Global Journal of Researches in Engineering
Electrical and Electronics Engineering
Volume 13 Issue 7 Version 1.0 Year 2013
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals Inc. (USA)
Online ISSN: 2249-4596 & Print ISSN: 0975-5861

A Review on UPQC for Power Quality Improvement in Distribution System

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Abstract - In recent years, Power engineers are increasingly concerned over the quality of the electrical power. In modern power system consists of wide range of electrical, electronic and power electronic equipment in commercial and industrial applications. Since most of the electronic equipments are nonlinear in nature these will induce harmonics in the system, which affect the sensitive loads to be fed from the system. One among the many compensating devices is Unified Power Quality Conditioner (UPQC) which specifically aims at the integration of series-active and shunt-active power filters to mitigate any type of voltage and current fluctuations and power factor correction in a power distribution network, such that improved power quality can be made available at the point of common coupling. In This paper presents a comprehensive review on the unified power quality conditioner (UPQC) to enhance the electric power quality at distribution levels. This is intended to present a broad overview on the different possible UPQC system configurations.

Keywords : power quality (PQ), harmonics, voltage sag, voltage swell, active power filter (apf), unified power quality conditioner (UPQC).

GJRE-F Classification : FOR Code: 090607, 290903p

A REVIEW ON UPQCFORPOWERQUALITYIMPROVEMENTINDISTRIBUTIONSYSTEM

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A Review on UPQC for Power Quality Improvement in Distribution System

B. Gopal[α], Pannala Krishna Murthy[σ] & G.N. Sreenivas[ρ]

Abstract - In recent years, Power engineers are increasingly concerned over the quality of the electrical power. In modern power system consists of wide range of electrical, electronic and power electronic equipment in commercial and industrial applications. Since most of the electronic equipments are nonlinear in nature these will induce harmonics in the system, which affect the sensitive loads to be fed from the system. One among the many compensating devices is Unified Power Quality Conditioner (UPQC) which specifically aims at the integration of series-active and shunt-active power filters to mitigate any type of voltage and current fluctuations and power factor correction in a power distribution network, such that improved power quality can be made available at the point of common coupling. In This paper presents a comprehensive review on the unified power quality conditioner (UPQC) to enhance the electric power quality at distribution levels. This is intended to present a broad overview on the different possible UPQC system configurations.

Keywords : power quality (PQ), harmonics, voltage sag, voltage swell, active power filter (apf), unified power quality conditioner (UPQC).

I. Introduction

The quality of the power is effected by many factors like harmonic contamination, due to the increment of non-linear loads, such as large thyristor power converters, rectifiers, voltage and current flickering due to arc in arc furnaces, sag and swell due to the switching (on and off) of the loads etc. These problems are partially solved with the help of LC passive filters. However, this kind of filter cannot solve random variations in the load current waveform and voltage waveform. Active filters can resolve this problem, however the cost of active filters is high, and they are difficult to implement in large scale. Additionally, they also present lower efficiency than shunt passive filters [1].

This paper focuses on a unified power quality condition (UPQC). The UPQC is one of the APF family members where shunt and series APF functionalities are integrated together to achieve superior control over several power quality problems simultaneously. It is noticed that more than half of the papers on UPQC have been reported in the last five years, which indeed suggest the rapid interest in utilizing UPQC to improve the quality of power at the distribution level [2],[3].

The UPQC is a combination of series and shunt active filters connected through 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].

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II. 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. 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 1 : Interruption

An interruption is defined as complete loss of supply voltage or load current as shown in Fig. 2.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

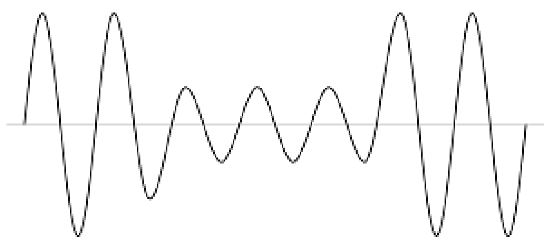

Figure 2 : Voltage Sags

Voltage sags (dips) are short duration reductions inrms voltage caused by short duration increases of the current. The most common causes of the over currents 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 as shown in Fig. 3.

c) Voltage Swells

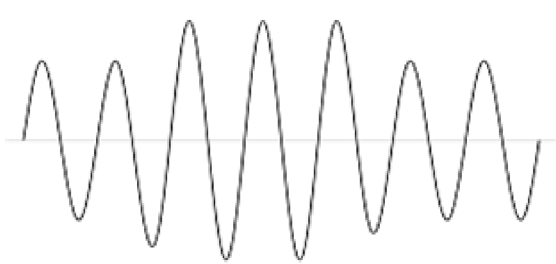

Figure 4 : Voltage Swells

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 swells are normally due to lightning, switching and sudden decreasing in loads, which leads to damage to the motors, electronic loads and other equipments. The severity of voltage swell during a fault condition is a function of fault location, system impedance and grounding.

d) Waveform Distortion

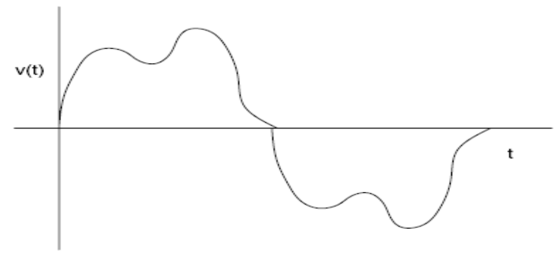

Figure 3 : Distorted Waveform

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.

e) Harmonics

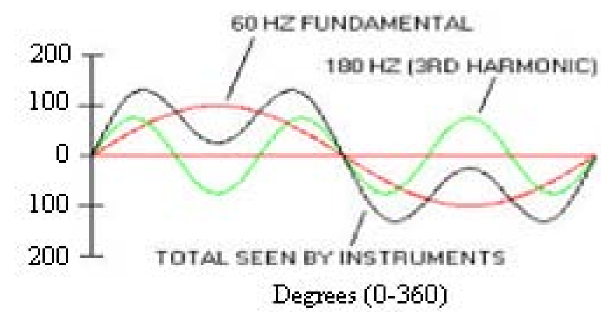

Figure 4 : Waveform with 3rd Harmonic

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

In order to meet PQ standard limits, it may be necessary to include some sort of compensation. Modern solutions can be found in the form of active rectification or active filtering. A shunt active power filter is suitable for the suppression of negative load influence on the supply network, but if there are supply voltage imperfections, a series active power filter may be needed to provide full compensation

III. Basic Configuration of UPQC

In recent years, solutions based on flexible ac ransmission systems (FACTS) have appeared. The application of FACTS concepts in distribution systems has resulted in a new generation of compensating devices. A unified power-quality conditioner (UPQC) is the extension of the unified power-flow controller (UPFC) concept at the distribution level. It consists of combined series and shunt converters for simultaneous compensation of voltage and current imperfections in a supply feeder. However, a UPFC only needs to provide balance shunt and/or series compensation, since a power transmission system generally operates under a balanced and distortion free environment. On the other hand, a power distribution system may contain dc components, distortion, and unbalance both in voltages and currents. Therefore, a UPQC should operate under this environment while performing shunt and/or series compensation [5].

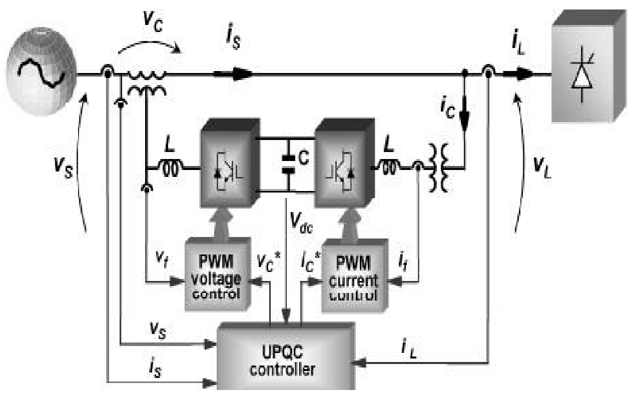

Figure 5 : Basic Configuration of the UPQC

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. Fig.1 shows a single-line representation of the UPQC system configuration. The key components of this system are as follows.

1. Two inverters one connected across the load which acts as a shunt APF and other connected in series with the line as that of series APF.
2. Shunt coupling inductor L_{Sh} is used to Interface the shunt inverter to the network. It also helps in smoothing the current wave shape. Sometimes an isolation transformer is utilized to electrically isolate the inverter from the network.
3. A common dc link that can be formed by using a Capacitor or an inductor. In Fig. 1, the dc link is realized using a capacitor which interconnects the two inverters and also maintains a constant self supporting dc bus voltage across it.
4. An *LC* filter that serves as a passive low-pass filter (LPF) and helps to eliminate high- frequency switching ripples on generated inverter output voltage.
5. Series injection transformer that is used to connect the series inverter in the network. A uitable turn ratio is often considered to reduce the current or and voltage rating of the series inverter.

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 [6], [7].

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:

$$I_C(\omega t)=I^*_L(\omega t)-I_S(\omega t) \quad (1)$$

Where $I_C(\omega t)$, $I^*_L(\omega t)$, and $I_S(\omega t)$ represent the shunt inverter current, reference load current, and actual source 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:

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

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[8] [9].

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.

1. Converter based classification
   a. VSI (voltage source inverter)
   b. CSI (current source inverter)
2. Supply system based classification
   a. Single-phase
      i. Two H-bridge (total 8 switches)
      ii. 3-Leg topology (total 6 switches)
      iii. Half Bridge (total 4 switches)
   b. Three-Phase
      i. Three-wire
      ii. Four-wire
- Four-Leg
- Split Capacitor
- Three-H Bridge
3. UPQC Configuration based classification
   a. UPQC-R (Right Shunt)
   b. UPQC-L (Left Shunt)
   c. UPQC-I (Interline)
   d. UPQC-MC (Multi-Converter)

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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.

1. UPQC-P (Active Power Control)
2. UPQC-Q (Reactive Power Control)
3. UPQC-VAmin (Minimum VA Loading)
4. UPQC-S (Active-Reactive Power Control)

Table 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 life time 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 Fig. 7.	5. The CSI based UPQC system configuration is shown in given Fig. 8.

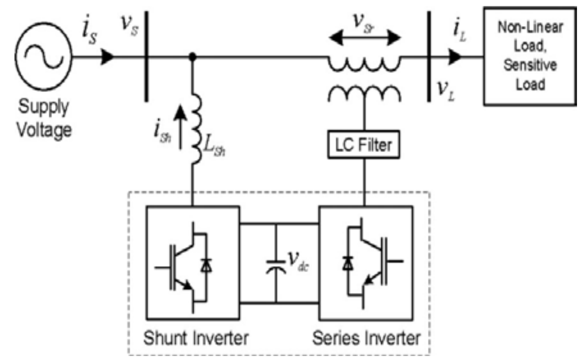

Figure 6 : VSI based UPQC system configuration

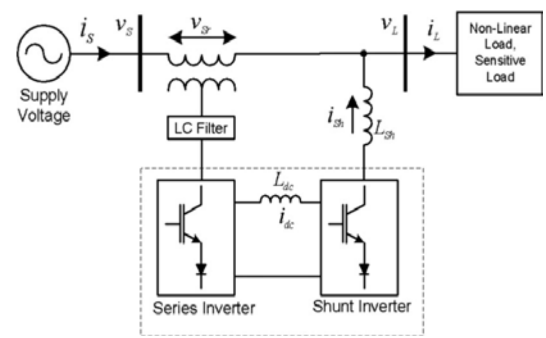

Figure 7 : CSI based UPQC system configuration

From the comparison given in TABLE-1one can find that VSI based UPQC topology is more popular than CSI based UPQC topology.

To mitigate power quality problems in the distribution system and 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-Hbridge UPQC configuration is as shown in Fig. 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 alf-bridge topology, 2 switches are used in series inverter and 2 switches used in shunt inverter [10].

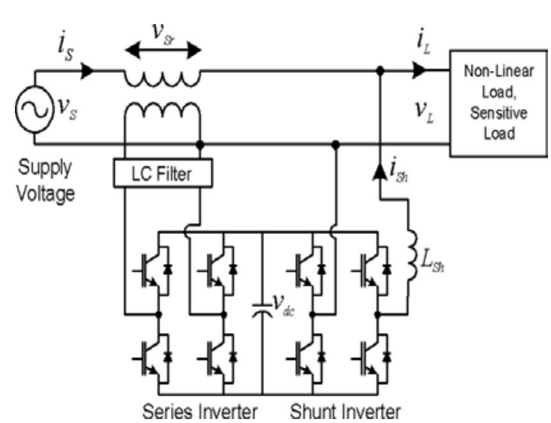

Figure 8 : Single-phase Two-wire UPQC based on

Two H-bridge configuration (eight switches)

Three-phase three-wire UPQC configuration is as shown in Fig 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 [11] [12].

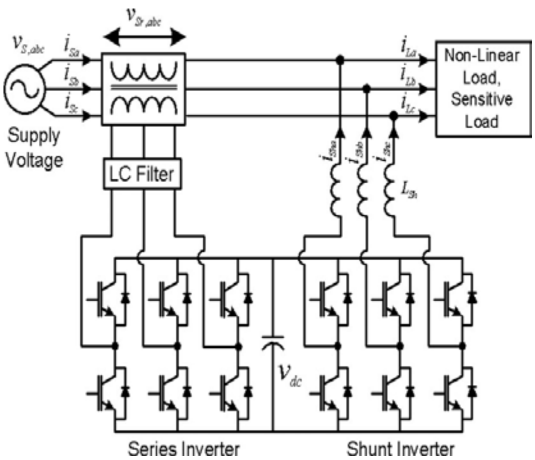

Figure 9 : Three-phase Three-wire (3P3W) UPQC

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

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) [13] [15].

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. In this paper three-phase four-wire based on four-leg (4L) shunt inverter topology [24], is shown in Fig. 11.

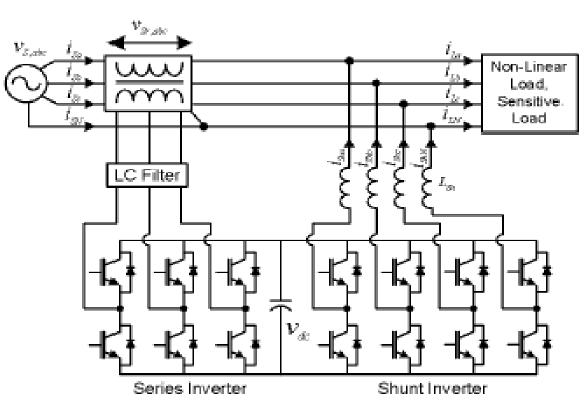

Figure 10 : Three-phase Four-wire (3P4W) UPQC based on Four-leg (4L) shunt inverter topology

The comparison of single-phase UPQC and three- phase UPQC is given in TABLE-2 which gives detailed information about both the sources.

Table 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: (i) Two H-bridge (ii) 3-Leg topology (iii) Half Bridge	2. Three-phase four-wire UPQC is further classified 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 com-pensation is required in three-phase system

There are various types of configurations of UPQC is given in above classification. Fig. 7 to 11 all are represents right shunt UPQC (UPQC-R) and when in Fig. 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. The UPQC-L is rarely used due to interference between shunt inverter and passive filters.

First, the comparison between Interline UPQC (UPQC-I) and Multi-converter UPQC (UPQC-MC) [23] is given in TABLE-3.

Table 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	3. It can control and

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manage flow of real power between two feeders.	manage flow of real power between multi feeders.

Second, the comparison between Modular UPQC (UPQC-MD) and Multi-level UPQC (UPQC-ML) [20], [26], [27] is given in TABLE-4.

Table 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 conne-cted 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 with 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) [14] [16] [19] [21], is given in TABLE-5.

Table 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 3P-4W system is realized by using 3P3W system.	1. The UPQC can be integrated with one or several DG systems which are nown 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 com-pensate voltage and current related problems.
3. Fourth leg is added to 3P 4WUPQC 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-6.

Table 6 : 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 requires smaller magnitude of series injection voltage compared to UPQC-Q.	3.To compensate equal percentage of sag UPQC-Q requires larger magnitude of series injection voltage compared to UPQC-P.

The comparison between Minimum VA Loading (UPQC-VAmin) and Active-Reactive Power Control (UPQC-S) [29],[30], [31], is given in TABLE-7.

Table 7 : 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 com-pensation 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 Com pensating commands in terms of voltage and current levels are derived.

ii. The gating signals for semiconductor Switches of UPQC are generatedusing PWM, hysteresis or fuzzy logic based control techniques

iii. 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.

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 the 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 eals 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.

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 [25] [28].

VI. Technical and Economical Consideration

Technical literature on the APFs can be found since early 1970s [1]. However, the use of UPQC to enhance electric power system quality is reported since mid 1990s [3]. Among the various power quality enhancement devices, STATCOM and few others are commercially available [2]. The technology to develop commercial UPQC system is available today; however, the overall cost and complexity of such a system still imposes some limitations. A 250-kVA prototype developed at C-DAC, Thiruvananthapuram, India [17], is the most viable reported prototype.

The capacity of small and large-scale renewable energy systems based on wind energy, solar energy, etc., installed at distribution as well as transmission levels is increasing significantly. These newly emerging DG systems are imposing new challenges to electrical power industry to accommodate them without violating standard requirements (such as, IEEE 1547, IEEE 519). In terms of power quality, the excessive feeder voltage rise due to reverse power flow from DG system and power system stability is of significant importance. Moreover, most of the DG systems utilize power electronic converters as interfacing device to deliver the generated power to the grid. The switching operation of these systems is contributing as increased harmonic levels both in the grid voltages and currents.

In this paper, several UPQC configurations and topologies have been discussed. Among these configurations, UPQC-DG could be the most interesting topology for a renewable energy based power system. This configuration can offer multifunctional options, namely, active power delivery from DG system to grid (normal DG operation), voltage and current related power quality compensation (UPQC operation), and uninterruptible power supply operation. Commercial products have started to appear in the market to increase the renewable energy system connectivity by compensating some of these problems. As the penetration levels of DG system on the existing power system continue to increase, the utilization of active compensating technologies (such as, flexible ac transmission system devices and APFs) is expected to increase gradually.

VII. 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 a review on the UPQC as a tool 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. Among all these configurations, UPQC-DG and UPQC-ML are the most vital topologies to achieve better reliability and power quality at higher power rating of the system. Therefore with the help of these topologies can meet required load demand in future, increase the production in industries and increase the economy of the country.

Acknowledgements

The author B. Gopal express sincere thanks to the Management, the Principal and the Staff members of the Department of EEE of Khammam Institute of Technology & Sciences, Khammam for the continued support in executing this work.

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