New Control Algorithms for Three-Phase Four-Wire Unified Power Quality Conditioner — a simulation study

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Summary: In this paper, some new control algorithms are proposed for a three-phase four-wire Unified Power Quality Conditioner. These control algorithms are based on the combination of Unit Vector Template Generation (UVTG) with Power Balance Theory (PBT), single phase d-q theory, Synchronous Current Detection (CSD) technique, and I CosΦ theory. The performance of each control algorithm of UPQC is evaluated in terms of power factor correction, load balancing and source neutral current mitigation, and voltage and current harmonic mitigation. The performance of proposed control algorithms are compared with synchronous reference frame (SRF) based control algorithm. In each proposed control scheme of the three-phase four-wire UPQC, the current/voltage control is applied over the fundamental supply currents/ load voltages instead of fast changing APFs currents/ voltages, thereby reducing the effects of computational delay. Moreover, the load neutral or shunt APF neutral currents are not sensed hence the required current sensors are reduced. MATLAB/ Simulink based simulations are obtained, which support the functionality of the UPQC.

1. INTRODUCTION

The main power quality problems on a three-phase four-wire distribution systems are poor voltage regulation, high reactive power demand and harmonics current burden, load unbalancing, excessive neutral current, voltage harmonics, voltage sag and swells. The quality degradation leads to low power-factor, low efficiency, overheating of transformers and so on. Moreover, in case of the distribution system, the overall load on the system is seldom found balanced, which cause excessive neutral currents in a three-phase four-wire distribution system. Because of fundamental and high frequency contents in the neutral current, the overheating of the neutral conductor occurs [1–3]. With the application of sophisticated and more advanced software and hardware for the control systems, the power quality has become one of the most important issues for power electronics engineers. In order to control the power quality problems, many standards are proposed by different agencies such as IEEE-519 standard [4]. Ideally, voltage and current waveforms are in phase, power factor of load equals unity, and the reactive power consumption is zero; this situation enables the most efficient transport of active power, leading of the cheapest distribution system. In the past, the solutions to mitigate these identified power quality problems were through using conventional passive filters. But their limitations such as, fixed compensation, resonance with the source impedance and the difficulty in tuning time dependence of filter parameters have ignited the need of active and hybrid power filters [5–7]. Under this circumstance, a new technology called custom power emerged [8–9], which is applicable to distribution systems for enhancing the reliability and quality of the power supply.

The Unified Power Quality Conditioner (UPQC) is one of the best solutions to compensate both current and voltage related problems, simultaneously [10–12]. As the UPQC is a combination of series and shunt APFs, two APFs have different functions. The series APF suppresses and

isolates voltage-based distortions. The shunt APF cancels current-based distortions. At the same time, it compensates reactive current of the load and improves power factor. There are many control strategies reported in the literature to determine the reference values of the voltage and the current of three-phase four-wire UPQC, the most common are the p-q-r theory [13], modified single-phase p-q theory [14], Synchronous Reference Frame (SRF) theory [15], Instantaneous Symmetrical Component Theory (ISCT) [16], and Unit Vector Template Generation (UVTG) [17] etc. Apart from this one cycle control (OCC) [18] (without reference calculation) is also used for the control of three-phase, four-wire UPQC. In this paper different control strategies based on the combination of I CosΦ theory [20–21], power balance theory (PBT) [22], single-phase d-q theory [29] and I CosΦ theory [21] with UVTG [17] technique are proposed for the control of three-phase four-wire UPQC. In these proposed control algorithms the control of shunt active power filter (APF) of UPQC are based on Power Balance Theory (PBT), Synchronous Current Detection (CSD) technique, I CosΦ theory and single phase d-q theory, while a control algorithm based on UVTG is common for the control of series APF in each case. The algorithms based on I CosΦ theory [21], single-phase d-q theory [29], CSD [28] and PBT [22] have been reported for the control of APFs but these control algorithms are attempted first time in this paper, for the control of shunt APF of three-phase four-wire UPQC. The proposed control techniques are capable of extracting most of the load current and source voltage distortions successfully. The series APF is controlled to eliminate supply voltage harmonics from the load terminal voltage, while the shunt APF is controlled to alleviate the supply current from harmonics, negative sequence current, reactive power and load balancing.

For the mitigation of neutral current along with other power quality compensations in the supply currents, different topologies reported in literature for the shunt APF of three-phase four-wire UPQC, are three-leg VSI with split capacitor [13], three-single phase VSI [16], four
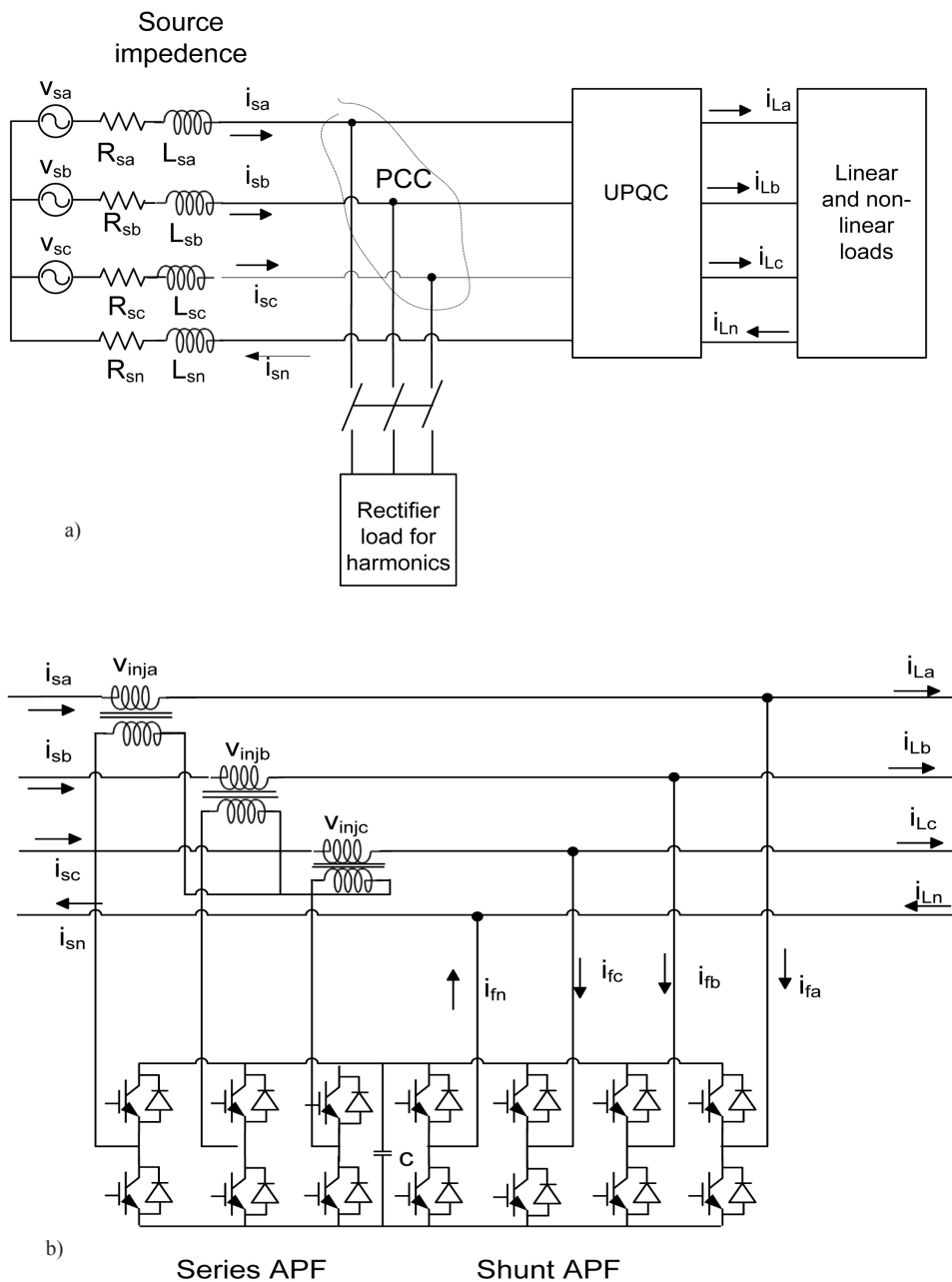
Fig.1(a). Basic block diagram of UPQC connected in a 3P4W distribution system Fig. 1(b) Detailed diagram of 3P4W UPQC

leg VSI [14], [18], Current Source Inverter [19] etc. As UPQC is a combination of series and shunt APF, six single-phase VSI based UPQC requires 24 semiconductor devices, and hence, is not attractive, and the three-leg VSI with split capacitor [19] has the difficulty in maintaining equal DC voltage of two series connected capacitors. Hence, four-leg VSI based [23] UPQC is a better choice in terms of the number of switches, complexity, cost etc. Therefore, in this paper the shunt APF of the three-phase four-wire UPQC is realized using a four-leg VSI, while a three-leg VSI is used for series APF. The performance of the proposed system and each control algorithm is demonstrated through simulated waveforms using MATLAB SPS /Simulink environment.

2. SYSTEM CONFIGURATION

Figure 1(a) shows a three-phase, four-wire UPQC connected to a power system feeding a combination of linear and non-linear unbalanced load. The harmonics in source voltage is created by switching on a three-phase diode bridge rectifier with resistive load on DC side at PCC. The detailed block diagram of three-phase four-wire UPQC is shown in Fig. 1(b). It consists of three leg voltage controlled VSI used as a series APF and a four leg current controlled VSI used as a shunt APF. The DC link of both APFs is connected to a common DC link capacitor. The four-leg VSI based shunt APF is capable of suppressing the harmonics in the source currents, load balancing and power-factor correction.
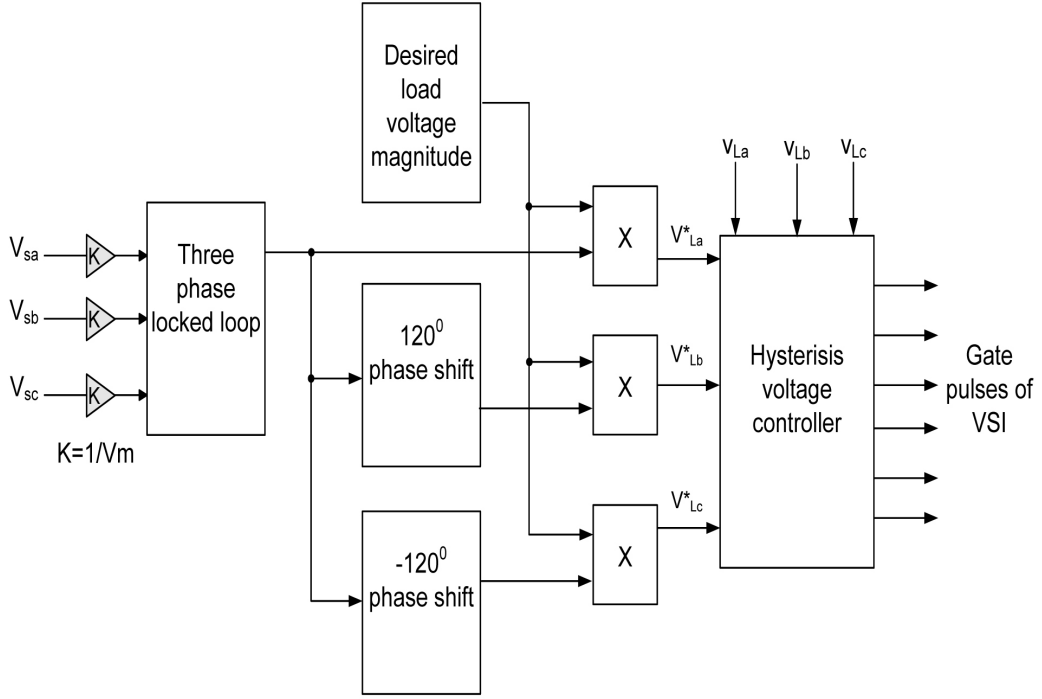
Fig. 2. Control scheme of series APF of UPQC

The fourth leg of the shunt VSI topology is considered to compensate the source neutral current. The series APF is connected between the supply and load terminals using three single-phase transformers with turn's ratio of 5:1. The primary windings of these transformers are star connected and the secondary windings are connected in series with the three-phase supply. In addition to injecting the voltage, these transformers are used to filter the switching ripple content in the series APF. A small capacity rated R-C filter is connected in parallel with the secondary of each series transformer to eliminate the high switching ripple content in the series active filter injected voltage. The VSIs for both the series and shunt APFs are implemented with Insulated Gate Bipolar Transistors (IGBTs).

3. CONTROL SCHEME OF SERIES APF OF UPQC

The main objective of the control algorithms for series APF is to compute mainly the three-phase reference voltages at the load terminal ($v*_{la}$, $v*_{lb}$ and $v*_{lc}$). The series APF is controlled such that it injects voltages (v_{inja}, v_{injb} and v_{injc}), which cancel out the distortions present in the supply voltages (v_{sa}, v_{sb} and v_{sc}), thus making the voltage at load terminals (v_{la}, v_{lb} and v_{lc}) perfectly sinusoidal with the desired amplitude. The control strategy for the series APF is shown in Figure 2. Since, the supply voltage is distorted; a Phase Locked Loop (PLL) is used to achieve synchronization with the supply voltage [17]. Three-phase distorted supply voltages are sensed and given to PLL which generates two quadrature unit vectors ($\sin wt$, $\cos wt$). The in-phase sine and cosine outputs from the PLL are used to compute the supply in phase, 120° displaced three unit vectors (u_a, u_b, u_c) using eqn. (1) as:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\dfrac{1}{2} & -\dfrac{\sqrt{3}}{2} \\ -\dfrac{1}{2} & \dfrac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \sin\theta \\ \cos\theta \end{bmatrix} \quad (1)$$

The computed three in-phase unit vectors then multiplied with the desired peak value of the PCC phase voltage ($V*_{lm}$), which becomes the three-phase reference PCC voltages as:

$$\begin{bmatrix} v_{la}^* \\ v_{lb}^* \\ v_{lc}^* \end{bmatrix} = V_{lm}^* \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \quad (2)$$

The desired peak value of the PCC voltage under consideration is 338V (=415sqrt (2)/sqrt(3)). The computed voltages from reference voltages ($v*_{la}$, $v*_{lb}$ and $v*_{lc}$) from eqn. (2) are then given to the hysteresis controller along with the sensed three phase PCC voltages (v_{la}, v_{lb} and v_{lc}). The output of the hysteresis controller is switching signals to the six switches of the VSI of series APF. The hysteresis controller generates the switching signals such that the voltage at PCC becomes the desired sinusoidal reference voltage. Therefore, the injected voltage across the series transformer through the ripple filter cancels out the harmonics present in the supply voltages.

4. CONTROL SCHEME OF SHUNT APF OF UPQC

The control algorithms for shunt APF consists of the generation of three-phase reference supply currents (i^*_{sa}, i^*_{sb}
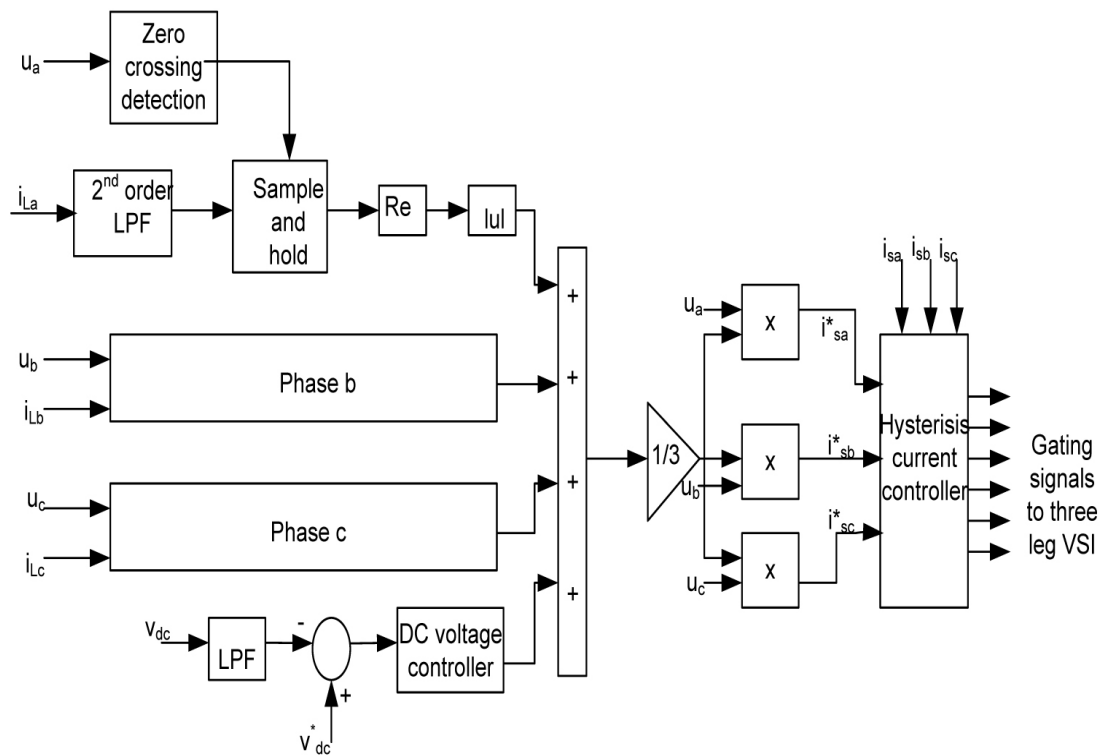
Fig. 3. Control scheme of shunt APF of UPQC using I CosΦ theory

and i^*_{sc}). In these proposed control algorithms, the sensed (i_{sa}, i_{sb} and i_{sc}) and reference source currents (i^*_{sa}, i^*_{sb} and i^*_{sc}) are compared in a hysteresis current controller to generate the switching signals to the switches of the shunt APF, which makes the supply currents sinusoidal, balanced in- phase with the voltage at PCC.

4.1. Control algorithm using I CosΦ theory

The control algorithm based on the modified ICosΦ algorithm is shown in Figure 3. The amplitude of active components of fundamental load currents are given as:

$$
\begin{aligned}
I_{Lap} &= \left| Re\ (I_{La1})\ \right| = \left| I_{La} \right| Cos\ \varphi_a \\
I_{Lbp} &= \left| Re\ (I_{Lb1})\ \right| = \left| I_{Lb} \right| Cos\ \varphi_b \\
I_{Lcp} &= \left| Re\ (I_{Lc1})\ \right| = \left| I_{Lc} \right| Cos\ \varphi_c
\end{aligned}
\tag{3}
$$

The amplitude of active component (ICosΦ) of fundamental load current is extracted at zero crossing of the unit template in phase of PCC voltage from the load currents by +90º, using a set of low pass filters. The filters are with 50 Hz cut-off frequency to extract the fundamental load current. A Zero crossing detector and a "sample and hold" circuit are used to extract the ICosΦ (amplitude of fundamental load current at zero crossing of corresponding in phase unit template). Since the load current drawn by each phase may be different due to unbalanced loads, therefore instantaneous real power for each phase may not be the same. In order to make this load unbalanced power demand, seen from the utility side, as a perfectly balanced fundamental three-phase active power, the unbalanced load power should be properly redistributed between utility, UPQC, and load such that the total load seen from the source side would be balanced and linear load. Hence, for balance source currents, the magnitude of active component of reference source currents can be expressed as:

$$
I^*_{sP} = \left(\left| I_{La} \right| Cos\varphi_a + \left| I_{Lb} \right| Cos\varphi_b + \left| I_{Lc} \right| Cos\varphi_c + I_{loss} \right) / 3 \tag{4}
$$

where $\left| I_{La} \right| Cos\varphi_a ; \left| I_{Lb} \right| Cos\varphi_b ; \left| I_{Lc} \right| Cos\varphi_c$, are the amplitude of the load active currents in phase a, b and c, respectively and I_{loss} which is required for the self supporting DC bus of the UPQC.

The three-phase component of source currents can be obtained with in-phase unit templates as:

$$
\begin{bmatrix} i^*_{sa} \\ i^*_{sb} \\ i^*_{sc} \end{bmatrix} = I^*_{sp} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}
\tag{5}
$$

4.2. Control algorithm using PBT

Figure 4 shows the control algorithm based on power balance theory. In this scheme the unit templates are generated using PLL. The active power of load can be calculated as:

$$
p_L = V_{tmn} \left(u_a i_{La} + u_b i_{Lb} + u_c i_{Lc} \right) \tag{6}
$$

$$
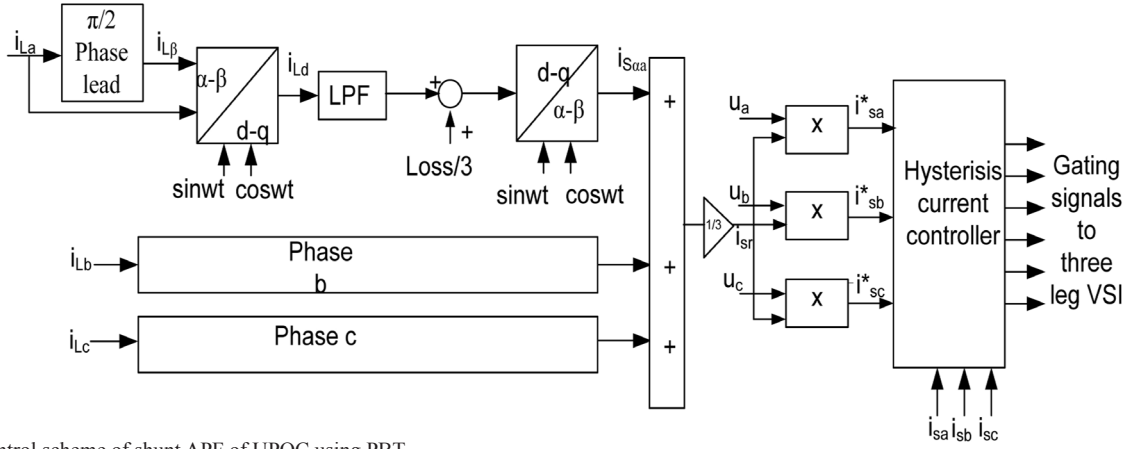p_L = p_{dc} + p_{ac} \tag{7}
$$

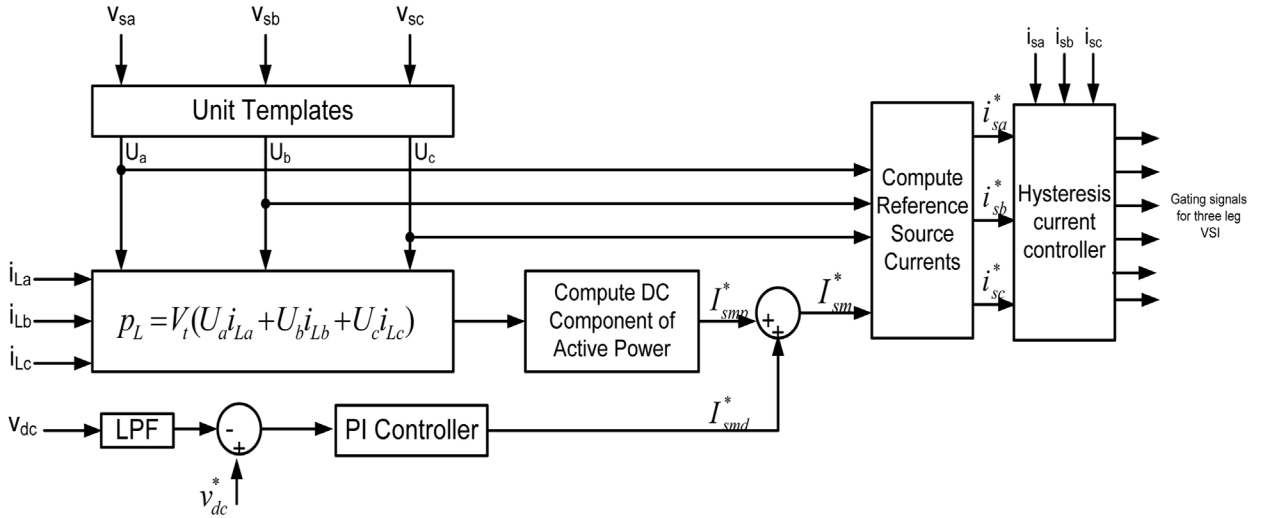Fig. 4. Control scheme of shunt APF of UPQC using PBT

Fig. 5. Control Scheme of shunt APF of UPQC using single-phase d-q Theory

This instantaneous active load power has two components. First one is a DC component and second one is an AC component. The DC component of the load power can be filtered by a set of either a low pass filter or a moving average filter. For power-factor correction mode, only DC component of the load active power must be supplied by the source. The active component of the source currents has two parts. First one is I^*_{smp}, which is required DC component of the load active power and the second one is I_{loss} which is required for the self supporting DC bus of the UPQC.

The active component of the load current I^*_{smp} can be expressed as:

$$I^*_{smp} = \left(\frac{2}{3}\right) p_{dc} / V_{tmn} \qquad (8)$$

where V_{tmn} is peak value of the fundamental component of load voltage. The amplitude of the active component of the reference source current I^*_{sm} is:

$$I^*_{sm} = I^*_{smp} + I_{loss} \qquad (9)$$

The three-phase reference sources currents for power factor correction mode are obtained as:

$$\begin{bmatrix} i^*_{sa} \\ i^*_{sb} \\ i^*_{sc} \end{bmatrix} = I^*_{sm} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \qquad (22)$$

4.3. Control algorithm using single-phase d-q theory

Liu et al [30] have proposed an approach by which a single-phase system can be represented directly in α-β frame without using any transformation matrix. In this approach an imaginary variable, orthogonal to α, is generated from the original variable voltage/current by shifting it by 90º. The original signal along with the imaginary signal thus can be considered as equivalent representation of a single-phase system in orthogonal α-β frame. Using the concept of single-phase p-q theory [26], the load current in α-β frame can be represented as:

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \begin{bmatrix} i_L(wt+\varphi) \\ i_L\left(wt+\varphi+\frac{\pi}{2}\right) \end{bmatrix} \qquad (10)$$

This approach of using an imaginary variable is further extended by Zhang et al [31] to represent the single-phase

5

system in d-q frame. The variable in α-β frame can be converted to d-q frame representation of single-phase system using eqn. (11) as follows:

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \begin{bmatrix} Sin(w_1t) & -Cos(w_1t) \\ Cos(w_1t) & Sin(w_1t) \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \quad (11)$$

In eqn. (11), i_{Ld} and i_{Lq} are the 'd' and 'q' components of the load current. The i_{Ld} and i_{Lq} of the load current have two components first one DC component and second one AC component. The DC component (i_{LDCD}) of these load currents can be extracted with a set of moving average filter with a time equal to half of the cycle time of supply frequency. The AC and DC components can be easily extracted from i_{Ld} and i_{Lq} using low pass filter (LPF) and high pass filter (HPF), respectively.

Therefore required reference d-q components are as follows:

$$\begin{bmatrix} i*_{Ld} \\ i*_{Lq} \end{bmatrix} = \begin{bmatrix} i_{LDCD} \\ 0 \end{bmatrix} \quad (12)$$

where i_{LDCD} is DC component of i_{Ld}. The reference source current signals in α-β frame can be generated by replacing i_{Ld} and I_{Lq} with $i_{Ld}*$ and $i_{Lq}*$ in eqn. (12) and taking its inverse transform using eqn. (13) as follows:

$$\begin{bmatrix} i*_{S\alpha} \\ i*_{S\beta} \end{bmatrix} = \begin{bmatrix} Sin(w_1t) & Cos(w_1t) \\ -Cos(w_1t) & Sin(w_1t) \end{bmatrix} \begin{bmatrix} i_{LDCD} + I_{loss} \\ 0 \end{bmatrix} \quad (13)$$

The $i*_{S\beta}$ is an imaginary component of the source current, which can be discarded for power factor correction. I_{Loss} is the output of DC bus voltage PI controller for self supporting DC bus of the UPQC. The block diagram for the reference current using single-phase d-q theory is shown in Figure 5.

4.4. Control algorithm using CSD technique

In a single-phase system, it can be considered that for average load power P, the active current can be calculated as [28]:

$$i_s(t) = \left[\frac{2P}{V_m^2}\right] v(t) \quad (14)$$

where P is the average load power, V_m is the peak value of the phase voltage and v(t) is the instantaneous phase voltage. Same concept can be applied to a three-phase system.

The three phase load active power can be calculated as:

$$P_L = v^*_{La}i_{La} + v^*_{Lb}i_{Lb} + v^*_{Lc}i_{Lc} \quad (15)$$

where v^*_{La}, v^*_{Lb} and v^*_{Lc} are reference load voltages for phase a, b and c respectively. The instantaneous real power has two components, first one DC and second one AC component. The DC component of the power can be extracted with a set of moving average filter with a time equal to half time of supply frequency and it can be expressed as P_{LDC}.

Hence the reference source currents can be expressed as

$$i^*_{sar} = \left\{2\left(P_{LDC} + P_{Loss}\right)v^*_{La}\right\} / \left\{V_{am}\left(V_{am} + V_{bm} + V_{cm}\right)\right\}$$

$$i^*_{sbr} = \left\{2\left(P_{LDC} + P_{Loss}\right)v^*_{Lb}\right\} / \left\{V_{bm}\left(V_{am} + V_{bm} + V_{cm}\right)\right\} \quad (16)$$

$$i^*_{scr} = \left\{2\left(P_{LDC} + P_{Loss}\right)v^*_{Lc}\right\} / \left\{V_{cm}\left(V_{am} + V_{bm} + V_{cm}\right)\right\}$$

where V_{am}, V_{bm} and V_{cm} are the peak voltage of the PCC voltage of three phases respectively and P_{Loss} is the output of DC bus voltage PI controller for self supporting DC bus of the UPQC. The block diagram for the reference source current using CSD technique is shown in Figure 6.

It is to be noted here that the I_{Loss} in eqns. (4), (9), (13) and P_{loss} in eqn. (16) are required for the self supporting DC bus of the UPQC and meeting out the losses in UPQC. It is calculated as per eqn. (17) below.

$$i_{loss} = p_{loss} = P_{loss} = I_{loss(n)} =$$
$$= I_{loss(n-1)} + K_{pd}\left\{V_{de(n)} - V_{de(n-1)}\right\} + K_{id}V_{de(n)} \quad (17)$$
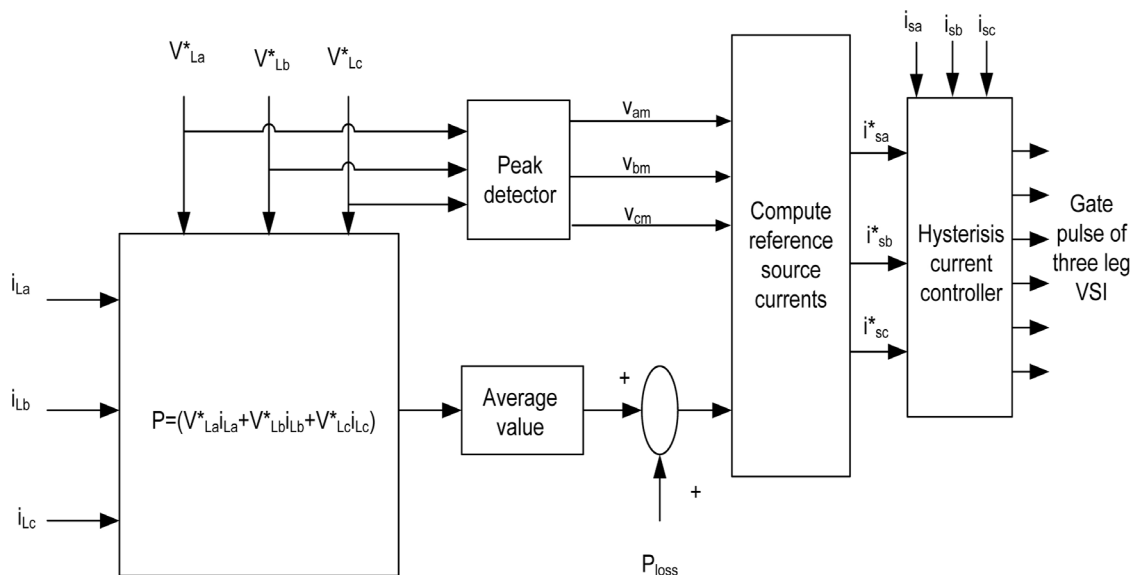

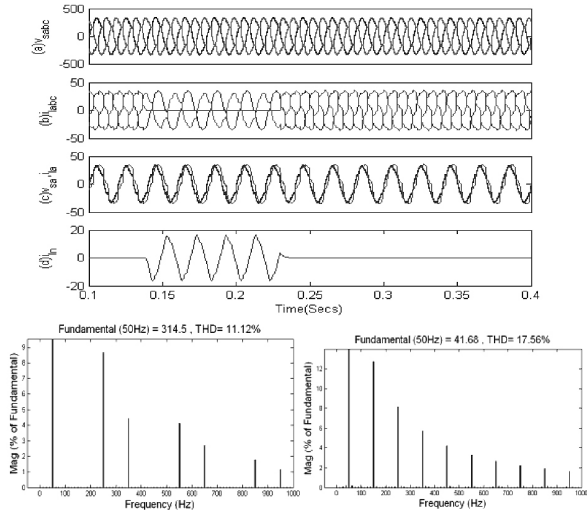Fig. 6. Control Scheme of Shunt APF of UPQC using CSDT

Fig. 7. Power quality problems and its harmonic spectra before compensation on a 3P-4W distribution system

where $V_{de(n)} = V_{dcr} - V_{dca(n)}$ denotes the error in V_{dc} calculated over reference value of V_{dc} and average value of V_{dc}. K_{pd} and K_{id} are proportional and integral gains of the dc bus voltage PI controller.

In each control algorithm of Shunt APF the source neutral current is compensated by following a reference signal of magnitude "zero" by switching the fourth leg of Shunt APF through hysteresis current controller. By doing so the load/ shunt APF neutral current is not sensed, hence required number of current sensors are reduced.

5. PROPOSED CONTROL ALGORITHMS FOR 3P4W UPQC

To evaluate the performance of three-phase four-wire UPQC following control algorithms are developed in MATLAB/SIMULINK.
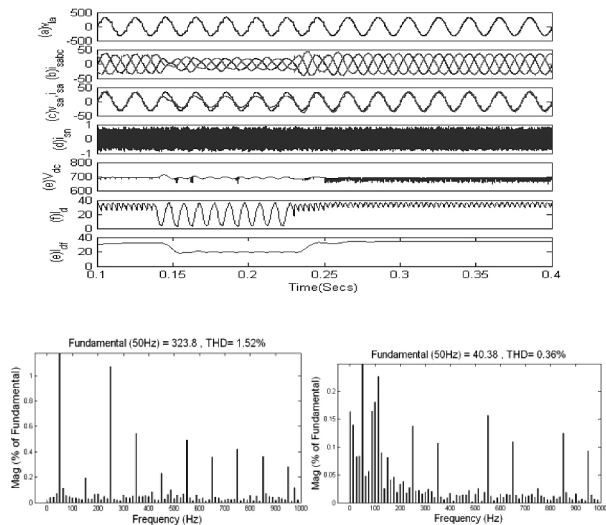
— UVTG and ICosφ based control algorithm

— UVTG and single-phase d-q theory based control algorithm
— UVTG and PBT based control algorithm
— UVTG and CSD based control algorithm.

In all proposed control algorithms for the shunt APF of three-phase four-wire UPQC, the sensed (i_{sa}, i_{sb} and i_{sc}) and reference source currents (i^*_{sa}, i^*_{sb} and i^*_{sc}) are compared in a hysteresis current controller to generate the switching signals to the switches of the shunt APF which makes the supply currents sinusoidal, balanced in- phase with the voltage at PCC. Hence the supply current contains no harmonics or reactive power component. The source neutral current is compensated to follow a reference signal of zero magnitude by switching the fourth leg of the VSI, through the hysterisis controller as shown in Figs. 3–6. By doing this, the supply neutral current can be eliminated. In all proposed control schemes, the current control is applied over the fundamental supply currents/ load voltages instead of the fast changing APF currents/voltages, thereby reducing the effect of computational delay. Moreover, the load neutral or the filter neutral current are not sensed, thereby reducing the required number of current sensors.

6. RESULTS AND DISCUSSIONS

The three-phase four-wire UPQC, realized by four-leg VSI and three-leg VSI is modeled and simulated using MATLAB and its Simulink and Power System Blockset (PSB) toolboxes. The load under consideration is a combination of non-linear and linear load. Three single-phase diode bridge rectifier with R-L load on the DC side is considered as a non-linear load, while three single-phase lagging power factor load is connected between phase and the neutral. The distortion in utility voltage is introduced deliberately by switching "on" a three-phase diode bridge rectifier with resistive loading on DC link at PCC. Figure 7 shows different PQ problems on a 3P-4W system along with harmonic spectra of load voltage and source current before compensation. The load terminal voltage in phase
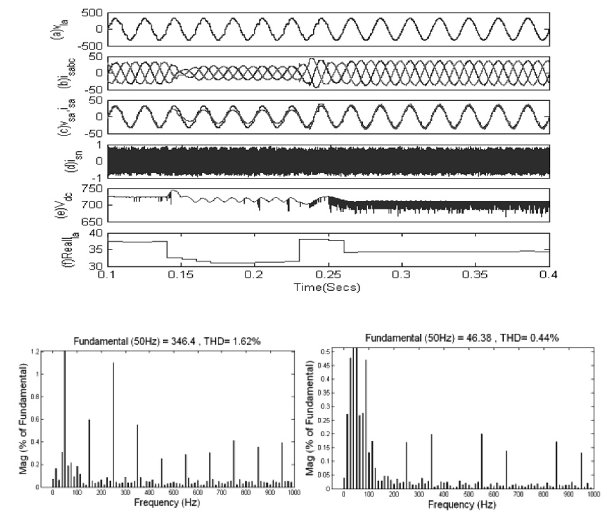

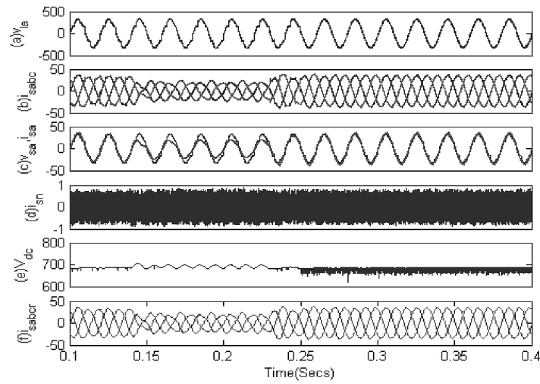Fig. 8. Performance and harmonic spectra of UVTG and SRF theory controlled UPQC

Fig. 9. Performance and harmonic spectra of UVTG and ICosΦ theory controlled UPQC

Fig. 10. Performance and harmonic spectra of UVTG and PBT controlled UPQC

Fig. 11. Performance and harmonic spectra of UVTG and single-phase d-q controlled UPQC

'a' (v_{la}), source currents (i_{sabc}), source voltage and source current in phase 'a' (v_{sa}, i_{sa}), neutral source current (i_{sn}), DC bus voltage (V_{dc}) along with harmonic spectra of load voltage and source current after compensation are demonstrated for evaluating the performance of each algorithm of three-phase four-wire UPQC. To visualize the shunt APF and series APF performance individually, both APFs are put into operation at different instants of time.

6.1. Performance of UVTG and SRF theory controlled 3P4W UPQC

Figure 8 shows the response of UPQC for load balancing, power factor correction, voltage and current harmonic mitigation and compensation of neutral source current using a combination of UVTG and SRF theory. Fig. 8(f-g) shows the 'd' component of load current before and after filtering, respectively.

6.2. Performance of UVTG and ICosΦ theory controlled 3P4W UPQC

Figure 9 shows the response of UPQC for load balancing, power factor correction, voltage and current harmonic mitigation and compensation of neutral source current using a combination of UVTG and I CosΦ theory. Fig.9 (f) shows the real component of the load current in phase 'a'.

6.3. Performance of UVTG and PBT controlled 3P4W UPQC

Figure 10 shows the response of UPQC for load balancing, power factor correction, voltage and current harmonic mitigation and compensation of neutral source current using a combination of UVTG and PBT. Figure 10(f) shows the reference source currents using a control algorithm based on the combination of UVTG and PBT.
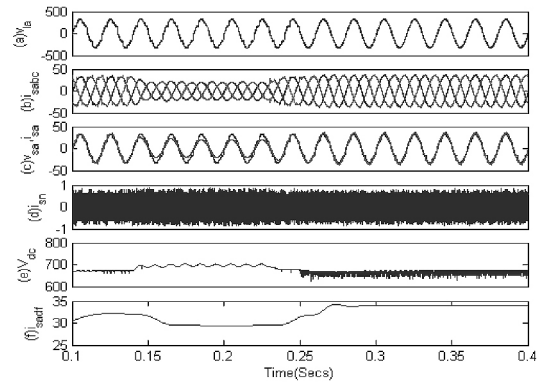
6.4. Performance of UVTG and single-phase d-q theory controlled 3P4W UPQC

Figure 11 shows the response of UPQC for load balancing, power factor correction, voltage and current harmonic mitigation and compensation of neutral source current using a combination of UVTG and single-phase d-q theory. Fig. 11 (e) shows the 'd' component of load current in phase 'a' after filtering.
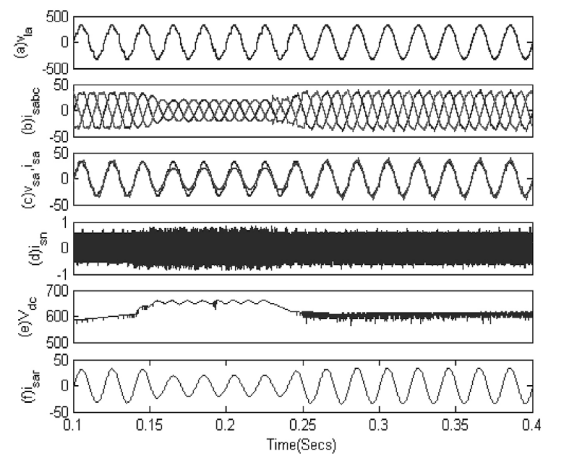

Fig. 12. Performance and harmonic spectra of UVTG and CSD technique controlled UPQC.

6.5. Performance of UVTG and CSD technique controlled 3P4W UPQC

Figure 12 shows the response of UPQC for load balancing, power factor correction, voltage and current harmonic mitigation and compensation of neutral source current using a combination of UVTG and CSD technique. Figure 12(e) shows the reference source current in phase 'a' using a control algorithm based on the combination of UVTG and CSD technique.

Figures 8 to 12 show the performance of three-phase four-wire UPQC for power factor correction, load balancing, current harmonic mitigation, source neutral current mitigation, and mitigation of voltage harmonics using various control algorithms. In each simulation result the shunt APF takes care of the power factor correction, load balancing, current harmonic mitigation, source neutral current mitigation, while the series APF mitigates the voltage harmonics.

To visualize the shunt and series APFs performance individually, both APFs are put into operation at different instants of time. Initially the shunt APF is switched 'on', whereas the series APF is in 'off' state. It is observed from these simulation results that the supply currents are balanced; sinusoidal and in-phase with the voltages even under non-sinusoidal utility voltage. The shunt APF currents i_{cabc} compensates the reactive power, unbalance and the harmonics of the load current, thus the source currents are balanced, sinusoidal and in phase with the voltage at PCC. In these simulation results, during unbalanced operation, the source neutral is compensated using the fourth leg of the four-leg VSI based shunt APF. Once the series APF is switched 'on', it starts compensating voltage harmonics by injecting out of phase harmonic voltage, making the voltage at load distortion free.

7. CONCLUSIONS

Various control algorithms are developed in MATLAB/Simulink to control three-phase four-wire UPQC for the mitigation of current and voltage harmonics, load balancing, power-factor correction and mitigation of source neutral current. It is observed from the simulation results that each control algorithm is effective for the mitigation of different power quality problem. Moreover, a comparison of different control algorithm on the basis of % THD in load voltages and source voltages are given in Table I. It is observed from these results that all the control algorithms are equally effective for load balancing, power factor correction and mitigation of voltage and current harmonics. The % THD given in table is within limits as specified by the IEEE 519 standard. It is also observed from these results that the control algorithm based on SRF theory and I CosΦ based control algorithms are independent of the source/utility voltage, hence these control algorithm are not affected under distorted voltage conditions, while other control algorithms based on PBT and CSD technique have to be modified in the presence of distorted voltages.

8. APPENDIX

The system parameters used are as follows:
— Supply voltage and frequency: 415 V L-L, f=50 Hz
— Source impedance: R_s=0.1 Ω, L_s=1.5 mH
— Loads: Three single-phase lagging power factor load each phase (6 KW, 4 KVar) and a single-phase diode bridge rectifier load with R=10 Ω and L=25 mH.
— Ripple Filter: R=7 Ω, C=5 μF
— DC bus capacitance: C_{dc}=3000 μF
— DC bus voltage of UPQC: V_{dc}=700 V
— Series Transformer: 2.5 KVA, 1.1 KV/5.5 KV
— Interfacing Inductors: R_{sh}=0.1 Ω, R_{se}=0.01 Ω, L_{sh}=5 mH, L_{se}=5 mH
— Proportional and Integral gains: k_p=2, k_i=2

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Table 1. % THD comparison of load voltages and source current with and without compensation using different control algorithms of 3P4W UPQC

	% THD Load voltage						%THD Source current					
	Without compensation			With Compensation			Without compensation			With Compensation		
	Phase 'a'	Phase 'b'	Phase 'c'	Phase 'a'	Phase 'b'	Phase 'c'	Phase 'a'	Phase 'b'	Phase 'c'	Phase 'a'	Phase 'b'	Phase 'c'
UVTG+SRF Theory	11.12	11.11	11.11	1.59	2.25	1.32	17.57	17.78	17.55	0.35	0.37	0.35
UVTG + I CosΦ theory	11.12	11.11	11.12	1.51	2.20	1.24	17.45	17.65	17.43	0.27	0.27	0.28
UVTG+ Single-phase d-q theory	11.12	11.11	11.12	1.79	2.40	1.46	17.76	18.01	17.70	0.44	0.40	0,43
UVTG+PBT	11.12	11.12	11.12	1.67	2.26	1.31	17.70	17.81	17.62	0.44	0.42	0.42
UVTG+CSD	11.37	11.34	11.37	3.30	3.47	2.65	18.27	18.56	18.25	3.20	3.22	3.30

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