Abstract—There is a growing interest in equipment for mitigation of power quality disturbances, especially in newer devices based on power electronics called “custom power devices”, able to deliver customized solutions to power quality problems. UPQC (Universal Power Quality Conditioner) is the youngest member of a join that family. The function of UPQC includes mitigation of disturbance that affects the performance of the critical load. The UPQC can compensate voltage sag/swell, voltage and current imbalance; mitigate current and voltage harmonics and control the power flow and voltage stability. Considering the economic feasibility of UPQC its application should be case specific because it covers a wide range of operations. So in specific case as per the need, mode of operation should follow the same. This implies the need for specific control strategy also. Till date a considerable number of publications exist regarding the control strategies of UPQC in both time-domain and frequency-domain. In this paper typical control strategies in time-domain for harmonic detection, reactive power compensation, voltage sag and swell, voltage and current imbalance have been simulated and the results are analyzed and finally ending up with conclusions on the feasibility of application of that particular control strategy in specific case.

I. INTRODUCTION

In the past, equipment used to control industrial process was mechanical in nature, being rather tolerant of voltage disturbances, such as voltage sags, spikes, harmonics, etc. In order to improve the efficiency and to minimize costs, modern industrial equipment typically uses a large amount of electronic components, such as programmable logic controllers (PLC), adjustable speed drives (ASD), power supplies in computers, and optical devices. Nevertheless, such pieces of equipment are more susceptible to malfunction in the case of a power system disturbance than traditional techniques based on electromechanical parts. As a result minor power disruptions may completely interrupt whole automated factories because of sensitive electronic controllers. It is thus natural that electric utilities and end-users of electrical power are becoming increasingly concerned about the quality of electric power in distribution systems. The term “power quality” has become one of the most common expressions in the power industry during the current decade.

Regarding transmission systems, they were over dimensioned in the past, with large stability margins. Therefore, dynamic compensators, such as synchronous condensers, were seldom required. Over the last 10-20 years, this situation has been changed since the construction of generation facilities and new transmission lines has become unfeasible due to financial and environmental constraints.

From the economical point of view, the most important factor has been the progressive deregulation of the electrical energy transmission/distribution market worldwide. The utilities are aware of the importance of delivering to their customers a voltage with “good quality” in order to satisfy and consequently retain them.

Electronic filters in both active and passive form is extensively used in different applications especially in Signal Processing. Communication circuits and many more but all those had the basic drawback of handling high power signals at power frequency in electrical systems. Either they malfunction or get damaged early so it was not feasible for application in power circuits. With the evolution of power electronics we eventually have electronic devices that are capable of handling high power circuits at power frequency. From then the journey had started with invention of Power Diodes, continues with Power BJT’s, Power MOSFET’s, Thyristors, GTO’s, IGBT’s and many more. Eventually it became possible to develop High Power Rectifiers, Inverters that can be easily used in power circuits. Also the development has been heavily accelerated with invention of highly sophisticated firing circuits using PWM, SVPWM, and Hysterisis Controller to achieve a controlled output over a wide range. The recent advancements include Multi-level and Multi-pulse controlled inverter and rectifier that has the capability of generating most precise output also with minimum ripples or harmonics.

A three-phase UPQC consists of two three-phase voltage source inverters connected in cascade through a common dc link. Series Inverter (SEI) is connected in series with the incoming utility supply through a low-pass filter and a voltage injecting transformer and Shunt Inverter (SHI) is connected in parallel with the sensitive load, whose power quality needs to be strictly maintained. The main purpose of SHI is to provide required VAR support to the load, and to suppress the load current harmonics from flowing towards the utility and it is operated in current controlled mode. SEI is responsible for compensating the deficiency in voltage quality of the incoming supply, such that the load end voltage remains insensitive to the variation of utility supply. UPQC also has a few other important components that are essential for interfacing of the same.

II. SHUNT INVERTER CONTROL STRATEGIES

A. Synchronous Detection Method [1]

In this method, the three-phase source currents are assumed to be balanced after compensation. Thus \( I_{sa} = I_{sb} = I_{sc} \)
where $I_{sa}$, $I_{sb}$ and $I_{sc}$ are the amplitude/peak value of the three-phase source currents after compensation.

The real power consumed by the load can be represented as:

$$P = [v_{La} \ v_{Lb} \ v_{Lc}] [I_{La} \ I_{Lb} \ I_{Lc}] \ldots \ldots (1)$$

Where $v_i$ and $i_i$ represents load voltage and current respectively.

Fig. 1 represents the block diagram of the system. The real power $P$ is sent to a low-pass filter to obtain its average value $P_{dc}$. The required expressions are illustrated in the following section.

The real power is then split into the three phases of the mains supply by the following:

$$P_a = \frac{P_{dc} \ V_a}{V_{sa}} \ \ \ \ P_b = \frac{P_{dc} \ V_b}{V_{sb}} \ \ \ \ P_c = \frac{P_{dc} \ V_c}{V_{sc}} \ldots \ldots (2)$$

Here $V_a$, $V_b$ and $V_c$ are the amplitude/peak value of the load voltages and $V_{sa}$ is the sum of them. The desired source currents can be calculated as:

$$I_{sa} = \frac{2v_{La} \ P_a}{V_a^2} \ \ \ \ I_{sb} = \frac{2v_{Lb} \ P_b}{V_b^2} \ \ \ \ I_{sc} = \frac{2v_{Lc} \ P_c}{V_c^2} \ldots \ldots (3)$$

The reference compensation currents are calculated as:

$$I_{sa} = I_{sa} - I_{sa} \ \ \ \ I_{sb} = I_{sb} - I_{sb} \ \ \ \ I_{sc} = I_{sc} - I_{sc} \ldots \ldots (4)$$

This method can be extensively used for compensation of reactive power, current imbalance and mitigation of current harmonics. It can be concluded as the simplest method as it requires minimum calculations. However this method suffers a drawback from individual harmonic detection and its mitigation.

B. Synchronous Fundamental d-q Frame Method [2], [3]

This method is derived from the space vector transformation of the input signals in the a-b-c coordinates (stationary reference frame) from the input sensors and then transformed into the orthogonal d-q coordinates (rotating reference frame with fundamental frequency) by means of the Park’s Transformation. The d-q frame rotates with the fundamental angular frequency that makes the fundamental signals to appear as dc components and the harmonic components are represented as ac signals.

Using this method current harmonics of all orders can be separated from the fundamental by using a low-pass filter or using a high-pass filter. In case of using low-pass filter the output is purely dc signal which can be transformed back to a-b-c co-ordinates to obtain the fundamental current signal.

The above block diagram (Fig. 2) demonstrates the method. The d-q components of current signal contains both dc and ac signals and using Low-Pass Filter (LPF) the signal is filtered and applying reverse transformation we can obtain the fundamental value of the given input current signal. The generation of reference compensation is same as in previous case. To maintain a constant frequency a virtual PLL circuit is used in the simulation.

In this method the a-b-c to d-q transformation or Park’s Transformation is obtained by using the following transformation matrix followed by the inverse transformation.

$$\begin{bmatrix} i_d \\ i_q \\ \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos \left(\theta - \frac{2\pi}{3}\right) & \cos \left(\theta - \frac{4\pi}{3}\right) \\ \sin \theta & \sin \left(\theta - \frac{2\pi}{3}\right) & \sin \left(\theta - \frac{4\pi}{3}\right) \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \ldots \ldots (5)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \cos \left(\theta - \frac{2\pi}{3}\right) & -\sin \left(\theta - \frac{2\pi}{3}\right) & 0 \\ \cos \left(\theta + \frac{2\pi}{3}\right) & -\sin \left(\theta + \frac{2\pi}{3}\right) & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ \end{bmatrix} \ldots \ldots (6)$$

this is the simplest of methods that uses transformation. In addition to harmonic identification it can also compensate current imbalance to some extent as imbalance also induces some ac component that comes into the picture when d-q transformation is applied to that signal containing imbalance.
in both magnitude and phase. Particularly in absence of neutral wire in a three phase system imbalance affects the other phases also. It is used in both SEI and SHI control strategies in UPQC for harmonic mitigation and imbalance compensation. But it cannot detect individual harmonics so selective harmonic mitigation is not possible using this method.

C. Instantaneous Power Method [4], [5], [6]

This method utilizes the space vector transformation of the input signals in the a-b-c coordinates (stationary reference frame) from the input sensors and then transformed into the d-q coordinates (rotating reference frame with fundamental frequency) by means of the Park’s Transformation. The d-q frame rotates with the fundamental angular frequency that makes in this frame the fundamental signals to appear as dc components and the harmonic components are represented as ac signals.

Applying this transformation both system voltage and system current signals extracted from the sensors is transformed into orthogonal d-q coordinates. The using these system power (active and reactive) are calculated. These power signals contain both ac and dc signals where dc signal represent the actual power and ac signals represents the power due to the presence of harmonic components.

Fig. 3. Block diagram representation of Instantaneous Power Theorem.

Hence the power signals are filtered using a low-pass filter and the output dc component is separated. Again using further calculations d-q component of the system fundamental current is calculated and after reverse transformation the fundamental a-b-c signal of the system current is derived. The overall block diagram is shown in Fig. 3.

Mathematical equations are shown below:

\[
\begin{align*}
\begin{pmatrix}
    i_d \\
    i_q
\end{pmatrix}
&= \begin{pmatrix}
    \cos \theta & \cos \left( \theta + \frac{2\pi}{3} \right) \\
    \sin \theta & \sin \left( \theta + \frac{2\pi}{3} \right)
\end{pmatrix}
\begin{pmatrix}
    i_a \\
    i_b \\
    i_c
\end{pmatrix} = \ldots (7)
\end{align*}
\]

\[
\begin{align*}
\begin{pmatrix}
    v_d \\
    v_q
\end{pmatrix}
&= \begin{pmatrix}
    \cos \theta & \cos \left( \theta + \frac{2\pi}{3} \right) \\
    \sin \theta & \sin \left( \theta + \frac{2\pi}{3} \right)
\end{pmatrix}
\begin{pmatrix}
    v_a \\
    v_b \\
    v_c
\end{pmatrix} = \ldots (8)
\end{align*}
\]

Power calculation and inverse calculations for current:

\[
\begin{align*}
\begin{pmatrix}
    p \\
    q
\end{pmatrix}
&= \begin{pmatrix}
    v_d & v_q \\
    -v_q & v_d
\end{pmatrix}
\begin{pmatrix}
    i_d \\
    i_q
\end{pmatrix} = \ldots (9)
\end{align*}
\]

\[
\begin{align*}
\begin{pmatrix}
    i_d \\
    i_q
\end{pmatrix}
&= \frac{1}{v_d + v_q}
\begin{pmatrix}
    v_d & v_q \\
    -v_q & v_d
\end{pmatrix}
\begin{pmatrix}
    p \\
    q
\end{pmatrix} = \ldots (10)
\end{align*}
\]

Applying this theorem reactive power can also be compensated by setting the reactive power \( q = 0 \) in during current calculation. In that case the fundamental current is in phase with the system voltage but for this compensation the rating of the SHI has to be judiciously chosen. Again unlike the previously explained methods selective harmonic elimination is not possible in this method.

Also this theorem is valid for three phase balanced supply and in the case of UPQC it is assumed that the SEI eliminates the disturbances in the supply voltage so this theorem is valid for UPQC system.

D. Synchronous Harmonic d-q Frame.[7], [8]

This method is almost the same as Synchronous Fundamental d-q Frame method, but the main difference is here the reference rotating frame is rotated at the desired harmonic frequency to obtain the individual harmonic signal and its details. By using this method, harmonic of any order can be individually identified from any signal containing that harmonic. In previous methods it is not possible to detect individual harmonic component which is possible in this method.

Fig. 4. Block diagram representation of Synchronous Harmonic d-q Frame Method. ‘N’ is the order of the desired harmonic order to be identified.

The speed of the rotating frame is changed by changing the output of the PLL circuit according to the harmonic order required to be identified. In this method the a-b-c to d-q transformation is obtained by using the following transformation matrix followed by the inverse transformation. ‘N’ is the desired harmonic order that requires to be identified.

This method can be considered as the substitute of Fourier Transform method because earlier to this it is the only method to analyze a signal and also in frequency domain. This method is totally in time domain and naturally involves the lesser time for computation as the calculation is much simpler than frequency domain calculation.
III. SERIES INVERTER CONTROL STRATEGIES

A. Modified Synchronous Fundamental d-q Frame

A pure balanced sinusoidal three phase balanced wave when transformed into d-q frame ideally the d-axis value will be constant and q-axis value will be 0. Using this basic principle this method is developed

In this method a constant value is transformed from d-q to a-b-c coordinates using Inverse Park’s Transform to get the desired sinusoidal wave and the output sinusoidal wave is compared with the system wave and by this principle the compensating wave is extracted. The following block diagram (Fig. 5) illustrates the procedure. The system wave inputs are in per unit values.

![Block diagram representation of Modified Synchronous Fundamental d-q Frame Method.](image)

This method is effective for compensation of Voltage Imbalance, Voltage Sag and Swell; as the system voltage is always tried to maintain at its rated value so form that context this method is effective. This method can be further modified to the following shown in following block diagram.

In this method the system waves are measured in per unit values and they are transformed into d-q frame. Then using low pass filter first the dc component is extracted and harmonics are separated by negation of the dc component with the original transformed component. Followed by the comparison of that dc component with the reference i.e. d-axis value=1 and q-axis value=0. Further these two components are summed up to get the get the compensating component in d-q frame. As a result any abnormality in the voltage signal gets compensated in this method. Further inverse transform yields the compensating voltage wave that required to be generated by the series inverter.

IV. SIMULATION

The software used for performing the simulation is SIMULINK® 7.0 which is in built toolbox included in MATLAB® 7.3 (Release 2006a). Discrete Variable Step (ODE 23t) solver is used for calculations during simulation.

The simulation is performed in a three-phase three-wire system. The system voltage is sensed in actual and per unit value both. The three-phase nonlinear load injects 5th, 7th, 11th, 13th and 17th harmonics in the system current.

V. RESULTS

A. Shunt Inverter Control strategies

1) Synchronous Detection Method: Assuming the nonlinear load affects the system equally in all the phases the phase-a result are shown in following Fig. 6

![Fig. 6. Results of the simulation of Synchronous Detection Method. The system signal is compensated after 0.2 sec of start.](image)

It can be clearly seen from the plot that after compensation the system current is purely sinusoidal (THD= 0.1%) and also the phase lag is being compensated. The Fourier analysis of the system wave fundamental and compensated wave fundamental completely verifies the conclusion.

The Fourier analysis plots shown above in Fig. 7 represent the plot of magnitude and phase of the fundamental wave of system. It is clear from the plot that after compensation the phase has been modified but with that the peak value of the compensated current fundamental is reduced.

![Fig. 7. Fourier analysis of the fundamental signal in Fig. 6](image)

2) Synchronous Fundamental d-q Frame Method: This method in basically used for harmonic detection only. But the main drawback associated with this method is it cannot detect the individual harmonics or rather can provide us any information regarding that. During simulation the cut off frequency of the low-pass filter is set to 20Hz.

![Fig. 8. Results of the simulation of Synchronous Fundamental d-q Frame Method. Compensation is applied after 0.2 sec of start.](image)
The compensated wave (Fig. 8) is free from harmonics and purely sinusoidal. Also from the Fourier analysis plot in Fig. 9 it is clear that the compensation is achieved without any change in magnitude or in phase of system fundamental wave.

3) Instantaneous Power Method: Fig. 10 shows the results of simulation of this method. Here both harmonics and reactive power are being compensated as the phase of the compensated wave is nearly matching to the phase of system phase. Following Fourier analysis (Fig. 11) supports the fact but it is also clear from that that the compensated wave fundamental magnitude somehow decreases.

4) Synchronous Harmonic d-q Frame Method: Apart from Fourier analysis for detection of harmonics or information about magnitude and phase, this method enables us to get information of three phase system without individual calculations for each phase.

In this simulation the 5th, 7th, 11th and 13th harmonic is identified and injected into the system wave and the compensated waveform (Fig. 12) and its subsequent Fourier analysis plots (Fig. 13) are presented in figure respectively. Here also it can be concluded that the system wave fundamental and the compensated wave fundamental matches each other in both magnitude and phase.

B. Series inverter Control Strategies

Here the simulation is performed twice. First time it is performed for harmonics compensation and voltage sag compensation and second time for compensation of voltage imbalance

1) Modified Synchronous Fundamental d-q Frame: In this method reference voltage wave is compared with the system voltage wave to minimize the drawbacks of conventional synchronous fundamental d-q frame method used. The results Fig. 15-16 show that the modified method bought satisfactory
Fig. 16. Results of voltage sag simulation of Modified Synchronous Fundamental d-q Frame Method. Compensation is applied after 0.125 sec of start improvement with respect to the previously stated method. The basics for applying this method is unlike system current the system voltage ideally should not change with change in load i.e. it should always remain to its rated value i.e. 1p.u value. But it is also fact that system voltage may deviate from its rated value to some extent but when the deviation exceed the specified limit then and only then it should be considered as voltage sag. So in practical application some tolerance limit should be set for the implementation in case of voltage sag/swell compensation.

Here in simulation voltage imbalance is considered in both magnitude as well as phase. Also voltage sag considered here is 20% in all three phases and for 6 fundamental cycles.

VI. CONCLUSION

For the shunt inverter, simulation of control strategies is performed mainly to mitigate harmonics and compensate reactive power. Considering harmonics mitigation all the strategies provide excellent results. The Fourier analysis plot clearly reveals that the compensated current purely matches the fundamental current of the system. And also unlike the others Synchronous Harmonic d-q Frame method can also provide selective harmonic elimination as in the other methods are unable to perform that. Also this particular method holds the advantage of extracting information regarding three phase system without using Fourier analysis.

Considering reactive power compensation Synchronous Detection Method and Instantaneous Power Theorem provides satisfactory results that can be concluded from the Fourier analysis phase plots where it can be seen that after compensation the system current nearly matches the system voltage phase that can be considered as system phase reference. But one important fact for the Instantaneous power theorem that system voltage should be purely balanced and in case of UPQC the series inverter in connected towards the source side which takes care of all the disturbance regarding voltage then it can be assured that the voltage that has to be sensed for this particular method is purely sinusoidal and free of disturbances.

In case of series inverter the voltage harmonics is not that much serious as harmonics mainly occurs in system current but the important problems regarding voltage disturbance is Voltage Sag/Swell and Voltage imbalance. The Synchronous d-q Frame method is excellent in harmonic mitigation but an average performer when it comes to compensate these two problems discussed earlier here. But for the other method the simulation results provide excellent support in compensating these problems. In addition to voltage harmonics compensation, both Voltage Sag/Swell as well as Voltage imbalance can be totally compensated in this method.

REFERENCES