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A Comparative Analysis of UPQC for Power Quality Improvement

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Abstract - The widespread use of Power Electronics based equipment has produced a significant impact on quality of electric power supply. Conventional power quality mitigation equipment is providing to be inadequate for an increasing number of applications. One modern and very promising solution that deals with both load current and supply voltage imperfections is the Unified Power Quality Conditioner (UPQC). This paper presents a review on the UPQC to improve the electric power quality at distribution levels.

Keywords - Active power filter (APF), Power quality, Unified Power Quality Conditioner (UPQC), Voltage sag and swell compensation.

I: INTRODUCTION

The term "Power Quality"(PQ) are most important facets of any power delivery system today. Low quality power affects electricity consumers in many ways. The lack of quality power can cause loss of production, damage of equipment or appliances, increased power losses, interference with communication lines and so forth. The widespread use of power electronics based equipment has produced a significant impact on quality of electric power supply by generating harmonics in voltages and currents. Therefore, it is very important to maintain a high standard of power quality [1].

Conventional power quality mitigation equipment use passive elements and do not always respond correctly as nature of power system condition change. The term active power filter (APF) is a widely used terminology in the area of power quality improvement. One modern solution that deals with both load current and supply voltage imperfections is the UPQC. The UPQC is one of the APF family members [2,3].

The UPQC is a combination of series and shunt active filters connected in cascade via a common DC link capacitor. The main purpose of a UPQC is to compensate for supply voltage power quality issues such as, sags, swells, unbalance, flicker, harmonics, and for load current power quality problems such as, harmonics, unbalance, reactive current and neutral current [4].

II: BASIC CONFIGURATION OF UPQC

UPQCs consist of combined series and shunt APFs for simultaneous compensation of voltage and current. The series APF inserts a voltage, which is added at the point of common coupling (PCC) such that the load end voltage remains unaffected by any voltage disturbance, whereas, the shunt APF is most suitable to compensate for load reactive power demand and unbalance, to eliminate the harmonics from supply current, and to regulate the common DC link voltage [2].

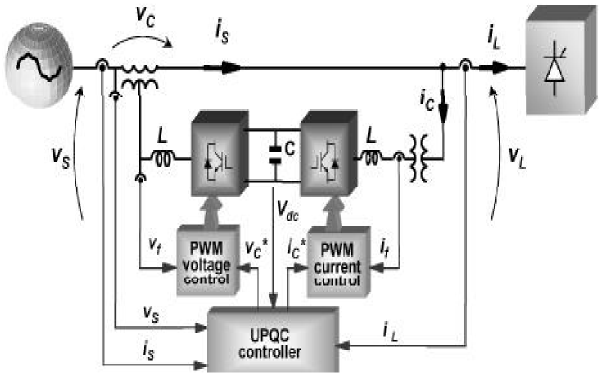

Figure 1. Basic configuration of the UPQC

Figure 1 shows the basic configuration of the UPQC. The UPQC has two distinct parts:

- Power circuit formed by series and shunt PWM converters
- UPQC controller

The series PWM converter of the UPQC behaves as a controlled voltage source, that is, it behaves as a series APF, whereas the shunt PWM converter behaves as a controlled current source, as a shunt APF. No power supply is connected at the DC link. It contains only a relatively small DC capacitor as a small energy storage element.

The integrated controller of the series and shunt APF of the UPQC to provide the compensating voltage reference V_C^* and compensating current reference I_C^* to be synthesized by PWM converters.

The shunt active power filter of the UPQC can compensate all undesirable current components, including harmonics, imbalances due to negative and zero sequence components at the fundamental frequency. In order to cancel the harmonics generated by a nonlinear load, the shunt inverter should inject a current as governed by the following equation:

$$I_C(\omega t) = I^*_S(\omega t) - I_L(\omega t) \qquad (1)$$

Where $I_C(\omega t)$, $I^*_S(\omega t)$, and $I_L(\omega t)$ represent the shunt inverter current, reference source current, and load current, respectively.

The series active power filter of the UPQC can compensate the supply voltage related problems by injecting voltage in series with line to achieve distortion free voltage at the load terminal. The series inverter of the UPQC can be represented by following equation:

$$V_C(\omega t) = V^*_L(\omega t) - V_S(\omega t) \qquad (2)$$

Where $V_C(\omega t)$, $V^*_L(\omega t)$, and $V_S(\omega t)$ represent the series inverter voltage, reference load voltage, and actual source voltage, respectively.

III: POWER QUALITY PROBLEMS

Power quality is very important term that embraces all aspects associated with amplitude, phase and frequency of the voltage and current waveform existing in a power circuit. Any problem manifested in voltage, current or frequency deviation that results in failure of the customer equipment is known as power quality problem.

The increasing number of power electronics based equipment has produced a significant impact on the quality of electric power supply. Low quality power affects electricity consumers in many ways. The lack of quality power can cause loss of production, damage of equipment or appliances, increased power losses, interference with communication lines and so forth. Therefore, it is obvious to maintain high standards of power quality [3].

The major types of power quality problems are: Interruption, Voltage-sag, Voltage-swell, Distortion, and Harmonics.

(a) Interruption

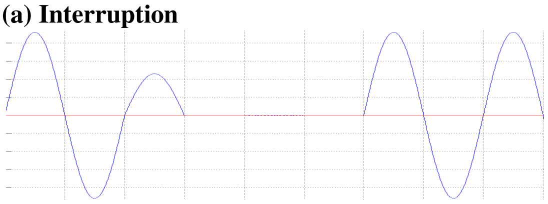

Figure 2. Interruption

An interruption is defined (Fig 2) as complete loss of supply voltage or load current. Interruptions can be the result of power system faults, equipment failures, and control malfunction. There are three types of interruptions which are characterized by their duration:

1. The momentary interruption is defined as the complete loss of supply voltage or load current having a duration between 0.5 cycles & 3 sec.
2. The temporary interruption is the complete loss lasting between 3 seconds and 1 minute,
3. The long term interruption is an interruption which has a duration of more than 1 minute.

(b) Voltage Sags

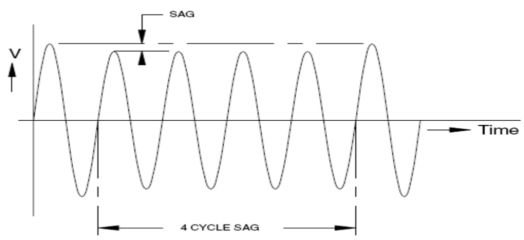

Figure 3. Voltage Sags

Voltage sags (dips) are short-duration reductions in rms voltage caused by short-duration increases of the current. The most common causes of the overcurrents leading to voltage sags are motor starting, transformer energizing and faults. A sag is decrease in voltage at the power frequency for duration from 0.5 cycle to 1min. Voltage sags are usually associated with system faults but can also caused by energisation of heavy loads at starting of large motors (Fig 3).

(c) Voltage Swells

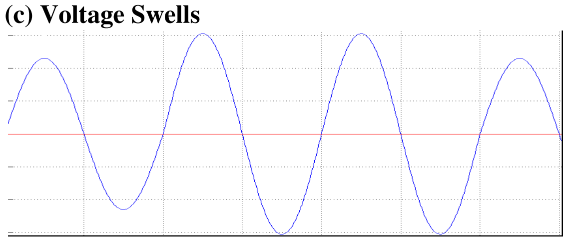

Figure 4. Voltage Swells

Voltage swell is an rms increase in the ac voltage, at the power frequency, for duration from a half cycle to a few seconds. As shown in Fig 4., Voltage can rise above normal level for several cycles to seconds. Voltage swells will normally cause damage to lighting, motor and electronic loads and will also cause shutdown to equipment. The severity of voltage swell during a fault condition is a function of fault location, system impedance and grounding.

(d) Waveform Distortion

Voltage or current waveforms assume non-sinusoidal shape called distorted wave as shown in Fig 5. When a waveform is identical from one cycle to the next, it can be represented as a sum of pure sine waves in which the frequency of each sinusoid is an integer multiple of the fundamental frequency of the distorted wave.

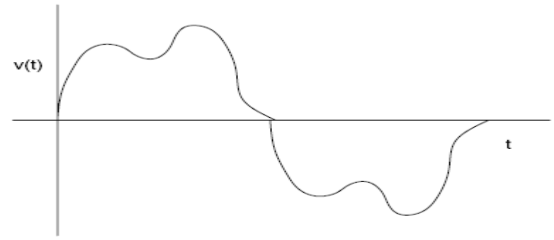

Figure 5. Distorted Waveform

It is defined as the steady state deviation from an ideal sine wave, due to harmonics, which are sinusoidal voltages or currents having frequencies that are whole multiples of frequency at which supply system is designed to operate (50 HZ).

(e) Harmonics

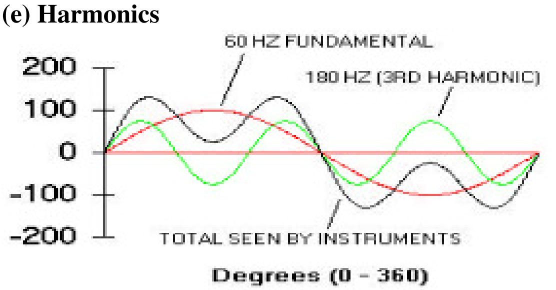

Figure 6. Waveform with 3rd Harmonic

Harmonics are sinusoidal voltages or current having frequency that are integer multiples of the fundamental frequency. Here, 3rd harmonics is seen in the figure 6.

IV: CLASSIFICATION OF UPQC

The Unified Power Quality Conditioner are classified on various bases like converter used, topology, supply type and compensation method. The UPQC is classified in two main groups which is based on, Physical structure and Voltage sag compensation [4].

(A) Physical structure

The key parameters that attribute to these classifications are: Type of energy storage device used, Number of phases, and Physical location of shunt and series inverter.

(A1) Converter based classification
- a) VSI (voltage source inverter)
- b) CSI (current source inverter)

(A2) Supply system based classification
- a) Single-Phase
  - a1) Two H-bridge (total 8 switches)
  - a2) 3-Leg topology (total 6 switches)
  - a3) Half Bridge (total 4 switches)
- b) Three-Phase
  - b1) Three-Wire
  - b2) Four-Wire
    - b2.1) Four-Leg
    - b2.2) Split Capacitor
    - b2.3) Three-H Bridge

(A3) UPQC Configuration based classification
- a) UPQC-R (Right Shunt)
- b) UPQC-L (Left Shunt)
- c) UPQC-I (Interline)
- d) UPQC-MC (Multi-Converter)
- e) UPQC-MD (Modular)
- f) UPQC-ML (Multilevel)
- g) UPQC-D (Distributed)
- h) UPQC-DG (Distributed Generator integrated)

(B) Voltage Sag Compensation

The voltage sag on a system is considered as one of the important power quality problems. There are mainly four methods to compensate the voltage sag in UPQC-based applications.
- (B1) UPQC-P (Active Power Control)
- (B2) UPQC-Q (Reactive Power Control)
- (B3) UPQC-VAmin (Minimum VA Loading)
- (B4) UPQC-S (Active-Reactive Power Control)

TABLE-1.1: Comparison between Voltage Source Inverter and Current Source Inverter

Voltage Source Inverter (VSI) based	Current Source Inverter (CSI) based
1. The UPQC may be developed using PWM voltage source inverter	1. The UPQC may be developed using PWM current source inverter
2. VSI shares a common energy storage capacitor (C_{dc}) to form the dc-link	2. CSI shares a common energy storage inductor (L_{dc}) to form the dc-link
3. Advantages: - Lower cost, - Smaller physical size, - Lighter in weight, - Cheaper, - Capability of multilevel operation, - Flexible overall control, - High efficiency near nominal operating point.	3. Advantages: - Open loop current control is possible, - High efficiency when the load power is low.
4. Disadvantages: - Low efficiency when the load power is low, - Limited lifetime of the electrolyte capacitor.	4. Disadvantages: - Bulky and heavy dc inductor, - High dc-link losses, - Low efficiency near nominal operating point, - It cannot be used in

	multilevel operation.
5. The VSI based UPQC system configuration is shown in given figure 7.	5. The CSI based UPQC system configuration is shown in given figure 8.

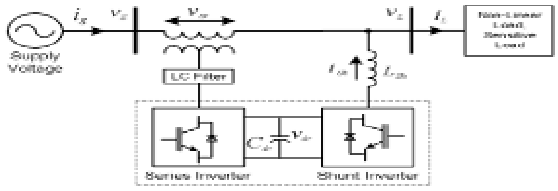

Figure 7. VSI based UPQC system configuration

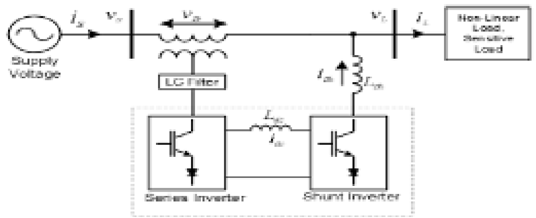

Figure 8. CSI based UPQC system configuration

From the comparison given in TABLE-1.1 one can find that VSI based UPQC topology is more popular than CSI based UPQC topology.

To mitigate power quality problems in the UPQC's different configurations are classified based on the type of supply system. There are mainly two types of supply a) single-phase and b) three-phase.

Single-phase two-wire two-H bridge UPQC configuration is shown in figure 9. Another two topologies first is 3-leg topology (total 6 switches). Apart from total 6 switches, 4 switches are used in series inverter and 2 switches are used in shunt inverter. Second is half-bridge topology (total 4 switches). In this half-bridge topology, 2 switches are used in series inverter and 2 switches used in shunt inverter.

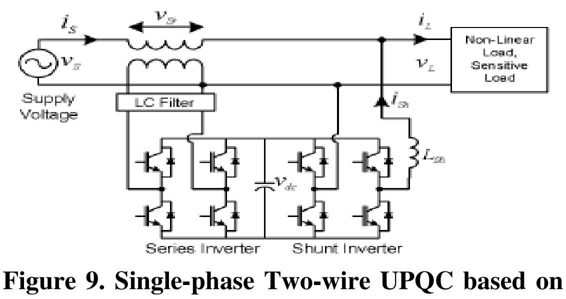

Figure 9. Single-phase Two-wire UPQC based on Two H-bridge configuration (eight switches)

Three-phase three-wire UPQC configuration is shown in figure 10. Several non-linear loads, such as, diode rectifier, adjustable speed drives (ASD), controlled rectifier etc. are fed from three-phase three-wire UPQC system [6].

The combination of three-phase and single-phase loads are supplied by three-phase four-wire (3P4W) UPQC configuration.

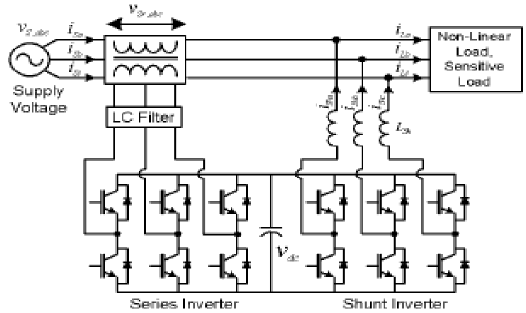

Figure 10. Three-phase Three-wire (3P3W) UPQC

. For neutral current compensation in three-phase four-wire (3P4W) system, various shunt inverter configurations are given, namely, four-leg (4L), two split-capacitor (2C) and three-H bridge (3HB).

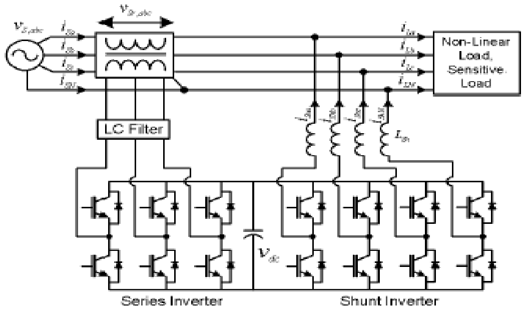

Figure 11. Three-phase Four-wire (3P4W) UPQC based on Four-leg (4L) shunt inverter topology

The 3HB topology use three single-phase H-bridge inverter connected to same dc bus of the UPQC. The 2C topology use two split-capacitor on dc side and the midpoint of two capacitor is at zero potential which is used as connection point for the fourth wire. Among all three topologies four-leg (4L) is give better control over neutral current due to four leg. So, in this paper three-phase four-wire based on four-leg (4L) shunt inverter topology is shown in figure 11.

The comparison of single-phase UPQC and three-phase UPQC is given in TABLE-1.2 which gives detailed information about both source.

TABLE-1.2: Comparison between Single-phase UPQC and Three-phase UPQC

Single-phase UPQC (1P UPQC)	Three-phase UPQC (3P UPQC)
1. Single-phase UPQC is possible in single-phase two-wire (1P2W)	1. Three-phase UPQC is possible in three-phase three-wire or three-phase four-wire (3P3W or 3P4W)
2. Single-phase UPQC is further classified on:	2. Three-phase four-wire UPQC is further classified

(i) Two H-bridge (ii) 3-Leg topology (iii) Half Bridge	on: (i) Four-Leg (ii) Split Capacitor (iii) Three-H Bridge
3. In single-phase system load reactive current, current harmonics are major problems	3. - In three-phase three-wire system apart from reactive current, current harmonics additional problem is current unbalance - In three-phase four-wire system additional neutral current problem
4. Voltage related power quality problems are similar for both single and three-phase system except voltage unbalance compensation is not required in single-phase system	4. Voltage related power quality problems are similar for both single and three-phase system except voltage unbalance compensation is required in three-phase system

There are various types of configurations of UPQC is given in above classification. Figure 7 to 11 all are represents right shunt UPQC (UPQC-R) and when in figure 7 to 11 shunt inverter is located in left at that time it is called left shunt UPQC (UPQC-L). Among this two configurations UPQC-R is commonly used because current flow through series transformer is mostly sinusoidal in UPQC-R configuration. The UPQC-L is rarely used when to avoid interference between shunt inverter and passive filters.

First, the comparison between Interline UPQC (UPQC-I) and Multi-converter UPQC (UPQC-MC) is given in TABLE-1.3.

TABLE-1.3: Comparison between Interline UPQC and Multi-converter UPQC

Interline UPQC (UPQC-I)	**Multi-converter UPQC (UPQC-MC)**
1. In Interline UPQC two inverters are connected between two distribution feeders.	1. In UPQC-MC third converter is added to support dc bus.
2. One inverter is connected in series with one feeder while other inverter is connected in shunt with other feeder.	2. The third converter is connected either series or parallel with feeder.
3. UPQC-I can control and manage flow of real power between two feeders.	3. To improve system performance, use of storage battery or super capacitor at third converter.

Second, the comparison between Modular UPQC (UPQC-MD) and Multi-level UPQC (UPQC-ML) is given in TABLE-1.4.

TABLE-1.4: Comparison between Modular UPQC and Multi-level UPQC

Modular UPQC (UPQC-MD)	**Multi-level UPQC (UPQC-ML)**
1. In UPQC-MD several H-bridge modules are connected in cascade in each phase.	1. UPQC-ML is based on 3-level neutral point clamped topology.
2. The H-bridge modules for shunt inverter is connected in series through multi-winding transformer, while, series inverter is connected in series without using series transformer.	2. In UPQC-ML three-level topology require double semiconductor switches.
3. UPQC-MD can be useful to achieve higher power levels.	3. UPQC-ML can also be useful to achieve higher power levels.

Third, the comparison between Distributed UPQC (UPQC-D) and Distributed Generator Integrated UPQC (UPQC-DG) is given in TABLE-1.5

TABLE-1.5: Comparison between UPQC-D & UPQC-DG

Distributed UPQC (UPQC-D)	**Distributed Generator Integrated UPQC (UPQC-DG)**
1. UPQC-D topology is also known as 3P3W to 3P4W Distributed UPQC because 3P4W system is realized by using 3P3W system.	1. The UPQC can be integrated with one or several DG system which is known as UPQC-DG.
2. In UPQC-D system the neutral of series transformer is used as neutral of 3P4W system.	2. The output of DG system is connected to dc bus of UPQC to compensate voltage and current related problems.
3. Fourth leg is added to 3P3W UPQC to compensate neutral current flowing towards transformer neutral point.	3. In UPQC-DG battery can be added at dc bus which is used as stored power and used as backup which give benefit for removing voltage interruption.

Finally, the classification is based on voltage sag compensation is given in this section. There are mainly four methods to compensate voltage sag in UPQC based applications, The comparison between Active Power Control (UPQC-P) and Reactive Power Control (UPQC-Q) is given in TABLE-2.1

TABLE-2.1: Comparison between Active Power Control and Reactive Power Control

Active Power Control (UPQC-P)	**Reactive Power Control (UPQC-Q)**
1. The voltage sag is mitigated by injecting active power through series inverter of UPQC.	1. The voltage sag is mitigated by injecting reactive power through series inverter of UPQC.
2. In Active Power Control P is referred as active power.	2. In Reactive Power Control Q is referred as reactive power.
3. To compensate equal percentage of sag UPQC-P	3. To compensate equal percentage of sag UPQC-Q

requires smaller magnitude of series injection voltage compared to UPQC-Q.	requires smaller magnitude of series injection voltage compared to UPQC-P.

The comparison between Minimum VA Loading (UPQC-VAmin) and Active-Reactive Power Control (UPQC-S) is given in TABLE-2.2

TABLE-2.2: Comparison between Minimum VA loading and Active & Reactive Power Control

Minimum VA loading (UPQC-VAmin)	Active & Reactive Power Control (UPQC-S)
1. This method is used which is injected certain optimal angle with respect to source current.	1. In UPQC-S the series inverter is delivered both active and reactive power.
2. The series voltage injection and the current drawn by shunt inverter must need for determining Minimum VA loading of UPQC.	2. The series inverter of UPQC-S perform voltage sag and swell compensation and sharing reactive power with shunt inverter.

V: CONTROL STRATEGIES OF UPQC

Control strategy play very important role in system's performance. The control strategy of UPQC may be implemented in three stages:

i. Voltage and current signals are sensed
ii. Compensating commands in terms of voltage and current levels are derived
iii. The gating signals for semiconductor switches of UPQC are generated using PWM, hysteresis or fuzzy logic based control techniques

In the first stage voltage signals are sensed using power transformer or voltage sensor and current signals are sensed using current transformer or current sensor [7].

In second stage derivation of compensating commands are mainly based on two types of domain methods: (1) Frequency domain methods, and (2) Time domain method. Frequency domain methods, which, is based on the Fast Fourier Transform (FFT) of distorted voltage or current signals to extract compensating commands. This FFT are not popular because of large computation, time and delay.

Control methods of UPQC in time-domain are based on instantaneous derivation of compensating commands in form of either voltage or current signals. There are mainly two widely used time domain control techniques of UPQC are:

- The instantaneous active and reactive power or p-q theory, and
- Synchronous reference frame method or d-q theory.

In *p-q* theory instantaneous active and reactive powers are computed, while, the *d-q* theory deals with the current independent of the supply voltage. Both methods transforms voltages and currents from abc frame to stationary reference frame (p-q theory) or synchronously rotating frame (d-q theory) to separate the fundamental and harmonic quantities [8].

In third stage the gating signals for semiconductor switches of UPQC based on derive compensating commands in terms of voltage or current. Then, these compensating commands are given to PWM, hysteresis or fuzzy logic based control techniques.

VI: CONCLUSION

The power quality problems in distribution systems are not new but customer awareness of these problems increased recently. It is very difficult to maintain electric power quality at acceptable limits. One modern and very promising solution that deals with both load current and supply voltage imperfections is the Unified Power Quality Conditioner (UPQC). This paper presented review on the UPQC to enhance the electric power quality at distribution level. The UPQC is able to compensate supply voltage power quality issues such as, sags, swells, unbalance, flicker, harmonics, and for load current power quality problems such as, harmonics, unbalance, reactive current and neutral current. In this paper several UPQC configurations have been discussed. Among all these configurations, UPQC-DG could be the most interesting topology for a renewable energy based power system.

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