Different Modeling Aspects and Energy Systems of Unified Power Quality Conditioner (UPQC): An Overview

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Abstract- This paper highlights the classification of Unified Power Quality Conditioner (UPQC) to enhance the electric power quality at distribution levels. It aims to present a broad overview on the different possible UPQC system configurations for single-phase (two-wire) and three-phase (three-wire and four-wire) networks, different modeling approaches and backup energy storages, and recent developments in the field. It is noticed that several researchers have used different names for the UPQC based on the unique function, task, application, or topology under consideration. Therefore, an acronymic list is developed and presented to highlight the distinguishing feature offered by a particular UPQC. In all 12 acronyms are listed, namely, UPQC-D, UPQC-DG, UPQC-I, UPQC-L, UPQC-MC, UPQC-MD, UPQC-ML, UPQC-P, UPQCQ, UPQC-R, UPQC-S, and UPQC-VA$_{min}$.

Keywords- Active Power Filter (APF), harmonic compensation, power quality, energy storage devices, unified power quality conditioner (UPQC).

1. Introduction

It has been always a challenge to maintain the quality of electric power within the acceptable limits [1]–[7]. The adverse effects of poor power quality are discussed in [1], [2], [5]–[7]. In general, poor power quality may result into increased power losses, abnormal and undesirable behavior of equipments, interference with nearby communication lines, and so forth. The widespread use of power electronic based systems has further put the burden on power system by generating harmonics in voltages and currents along with increased reactive current. The term active power filter (APF) is a widely used terminology in the area of electric power quality improvement [8]–[10]. 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 several interesting topologies/configurations can be realized to form a UPQC system [11], [12], [13], [14], [15], [16], [17], [18]. The UPQC is then categorized based on the 1) type of converter (current or voltage source); 2) supply system (single phase two-wire, three-phase three-wire and four-wire); and 3) recently developed new system configurations for single-phase and/or three-phase system. Furthermore, it is found that there are several acronyms, such as, UPQC-P, UPQC-Q, UPQC-L, and UPQC-R that are typically addressed by researchers. This paper aims at developing an acronymic list to cover different UPQC aspects with different energy storages. In all 12 acronyms are identified, alphabetically, UPQC-D, UPQCDG, UPQC-I, UPQC-L, UPQC-MC, UPQC-MD, UPQC-ML, UPQC-P, UPQC-Q, UPQC-R, UPQC-S, and UPQC-VAmin.

2. System Configuration of Upqc

The Unified Power Quality Conditioner is a custom power device that is employed in the distribution system to mitigate the disturbances that affect the performance of sensitive and/or critical load [19]. It is a type of hybrid APF and is the only versatile device which can mitigate several power quality problems related with voltage and current simultaneously therefore is multi functioning devices that compensate various voltage disturbances of the power supply, to correct voltage fluctuations and to prevent harmonic load current from entering the power system.

Fig. 1 shows the system configuration of a single-phase UPQC. Unified Power Quality Conditioner (UPQC) consists of two IGBT based Voltage source converters (VSC), one shunt and one series cascaded by a common DC bus. The shunt converter is connected in parallel to the load. It provides VAR support to the load and supply harmonic currents. The series converter connected in series to the load provides voltage compensation [20]. Thus UPQC improves the power quality by preventing load current harmonics and by correcting the input power factor.

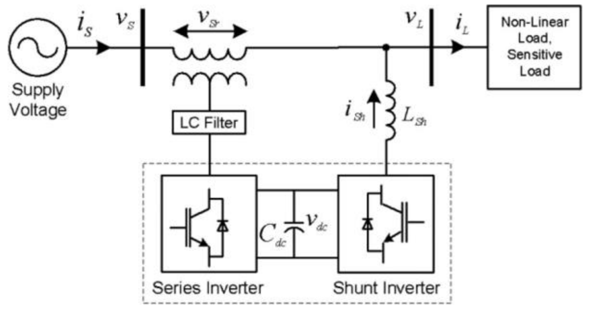

Fig. 1. UPQC general block diagram

The main components of a UPQC are series and shunt power converters, DC capacitors, low-pass and high-pass passive filters, and series and shunt transformers:

2.1. Series Converter

It is a voltage-source converter connected in series with the AC line and acts as a voltage source to mitigate voltage distortions. It is used to eliminate supply voltage flickers or imbalance from the load terminal voltage and forces the shunt branch to absorb current harmonics generated by the nonlinear load. Control of the series converter output voltage is usually performed using sinusoidal pulse-width modulation (SPWM). The gate pulses required for converter are generated by the comparison of a fundamental voltage reference signal with a high-frequency triangular waveform.

2.2. Shunt Converter

It is a voltage-source converter connected in shunt with the same AC line and acts as a current source to cancel current distortions, compensate reactive current of the load, and improve the power factor. It also performs the DC-link voltage regulation, resulting in a significant reduction of the DC capacitor rating. The output current of the shunt converter is adjusted using a dynamic hysteresis band by controlling the status of semiconductor switches so that output current follows the reference signal and remains in a predetermined hysteresis band.

2.3. Midpoint-to-ground DC Capacitor Bank

It is divided into two groups, which are connected in series. The neutrals of the secondary transformers are directly connected to the DC link midpoint. As the connection of both three-phase transformers is Y/Yo, the zero-sequence voltage appears in the primary winding of the series-connected transformer in order to compensate for the zero-sequence voltage of the supply system. No zero-sequence current flows in the primary side of both transformers. It ensures the system current to be balanced even when the voltage disturbance occurs.

2.4. Low-pass Filter

It is used to attenuate high frequency components at the output of the series converter that are generated by high-frequency switching.

2.5. High-pass Filter

It is installed at the output of shunt converter to absorb current switching ripples.

3. Equivalent Circuit

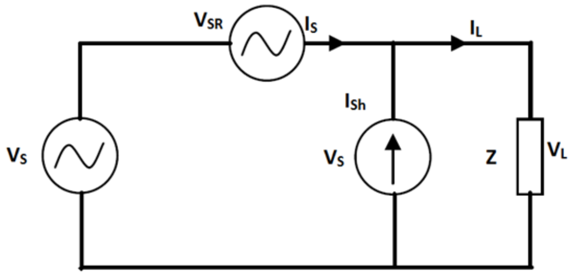

Fig. 2. Equivalent circuit for UPQC

V_S: Voltage at power supply

V_{SR}: Series-APF for voltage compensation,

V_L: Load voltage and

I_{Sh}: Shunt-APF for current and V_{SR} compensation.

Due to the voltage distortion, the system may contain negative phase sequence and harmonic components.

In general, the source voltage in Figure 2 can be expressed as:

$$V_s + V_{SR} = V_L \tag{1}$$

To obtain a balance sinusoidal load voltage with fixed amplitude V, the output voltages of the series-APF should be given by:

$$V_{SR} = (V - V_{1p}) \sin(\omega t + \theta_{1P}) - V_{Ln}(t) - \sum_{K}^{\infty} = 2 V_k(t) \qquad (2)$$

Where, V_{1p}: Positive sequence voltage amplitude fundamental frequency

θ_{1p}: Initial phase of voltage for positive sequence

V_{Ln}: Negative sequence component

The shunt-APF acts as a controlled current source and its output components should include harmonic, reactive and negative-sequence components in order be to compensate these quantities in the load current, when the output current of shunt APF I_{sh} is kept to be equal to the component of the load as given in the following equation:

$$I_L = I_{1p} \cos(\omega t + \theta_{1P}) \sin\varphi_{1P} + I_{Ln} + \sum_{K}^{\infty} = 2 \; I_{LK} \qquad (3)$$

$$\phi_{1P} = \varphi_{1P} - \theta_{1P} \qquad (4)$$

Where, φ_{1P}: Initial phase of current for positive sequence.

As seen from the above equations that the harmonic, reactive and negative sequence current is not flowing into the power source. Therefore, the terminal source current is harmonic-free sinusoid and has the same phase angle as the phase voltage at the load terminal

$$\begin{aligned} I_S &= I_L - I_{Sh} \\ &= I_{1p} \sin(\omega t - \theta_{1P}) \cos\varphi_{1P} \qquad (5) \end{aligned}$$

4. Functions of Upqc

4.1. Reactive Power Compensation

4.2. Voltage Regulation

4.3. Compensation for voltage sag and swell

4.4. Unbalance Compensation for current and voltage (for 3-phase systems

4.5. Neutral Current Compensation (for 3-phase 4-wire systems).

5. Classification of Upqc

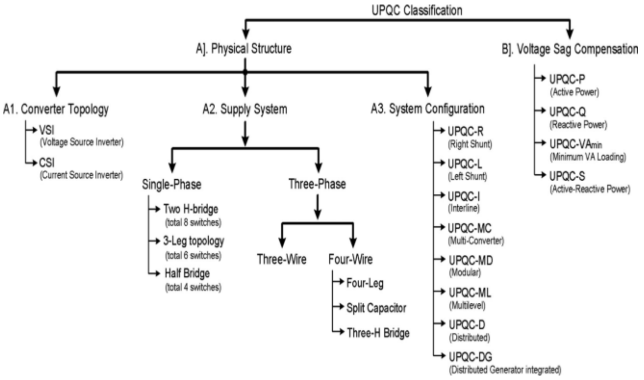

Fig. 3. Classification of UPQC

In this section, the classification of UPQC is given. Fig. 3 shows a pictorial view for the classification of UPQC. The UPQC is classified in two main groups:

A) Based on the physical structure and

B) On the voltage sag compensation approach used.

Former type is considered as voltage sag compensation is one of the important functionalities of UPQC.

5.1. Physical Structure

The UPQC can be classified based on the physical structure used to tackle the power quality problems in a system under consideration. The key parameters that attribute to these classifications are:

1) Type of energy storage device used;

2) Number of phases; and

3) Physical location of shunt and series inverters.

Recently developed new topologies and/or system configurations for UPQC have been also discussed in the following section.

5.2. Classification Based on the Voltage Sag Compensation Approach

The voltage sag on a system is considered as one of the important power quality problems. A special attention on mitigating the voltage sag on a system using UPQC can be noticed. In this section, the classification of UPQC based on the approach used to mitigate the voltage sag is carried out. The existing literature suggests four major methods to compensate the voltage sag in UPQC-based applications.

Several acronyms of UPQC based on the particular functionality, topology, or application have been described. These 12 key acronyms, namely, UPQC R, UPQC-L, UPQC-I, UPQC-MC, UPQC-MD, UPQC-ML, UPQC-D, UPQC-DG, UPQC-P, UPQC-Q, UPQC-S, and UPQC-VAmin, are listed in Table I. These acronyms could be useful to highlight the key features of UPQC in an application more concisely. In general, the UPQC-I,UPQC-MC,UPQC MD, UPQC-ML, UPQC-D, and UPQC-DG can be based on VSI or CSI converter topology.

Additionally, these topologies can be configured as UPQC-R or UPQC-L. Expect UPQC-D (which represents a unique case for 3P4W system), all other configuration can be realized for 1P2W, 3P3W, and 3P4W systems. Moreover, the UPQC controller could be based on UPQC-P, UPQC-Q, UPQC VAmin, or UPQC-S approaches. Based on the aforementioned discussed classifications, there are more than 50 possibilities in which a UPQC can be categorized.

Table 1. Key UPQC Acronyms

UPQC-D	3P3W to 3P4W distributed UPQC
UPQC-DG	Distributed Generator integrated with UPQC
UPQC-I	Interline UPQC
UPQC-L	Left shunt UPQC
UPQC-MC	Multi-Converter UPQC
UPQC-MD	Modular UPQC
UPQC-ML	Multi-Level UPQC
UPQC-P	UPQC mitigates sag by controlling active power
UPQC-Q	UPQC mitigates sag by controlling reactive power
UPQC-R	Right shunt UPQC
UPQC-S	UPQC mitigates sag by controlling both active and reactive power. Also, load reactive power support using both the inverters in the steady-state.
UPQC-VA$_{min}$	Minimum VA loading in UPQC

6. Modeling Aspects of Upqc

To realize the model, it is first transformed as an equivalent discrete system model and then to a linear equivalent discrete system model by states reconstruction and linearization. Furthermore, the output feedback periodical switched controller is designed to stabilize the closed-loop system. It is observed that the system is nonlinear on its states as well as on its outputs. In a UPQC mathematical model is realized using switching functions. A small signal model for the UPQC system has been developed that shows the UPQC system can be modeled as a typical switched linear system.

The control of dc-link voltage plays an important role in achieving the desired UPQC performance. During the system dynamic conditions, such as sudden load change, voltage sag, the dc-link feedback controller should respond as fast as possible to restore the dc-link voltage at set reference value, with minimum delay as well as lower overshoot.

It is the control strategy which decides the behavior and desired operation of a particular system. The effectiveness of a UPQC system solely depends upon its control algorithm. The UPQC control strategy determines the reference signals (current and voltage) and, thus, decides the switching instants of inverter switches, such that the desired performance can be achieved. Thus control strategy plays the most significant role in any power electronics based system. There are several control strategies/algorithm/techniques available in the existing literature those have successfully applied to UPQC systems.

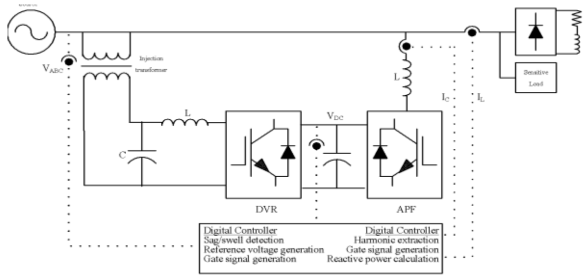

Fig. 4. Control unit of UPQC with specified power circuit topology

Two types of control strategies used are Frequency Domain & Time Domain Analysis. Frequency domain methods, such as, based on the Fast Fourier Transformer (FFT), are not popular due to large computation time and delay in calculating the FFT. Whereas time domain analysis methods are based on instantaneous derivation of compensating commands in the form of either voltage or current signals. This paper also deals with the modeling aspects of UPQC using different control algorithms based on time domain analysis.

7. Different Time Domain Control Techniques for Upqc

Different time domain control techniques used are as given below:

1) Instantaneous active & reactive power or 3phase pq theory
2) Synchronous reference frame or 3phase dq theory (SRF)
3) Unit Vector Template Generation (UVTG)
4) One Cycle Control (OCC)
5) H∞-based model matching control
6) Model Predictive Control (MPC)
7) Deadbeat Control
8) Artificial Neural Network (ANN) technique
9) Feed forward & feedback theory
10) Multi Output ADAptive LINear Approach (MO-ADALINE)

A simple controller scheme for UPQC, called as unit vector template generation (UVTG) method uses a phase-locked loop (PLL) to generate unit vector template(s) for single-/three-phase system [22]. On the other hand, Khoor and Machmoum [23] have given an analogical method for current and voltage perturbation detection. This method does not need a frequency synchronizer, such as pole shift control technique for UPQC [24]. It is a discrete-time control technique in which the closed-loop poles are chosen by radically shifting the open-loop poles toward the origin.

One cycle control (OCC) of switching converters concept based controller can also be developed for the UPQC. The OCC controller generally uses an integrator with reset feature to force the controlled variables to meet the control goal in each switching cycle [25] [26]. The OCC has the advantages of fast response and high precision. Authors suggest that during normal operating condition, the series inverter of UPQC is not utilized up to its true capacity.

In order to maximize the series inverter utilization, a concept named as power angle control (PAC) of UPQC has been developed. The concept of PAC of UPQC proves that with proper control of power angle between the source and load voltages, the load reactive power demand can be shared by both shunt and series inverters without affecting the overall UPQC rating [27]. This indeed helps to reduce the overall rating of the shunt inverter of the UPQC.

A model predictive control (MPC) that takes into account system dynamics, control objectives, and constraints is proposed for UPQC by Zang et,al [28]. The MPC can handle multivariable control problem and has relatively simple online computations.

Another control strategy has been suggested a H∞-based model matching control to track the inverter output waveforms for effective and robust control of UPQC [29]. Furthermore, a model-based solution via H∞ loop shaping for UPQC has been presented. Here the UPQC is modeled as a multi-input multi output system to deal with the coupling effect between the series and shunt inverters [30]. Additionally, Kalman filter can be integrated to extract the harmonics in supply voltage/load current [31].

Kamran and Habetler [32] have put forward a technique based on deadbeat control in which the UPQC inverter combination is treated as a single unit. The overall system can be modeled as a single multi-input, multi output system. This results in improved control performance over the separately controlled converters and/or reduced inter converter energy storage. The system can have fast dynamic response and high steady-state accuracy.

A nonlinear control law based on linearization [33] and [34]. A sliding mode controller with a constant frequency scheme is utilized to control the series inverter of UPQC. Particle swarm optimization technique has also been utilized to develop the controller for UPQC.

Another model with the use of ANN technique can also handle the multi-input multi output control system effectively [35],[36],[37]. Thus, the ANN technique can be utilized to develop the controller for the UPQC to compensate different voltage and/or current related problems. A feed forward ANN scheme is reported by Banaei and Hosseini [38] to separate the harmonics contents in the nonlinear load. The time-domain and frequency-domain techniques have certain drawbacks and limitations. To overcome their problems, a wavelet analysis technique, a tool for fault detection, localization, and classification of different power system transients, is proposed by certain researchers. By using multi resolution analysis, the wavelet transform can represent a time-varying signal in terms of frequency component.

A symmetrical component theory is generally a choice in the UPQC applications to extract the fundamental positive sequence component when the system supply voltages are unbalanced [39] and [40]. A special attention on compensating the problem of voltage flicker and/or voltage unbalance can be noticed. The UPQC could be the most effective power quality conditioner to solve the flicker problems caused by an arc furnace load.

Out of above mentioned theories, two most widely used time-domain control techniques for UPQC are the instantaneous active and reactive power or three phase *pq* theory and synchronous reference frame method or three-phase *dq* theory. These methods transfer the voltage and current signals in ABC frame to stationary reference frame (*pq* theory) or synchronously rotating frame (*dq* theory) to separate the fundamental and harmonic quantities [7].

In *pq* theory, instantaneous active and reactive powers are computed, while, the *d-q* theory deals with the current independent of the supply voltage. The interesting feature of these theories is that the real and reactive powers associated with fundamental components (*pq* theory), and the fundamental component in distorted voltage or current (*dq* theory), are dc quantities. These quantities can easily be extracted using an LPF or a high-pass filter (HPF). Due to the dc signal extraction, filtering of signals in the $\alpha\beta$ reference frame is insensitive to any phase shift errors introduced by LPF. However, the cutoff frequency of these LPF or HPF can affect the dynamic performance of the controller [41]-[43].

The original three-phase *pq* theory exhibits limitations when the supply voltages are distorted and/or unbalanced. To overcome these limitations, the original *pq* theory has been modified and generally referred as *pqr* [44]. Furthermore, both three-phase *pq* and three-phase *dq* theories have been modified such that the advantages offered by these methods are widen for single-phase APFs including single-phase UPQC systems.

Thus, the UPQC, which has two inverters that share one dc link capacitor, can compensate the voltage sag and swell, the harmonic current and voltage, and control the power flow and voltage stability. However, the UPQC cannot compensate for the voltage interruption because it has no energy storage in the dc link. Hence many researchers have used various energy storage devices that act as backup storage devices to compensate the voltage interruption. The brief classification of various backup storage devices with their advantages and disadvantages is given below.

8. Various Backup Storage Devices Used in Upqc [45]

8.1. DC storage capacitors

- Store energy in their capacitance.
- Useful for short ride through times.
- Require DC/DC converter between the constant voltage bus and the capacitance.
- Cost increases with the increase in ride through time.

8.2. Batteries

- Most common method of storing energy.
- Do not require DC/DC converter as they are directly connected to VSC.
- Capacitor can compete with batteries but only for short ride through times.
- Utilize environmentally unfriendly materials.
- Have limited life time.
- Require regular maintenance.
- Some new types of batteries do not have above mentioned limitations but have higher cost.

8.3. Super Capacitors

- Energy densities comparable to batteries.
- Improve equipment voltage tolerance.
- Have much longer lifetime than batteries.
- Require much less maintenance than batteries.
- Discharge time is not less than 1 minute.
- Faster than batteries but much slower than capacitors.
- Only available for voltages of a few volts

8.4. Flywheels

- Store energy in fast-spinning flywheels.
- Stored energy cannot be extracted fully.
- Require an additional DC/DC converter.

8.5. Superconducting coils

- Energy is stored in superconducting magnetic energy storage (SMES) coils.
- Most cost attractive solution for high power short time ride through applications.
- Fast extraction of energy as compared to batteries.
- Have reduced size and lower maintenance cost as compared to batteries.
- Can be quickly and easily installed with short lead times.
- Have modular design to meet future load growth and are portable
- Require an additional DC/DC converter between SMES and constant voltage bus

9. Practical Applications of Upqc

Digital control based UPQC has been developed for a laboratory prototype in some of the studies [46], [47], [87]. A 250-kVA UPQC system is developed at the Centre for the Development of Advanced Computing (CDAC), Thiruvananthapuram, India [48]. Additional significant UPQC prototypes and testing at higher power ratings: 20, 15, 12, 10 kV [49], [50] and so on. 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) power quality issues suggest potential applications of UPQC in renewable-energy based power systems. In this paper, several UPQC configurations and topologies have been discussed.

10. Conclusion

A comprehensive review on the UPQC to enhance the electric power quality at distribution level has been reported in this paper. Recent rapid interest in renewable energy generation, especially front-end inverter-based large-scale photovoltaic and wind system, is imposing new challenges to accommodate these sources into existing transmission/distribution system while keeping the power quality indices within acceptable limits. UPQC in this context could be useful to compensate both voltage- and current-related power quality problems simultaneously.

Different aspects of UPQC and up to date developments in this area of research have been briefly addressed. 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.

11. Future Aspects

Among above mentioned 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 the problem.

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