CHAPTER 2
UNIFIED POWER QUALITY CONDITIONER: STUDY
AND SYSTEM CONFIGURATION

2.1. INTRODUCTION

The aim of this chapter is to develop background knowledge and briefly discusses about the recent development in the unified power quality conditioner. This chapter begins with system configuration and detailed description on the operating principle of the UPQC. Later on in this chapter, a systematic literature survey on UPQC is presented. From the survey, it is found that the UPQC is a promising versatile compensating device among custom power devices for simultaneous compensation of voltage and current related power quality (PQ) distortions [55]. And a detailed study was carried on the role of series and shunt active power filter (APF) and classification of UPQC based on supply system and converter topology. An interesting analytical study was done on how the UPQC could compensate the PQ distortions under different operating conditions.

2.2. UPQC – CONCEPT AND SYSTEM CONFIGURATION

The major types of custom power devices are series APF, shunt APF and UPQC. The series APF is most promising to mitigate the voltage related PQ distortions and the shunt APF is the most suitable to compensate the current related PQ distortions. In the modern distribution system, both voltage and current related PQ distortions simultaneously deteriorate the performance of the load. However, installing series APF and shunt APF independently may not be cost effective solutions and also it is not suitable for simultaneous compensation of voltage and current PQ distortions. Moran introduced a new topology in which series APF and shunt APF were connected back to back with a common DC link reactor and the topology was named as line voltage regulator/conditioner (LVRC) [56]. Later in 1998, this topology gained more attention when Fujita and Akagi proved the practical application of this topology for simultaneous compensation of voltage and current related PQ distortions [48]. These authors named the device as unified power quality conditioner (UPQC) and then this name became popular used by many researchers.

The configuration of three-phase UPQC is shown in Fig. 2.1 and the key components are highlighted in this figure. The UPQC was constructed from two voltage source inverters, DC link capacitor, three single-phase coupling transformers
and interfacing impedances. The DC link of the two voltage source inverters were connected back to back with a common DC link capacitor. One voltage source inverter (VSI) was connected in series with the source through coupling transformers via., series interfacing impedance. This was named as series VSI. Another VSI was connected in parallel between the coupling transformer and load impedance through shunt interfacing impedance known as shunt VSI. The highlighted components in Fig. 2.1 are discussed below:

- **C1-** Component 1 represents series VSI and it was constructed using six IGBT switches such as S1, S2, S3, S4, S5 and S6. S1, S3 and S5 represent upper switches and S2, S4 and S6 represent lower switches of phase A, B and C respectively. The series VSI are controlled to function as series APF and it suitable for compensating voltage related PQ distortions.

- **C2-** Component 2 represents shunt VSI and it was designed using six IGBT switches such as P1, P2, P3, P4, P5 and P6. P1, P3 and P5 represent the upper switches and P2, P4 and P6 represent the lower switches of phase A, B and C respectively. The shunt VSI is controlled to function as shunt APF and is suitable for compensating current related PQ distortions.

- **C3 –** Component 3 is DC link capacitor \( (C_{dc}) \) and it is connected to the DC link of the series VSI and shunt VSI. It acts as a common storage component for both series VSI and shunt VSI. The voltage stored in the DC link capacitor is termed DC link voltage \( (V_{dc}) \). The robust control of DC link voltage results in optimum compensation capability of the UPQC. An appropriate control technique is designed to control DC link voltage to act as source for reactive power.

- **C4 -** Component 4 is a coupling transformer and it is used to connect series VSI to the network. It consists of three single-phase transformers and it is also termed as series coupling transformer. The current flow through the series coupling transformer is significantly minimized by choosing suitable turn ratio. The series coupling transformer is used to inject the compensation voltage into the network that forced to maintain rated sinusoidal voltage across the load terminal.

- **C5 –** Component 5 is shunt interfacing impedance and it consists of series connected shunt resistor \( (R_{sh}) \), shunt inductor \( (L_{sh}) \) and parallel connected shunt capacitor \( (C_{sh}) \).
Fig. 2.1 Detailed configuration of conventional UPQC

1 C1 – Series VSI
2 C2 – Shunt VSI
3 C3 – DC link capacitor
4 C4 – Coupling Transformers
5 C5 – Shunt interfacing Impedance
6 C6 – Series interfacing Impedance
7 C7 – Load interfacing Impedance
8 C8 – Source interfacing Impedance
The shunt VSI is connected to the network through shunt interfacing impedance. The shunt interfacing impedance smoothens the compensation current before injected to the network. The compensation current \((I_{sh})\) is the reason for maintaining sinusoidal source current with unity power factor.

- **C6** – Component 6 represents series interfacing impedance and it consists of series connected series resistor \((R_{sr})\) and series inductor \((L_{sr})\) and capacitor \((C_{sr})\). The series VSI is connected to the series coupling transformer through series interfacing impedance. The series interfacing impedance is used to smoothen the compensation voltage.

- **C7** – Component 7 is load interfacing impedance and it is a series connected load interface resistor \((R_{L})\) and load interface inductor \((L_{L})\). It is used to smooth the voltage and current at the load terminal.

- **C8** – Component 8 is source interfacing impedance and it is a series connected source resistor \((R_{s})\) and source interface inductor \((L_{s})\). It is used to represent the utility loss in the distribution system.

After connecting UPQC, the network consists of four sides such as source side, series APF, shunt APF and load terminal. The voltage, current and power at the source terminal are termed source voltage \((V_{s})\), source current \((I_{s})\), source real power \((P_{s})\) and source reactive power \((Q_{s})\). The voltage, current and power at the load terminal are labeled as load voltage \((V_{L})\), load current \((I_{L})\), load real power \((P_{L})\) and load reactive power \((Q_{L})\). The current injected by the shunt APF is termed compensation current \((I_{sh})\), real power and reactive power injected by the shunt APF are termed shunt real power \((P_{sh})\) and shunt reactive power \((Q_{sh})\) respectively. The voltage injected by the series APF is termed compensation voltage \((V_{sr})\), real power and reactive power injected by the series APF are termed series real power \((P_{sr})\) and series reactive power \((Q_{sr})\) respectively. The shunt APF regulates the source current and the series APF controls the load voltage.

### 2.3. Operating Principle of the UPQC

This section demonstrates the compensation of PQ distortions using UPQC by the operation of shunt APF and series APF under different operating conditions. For better understanding, the operation of shunt APF and series APF are separately described in the following subsections.
Fig. 2.2 (a) Configuration of shunt part of UPQC, (b) Source current waveform, (c) Load current waveform and (d) Compensation current waveform.
2.3.1. Operating Principle of Shunt Part of the UPQC

The shunt VSI in the UPQC is realized as shunt APF and is applied to solve the current related PQ distortions current harmonic distortion, reactive power demand, unbalanced loads. The configuration of shunt APF in the UPQC is shown in Fig. 2.2 (a). The main objective of the shunt APF is to prevent the entering load imperfections into utility. The compensated source current is shown in Fig. 2.2 (b), the typical distorted load current is shown in Fig. 2.2 (c) and compensation current injected by the shunt APF is shown in Fig. 2.2 (d). The operating condition taken for this study is rectifier load is connected upto 0.3 sec, 0.8 PF RL load connected between 0.3 sec to 0.4 sec, unbalance load connected between 0.4 sec to 0.5 sec and R load connected after 0.5 sec. For the rectifier load, the shunt APF detects the harmonic distortions and injects the harmonic distortion in the opposite direction. It cancels the harmonic distortion in the source current. For RL load, the shunt APF detects the reactive component of load current and injects it from the opposite direction. It cancels reactive component current and maintains the source current at unit PF; under unbalanced load, the shunt APF maintains balanced current at the source terminal. For R load, the compensation current is found to be nearly zero. From this study, it is clearly observed that the shunt APF maintains the source current at unity power factor and with very minimum harmonic distortion. To fulfill these objectives, the shunt inverter is forced to inject the compensation current as given in following equation:

\[
\begin{bmatrix}
I_{sha}^* \\
I_{shb}^* \\
I_{shc}^*
\end{bmatrix}
= \begin{bmatrix}
I_{sa}^* \\
I_{sb}^* \\
I_{sc}^*
\end{bmatrix}
- \begin{bmatrix}
I_{La} \\
I_{Lb} \\
I_{Lc}
\end{bmatrix}
\] (2.1)

The three-phase reference source current \( I_r^* \) is generated using appropriate control scheme of shunt APF. From the overall study, the basic operating principle of shunt part of the UPQC can be stated as the shunt APF which injects harmonic current as well as reactive current drawn by the load with opposite polarity to maintain the balanced sinusoidal source current with unity power factor [57].

2.3.2. Operating Principle of Series Part of the UPQC

The series VSI in the UPQC is regulated to function as series APF and is used to solve the voltage related PQ distortions such as voltage sag, swell, unbalanced, flickers notches, etc., at the load terminal.
Fig. 2.3 (a) Configuration of series part of UPQC, (b) Source voltage waveform, (c) Load voltage waveform and (d) Compensation voltage waveform
The configuration of series part of the UPQC is shown in the Fig. 2.3 (a). The objective of the series APF is to protect the load from source side distortions. A typical distorted source voltage with 30% sag, 30% swell and unbalanced voltage is shown in Fig. 2.3 (b). The compensated load voltage is shown in Fig. 2.3 (c) and Fig. 2.3 (d) shows the compensation voltage injected by the series APF. For sag condition, the series APF detects the voltage drop and injects the required voltage through the series coupling transformer. It maintains the rated voltage across the load terminal. As for the voltage swell condition, the series APF detects the increased voltage and inject the compensation voltage to cancel the increased voltage thereby the rated voltage across the load terminal is maintained. This operation is similar to maintain the rated voltage under unbalanced source voltage. This operation is fulfilled by forcing the series VSI to inject the compensation voltage using following equation,

\[
\begin{bmatrix}
V_{sra} \\
V_{srb} \\
V_{src}
\end{bmatrix} = \begin{bmatrix}
V_{La}^* \\
V_{Lb}^* \\
V_{Lc}^*
\end{bmatrix} - \begin{bmatrix}
V_{sa} \\
V_{sb} \\
V_{sc}
\end{bmatrix}
\]

(2.2)

An appropriate series control scheme is designed to generate the three-phase reference voltage signal \(V_L^*\). In general, the operation of the series part of the UPQC can be described as rapid detection of voltage variations at source and it injects the compensation voltage which maintains rated voltage across the load terminal [58].

### 2.3.3. Role of Series and Shunt Inverters

The series inverter injected the compensation voltage in series with source voltage and load voltage is found to be the sum of source voltage and compensation voltage. In the event of source voltage being imbalanced and non-sinusoidal, the series voltage is injected at the required magnitude and phase angle and this result in the regulation of rated sinusoidal voltage in the load bus. Hence, the system has been protected from voltage related PQ problems such as voltage sag, swell, imbalance, flicker etc. The phase angle of injected voltage varies from 0 to 360° and the series inverter may absorb or supply real power in addition to the reactive power. This implies that is has no self-supporting from the DC link capacitor. In order to obtain the support from the DC link, the series inverter has been integrated with shunt inverter by sharing a common DC link [59].
The shunt inverter has the ability to regulate the DC link voltage and to compensate the current related PQ issues such as harmonics, interharmonics, reactive power requirements etc. These objectives are made by the parallel inverter to perform the role of shunt APF. The compensation capability of both inverters is achieved by regulating the DC link capacitor voltage and it is possible by means of a proper control of shunt inverter. Hence the shunt inverter not only performs compensation of current PQ issues but also it supplies or absorbs the reactive power required by the series inverter [60].

2.4. LITERATURE SURVEY ON UPQC

From 1998 till now many researchers have been discussing the construction, operation and control strategies for UPQC in different ways. An extensive work has been reported in this literature survey that includes recent development, modeling, parameter selection, practical consideration, standard limits to maintain PQ distortions etc. The major contribution of this thesis resolves around enhancement of the compensation capability of UPQC by proposing an appropriate control technique and subsequently other basic procedures are referred to from the survey.

Hideaki Fujita et al. integrated the series APF and shunt APF and named the topology as unified power quality conditioner [48]. The topology was experimentally validated for the 20 KVA laboratory model for simultaneous compensation of voltage flickers, sag, unbalanced and current harmonic distortions, reactive power and negative sequence current. The instantaneous active and reactive power based control strategy was developed for the UPQC. Mauricio Aredes et al. developed an active power line conditioner by integrating series APF and shunt APF with a common DC link capacitor. This topology incorporates not only the compensated distortions at fundamental frequency like a unified power flow controller but also it has the capability for active harmonic mitigation [61]. Dusan Graovac et al. analyzed the performance of UPQC by adding another shunt APF for better compensation of voltage and current distortions [62].

B. Han et al. combined the distribution generator and UPQC [63]. The distribution generator connected to the DC link of the UPQC and this topology has the capability of mitigating voltage interruption, voltage sag, swell, harmonic distortion and reactive power demand either in grid connected mode or in standalone
mode. This topology can improve the PQ at the point of installation in the distribution system or in industrial power system. Yashomani et al. optimized UPQC with minimum VA loading. The series part of the UPQC was forced to inject the compensation voltage at an optimum angle which regulated the rated load voltage with minimum VA loading [64].

Vinod Khadkikar et al. developed a new control scheme of the UPQC terming it power angle control (PAC). In PAC, the power angle was introduced in the load voltage that resulted in two major advantages. One was coordinated sharing of load reactive power demand by both series APF and shunt APF. The second advantage that it helped to reduce the rating of the shunt APF and all it reduced the cost of the UPQC. These advantages resulted in better compensation of PQ distortions [52].

Vinod Khadkikar et al. developed a new configuration in the UPQC topology for analyzing the PQ issues in three-phase-four-wire distribution system [65]. The new configuration added the fourth leg in the shunt VSI for compensating the current flow in the neutral line. Hamid Reza Mohammadi et al. discussed a new multi-converter - unified power quality conditioning system (MC-UPQC), capable of simultaneous compensation for voltage and current in multibus/multifeeder systems [66].

Iurie Axente et al. developed a laboratory 12 KVA UPQC using digital the DSP-controlled sequential based compensation strategy for compensating the supply voltage and the load current imperfections [67]. The delay time problem in the digital control was analyzed and overcome by suitable digital processor. Srinivas et al. designed a particle swarm optimization based feedback controller for the UPQC. And it exhibited the optimal performance under different operating conditions and proved robust to parameter uncertainty [68].

Ahmet Teke et al. proposed a reference signal generation method adopted for UPQC to compensate voltage and current related PQ distortions for sensitive loads. Controllers based on enhanced phase lock loop and nonlinear adaptive filters were developed. The fuzzy logic controller was used in the DC link voltage control strategy and also fast sag/swell detection method was presented [69]. Vinod Khadkikar et al. developed a new control strategy based on complex power UPQC and termed it UPQC-S to perform two major functions in the series APF: one was
sag/swell compensation and the second was coordinating the sharing load reactive power demand with shunt APF [70]. Sivakumar et al. designed the phase jump method based control strategy using adaptive neuro-fuzzy inference systems (ANFIS) for UPQC to compensate voltage and current related PQ distortions in the distribution system [71]. The authors identified that among all PQ distortions, voltage sag was a crucial problem in the distribution system and significantly affected the performance of the UPQC.

Vinod Khadkikar et al. presented a comprehensive review on the UPQC to enhance the power quality in the distribution system [72]. This review presented a broad overview on various system configurations i.e., single phase system (two-wire) and three-phase systems (three-wire and four-wire), different compensation approaches and recent developments in the field of UPQC.

Mahesh K. Mishra et al. stated that the UPQC was a custom power device which simultaneously compensated the voltage and current related PQ issues in the power distribution system [73]. The authors proposed the UPQC topology to use a capacitor in series with the interfacing inductor of the shunt APF. It avoided the requirement of the fourth leg in the (VSI) of the shunt active filter for three-phase four-wire network. This topology significantly reduced the average switching frequency and the switching losses in the inverters. And a detailed procedure for designing parameters was also presented.

Bharath Babu Ambati et al. introduced an optimum method to design the UPQC with the minimum VA rating based on the requirement of compensation [74]. A generalized equation of VA loading was derived and validated using various control approaches.

Sanjib Ganguly investigated the performance of UPQC for radial distribution system using particle swarm optimization method based on multi objective planning algorithm [75]. The procedure for designing the optimal parameters of the UPQC was presented to minimize following three objective functions such as network power loss, rating of UPQC and under voltage problems.

Bruno W. França et al. presented an improved controller algorithm for unified power quality conditioner and it was termed IUPQC. The IUPQC was applied to solve the PQ issues in the microgrid applications [76].
2.5. CLASSIFICATION ON UPQC

The systematic classification on UPQC is presented in this section and pictorial representation for the classification on UPQC is shown in Fig. 2.4. The classification is done on the basis of supply system and converter topology. This classification is elaborately discussed in the following subsections:

2.5.1. Classification Based on Supply System

In general, the loads or equipments are separated under supply system such as single-phase load or three-phase load. The single-phase loads are connected through two-wires. The single phase two-wire UPQC is applied to solve the power quality issues in the single phase system [77]. The configuration of single phase two-wire UPQC is shown in Fig. 2.5 (a). Adjustable speed drives refer to nonlinear loads commonly used in the industrial sectors and these loads connect to the three-phase supply through three-wire system.
Fig. 2.5 Configuration of (a) Single-phase two-wire UPQC, (b) Three-phase three-wire UPQC and (c) Three-phase four-wire UPQC
For these loads, three-phase three-wire UPQC is connected to compensate the power quality issues [78]. The configuration of three-phase three-wire UPQC is shown in Fig. 2.5 (b). However, three-phase three-wire UPQC is poor to mitigate the current flowing in the neutral line. And several nonlinear loads are connected in the three-phase four-wire system. The power quality issues for these loads are solved by connecting three phase four-wire UPQC [79]. The configuration of three-phase four-wire UPQC is presented in Fig. 2.5 (c). In the traditional method the fourth leg is connected in the shunt VSI to mitigate current flow in the neutral line.

2.5.2. Classification Based on Converter Topology

As discussed earlier, both series and shunt inverters in the UPQC share a common DC link. Current source inverter (CSI) topology is referred to as DC link of the pulse width modulated (PWM) inverter connected with the inductor [80]. The UPQC is referred to as CSI-UPQC which means that both series and shunt inverters shares a common storage inductor. The CSI based converter topology is shown in Fig. 2.6 (a). In CSI-UPQC current, the DC link current is regulated to compensate PQ issues [81]. The average input power to the CSI-UPQC is equal to the sum of average output power and UPQC power losses. However, CSI-UPQC doesn’t gain popularity due to very expensive and higher losses. The DC link of shunt and series inverters shares a common DC link capacitor and this means that the UPQC is referred to as VSI-UPQC. The voltage across the DC link capacitor is regulated to compensate the power quality problems [82]. The VSI based converter topology is shown in Fig. 2.6 (b). The VSI is commonly used as converter topology in the UPQC.

![Fig. 2.6 Topology (a) Current source inverter and (b) Voltage source inverter](image)

2.6. CONFIGURATION OF PROPOSED UPQC TOPOLOGY

The configuration of three-phase traditional UPQC is elaborately discussed in section 2.2. The configuration of proposed UPQC topology is shown in Fig. 2.7.
Distorted Source

1. C1 – Series VSI
2. C2 – Shunt VSI
3. C3 – DC link capacitor
4. C4 – Coupling Transformers
5. C5 – Shunt interfacing Impedance
6. C6 – Series interfacing Impedance
7. C7 – Load interfacing Impedance
8. C8 – Source interfacing Impedance

Fig 2.7 Detailed configuration of proposed UPQC
In traditional UPQC, different configurations of UPQC topology are required for the three-phase three-wire system and three-phase four-wire system. This issue is solved by the proposed topology and it can be used for both three-phase three-wire and three-phase four-wire systems. Hence, the proposed UPQC topology is applied to solve the PQ issues in both three-phase three-wire and three-phase four-wire systems. Similar to the traditional UPQC topology, in the proposed UPQC three legs voltage source inverters are used in the series VSI and shunt VSI. The major contribution in the proposed topology is done in shunt impedance and load impedance. The remaining components are designed similar to the traditional system configuration. In traditional shunt impedance, the shunt capacitor is connected in parallel with the load. In the proposed topology, the shunt capacitor is connected in series in the shunt impedance. And the capacitor is added in series to the load impedance and it is termed as load interface capacitor ($C_L$). The series VSI is connected in series with the source through the series coupling transformers via series impedance. The shunt VSI is connected in parallel between series coupling transformer and the load through shunt impedance with series connected capacitor. The source impedance $R_s$ and $L_s$ are the feeder impedance which represents losses in utility. Series resistance ($R_{sr}$) and shunt resistance ($R_{sh}$) represent the switching loss of the series and shunt inverters. In the proposed topology, the series connected shunt capacitor avoids the requirement of fourth leg in the shunt VSI and it significantly reduces the switching losses, switching frequency and it improves the control of DC link voltage at the desired level. The load interfacing capacitor a plays major role in maintaining the reactive power flow in the network and it significantly reduces the flow of current in the neutral line. Hence the proposed UPQC topology is applicable to solve the PQ problems in the three-phase three-wire and three-phase four-wire systems.

2.7. MATHEMATICAL MODEL

The mathematical modeling of the system is presented in this section for before and after connecting UPQC. The intensive of this study is to get clear view on how the UPQC is compensating the PQ distortion at the point of common coupling (PCC). State space model of proposed topology is given in Appendix – B.

2.7.1. Before Connecting UPQC

Before connecting to the UPQC, the load is directly connected to the source. The mathematical modeling is done in this section on the basis that no compensation
device is connected between the source and load. The load voltage is the source voltage and it is given in (2.3).

\[
\begin{align*}
V_{sa} &= V_{La} = V_{slm} \sin(\omega t) \\
V_{sb} &= V_{Lb} = V_{slm} \sin(\omega t - 120^\circ) + \sum_{n=2,3,4,5} V_{slm} \sin(n\omega t - 120^\circ) \\
V_{sc} &= V_{Lc} = V_{slm} \sin(\omega t + 120^\circ) + \sum_{n=2,3,4,5} V_{slm} \sin(n\omega t + 120^\circ)
\end{align*}
\]  

(2.3)

The load voltage is the sum of fundamental and harmonic source voltage. If the network is connected to the purely resistive load it would means that the fundamental voltage is delivered to the load. Under this case, the load is normally operated. When the network is connected with nonlinear loads it means that the harmonic distorted voltage is delivered to the load. This voltage significantly affects the performance of the load. A typical load current is given as

\[
\begin{align*}
I_{sa} &= I_{La} = I_{pa} + I_{qa} \\
I_{sb} &= I_{Lb} = I_{pb} + I_{qb} \\
I_{sc} &= I_{Lc} = I_{pc} + I_{qc}
\end{align*}
\]  

(2.4)

\[
\begin{align*}
I_{pa} &= I_{plm} \sin(\omega t) + \sum_{n=2,3,4,5} I_{pam} \sin(n\omega t) \\
I_{pb} &= I_{plm} \sin(\omega t - 120^\circ) + \sum_{n=2,3,4,5} I_{pam} \sin(n\omega t - 120^\circ) \\
I_{pc} &= I_{plm} \sin(\omega t + 120^\circ) + \sum_{n=2,3,4,5} I_{pam} \sin(n\omega t + 120^\circ)
\end{align*}
\]  

(2.5)

\[
\begin{align*}
I_{qa} &= I_{qlm} \sin(\omega t + \phi_q) + \sum_{n=2,3,4,5} I_{qam} \sin(n\omega t + \phi_q) \\
I_{qb} &= I_{qlm} \sin(\omega t - 120^\circ + \phi_q) + \sum_{n=2,3,4,5} I_{qam} \sin(n\omega t - 120^\circ + \phi_q) \\
I_{qc} &= I_{qlm} \sin(\omega t + 120^\circ + \phi_q)
\end{align*}
\]  

(2.6)

The load current is the sum of real current and reactive current. The real current is found to be the sum of fundamental and harmonic real current and the reactive current is found to be sum of fundamental and harmonic reactive current. When the R load is connected it means that only the fundamental real current is drawn from the source. For RL, the fundamental active and fundamental reactive current is drawn from the source. This issue results in drop in the utility voltage. When the nonlinear load is connected, both the fundamental and harmonic current is drawn from the source [83]. This issue creates distortions and drop in the source voltage. The power consumed by the load is given in (2.7). The consumed power is found to be the sum of fundamental active power, fundamental reactive power, harmonic active power and harmonic reactive power. For protecting the utility from the penetration of load imperfections, the load is forced to draw only the fundamental active power from the utility.
power = \begin{bmatrix} V_I I_p1 \cos(\phi_1) + V_I I_q1 \sin(\phi_1) \\ + \sum_{n=3,5,7} V_n I_{pn} \cos(\phi_n) + \sum_{n=3,5,7} V_n I_{qn} \sin(\phi_n) \end{bmatrix}

\begin{align}
2.7.2. & \text{ After Connecting UPQC} \\
& \text{For this case, the UPQC is connected between source and the load. The UPQC forces the system to draw only fundamental active current from the utility and maintained rated voltage across the load terminal. The UPQC achieves these objectives through shunt APF and series APF. The shunt APF delivers load reactive power demand and cancels the harmonic distortions at the source terminal which maintains sinusoidal source current with unity power factor. The series APF detects the voltage distortions at source terminal and injects required voltage to maintain rated sinusoidal voltage at the load terminal [84]. After connecting the UPQC, the network has four sections such as source terminal, load terminal, series APF and shunt APF. After connecting UPQC, the source current is found to be as follows}

\begin{align}
&\begin{bmatrix}
I_{sa} \\
I_{sb} \\
I_{sc}
\end{bmatrix} = \begin{bmatrix}
I_{La} \\
I_{Lb} \\
I_{Lc}
\end{bmatrix} + \begin{bmatrix}
I_{sha} \\
I_{shb} \\
I_{shc}
\end{bmatrix}
\end{align}

\begin{align}
&\begin{bmatrix}
I_{La} \\
I_{Lb} \\
I_{Lc}
\end{bmatrix} = \begin{bmatrix}
I_{p1m} \sin(\omega t) \\
I_{p1m} \sin(\omega t-120^\circ) \\
I_{p1m} \sin(\omega t+120^\circ)
\end{bmatrix} + \sum_{n=2,3,4,5} \begin{bmatrix}
I_{pnm} \sin(n \omega t) \\
I_{pnm} \sin(n \omega t-120^\circ) \\
I_{pnm} \sin(n \omega t+120^\circ)
\end{bmatrix}

&\begin{bmatrix}
I_{sha} \\
I_{shb} \\
I_{shc}
\end{bmatrix} = \begin{bmatrix}
I_{q1m} \sin(\omega t + \phi_1) \\
I_{q1m} \sin(\omega t - 120^\circ + \phi_1) \\
I_{q1m} \sin(\omega t + 120^\circ + \phi_1)
\end{bmatrix} + \sum_{n=2,3,4,5} \begin{bmatrix}
I_{qnm} \sin(n \omega t + \phi_n) \\
I_{qnm} \sin(n \omega t - 120^\circ + \phi_n) \\
I_{qnm} \sin(n \omega t + 120^\circ + \phi_n)
\end{bmatrix}
\end{align}
\[
\begin{bmatrix}
I_{sa} \\
I_{sb} \\
I_{sc}
\end{bmatrix} =
\begin{bmatrix}
I_{plm} \sin(\omega t) \\
I_{plm} \sin(\omega t - 120^\circ) \\
I_{plm} \sin(\omega t + 120^\circ)
\end{bmatrix}
\] (2.11)

The source current \((I_s)\) is found to be the sum of load current \((I_L)\) and compensation current \((I_{sh})\) injected by the shunt AFP [85]. The load current contains fundamental component of real current and reactive current and harmonic component of real current and reactive current and it is given in (2.9). The compensation current injected by the shunt APF is found to be the sum of fundamental reactive power and harmonic real and reactive current in the opposite direction and it is given in (2.10). The sum of load current and compensation current results in sinusoidal source current with unit power factor and this is given in (2.11).

\[
\begin{bmatrix}
V_{Lm} \sin(\omega t) \\
V_{Lm} \sin(\omega t - 120^\circ) \\
V_{Lm} \sin(\omega t + 120^\circ)
\end{bmatrix} =
\begin{bmatrix}
V_{sm} \sin(\omega t) \\
V_{sm} \sin(\omega t - 120^\circ) \\
V_{sm} \sin(\omega t + 120^\circ)
\end{bmatrix} +
\begin{bmatrix}
V_{sr} \sin(\omega t)
\end{bmatrix}
\] (2.12)

After connecting the UPQC, the load voltage \((V_L)\) is the sum of source voltage \((V_s)\) and the load compensation voltage \((V_{sr})\) injected by the series APF. Under 30% sag condition, 70% of rated voltage is delivered from the source voltage and the required 30% voltage is delivered from the compensation voltage and thereby the rated load voltage is maintained [86-88]:

\[
\begin{bmatrix}
P_L \\
Q_L
\end{bmatrix} = 3 \begin{bmatrix}
V_L I_L \cos(\phi_L)
V_L I_L \sin(\phi_L)
\end{bmatrix}
\] (2.13)

\[
\begin{bmatrix}
P_L \\
Q_L
\end{bmatrix} = \begin{bmatrix}
P_s + P_{sh} + P_{sr} \\
Q_s + Q_{sh} + Q_{sr}
\end{bmatrix}
\] (2.14)

\[
\begin{bmatrix}
P_s \\
Q_s
\end{bmatrix} = 3 \begin{bmatrix}
V_s I_s \cos(\phi_s)
0
\end{bmatrix}
\] (2.15)

\[
\begin{bmatrix}
P_{sh} \\
Q_{sh}
\end{bmatrix} = 3 \begin{bmatrix}
V_L I_{sh} \cos(\phi_{sh})
V_L I_{sh} \sin(\phi_{sh})
\end{bmatrix}
\] (2.16)

\[
\begin{bmatrix}
P_{sr} \\
Q_{sr}
\end{bmatrix} = 3 \begin{bmatrix}
V_{sr} I_{sr} \cos(\phi_{sr})
V_{sr} I_{sr} \sin(\phi_{sr})
\end{bmatrix}
\] (2.17)

The load real power \((P_L)\) and load reactive power \((Q_L)\) are computed using (2.13). Upon connecting the UPQC, the load real power is found to be the sum of the source real power \((P_s)\), shunt real power \((P_{sh})\) and series real power \((P_{sr})\). The load
reactive power is the sum of shunt reactive power \((Q_{sh})\) and series reactive power \((Q_{sr})\) and it is given in (2.14). The source real power is computed using (2.15) and the source reactive power \((Q_{s})\) is found to be zero. Equations (2.16) and (2.17) are used to compute shunt real and reactive powers and series real and reactive powers respectively.

2.8. **NEED FOR DC LINK VOLTAGE CONTROL**

As discussed earlier, both the shunt VSI and series VSI share a common DC link capacitor. The compensation capability of the UPQC is determined by the optimum control of DC link voltage [89-91]. The controlling DC link voltage is the process of reducing error between the reference and actual DC link voltage. This process is achieved by designing an appropriate control technique. To compensate PQ distortions, the rated voltage must be maintained across the DC link capacitor under normal and distorted environment [92-95]. The designing of control strategies for better control of DC link voltage is discussed in the next chapter.

2.9. **CONCLUSIONS**

The system configuration and operation of the UPQC for compensating PQ distortions are elaborately discussed. A detailed literature survey on the recent development in the UPQC for PQ enhancement is presented. From the information obtained from the literature survey, a systematic classification on UPQC is made in the aspect of supply system and converter. Form this overall study, it is found that different configurations of UPQC are required for compensating power quality issues in the three-phase three-wire and three-phase four-wire systems. The proposed UPQC topology is applicable to compensate the power quality issues in the three-phase three-wire and three-phase four-wire systems. The advantages of proposed UPQC topology are highlighted.