UPQC operation

The specifications of the power system are shown in the appendix. The specifications of the UPQC system are shown in Table 1. The system is three-phase four-wire, so zero-sequence current may flow through the fourth wire.

The filter, used in DC voltage control systems for eliminating DC link voltage oscillations is Butterworth of order 1 and the proportional gain of PI controller is 80 and its integrator gain is 800. The voltage of each capacitor of the DC link is 500 volt, so maximum rms value of the injected voltage by a series transformer without respect to the transformer ratio is 213.8 V, which is approximately equal to the single phase voltage of the system ($380/\sqrt{3}$).

Table 1. Specifications of shunt and series active power filter

Shunt active power filter	Passive filter	$R_{sh} = 0.6\,\Omega$ $L_{sh} = 1.5\ mH$ $C_{sh} = 10\ \mu F$
	Shunt transformer	Trans. Ratio =253.3/380 V $R_T = 0.01pu,\ X_T = 0.02pu$
Series active power filter	Passive filter	$R_{sh} = 2\,\Omega$ $L_{sh} = 5\ mH$ $C_{sh} = 1000\ \mu F$
	Series transformer	Trans. Ratio =330/110 V $R_T = 0.02pu,\ X_T = 0.05pu$

The passive filters connected to the output of the UPQC active filters should be accurately designed. If the series inductor of the shunt active power filter is selected greater than the specified value, the undesired oscillation of the active filter current and voltage will decrease, and the slope of the current and voltage will be limited. So a trade off must be taken for the value of the passive filter elements. Moreover, the resonance between this passive filter and the components of the power system can be avoided by designing suitable passive filters. It is noted that UPQC compensation starts at 0.04 sec, but before this time, the control system has extracted the compensating components.

Figure 11 shows that three-phase load currents amplitudes increase 50 percent in 0.06 seconds. It is assumed that the frequency is constant during simulation. The load currents contain harmonics and reactive currents which should be compensated using the shunt active power filter of the UPQC system. The fundamental component amplitudes of phase (a) estimated using FFT control strategy and the proposed control technique are shown in Fig 12. It is seen that the proposed technique estimates the exact value of amplitude faster than FFT algorithm. Other control strategy results (mentioned in the first part of this paper) are comparatively similar to the results of FFT algorithm between 0.06 and 0.08 seconds. The slope of the load current increment is near to the proposed technique estimation. It is noted that the load current amplitude does not increase sharply at 0.06 seconds, and so the slope of the proposed technique result is due to the slow increment rate of load current. The speed of estimation is so important because it can limit the operation range of the UPQC system. The reason will be illustrated as follows. FFT control strategy estimates the exact value of the fundamental component amplitude of load current with one period time delay. In this time interval, the source and load currents differ significantly. This difference in current should be injected by an active power filter, so the amount of active power filter currents and active power losses increase and dc link capacitor voltages oscillate greatly. In this condition, UPQC operation stability decreases. Therefore, operation range of UPQC must be limited to a narrow range of operation to avoid unstable operating condition. The operation of the UPQC system becomes more stable using the proposed method because it estimates load current amplitude quickly. Figure 13 shows the load and source currents obtained using the FFT control strategy and the proposed control technique of phase (a). It can be found that the source current obtained using the proposed technique is clearly more accurate than the FFT control strategy between 0.06 and 0.08 seconds.

Figure 14 shows DC link voltage variations. In the case of the proposed method, dc capacitor voltage increases because the proposed control strategy compensates unsymmetrical components, but the FFT control scheme does not compensate these components. Moreover, in the case of FFT control strategy, source and load current differences between 0.06 and 0.08 seconds cause dc voltage capacitor decreasing. Figure 15 shows source voltage, series active power filter voltage and load voltage of phase (a). The source voltages include unsymmetrical and harmonic components; however, the load voltages become sinusoidal using a series active power filter.

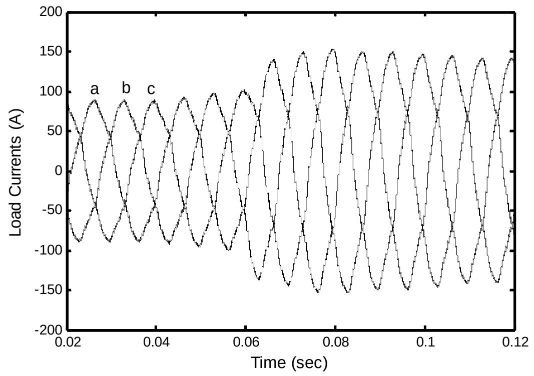

Fig. 11. Three-phase load currents

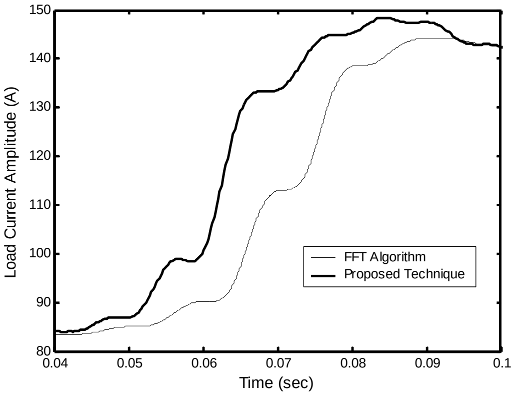

Fig. 12. Fundamental component of load current (phase (a))

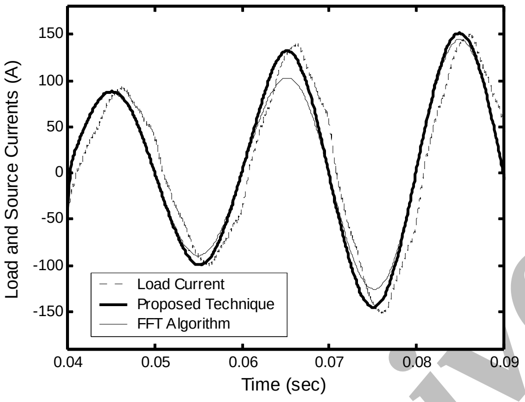

Fig. 13. Source currents and load current of phase (a)

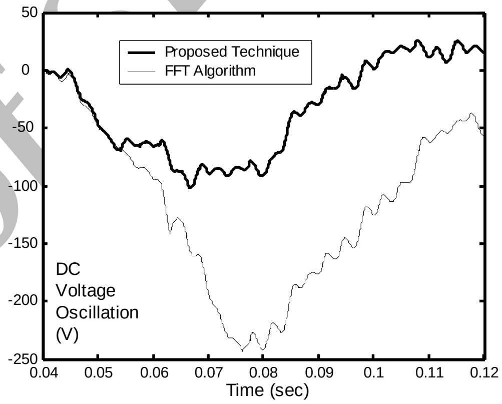

Fig. 14. DC link voltage variation

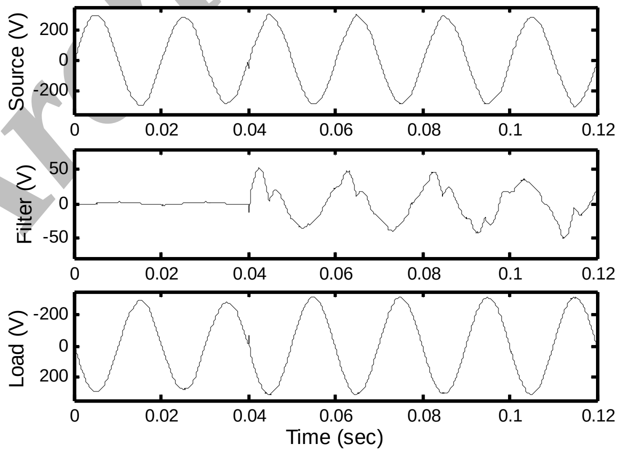

Fig. 15. Source voltage, series active power filter voltage, and load voltages of phase (a)

The control techniques which were used for the UPQC control system need fundamental frequency of the power system to determine current and voltage references. If the power frequency deviates from its nominal value, these algorithms can not extract the exact value of current and voltage references without determining the frequency, and so compensation becomes disrupted. The proposed control technique can estimate the exact value of the fundamental component of current and voltage quickly in this condition.

Then the reference currents and voltages will be synchronized with this estimated frequency. Other control strategies should be synchronized with the power frequency to increase their response accuracy; however, power frequency in the presence of harmonics can not be estimated quickly using the well-known frequency estimation methods. Note that UPQC does not generally compensate frequency deviation because it causes high transferred active power between the UPQC and the power system and so the stability of the UPQC operation decreases.

Simultaneous simulation is carried out to examine the capability of the proposed control technique to estimate phase angle and amplitude of waveforms under frequency variation condition. The power frequency increases from 50Hz to 51Hz at 0.06 seconds and the harmonic components are the same as the previous simulation. In practical cases, power frequency variation is slow, but in this simulation, a step increment is selected to assess the speed and accuracy of the proposed technique. Figure 16 shows the load current amplitude of phase (a) obtained using the FFT algorithm and proposed control techniques. The oscillation of the estimated amplitude using the FFT algorithm is due to frequency variation. The oscillation decreases by synchronizing the FFT algorithm with the power frequency, but it will be achieved after a time delay due to the low speed of the FFT algorithm for estimating the frequency in the presence of harmonic. In this case, the frequency is not compensated using the UPQC system with the proposed control strategy, but the error in frequency and amplitude estimation using FFT control strategy causes great injected voltage by the series active filter, and so more active power losses, DC voltage reduction and UPQC operation limitation. Figure 17 shows the DC voltage variations of both techniques. After increasing the frequency (0.06 second), it is shown that the DC voltage reduction become greater using FFT algorithm in comparison with the proposed control technique.

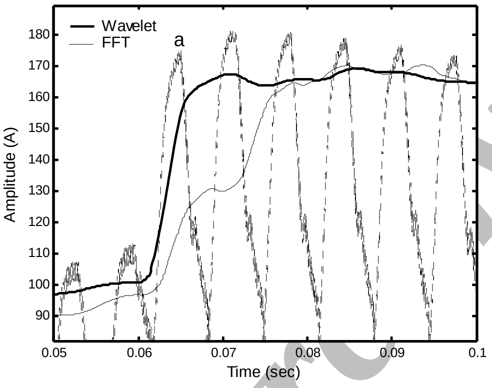

Fig. 16. Load current amplitudes in frequency step variation (phase a)

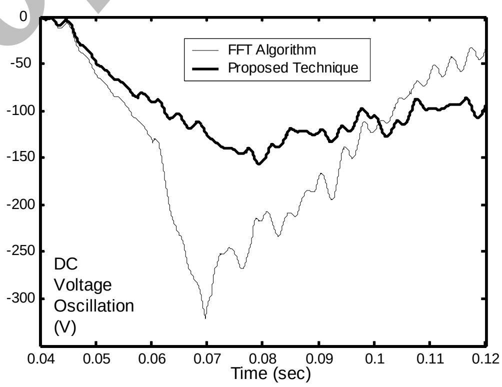

Fig. 17. DC link voltage variation of UPQC

5. CONCLUSION

This paper proposes a new current and voltage reference estimation technique for UPQC control system. This new technique uses wavelet transform decomposition to extract the distortions of currents and voltages, and then amplitudes and phase angles are estimated using the Least Square Method. The Least Square Method is used for estimating the frequency, phase angle and amplitude of a sine waveform obtained from wavelet transform decomposition. The operation of the algorithm is fast with an acceptable accuracy for generating current and voltage references. Also, a new control strategy is proposed for the UPQC control system using the proposed estimation technique. Although, frequency variation can be tracked accurately and fast, and frequency oscillation does not affect the results considerably, the proposed control strategy is designed to be insensitive to the power frequency.

The proposed control strategy for the UPQC control system has been compared with FFT control strategy to show the advantages of the new technique via simulation. Simulation results show that the proposed technique not only can estimate the fundamental component amplitude quickly and accurately, but also the effect of frequency variation is considerably eliminated. Moreover, the UPQC operation range can be enhanced using the proposed method by increasing the stability of the compensation operation.

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APPENDIX

Power network: $V_N = 20\,kV\ L-L,\quad f = 50\ Hz,\ Z_N = 2.5 + j25\Omega\quad R_{Neutral} = 5\,\Omega.$

Power transformer: $500\,kVA,\quad 20/0.38\ kV,\ Y_n/Y_n,\ Z_T = 0.01 + j0.02\,pu.$

Line impedances: $Z_1 = 0.01 + j0.025\Omega$, $Z_2 = j0.47\Omega$, $Z_3 = 0.01 + j0.0125\Omega$, $Z_4 = 0.01 + j0.0125\Omega$

Load impedance: $Z_L = 0.01 + j0.0125\Omega$

Unsymmetrical load impedances: $Z_a = 3 + j0.628\Omega$, $Z_b = 1 + j0.0314\Omega$, $Z_c = 5 + j0.942\Omega$