International Journal of Control Theory and Applications

ISSN : 0974-5572

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Volume 10 • Number 32 • 2017

Power Quality Profile Enhancement using Hybrid Neuro-Correlation Controller based UPQC

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Abstract: The power quality is most significant parameter in distribution system to meet quality requirements of modern end user sensitive equipment. This paper describes new controller design for Unified Power Quality Conditioner (UPQC) in distribution system with non linear loads to improve power quality. The UPQC is a custom power device consisting of series and shunt active power filters with common dc capacitor. The voltage injection and current injection schemes for UPQC has adapted the correlation based fuzzy logic control method which is proposed to improve power quality profile. The reference unit vectors for generating switching pulses are estimated for series and shunt active power filters by hybrid correlation approach and fuzzy controller in order to mitigate harmonics, voltage sag, voltage swell and load balancing. The mitigation of power quality issues is carried using proposed method through MATLAB/Simulink. The performance of hybrid correlation fuzzy controller based UPQC is observed to be satisfactory as compared with fuzzy PI controller under non linear and time varying load conditions.

Keywords: Unified Power Quality Conditioner; correlation approach; cross correlation approach; fuzzy control; Voltage sag mitigation; total harmonic distortion; Voltage swell mitigation; load balancing.

1. INTRODUCTION

In distribution systems from distribution substation to consumer end the power quality plays significant impact on consumer equipment functioning and lifetime. There may be large impact on better performance of sensitive electronics equipment for small improvement in power quality below IEEE 519 standard (<5%) [1]. UPQC is a custom power device provides series and shunt compensation which combines the benefits of two custom power devices i.e., dynamic voltage restorer (DVR) and distribution STATCOM (DSTATCOM). The present days research is going on in the area of application of adaptive control schemes of custom power devices for enhancing power quality in distribution systems particularly using soft computing techniques like genetic algorithm (GA), artificial neural networks (ANN), fuzzy logic etc. [2]. The maintaining of power quality means providing quality supply with voltage, current and frequency variations such that all end user equipments should operate without mal functioning through their extended period of duration especially sensitive electronic equipment under abnormal conditions [3]-[4]. The particle swarm optimization control method performance for three-phase unified power quality conditioner (UPQC) to mitigate the power quality problems under unbalanced load conditions and various non-ideal mains voltage was analyzed [5]. The switching pulses are generated for power converter using correlation method for system identification of digital control with FPGA. The multi period pseudo random binary signal (PRBS) based results are proven to be better than conventional control scheme [6] and fast computational speed with one computational operation can be achieved using cross correlation approach [7]. ANN-digital signal process based controller is designed for shunt active power filter and the system performance was better compared with conventional PI controller [8]. Total harmonic distortion has been improved by I cosα theory and synchronous reference theory (SRFT) and SRF theory has proved to be better [9]. Due to increasing non linear loads since nowadays all loads include control systems which consists of electronic devices, distribution system has poor quality of power. [10]-[11] proposed fuzzy based UPQC for improving power quality of lower power rating with voltage sag and harmonics mitigation. [12] has designed fuzzy based 3 MVA DSTATCOM for improvement of power quality and stability of distribution system. The analysis was carried out using noval Grey Wolf Optimization (GWO) algorithm with improved dynamic performance and voltage sag mitigation and compared with PI controller. [13] proposed comparative study on voltage source converter based DSTATCOM using least mean square based adaptive linear network and fuzzy logic. The fuzzy logic based the least mean square method was proven to be fast and better performance compared with adaptive linear network. Power quality can be improved with multi converter UPQC using modified synchronous reference frame theory (MSRFT) with fuzzy logic controller [14] under different abnormal conditions and voltage sag and harmonic distortion results are compared with conventional method.

2. SYSTEM CONFIGURATION AND PRINCIPLE

UPQC is a custompower device used to mitigate voltage sag, swell, eliminate harmonics, compensate reactive power and correct current and voltage imbalances. UPQC has series and shunt compensators, series compensation is used to eliminate voltage disturbances like sag, swell and imbalances etc. by injecting series voltage, whereas current disturbances are eliminated by shunt compensation by shunt current injection. The schematic diagram of basic configuration for integration of UPQC to three-phase distribution system is shown in Figure 1. The shunt Voltage Source Converter (VSC) is connected in parallel to the distribution system. Whereas series VSC is connected in series to distribution lines at Point of Common Coupling (PCC) through three- phase injection transformers. Figure 2 shows the phasor diagram of test system. From the phasor diagram the voltage and current equations are given as

$$V_S \angle \theta_S = V_{PCC} \angle \theta_{PCC} + V_{se} \angle \theta_{se} \tag{1}$$

$$I_L \angle \theta_L = I_S \angle \theta_S + I_{sh} \angle \theta_{sh} \tag{2}$$

The DC voltage is common dc link for both series and shunt compensation circuits. Fuzzy controller can regulate this dc voltage.

3. HYBRID FUZZY-CORRELATION CONTROL SCHEME

A. Series Controller Design

The schematic diagram of control scheme for series voltage source converter of three phase UPQC is shown in Figure 3. The reference inputs for series control scheme are three phase source voltages (v_{sabc}), three phase load voltages (v_{labc})and three phase load currents (i_{labc}). The three phase source voltages are transformed to qd0 using Park’s transformation as:

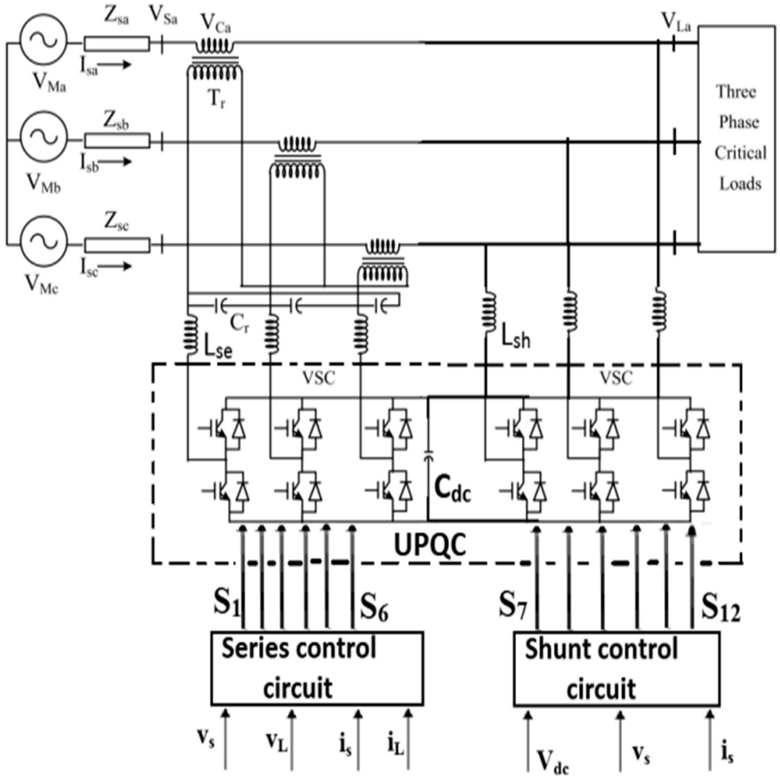


Figure 1: Basic configuration for integration of UPQC to three-phase distribution system

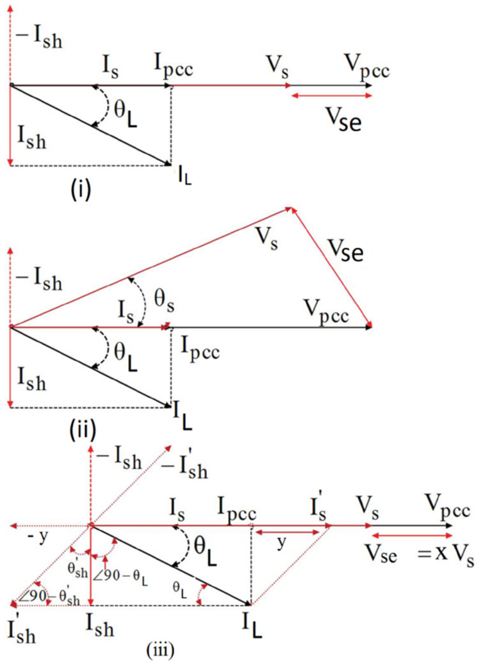


Figure 2: Phasor diagram of UPQC for (i) source voltage and Point of Common Coupling (PCC) voltage are in phase. (ii) Source voltage and PCC voltage are not in phase. (iii) In- phase voltage compensation scheme.

$$V_{sq} = \frac{2}{3}\left[\cos\varnothing \times V_{sa} + \cos\left(\varnothing - \frac{2\pi}{3}\right) \times V_{sb} + \cos\left(\varnothing + \frac{2\pi}{3}\right) \times V_{sc}\right] \tag{3}$$

$$V_{sd} = \frac{2}{3}\left[\sin\varnothing \times V_{sa} + \sin\left(\varnothing - \frac{2\pi}{3}\right)\times V_{sb} + \sin\left(\varnothing + \frac{2\pi}{3}\right)\times V_{sc}\right] \tag{4}$$

$$V_{so} = \frac{1}{3}[V_{sa} + V_{sb} + V_{sc}] \tag{5}$$

Similarly, for load voltages calculated using rotating reference frame.

These load voltages are as inputs for fuzzy controller and V_{qr} is the output of fuzzy controller. The reference for series VSC is difference signal of these two signals as expressed by equations (6) and (7) and (8).

$$V_q^* = V_{sq} - V_{qr} \tag{6}$$

$$V_d^* = V_{sd} - V_{dr} \tag{7}$$

$$V_0^* = 0 \tag{8}$$

The three phase (abc form) reference voltages for series VSC are:

$$V_{sea} = \left[\cos\varnothing \times V_q^* + \sin\varnothing \times V_d^* + V_O\right] \tag{9}$$

$$V_{seb} = \left[\cos\left(\varnothing - \frac{2\pi}{3}\right)\times V_q^* + \sin\left(\varnothing - \frac{2\pi}{3}\right)\times V_d^* + V_O\right] \tag{10}$$

$$V_{sec} = \left[\cos\left(\varnothing + \frac{2\pi}{3}\right)\times V_q^* + \sin\left(\varnothing + \frac{2\pi}{3}\right)\times V_d^* + V_O\right] \tag{1}$$

The estimated reference voltages (9), (10) & (11) are compared with source voltages and the subtracted signals are fed to pulse generator for generating gating pulses as S_1, S_2, S_3, S_4, S_5 and S_6 for series VSC of UPQC.

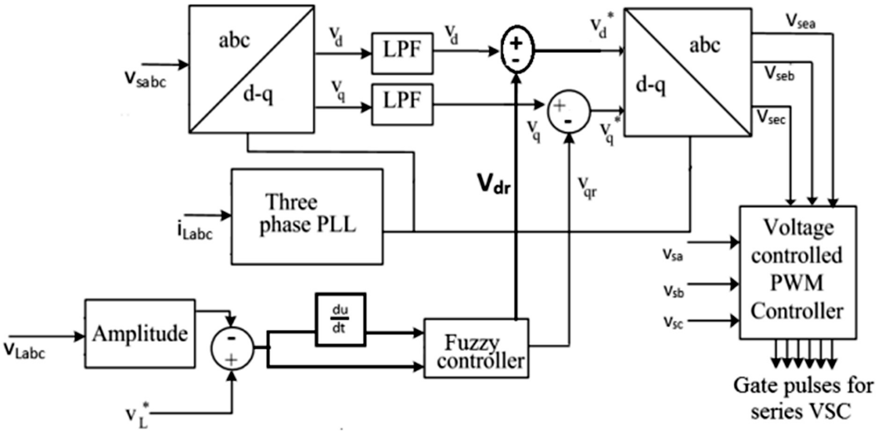


Figure 3: Control scheme for series VSC of UPQC

B. Shunt Controller Design

The amplitude of PCC voltage using sensed three phase source voltages is given by

$$v_p = \sqrt{\frac{2}{3}} \times \sqrt{v_{sa}^2 + v_{sb}^2 + v_{sc}^2} \tag{12}$$

The in-phase three-phase unit voltages are estimated as

$$e_{ap}=\frac{v_{sa}}{v_p};\ e_{bp}=\frac{v_{sb}}{v_p};\ e_{cp}=\frac{v_{sc}}{v_p} \tag{14}$$

The quadrature three-phase unit voltages are estimated as:

$$e_{aq}=\frac{\left(-e_{bp}+e_{cp}\right)}{\sqrt{3}};\ e_{bq}=\frac{\left(3e_{ap}+e_{bp}-e_{cp}\right)}{2\sqrt{3}};\ e_{cq}=\frac{\left(-3e_{ap}+e_{bp}-e_{cp}\right)}{2\sqrt{3}} \tag{14}$$

The instantaneous in phase source voltages (balanced) and non-linear load currents are given by

$$v_{spa}=\mathrm{V}_{\max a}\sin wt;\ v_{spb}=\mathrm{V}_{\max b}\sin\left(wt-\frac{2\pi}{3}\right);\ v_{spc}=\mathrm{V}_{\max c}\sin\left(wt+\frac{2\pi}{3}\right) \tag{15}$$

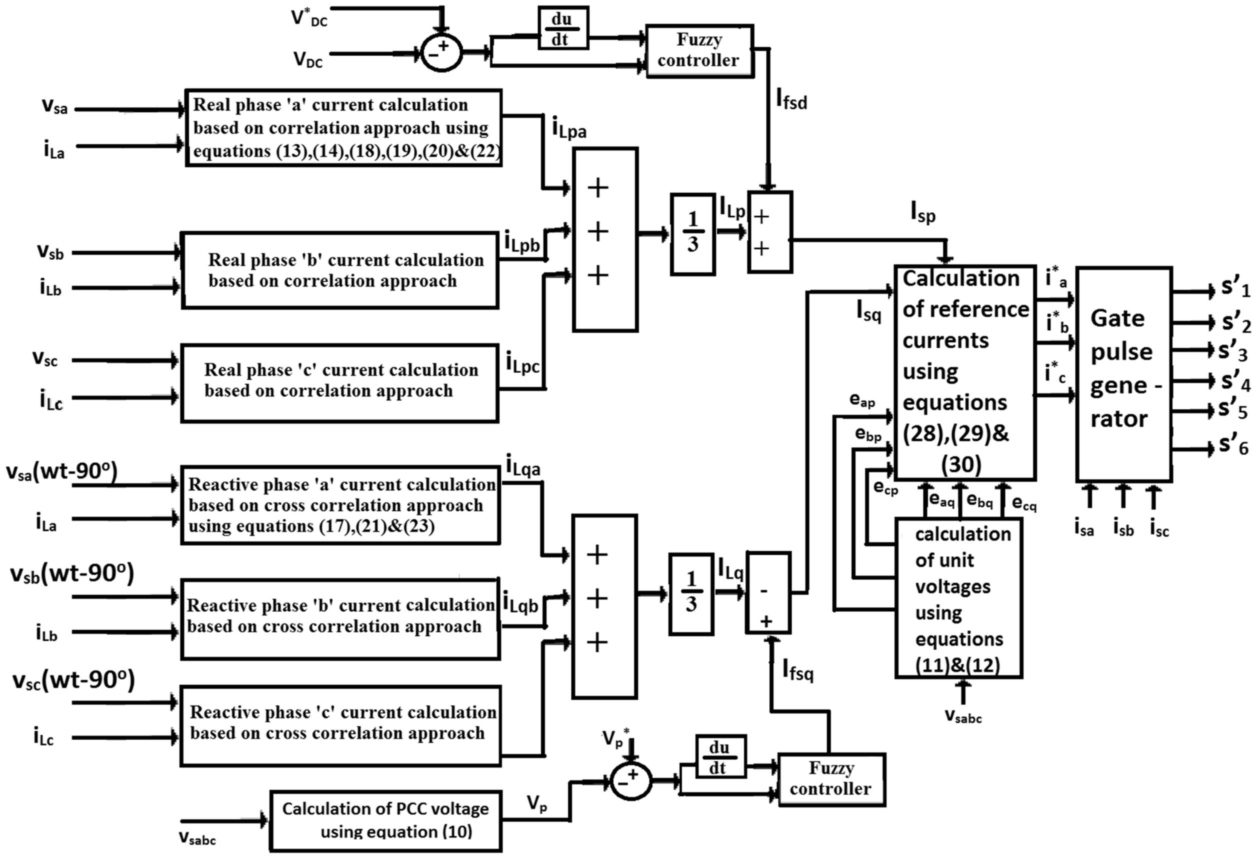


Figure 4: Control scheme for shunt VSC of UPQC

$$i_{La}=\mathrm{I}_{\max a1}\sin(\omega t-\varnothing_{a1})+\mathrm{I}_{\max a3}\sin(3\omega t-\varnothing_{a3})+\mathrm{I}_{\max a5}\sin(5\omega t-\varnothing_{a5})+-\ldots \tag{16}$$

$$i_{Lb}=\mathrm{I}_{\max b1}\sin(\omega t-\varnothing_{b1})+\mathrm{I}_{\max b3}\sin(3\omega t-\varnothing_{b3})+\mathrm{I}_{\max b5}\sin(5\omega t-\varnothing_{b5})+-\ldots \tag{17}$$

$$i_{Lc}=\mathrm{I}_{\max c1}\sin(\omega t-\varnothing_{c1})+\mathrm{I}_{\max c3}\sin(3\omega t-\varnothing_{c3})+\mathrm{I}_{\max c5}\sin(5\omega t-\varnothing_{c5})+-\ldots \tag{18}$$

The instantaneous in quadrature (with 90° delay) source voltages (balanced) are given by

$$v_{sqa}=\mathrm{V}_{\max a}\sin\left(wt-\frac{\pi}{2}\right);\ v_{sqb}=\mathrm{V}_{\max b}\sin\left(wt-\frac{7\pi}{6}\right);\ v_{sqc}=\mathrm{V}_{\max c}\sin\left(wt+\frac{\pi}{6}\right) \tag{19}$$

The non- negative RMS values of source voltage (v_{sa}) and load current (i_{La}) are:

$$\| v_{sa} \| = \sqrt{\frac{1}{\mathrm{T}} \int_0^{\mathrm{T}} v_{sa}^2 \, dt} \tag{20}$$

$$\| i_{\mathrm{L}a} \| = \sqrt{\frac{1}{\mathrm{T}} \int_0^{\mathrm{T}} i_{\mathrm{L}a}^2 \, dt} \tag{21}$$

where, 'T' is time period.

Correlation coefficient is given by

$$c_p = \left[\frac{(v_{sa}) \cdot (i_{\mathrm{L}a})}{(\| v_{sa} \|) \cdot (\| i_{\mathrm{L}a} \|)} \right] \tag{22}$$

where, $(v_{sa}) \cdot (i_{\mathrm{L}a}) = \frac{1}{\mathrm{T}} \int_0^{\mathrm{T}} (v_{sa} \cdot i_{\mathrm{L}a}) \, dt$

Cross correlation coefficient is given by

$$c_q = \left[\frac{(v_{sqa}) \cdot (i_{\mathrm{L}a})}{(\| v_{sqa} \|) \cdot (\| i_{\mathrm{L}a} \|)} \right] \tag{23}$$

The real component of phase 'a' load current is

$$i_{\mathrm{L}pa} = c_p \times \frac{v_{spa}}{\| v_{spa} \|} \times \| i_{\mathrm{L}a} \| \tag{24}$$

Similarly, other (b & c) phases real power components ($i_{\mathrm{L}pb}$ & $i_{\mathrm{L}pc}$) can be obtained.

The reactive power components of load currents are estimated using equations(15), (16), (17) & (21) as

$$i_{\mathrm{L}qa} = c_q \times \frac{v_{sqa}}{\| v_{sqa} \|} \times \| i_{\mathrm{L}a} \| \tag{25}$$

Similarly, other (b & c) phases reactive power components ($i_{\mathrm{L}qb}$ & $i_{\mathrm{L}qc}$) can be obtained.

The average amplitude of real and reactive power components of load currents are

$$\mathrm{I}_{\mathrm{L}p} = \frac{i_{\mathrm{L}pa} + i_{\mathrm{L}pb} + i_{\mathrm{L}pc}}{3} \tag{26}$$

$$\mathrm{I}_{\mathrm{L}q} = \frac{i_{\mathrm{L}qa} + i_{\mathrm{L}qb} + i_{\mathrm{L}qc}}{3} \tag{27}$$

The real power components of source currents are obtained by comparing dc capacitor voltage with reference dc voltage. The error in dc voltage and dc link voltage are given as inputs for fuzzy controller. The output of fuzzy controller is I_{fsd} will be added to average amplitude of real power load current to obtain real power component of reference current as:

$$\mathrm{I}_{sp} = \mathrm{I}_{fsd} + \mathrm{I}_{\mathrm{L}p} \tag{28}$$

The reactive power components of source currents are obtained by comparing PCC voltage (v_p) with reference PCC voltage (v_p^*). The error in PCC voltage and dc link voltage are given as inputs for fuzzy controller. The output of fuzzy controller is I_{fsq} will be added to average amplitude of reactive power load current to obtain reactive power component of reference current as in equation (29). The shunt control scheme is illustrated in Figure 4.

$$I_{sq} = I_{fsq} + I_{Lq} \tag{29}$$

Table 1
Fuzzy Rules

Δe e	*NH*	*NM*	*NL*	*Z*	*PL*	*PM*	*PH*
PH	Z	PL	PM	PH	PH	PH	PH
PM	NL	Z	PL	PM	PH	PH	PH
PL	NM	NL	Z	PL	PM	PH	PH
Z	NH	NM	NL	Z	PL	PM	PH
NL	NH	NH	NM	NL	Z	PL	PM
NM	NH	NH	NH	NM	NL	Z	PL
NH	NH	NH	NH	NH	NM	NL	Z

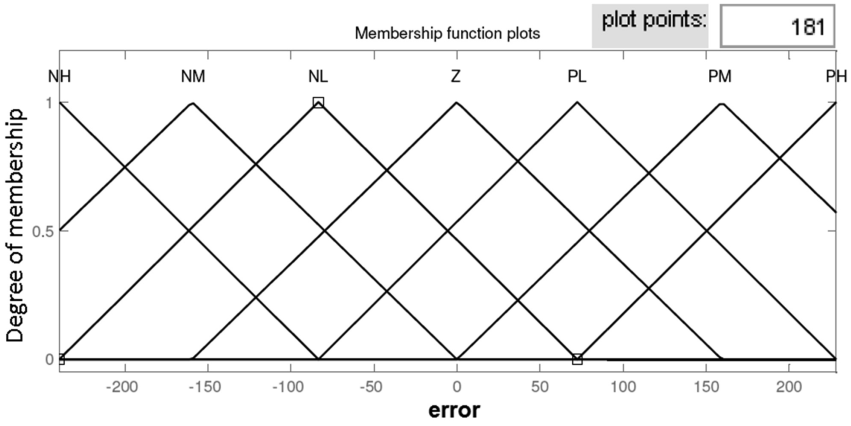


Figure 5: Membership functions for input error

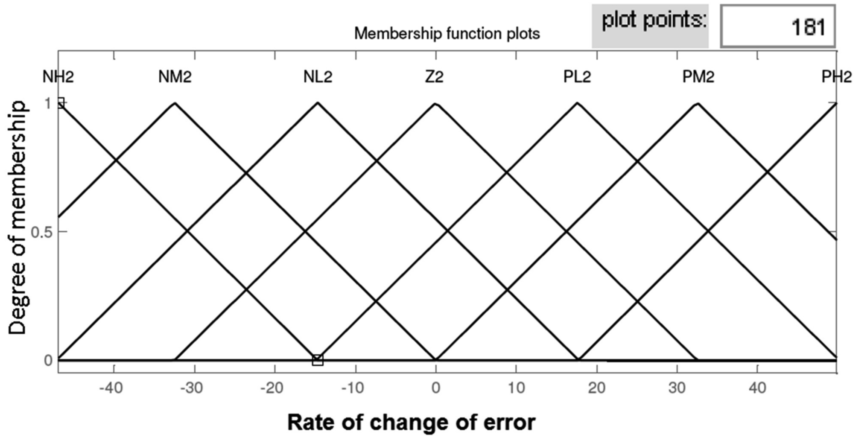


Figure 6: Membership functions for Rate of change of error

The three phase reference real and reactive source currents are estimated using magnitudes of real and reactive power source currents and in phase and quadrature components of unit voltages (11) & (12) as

$$i_{ap} = I_{sp} \times e_{ap};\ i_{bp} = I_{sp} \times e_{bp};\ i_{cp} = I_{sp} \times e_{cp} \tag{30}$$

$$i_{aq} = I_{sq} \times e_{aq};\ i_{bq} = I_{sq} \times e_{bq};\ i_{cq} = I_{sq} \times e_{cq} \tag{31}$$

The reference currents are addition of real and reactive power components of currents as

$$i_a^* = i_{ap} + i_{aq};\ i_b^* = i_{bp} + i_{bp};\ i_c^* = i_{cp} + i_{cq} \tag{32}$$

The estimated reference currents (30) are compared with source currents and the difference signals are fed to pulse generator for generating gating pulses as S'1, S'2, S'3, S'4, S'5 and S'6 for shunt VSC of UPQC. Reference currents are generated using hybrid correlation fuzzy logic controller whose membership functions are shown in Figure 5 and Figure 6 and fuzzy rules are formulated in Table 1. The fuzzy controlleris used to control the dc voltage and terminal voltage using and reference currents are estimated using correlation and cross correlation approach. Figure 7 shows the simulink model of fuzzy-correlation controller for UPQC.

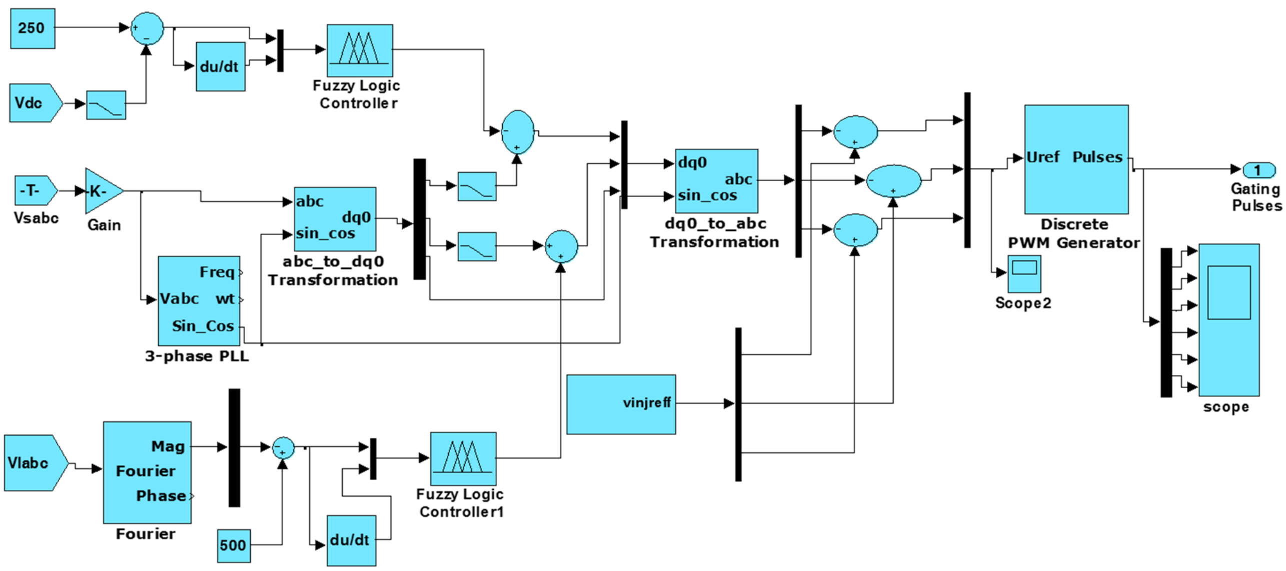


Figure 7: Simulink model of new controller for UPQC

4. RESULTS AND DISCUSSIONS

The performance of UPQC is carried using fuzzy-correlation approach on three phase AC distribution system of 415V, 50 Hz, connected to three phase non-linear load. The results are analyzed using MATLAB/SIMULINK with the source resistance of 0.25 ohm and source inductance of 1 mH. The common DC link voltage is 250V.

A. Sag

The performance of UPQC for voltage sag condition is simulated and dynamic performance using fuzzy-correlation approach is shown in Figure 8. The source voltage has voltage sag of 20% of nominal voltage for the duration of 0.1 sec (5 cycles) from 0.5 to 0.6 sec. It has been mitigated using fuzzy-correlation approach based UPQC and the phase 'a' RMS values of source voltage and mitigated PCC voltage versus duration are shown in Figure 8.

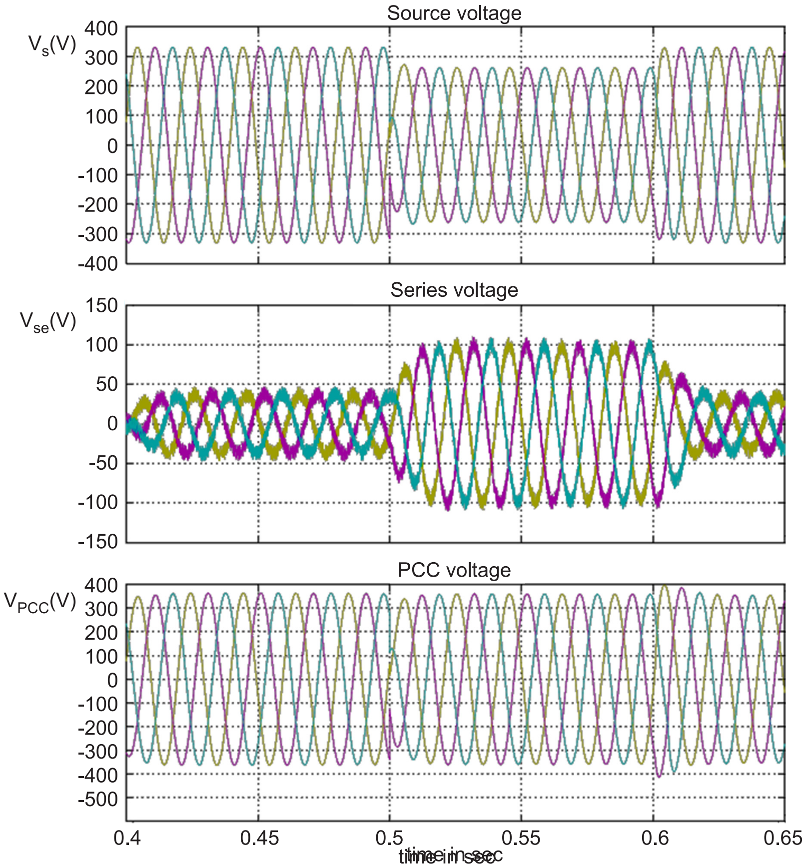


Figure 8: Dynamic performance of sag mitigation using fuzzy-correlation based UPQC

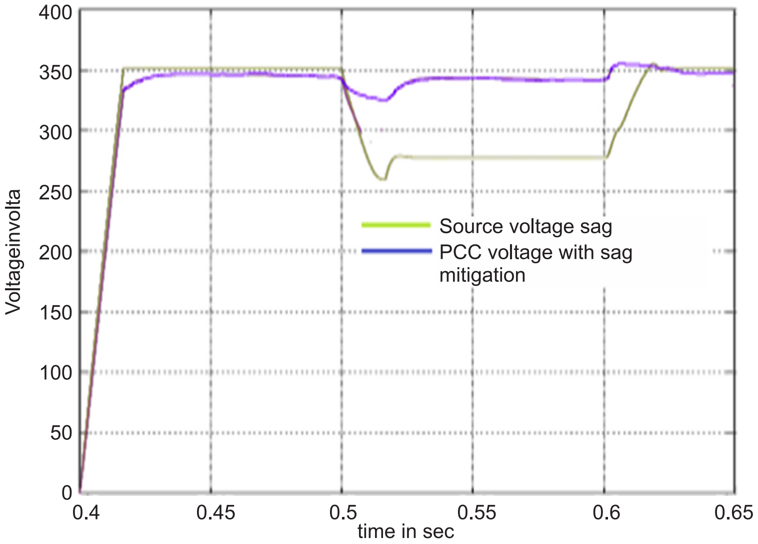


Figure 9: RMS value of Sag magnitude mitigationusing fuzzy-correlation based UPQC

B. Swell

The fuzzy-correlation based control of UPQC for voltage swell condition is simulated and its dynamic performance is shown in Figure 10. The source voltage has voltage swell of 120% of nominal voltage for the duration of 0.1 sec

(5 cycles) from 0.5 to 0.6 sec. It has been mitigated using fuzzy-correlation approach based UPQC and its RMS values of phase 'a' source voltage and voltage swell mitigated PCC voltage versus duration are shown in Figure 11.

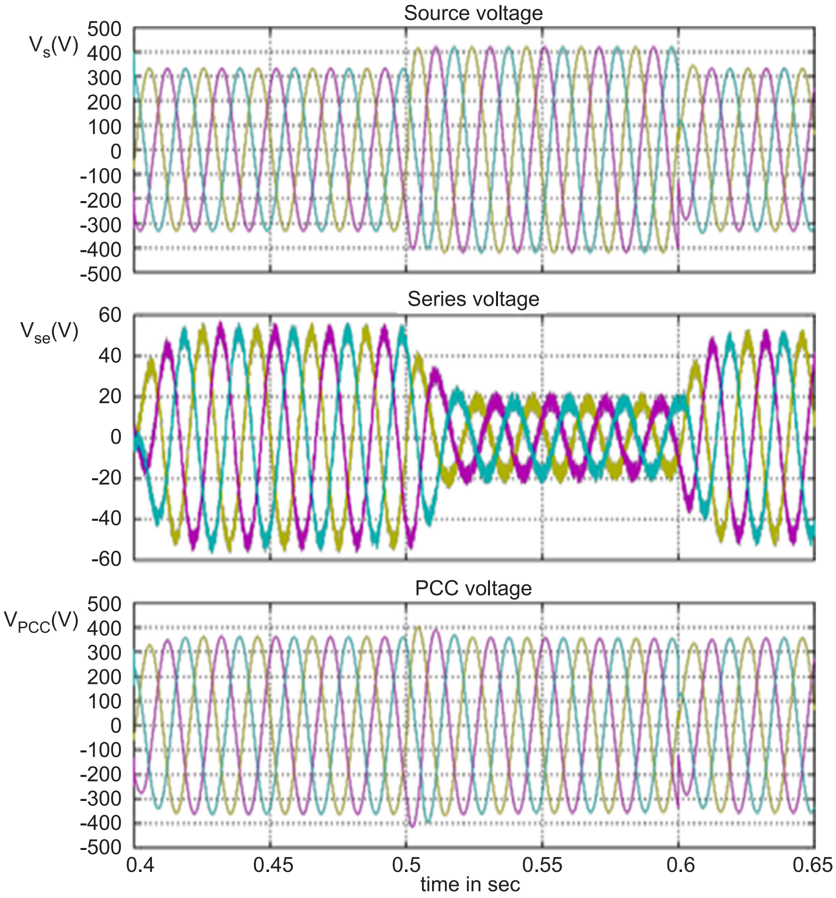


Figure 10: Dynamic performance swell mitigation using fuzzy-correlation based UPQC

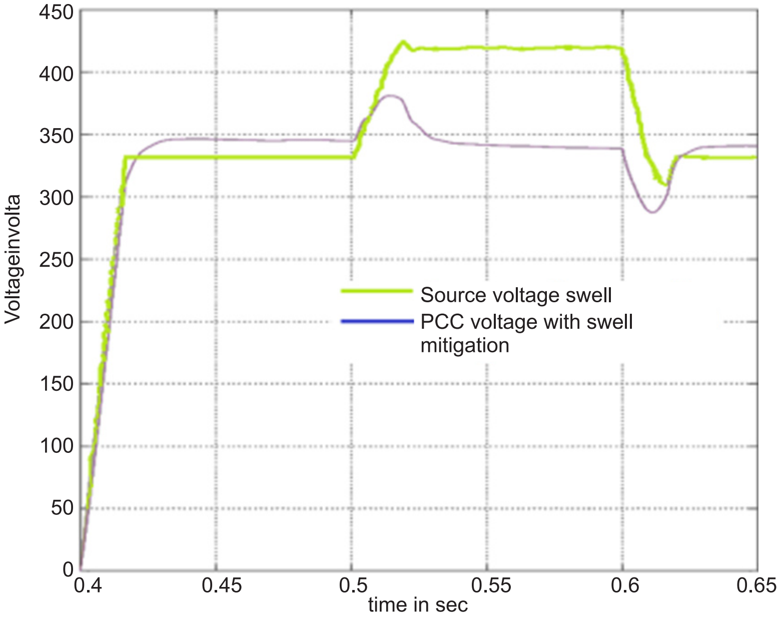


Figure 11: RMS value of Voltage swell mitigationusing fuzzy-correlation based UPQC

C. Sag_Swell

The fuzzy-correlation based control of UPQC for voltage sag_swell condition is simulated and its dynamic performance is shown in Figure 11. The source voltage has voltage sag of 20% from 0.2 to 0.3 sec and swell of 20% of nominal voltage from 0.4 to 0.5 sec. The sag and swell have been mitigated using fuzzy-correlation approach based UPQC and its RMS values of phase ‘a’ source voltage with sag swell and voltage sag swell mitigated PCC voltage versus duration are shown in Figure 13.

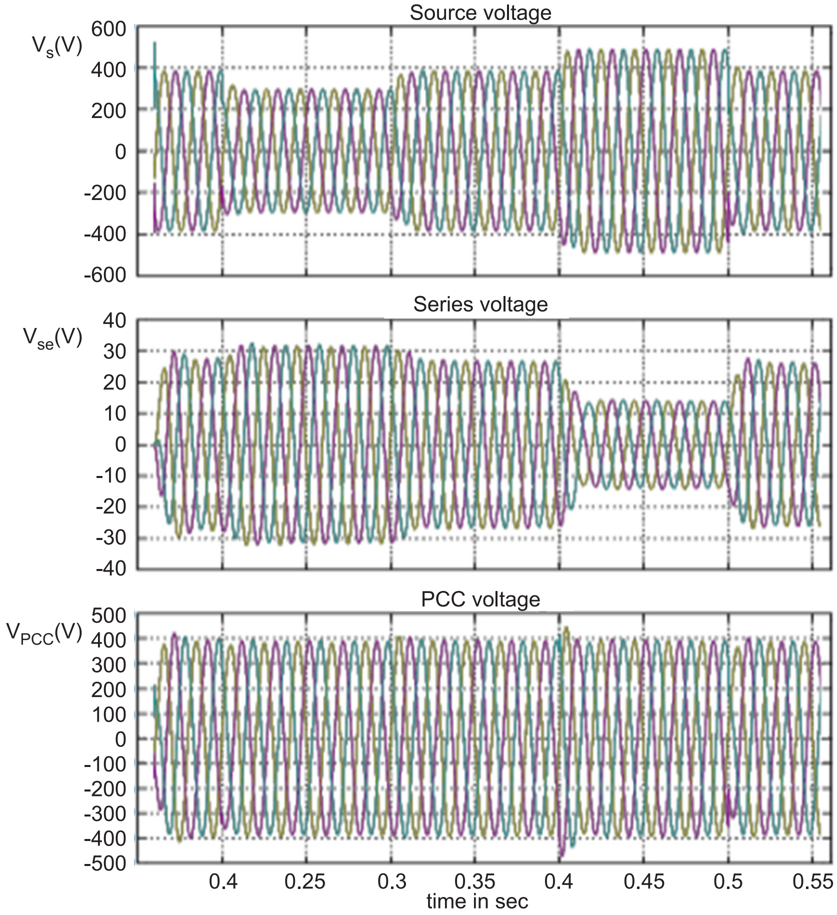


Figure 12: Dynamic performance of Voltage sag swell mitigation using fuzzy-correlation based UPQC

C. Total Harmonic Distortion

The UPQC can also mitigate the harmonics that exists in the three-phase distribution system due to non-linear loads. The shunt VSC compensates the reactive power and the load harmonics. The load current has Total Harmonic Distortion (THD) of 28.65% as shown in Figure 16 and due to this harmonic load current injection into the three-phase distribution system. The load voltage harmonic distorted waveform and its compensated waveform using fuzzy-correlation approach is shown in Figure 14. From Figures 15, 16 & 17, it is observed that the non-linear load current has THD of 28.65% and source current has THD of 2.24% using fuzzy PI controller and it has been reduced to 1.37% using fuzzy-correlation based controller. The PCC voltage has THD of 4.72% using fuzzy PI controller and it has been reduced to 0.93% using fuzzy-correlation based controller of UPQC and source voltage from 1.14% to 1.02% as shown in Figure 18. The performance comparison of THD using fuzzy PI and fuzzy-correlation based controller of UPQC is tabulated in Table 2.

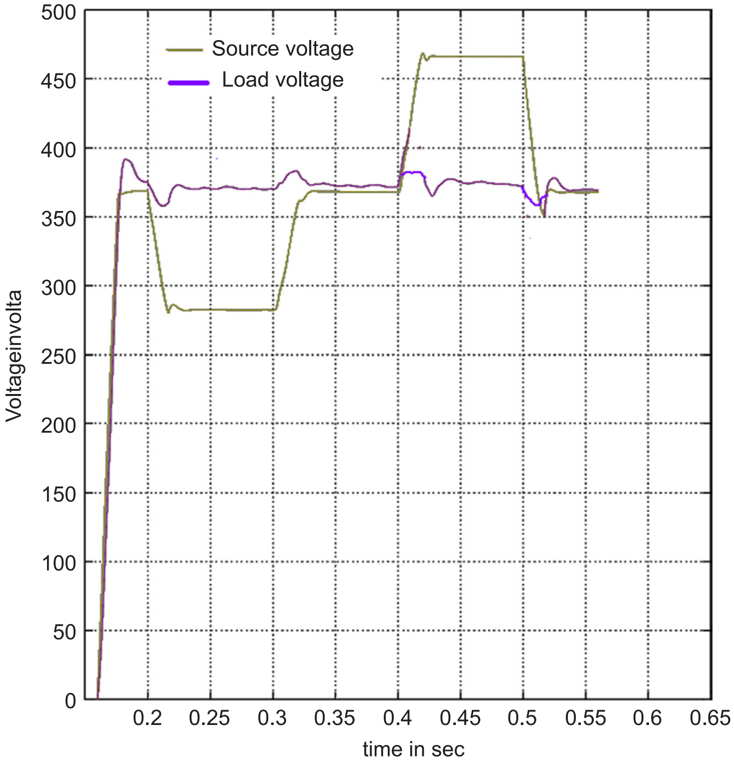


Figure 13: RMS value of sag swell magnitude mitigation using fuzzy-correlation based UPQC

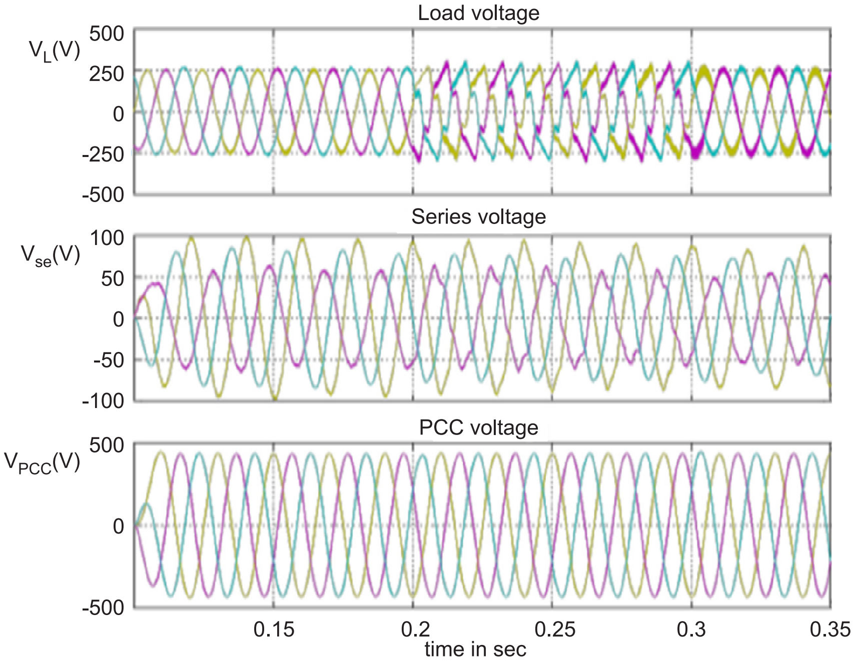
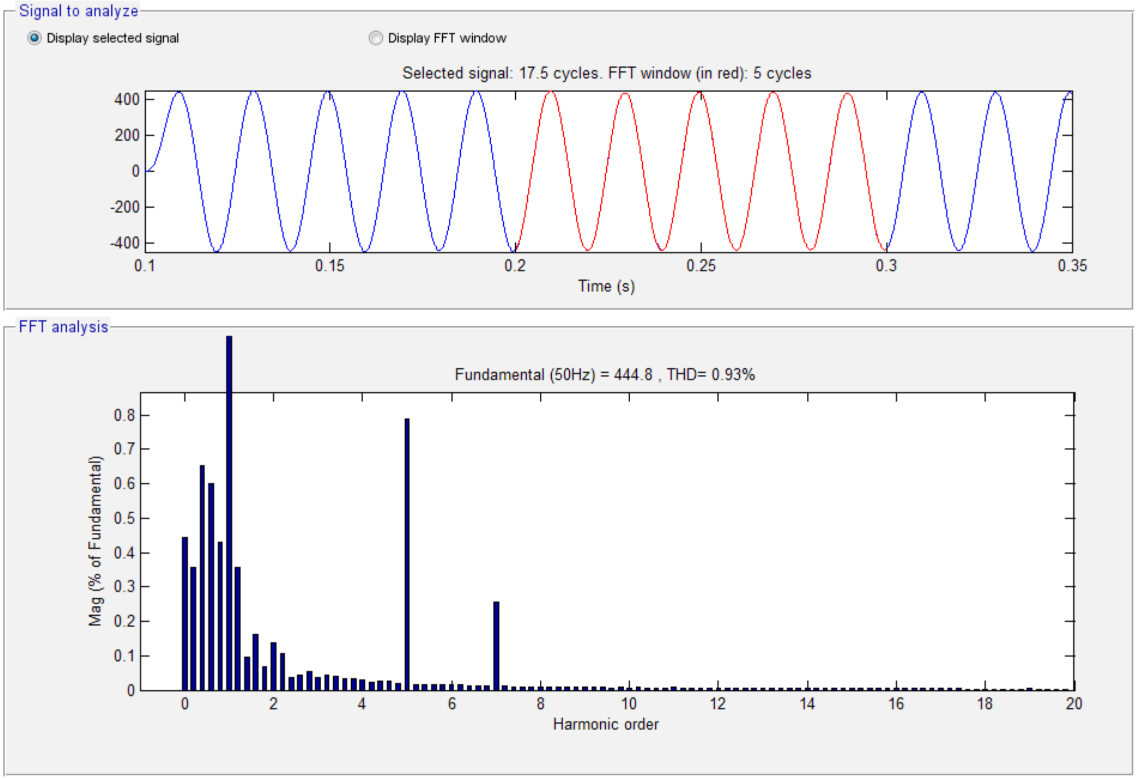


Figure 14: Harmonic distorted load voltage and its compensation using fuzzy-correlation based UPQC

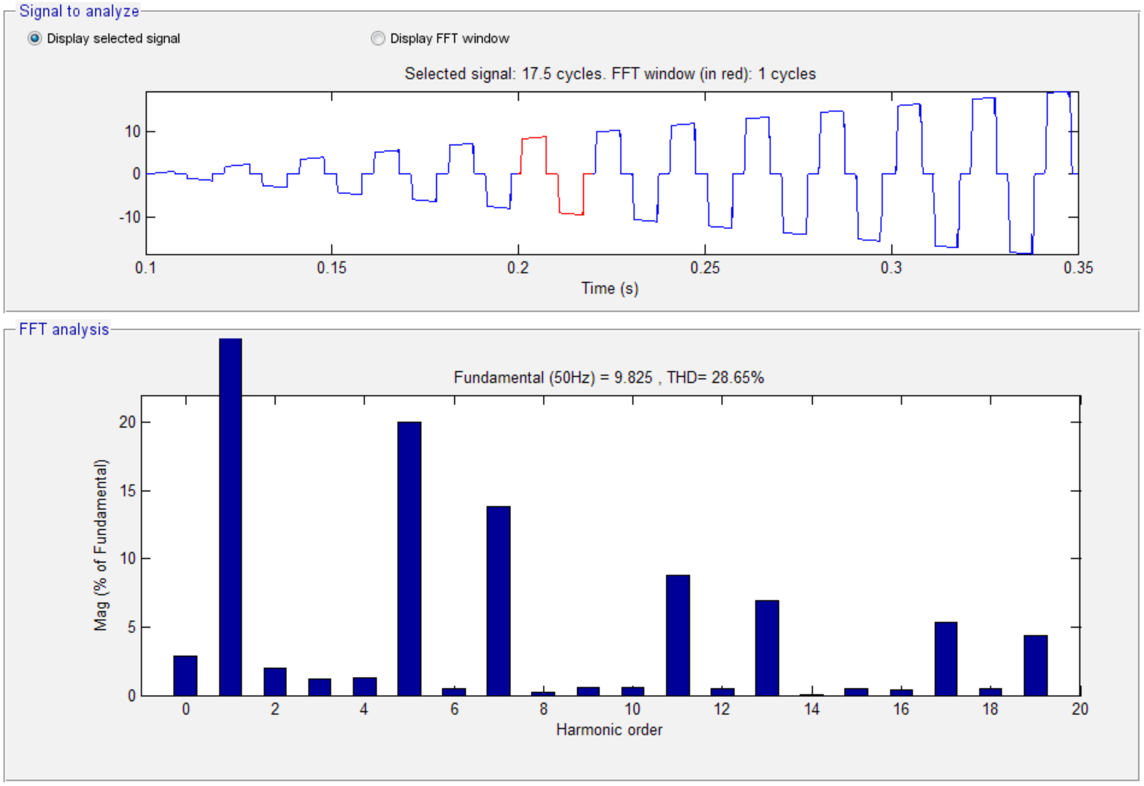


● Display selected signal ○ Display FFT window

Selected signal: 17.5 cycles. FFT window (in red): 5 cycles

Fundamental (50Hz) = 444.8 , THD= 0.93%

Figure 15: PCC voltage and total harmonic distortion using fuzzy-correlation based UPQC



● Display selected signal ○ Display FFT window

Selected signal: 17.5 cycles. FFT window (in red): 1 cycles

Fundamental (50Hz) = 9.825 , THD= 28.65%

Figure 16: Load current and total harmonic distortion

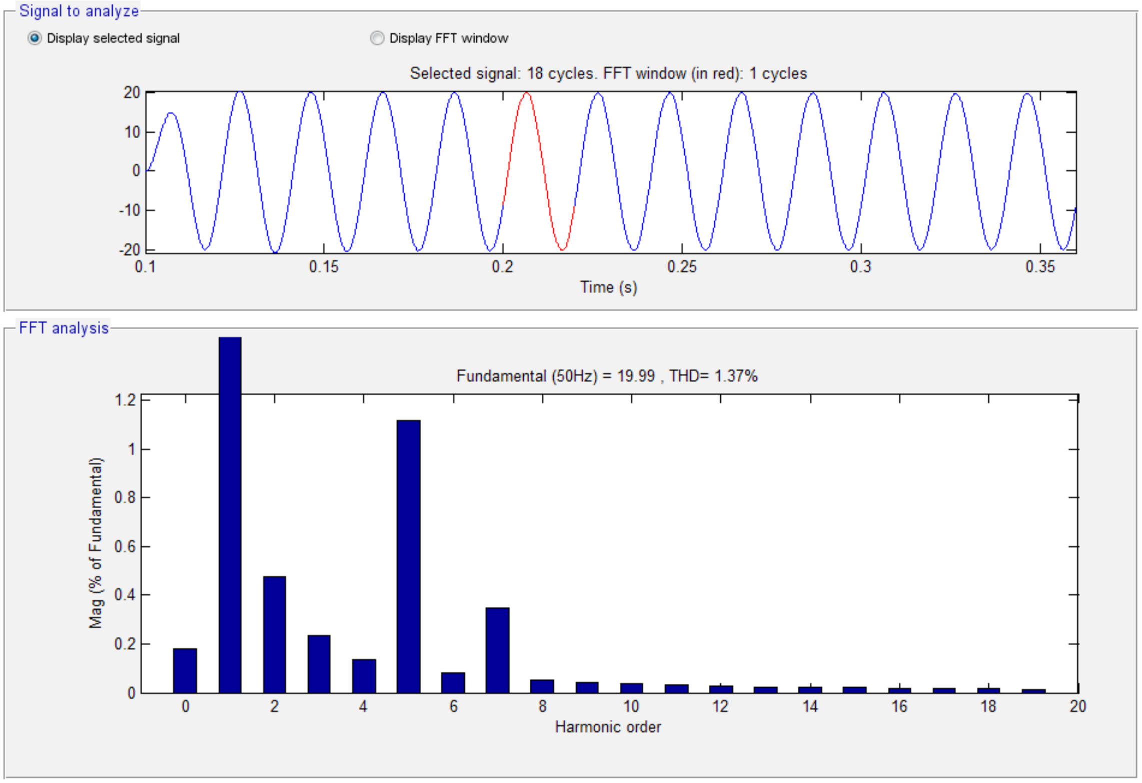


Figure 17: Source current and total harmonic distortion with fuzzy-correlation based UPQC

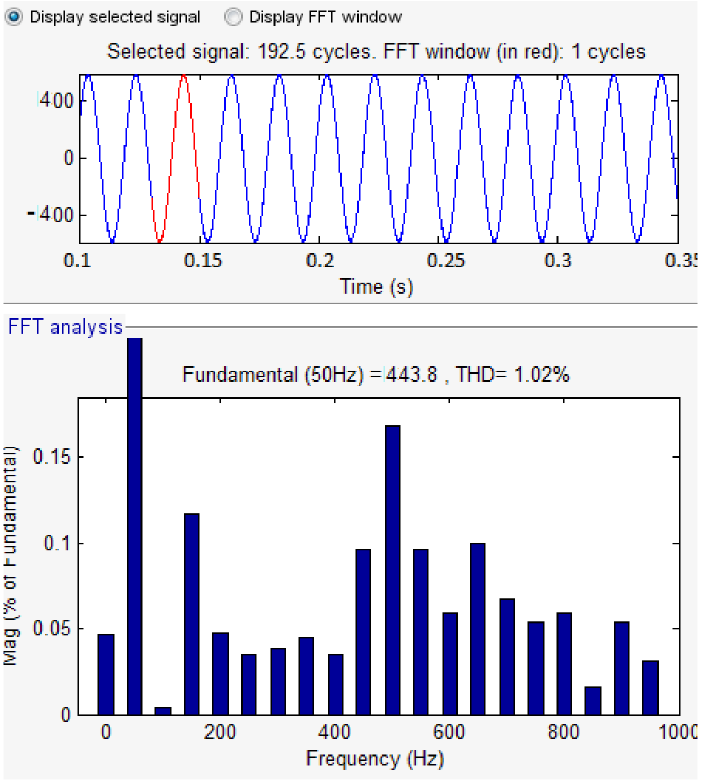


Figure 18: Source voltage and total harmonic distortion with fuzzy-correlation based UPQC

5. CONCLUSION

UPQC can mitigate voltage sag, swell, sag swell, harmonics and balancing of loads. The load current has total harmonic distortion of 28.65% and it has been reduced by80.29% at PCC and 10.52% reduction at source point and source current harmonics are reduced by 38.83% using the Unified Power Quality Conditioner with fuzzy-correlation control schemeas compared with fuzzy PI controller. The DC bus voltage of UPQC is regulated by using fuzzy controller and terminal voltage can be regulated with hybrid correlation – fuzzy control scheme. The proposed control scheme is used for estimation of gating pulses for series and shunt voltage source converters of UPQC. It is concluded that the proposed fuzzy–correlation control scheme based UPQC reduces total harmonic distortions than fuzzy PI controller within IEEE-519 standard limit (< 5%) [15].

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