POWER QUALITY ENHANCEMENT USING UPQC

Tushar Kumrawat[1], Deepak Bhataniya[2]

[1]M.Tech. Student JIT Borawan, Khargone (M.P.) INDIA
[2] Assistant Professor, Department of Electrical and Electronics JIT Borawan, Khargone (M.P.) INDIA

Abstract - *Harmonics are introduced into the supply system as a result of the advanced use of power electronic equipment, causing an issue with the quality of power delivered. In both the industrial and home sectors, good power quality is essential for our day-to-day use of appliances. The goal of this thesis is to apply control strategies such as SRF theory to the operation of the Unified Power Quality Conditioner (UPQC), which is a recent technology that includes both series and shunt active power filters operating at the same time, thereby improving all current and voltage related problems such as voltage sag/swell, flicker etc at the same time and helps in reduction of Total Harmonic Distortion (THD).*

In this thesis, a MATLAB simulation is used to demonstrate how the UPQC model can be used to reduce the percent THD in source voltage, source current, and load voltage waveforms caused by the use of non-linear/sensitive loads.

Key Words: **Active Power Filter, Unified Power Quality Conditioner, Total Harmonic Distortion, Power Quality, Phase Locked loop, Synchronous Reference Frame, Insulated Gate Bipolar Transistor**

1. INTRODUCTION

Electric utilities' primary goal is to provide their consumers with a continuous sinusoidal voltage of constant magnitude and frequency, as well as sinusoidal balanced currents at the AC mains. Today's AC distribution systems, on the other hand, are affected by major power quality (PQ) issues such as high reactive power, unbalanced loads, harmonic-rich load currents, and an excessive neutral current. Furthermore, these utilities are unable to avoid voltage sags, swells, surges, notches, spikes, flicker, unbalance, and harmonics in supply voltages across the load end of their customers. Many critical and sensitive loads require constant magnitude and frequency sinusoidal balanced voltages; otherwise, their protective systems will operate owing to power quality disturbances. Furthermore, these critical loads employ solid-state controllers and precision devices such as computers, processors, and other sensitive electronic components, which draw reactive power and harmonic currents, resulting in load unbalance and excessive neutral current.

Passive filters with tuned LC components were commonly used in the past to improve power quality by removing voltage and current harmonics. However, due to their expensive cost, resonance issues, enormous size, and the effect of source impedance on performance, among other factors, these filters are no longer widely used. The usage of active power filters has improved all of these issues (APF) As a result, compensating devices must be installed to eliminate harmonic currents created by nonlinear loads. One method for overcoming the aforesaid power quality issues is to utilise a unified power quality conditioner (UPQC). Control circuit designs for UPQCs have been the subject of extensive research in recent years. To achieve the right switch control signals, the goal is to obtain dependable control algorithms and fast reaction methods. Furthermore, in order to remain competitive, UPQCs must be used in a cost-effective manner while retaining their robustness and efficiency. . As a result, when designing control circuits for power quality devices, modern control theories are studied and adopted. A new control scheme for the UPQC for system harmonics compensation is proposed in this paper.

2. MAJOR POWER QUALITY PROBLEMS

The voltage quality that a consumer receives for load operation or from a specific utility is critical. The PQ problem is concerned with voltage/current waveforms that deviate from their ideal sinusoidal waveforms. The power quality deteriorated primarily at the typical sites where the grid's loads are connected. Power Quality has a variety of definitions and importance depending on how it is used in the process. From the standpoint of the designer, PQ means that there should be no fluctuation in voltage and that there should be no noise generated in the grounding system. It's voltage availability or outage minutes from the standpoint of a utility engineer.

2.1 Voltage Sag

Voltage sag refers to a drop in the rms voltage of a power frequency over a span of half a cycle to one minute. Voltage sag is a serious and drastic PQ issue, especially with voltage-sensitive loads like control processing equipment, adjustable speed drives (ASD), and computers.

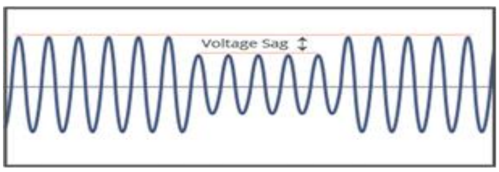


Fig-1 Voltage Sag found in Supply Voltage Effects

Relays getting tripped, loads malfunctioning, damage or complete failure of the equipment found in the load end are just a few of the drastic effects observed as a result of voltage sag difficulties.

2.2 Voltage Swell

Voltage swell is a sudden increase in the rms supply voltage varying in a range from 1.1p.u. to 1.7 p.u., with a approximate time range of from half a cycle to 1 min. These appear due to large loads sudden shutdown, capacitor banks getting energized, or due to few faults produced inside the power system. Its occurrence probability appear when compared to voltage sags is very much less, but these are more harmful to sensitive equipment/non-linear loads

Fig-2 Voltage Swell found in Supply Voltage

2.3 Interruption

Interruption is degradation in current or line voltage up to 0.1 pu of the nominal value. It is only for a duration of 60 seconds and does not extend beyond that. Equipment failures, power system faults, and control errors are the sources of interruption.

2.4 Waveform Distortion

A power system network tries to generate a sinusoidal voltage and current waveform, but it is unable to do so due to a problem, and distortions develop as a result.

There are many causes of waveform distortion:

(i) DC Offset: In an AC power system, a DC offset is the existence of DC voltage or current. The signal drifts from its real reference location due to DC offset.

(ii) Notching: When power electronics equipment is commutated, voltage disturbances are created regularly due to current transfer from one phase to another.

(iii) Harmonics: Harmonic currents and voltages are sinusoidal currents and voltages that operate at integer multiples of the fundamental frequency. Non-linear loads are the source of harmonics.

3. CLASSIFICATION OF UPQCS

UPQCs can also be classified based on the topology used, such as right shunt UPQCs and left shunt UPQCs.

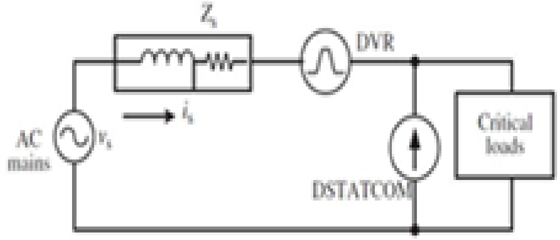


Fig-3 A right shunt UPQC as a combination of DSTATCOM and DVR

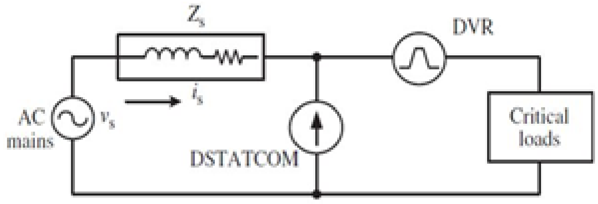


Fig -4 A left shunt UPQC as a combination of

DSTATCOM and DVR

4. BASIC CONFIGURATION

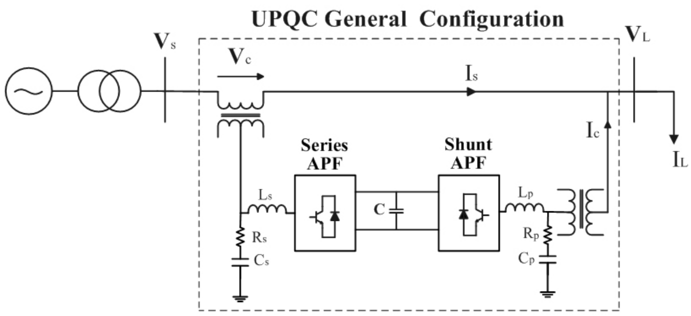


Fig -5 UPQC General Congiguration

4.1 Design of the system

The idea used here is to produce harmonic current having components which has 180° phase shift to the components of harmonic current which are generated by the use of nonlinear loads. The concept here, is totally based on injecting harmonic current in the ac system similar in amplitude but opposite in phase when compared with load current waveform harmonics.

In normal conditions, the source is assumed as a perfect sinusoidal voltage i.e

$V_s = V_m \sin(\omega t)$

Now after applying a non-linear load and as discussed above, the load current will have both fundamental component and also harmonics of higher order. This current we represent as:

$i_l(\mathrm{t}) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \theta_n)$

Now, the load power is expressed as:-

$p_l(\mathrm{t}) = V_s(\mathrm{t})\, i_l(\mathrm{t}) = I_1 V_m sin^2(\omega t) \cos\theta_1 + I_1 V_m \sin(\omega t) \cos(\omega t)\sin\theta_1 + \sum_{n=2}^{\infty} V_m \sin(\omega t)\, I_n \sin(n\omega t + \theta_n)$

$= \mathcal{P}_s(\mathrm{t}) + \mathcal{P}_c(\mathrm{t})$

In above eqn. we define $\mathcal{P}_s(\mathrm{t})$ as real power given by utility source, and $\mathcal{P}_c(\mathrm{t})$as the reactive power and the harmonic power.

From above discussion we know that APF will provide the reactive and harmonic power $pc\,(t)$, the current supplied by source is given as :-

$i_s(\mathrm{t}) = \frac{p_s(\mathrm{t})}{V_s(\mathrm{t})} = I_1 \cos\theta_1 \sin(\omega t) = I_s \sin(\omega t)$

The current $i_s(\mathrm{t})$ is and utility voltage is seen to be in phase and pure sinusoidal. At this time, the APF will provide the following compensation current i_c in the circuit.

$i_c(t) = i_l(t) - i_s(t)$

5. PQ THEORY & ANALYSIS

5.1 INSTANTANEOUS POWER THEORY

H.Akagi defined a theory based on instantaneous power in three phase systems, either with or without a neutral wire. This p-q technique works in all situations, including transient and steady-state operations. This theory employs various well-known transformation models, such as Clarke's Transformation. The voltage and current waveforms are measured here, and then transformed from a-b-c coordinates to zero coordinates. Following this transformation, we calculate active and reactive power using a series of equations, and then remove the power components with harmonics by passing them through a suitable low pass filter with a suitable frequency. We identify the reference source current in this frame only and then use Inverse Clarkes Transformation to convert this reference source current back to a-b-c coordinates using this new set of power and already derived new voltages in a different coordinate, namely zero coordinates. This new reference source current is then compared to actual observed source current waveforms, with the error being fed via a hysteresis controller with a specific band to obtain a different gate pulse for inverter operation. The following is a basic block diagram that explains the entire operation of this significant p-q theory:-

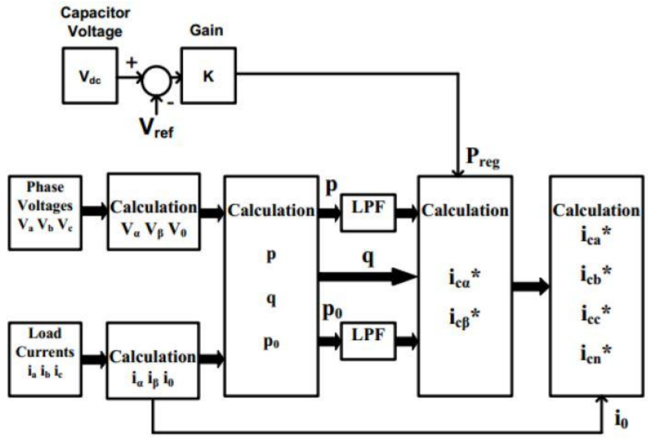


Fig -6 p-q control strategy to generate reference current

5.2 Analysis of P-Q Approach

Clarke's transformation needed for converting source voltage and current from a-b-c to $\alpha - \beta - 0$ coordinate is given by following matrix:-

$$\begin{bmatrix} V_{0s} \\ V_{\alpha s} \\ V_{\beta s} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix}$$

Similarly current transformation is:-

$$\begin{bmatrix} \mathrm{i}_{0s} \\ \mathrm{i}_{\alpha s} \\ \mathrm{i}_{\beta s} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \mathrm{i}_{sa} \\ \mathrm{i}_{sb} \\ \mathrm{i}_{sc} \end{bmatrix}$$

$P_{3\text{-}\phi}(\mathrm{t}) = V_{sa}i_{sa} + V_{sb}i_{sb} + V_{sc}i_{sc} = V_{\alpha s}i_{\alpha s} + V_{\beta s}i_{\beta s} + V_{0s}i_{0s}$

$= \mathcal{P}_a(\mathrm{t}) + \mathcal{P}_b(\mathrm{t}) + \mathcal{P}_c(\mathrm{t}) = \mathcal{P}_{\alpha s}(\mathrm{t}) + \mathcal{P}_{\beta s}(\mathrm{t}) + \mathcal{P}_{0s}(\mathrm{t})$

$= \mathcal{P}_r(\mathrm{t}) + \mathcal{P}_{0s}(\mathrm{t})$

Here we define $\mathcal{P}_r(t) = \mathcal{P}_{\alpha s}(\mathrm{t}) + \mathcal{P}_{\beta s}(\mathrm{t})$ as instantaneous real power & $\mathcal{P}_{0s}(\mathrm{t})$ as inst. Power of zero sequence. Here we can note down an important benefit of this transformation in which separation of system zero sequence component is easily done.

5.3 Compensation Strategy

In order to compensate $P_{\alpha q}$ & $P_{\beta q}$ by which $P_{\alpha q} + P_{\beta q} = 0$, the filter is injecting compensating current namely $i_{\alpha c}$ & $i_{\beta c}$ to reactive current such that:-

$i_{\alpha c} = i_{\alpha q}$ & $i_{\beta c} = i_{\beta q}$

The current $i_{\alpha c}$ is providing the power $P_{\alpha q}$ and $i_{\beta c}$ is providing the component $P_{\beta q}$. So the voltage $V_{\alpha s}$ & $V_{\beta s}$ need to provide only $P_{\alpha p}$ and $P_{\beta p}$. It can also be noted that, the power necessary to compensate for $i_{\alpha q}$ is equal to the negative of the power necessary to compensate for $i_{\beta q}$.

The current sources $i_{\alpha c}$ and $i_{\beta c}$ is representing APF, which is generated from the VSI inverter & they are controlled accordingly to produce $i_{\alpha q}$ and $i_{\beta q}$. Hence no source of DC is necessary and no large energy storage element is essential for compensating the reactive powers. The reactive power required by one phase is instantaneously supplied by the other phase. Hence size of capacitor is not depend on the amount of reactive power which needs to be compensated.

6. SYNCHRONOUS REFERENCE FRAME CONTROL OF UPQC

For the operation of the UPQC model, the SRF controlling approach is quite similar to the instantaneous reactive power theory method. The fact that only load current is required for the creation of reference current is a key characteristic of this algorithm, which means that disturbances in the source or voltage distortions will have no detrimental impact on the performance of the intended UPQC system. We optimised the system without using transformer voltage, load, or filter current measurements in the suggested SRF approach for UPQC. As a result, the number of measurements is reduced, and system performance is improved.

Signals of current and voltage are first sensed and then translated into a rotating frame (dq0) in this method. The transformation angle (ωt) denotes the suggested reference frame's angular position. This is coordinated with the 3-ac voltage and rotates at a consistent speed. PLL methods find load reactive currents and harmonic currents under the set condition of a nonlinear load. Then, to compensate for neutral current, harmonics, and reactive power, currents with the same amplitude but reverse phase are generated and injected into the proposed system. The α−β−0 coordinates are stationary in the stationary reference frame, whereas the d-q-0 coordinate rotates in synchronism with supply voltages in the SRF.

6.1 Id & Iq Components Definition

According to the suggested SRF theory, the "d" coordinate component of current, i.e., the positive-sequence component, is always in phase with voltage. The current's "q" coordinate component, iq, is discovered to be perpendicular to the current's "id" component. This iq is known as negative sequence reactive current. We call the "0" coordinate component of current the zero sequence component since it is orthogonal to both id and iq.

If iq is discovered to be negative, the load will pursue inductive reactive power; if it is found to be positive, the load will pursue capacitive reactive power. In the proposed nonlinear power systems, the id and iq components will have both oscillating (id & iq) and average components (id & iq), as shown in the equation below,

$$i_d = \overline{i_d} + \mathrm{i_d} \quad \& \quad i_q = \overline{i_q} + (\mathrm{i_q})$$

The oscillating part responds to the oscillating component in both coordinates, while the average part relates to active current (i_d) and reactive current (i_q). As a result, wherever APF applications are used, our goal will be to separate the fundamental positive sequence component in order to reduce or remove harmonics

6.2 Modified Phase Locked Loop

The typical PLL will function poorly for large distortion and unbalanced systems, and the transformation angle (ωt) will not vary completely linearly with time as required. Under highly distorted conditions, a modified PLL can be utilised to improve the quality of the UPQC filtering operation and results.

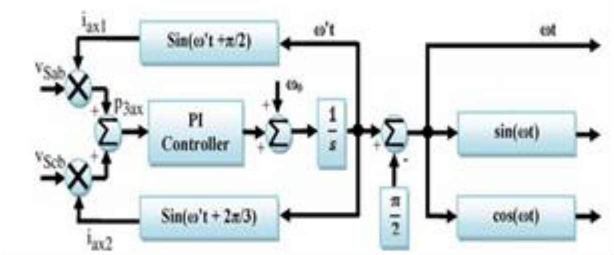


Fig -7 PLL block diagram

First we calculate the 3-Ø instantaneous source line voltages & $Vscb$. This measured line voltages is multiplied with auxiliary ($iax1$ & $iax2$) feedback currents of unity amplitude, in which one will lead leads 120° from the other to achieve auxiliary instantaneous active power (p_{3ax}). This is passed through a P-I controller. The referred fundamental angular frequency (ω_0 = 2πf) is added to result of P-I controller for the purpose to stabilize output. The result is then passed through an integrator block to get auxiliary transformation angle (ωt).The resultant produced ωt leads 90° to system's fundamental frequency; and hence −90° is added to integrator output for getting system fundamental frequency. When this instantaneous power p_{3ax} reaches zero or gets low frequency oscillation then PLL is said to reach a stable operating point. Also the output ωt will reach fundamental positive sequence component of line voltage.

6.3 Reference-Voltage Signal Generation for series APF

In the UPQC model, the control algorithm for series APF entails calculating the reference voltage that must be injected by the series transformer, which it does by comparing the component of positive sequence of source voltage with the load voltages. The source voltage is measured and then translated into the d-q-0 frame of reference using the matrix below:

$$\begin{bmatrix} V_{s0} \\ V_{sd} \\ V_{\beta s} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \sin(\omega t) & \sin(\omega t - 120^\circ) & \sin(\omega t + 120^\circ) \\ \cos(\omega t) & \cos(\omega t - 120^\circ) & \cos(\omega t + 120^\circ) \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix}$$

□□□ & Vsd are the instantaneous components in the new SRF and both of them has got oscillating (V_{sd}&V_{sq}) as well as average components (V_{sd}&V_{sq} in them. The oscillating part includes within it harmonic and negative sequent part of the utility voltage due to non-linear load. The average part has within it the positive sequence voltage component.

Hence we can say that :-

$V_{sd} = \bar{V}_{sd} + \bar{V}_{sq}$

The harmonic part is separated by passing the d-component voltage V_sdvia LPF. The output of this LPF is only the average component$\bar{V}$_sd. The zero and negative components namely Vsq & $Vs0$ of source voltage is terminated or made to zero for compensating harmonics of load voltage, and unbalance. The reference load voltage is calculated by passing the new set of components of d-q-0 frame via a inverse transformation which converts it again to the original a-b-c reference frame. This inverse transformation called Inverse Parks transformation is shown below:-

$$\begin{bmatrix} V^*_{la} \\ V^*_{lb} \\ V^*_{lc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \sin(\omega t) & \cos(\omega t) \\ \frac{1}{\sqrt{2}} & \sin(\omega t - 120^\circ) & \cos(\omega t - 120^\circ) \\ \frac{1}{\sqrt{2}} & \sin(\omega t + 120^\circ) & \cos(\omega t + 120^\circ) \end{bmatrix} \begin{bmatrix} 0 \\ \bar{V}_{sd} \\ 0 \end{bmatrix}$$

The resultant reference voltages as above (V^*_{la}, V^*_{lb} ,& V^*_{lc}) and actual sensed load voltages (V_{la} ,V_{lb} & V_{lc}) are compared and then passed via a sinusoidal pulse width modulation(PWM) for controlling switching or gate signals for the series filter operation of IGBT used and to fight against and remove all problems related with voltage, harmonics in voltage, sag/swell, voltage unbalance at the PCC. The whole idea of generating reference

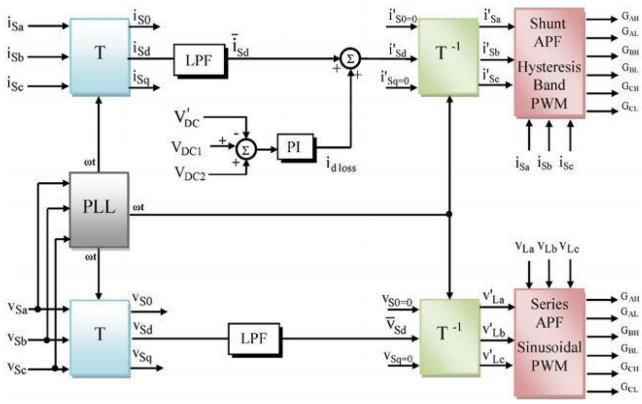


Fig-8 SRF control for UPQC operation

6.4 Reference-Source-Current Signal Generation for Shunt APF

The shunt APF as discussed earlier is useful for avoiding the problems related with the current harmonics generated in our UPQC model with nonlinear load. It also takes care for reactive power compensation. The sensed source current are transformed to d–q–0 coordinates by the same Parks transformation equation, where the angular frequency (ωt) comes from modified PLL.

$$\begin{bmatrix} i_{s0} \\ i_{sd} \\ i_{sq} \end{bmatrix} = T \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix}$$

T = Parks transformation matrix

The new transformed instantaneous source current in d-q-0 frame namely isd & isq again includes in it both oscillating components ($\tilde{\imath}_{sd}$ & $\tilde{\imath}$) and average components ($\bar{\imath}_{\bar{s}\bar{d}}$ & $\bar{\imath}_{\bar{s}\bar{q}}$) as well. Oscillating component will contain a combination of harmonics and negative sequence component whereas the average component includes only positive sequence current component which corresponds to reactive current. The zero sequence part ($is0$) will appear under unbalanced load conditions. In our SRF method average component of positive-sequence ($\overline{\imath s d}$) in the d-axis and the zero- and negative-sequence component ($is0$ & isq) in the 0- and q-axes of the source currents, in for compensating harmonics and unbalances produced in the non-linear load.

For compensating the active power losses of the UPQC power circuit, Series APF injects active power in the power system, which results in regulation of dc-link voltage across capacitor. To make dc-link voltage constant, a part of active power is taken from the power system by shunt APF. For this task, the voltage of dc-link is compared with a set reference value (Vdc), and then passed through a PI controller whose output is the required active current ($idloss$). The d-component of source current i.e isd is passed through a LPF to get its average component i.e $(\overline{isd})$ .Now this average component and required active current i.e *idloss* are added to get fundamental reference component.

$$i'_{sd} = i_{sd} + i_{dloss}$$

The zero sequence and negative sequence component of source current is set to zero to compensate, distortion, harmonics, and reactive power in source current. The reference source current is produced by inverse Parks transformation as mention below:-

$$\begin{bmatrix} i'_{sa} \\ i'_{sb} \\ i'_{sc} \end{bmatrix} = T^{-1} \begin{bmatrix} 0 \\ i'_{sd} \\ 0 \end{bmatrix}$$

Where, T^{-1} = inverse Parks transformation Both the measured and reference source current are compared now and passed through hysteresis band current controller for getting the gating signals for operation of shunt APF in the given UPQC model and thereby eliminating all the current related problem from the system.

7. RESULTS

7.1 System Parameters:

Supply voltage (three phase):	400 V	Non-linear rectifier load	R=60Ω, L=0.15mH
Frequency	50Hz	DC ref. voltage	700V
DC capacitor	100μF		

7.2 Performance of UPQC under voltage swell

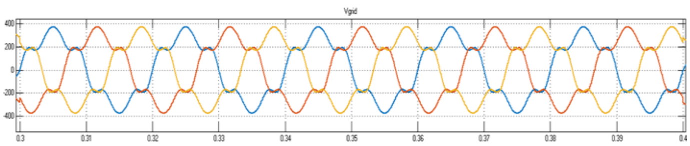


Fig-9 Grid Voltage

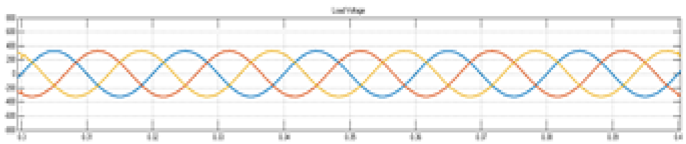


Fig-10 Load Voltage

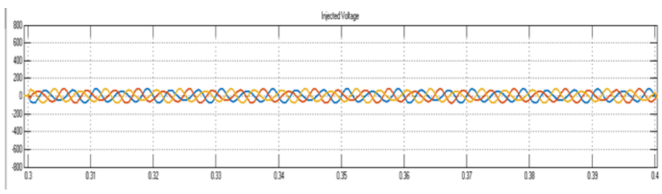


Fig-11 Injected voltage

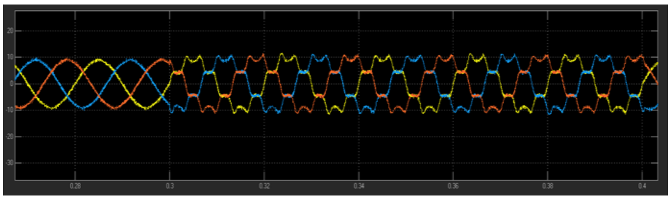


Fig-12 Source current under voltage swell

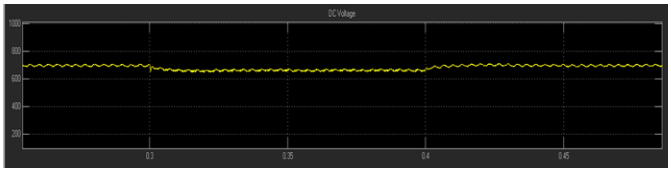


Fig-13 Performance of UPQC under voltage swell

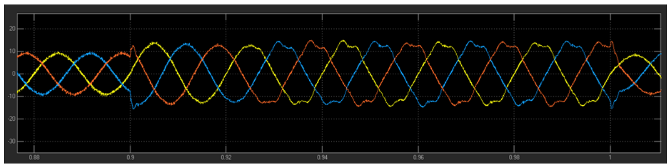


Fig-14 Source current under voltage sag

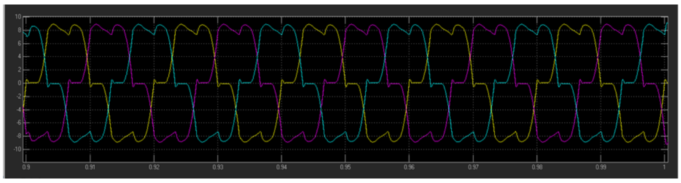


Fig-15 Load current under voltage sag

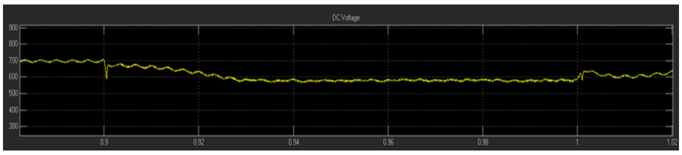
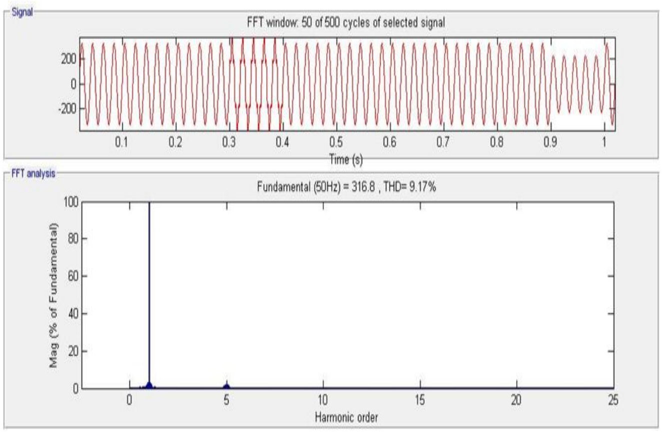
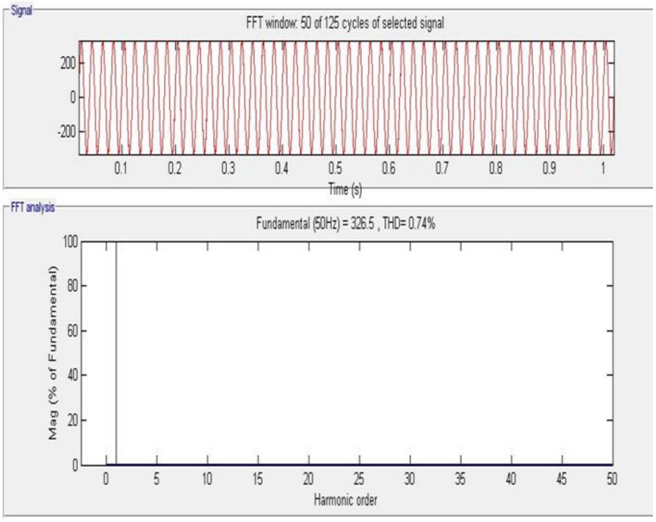


Fig-16 Performance of UPQC under voltage sag

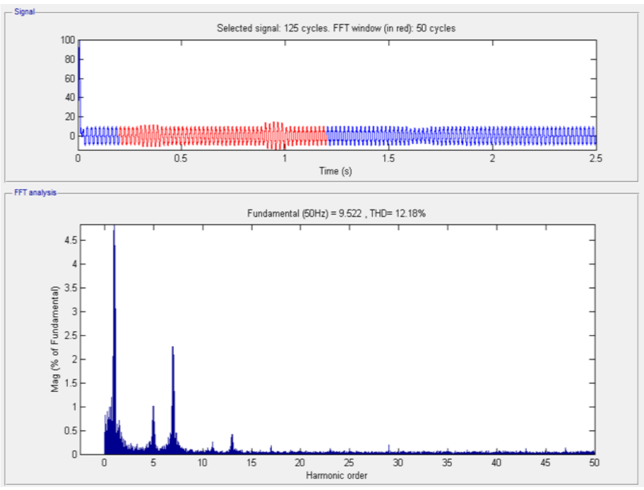
7.3 FFT analysis of Load voltage Without UPQC



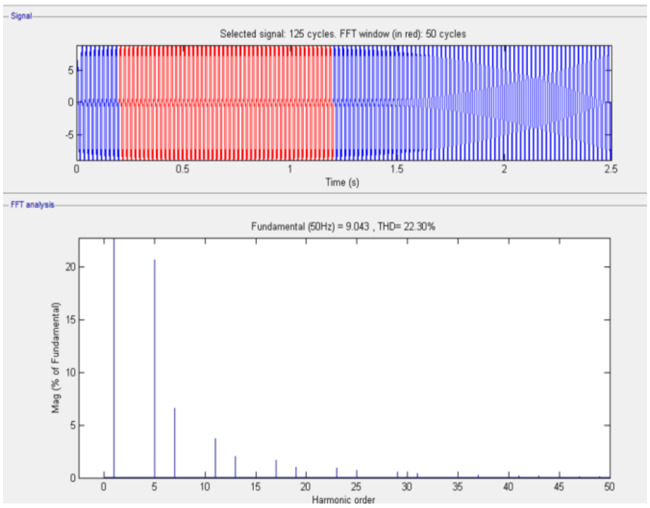
7.4 FFT analysis of Load voltage With UPQC



7.5 FFT analysis of source current



7.6 FFT analysis of load current



8. CONCLUSION

This work outlines an improved control method for the UPQC system's operation. For the APF operation, several control techniques are investigated, including p-q theory, SRF-based technique, and unit vector template creation. The SRF theory is used to simulate the UPQC model in MATLAB. The UPQC system's shunt portion eliminates all current-related harmonic problems, while the system's series-connected APF eliminates all voltage harmonics caused by the use of nonlinear loads. The total THD in the system has improved, as seen by the waveforms displaying the resultant THD before and after UPQC operation.

REFERENCES

[1] D. C. Bhonsle, R. B. Kelkar, “Design and Simulation of Single Phase Shunt Active Power Filter”, 2011 International Conference on Recent Advancements in Electrical, Electronics and Control Engineering.

[2] V. Khadkikar, P. Aganval, A. Chandra, “ A Simple New Control Technique For Unified Power Quality Conditioner (UPQC)”, 2004 11th International Conference on Harmonics and Quality of Power.

[3] Akagi, Y. Kanazawa, A. Nabae , “Generalized Theory of the Instantaneous Reactive Power in Three Phase Circuits”, in Proc. IPEC-Tokyo’83 Int. Conf. Power Electronics, Tokyo, pp. 1375-1386

[4] M.Kesler,E.Ozdemir,Senior Member, “Synchronous-Reference-Frame-Based Control Method for UPQC under unbalanced and distorted load conditions”, IEEE transactions on industrial electronics, vol. 58, no. 9, september 2011.

[5] I.Axente, M.Basu and M.Conlon, “dc link voltage control of UPQC for better dynamic performance”, Electric Power Systems Research 81 (2011) 1815–1824.

[6] Yash Pal, A. Swarup, Bhim Singh, “A control strategy based on UTT and Icosϕ theory of three phase , four wire UPQC for power quality improvement ” International Journal of Engineering, Science and Technology Vol. 3, No. 1, 2011, pp. 30-40.

[7] S.Shankar, A.Kumar and W.Gao “Operation of Unified Power Quality Conditioner under Different Situation,” IEEE Proc. Power and Energy Society General Meeting, July 2011, pp.1-10.

[8] B. Singh, A. Chandra and K. A. Haddad, Power Quality: Problems and Mitigation Techniques. London: Wiley, 2015.

[9] Design & performance analysis of 3-phase solar PV Integrated UPQC Sachin Devassy ; Bhim Singh,2016

[10] Metin Kesler and Engin Ozdemir, "A Novel Control Method for Unified Power Quality Conditioner(UPQC) Under Non-Ideal Mains Voltage and Unbalanced Load Conditions," IEEE Conference on Applied Power Electronics, Feb. 2010, pp. 374-379

[11] Mekri Fatiha, Machmoum Mohamed, Ait-Ahmed Nadia "New hysteresis control band of an unified power quality conditioner" M. Fatiha et al. /Electric Power Systems Research 81 (2011) 1743– 1753

[12] V. Khadkikar, "Enhancing electric power quality using UPQC: a comprehensive overview," *IEEE Transactions on Power Electronics*, vol. 27, no. 5, pp. 2284–2297, 2012.

[13] M. Kesler and E. Ozdemir, "Synchronous-reference-frame-based control method for UPQC under unbalanced and distorted load conditions," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 9, pp. 3967–3975, 2011.

[14] N. Zhu, D. Xu, B. Wu, F. Liu, N. R. Zargari, and M. Kazerani, "Common-mode voltage reduction methods for current-source converters in medium-voltage drives," *IEEE Transactions on Power Electronics*, vol. 28, no. 2, pp. 995–1006, 2013.

[15] P. E. Melin, J. R. Espinoza, L. A. Moran et al., "Analysis, design and control of a unified power-quality conditioner based on a current-source topology," *IEEE Transactions on Power Delivery*, vol. 27, no. 4, pp. 1727–1736, 2012.

[16] A. Terciyanli, M. Ermis, and I. Cadirci, "A selective harmonic amplification method for reduction of kVA rating of current source converters in shunt active power filters," *IEEE Transactions on Power Delivery*, vol. 26, no. 1, pp. 65–78, 2011.

[17] V. Kinhal, P. Agarwal, and H. O. Gupta, "Performance investigation of neural-network-based unified power-quality conditioner," *IEEE Transactions on Power Delivery*, vol. 26, no. 1, pp. 431–437, 2011.

[18] C. H. da Silva, R. R. Pereira, L. E. B. da Silva, G. Lambert-Torres, B. K. Bose, and S. U. Ahn, "A digital PLL scheme for three-phase system using modified synchronous reference frame," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 11, pp. 3814–3821, 2010.