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A Rigorous Overview of Unified Power Quality Conditioner for Alleviation of Power Quality Issues

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Abstract: ***In this paper, an absolute overview of the Unified Power Quality Conditioner (UPQC) is given. UPQC is a kind of custom power devices, employed in the distribution network to improve power quality. In the distribution system, due to the use of various non-linear loads (power electronic devices, computers, arc furnaces, LED lights, refrigerators, SMPS, etc.), various power quality issues take place. In this work, different power quality issues have been discussed with their impact on the equipment, its suggestive mitigating devices have been explained to address these power quality issues. The focal point of this work is to give a broad review of UPQC. Classification of UPQC is given in various categories viz. physical structure, configuration, function, task, and applications. Ample elaboration on the explanation of each type of UPQC has been provided along with its appropriate control strategies.***

Keywords: Power Quality, Flexible AC Transmission System (FACTS), Custom Power Devices (CPD), Unified Power Quality Conditioner (UPQC), Active Power Filter (APF)

1. Introduction

Managing good power quality across loads is a big task. In distribution network extensive use of various non-linear loads leads to degradation of power quality, many voltage related problems (flicker, voltage swell, voltage dip, harmonics, unbalance), current related problems (current imbalance, harmonics, neutral current), etc. Power quality is further debiliated when solar farms, wind farms and DG sets are connected with the large interconnected transmission network. Loads supplied with poor power quality causes technical inconveniences (increment in losses of the distribution network, failure of the capacitor banks, noise, and vibrations in electric machines, excessive current and overvoltage due to resonance, derating of cables, dielectric breakdown, negative sequence currents in generators and motors, rotor heating), huge capital loss, equipment failure (such as computer lockups), interference with communication systems, malfunctions of relay and breaker due to spurious signals, false metering, malfunction of digital controllers, and data handling equipment [1], [2], [3].

Passive Filters, (APF), Flexible AC Transmission System (FACTS), and Custom Power Devices (CPD) are utilized to reduce or remove the above-stated power quality issues. FACTS devices are used in the transmission network, while CPD in the distribution network and thus system reliability can be improved [4]. In [5], [6], [7] various FACTS devices (UPFC, IPFC, SSSC, SVC, TCSC, etc.) are discussed. Based on structure, CPD is classified into Distribution STATCOM (D-STATCOM), Dynamic Voltage Restorer (DVR), and Unified Power Quality Conditioner (UPQC) [4], [5], [8], [9].

A comprehensive overview of UPQC, right from its working principle, classification, to different control techniques has been discussed in detail. UPQC is a combination of DVR and D-STATCOM. It can be classified based on configuration, topology of converters, sag mitigation techniques, and type of supply [1], [4], [9], [10], [11]. There are two different control strategies used to generate reference signals in UPQC; Frequency domain control techniques and Time-domain control techniques. Instantaneous reactive power theory (p-q theory), Synchronous reference frame theory (d-q theory), neural network theory, PI controller-based algorithm, etc. are time-domain control strategies [1], [10]. Fast Fourier transform, Discrete Fourier transform, Fourier series, Control algorithm base on Kalman filter, etc. are frequency domain control strategies [1], [10].

There are seven sections in this paper. Section II talks about different power quality issues. Section III shows various types of equipment used to mitigate these issues. In section IV working principle and mathematical modeling of UPQC are discussed. Section V gives a broad classification of UPQC. Section VI briefs about numerous control strategies of UPQC. The conclusion of this work and how this can be utilized for further research are given in section VII.

2. Power Quality Issues

Power quality is defined in [12]. There are many reasons due to which power gets polluted viz. lightening, flashover, equipment failure, faults, and non-linear loads used at the customer's end [1]. Variouspower quality issues are listed below:

- Transients
- Small duration voltage change
- Long duration voltage change
- Voltage imbalance
- Voltage flicker
- Waveform distortion

2.1 Transients

When system transit from one steady-state to another steady-state there is a sudden change in voltage and/or current the component is called transient [13], which can be sorted in Impulsive or Oscillatory type.

Impulsive transients have unidirectional polarity either positive or negative. Its analysis can be done based on their rise time and decay time. They are produced due to lightning strokes. It can be detracted with the help of passive or active dampers.

Oscillatory transients have alternating nature. It shows that they have a damped oscillation of a frequency range from a few hundred Hertz to several Megahertz. They last for a duration larger than an impulsive transient. The switching of a transmission line or a capacitor bank is the cause of their production.

2.2 Small duration voltage change

Such voltage variation happens to survive for less than 1 minute and can be named as Voltage Sag, Voltage Swell, and Interruption.

Voltage sag takes place in the system due to the starting of large induction motors, energization of heavy loads, faults in the system (symmetrical or unsymmetrical type) switching of sources, etc. [13].

Voltage Swell is a consequence of de-energization of large loads, temporary voltage rise in the unfaulted phase during SLG fault, etc. [14].

There is an interruption in voltage or current or power due to equipment failures, control malfunction, blown fuse, or breaker opening [4]. It stays for less than a minute in the system.

2.3 Long duration voltage change

Sustained interruptions stay for more than a minute and they are the most severe. To get the system further in operation during sustained interruptions, human intervention is required. Undervoltage and Overvoltage can be defined similarly as voltage sag and voltage swell respectively, but the period for which they last is more than 1 minute.

2.4 Voltage Imbalance

Voltage Imbalance is defined rigorously in [12], [13] and [14] Blown fuse in any phase of a capacitor bank, single phasing, fault on any phase of the network are dominant causes of voltage imbalance.

2.5 Flicker

Flicker is the rapid fluctuation in the magnitude of the voltage which can be perceived by human eyes [13]. The operation of heavy inductive loads like arc furnace, welding transformer, etc. makes flickering available in the distribution system.

2.5 Waveform Distortion

Voltage and current waveform get distorted because of harmonics, notches, and DC-offset. An abbreviation is carried out on each here.

1) Harmonics: IEEE standard 519-2014 [15] discusses the definition of harmonics, their types, measurement techniques, and mitigation techniques. Analysis, elimination, impact on different power system equipment, monitoring, and computation of harmonics are discussed in [13], [14], and [16].
2) Notching: Notching is described in [14]. It occurs continuously and can be designated by the harmonic spectrum of affected voltage. Notching may occur due to the communication of the current of the adjacent phase.

DC offset: The presence of a significant amount of DC signal in an AC signal is called DC offset [4], [13], [14]. Equipment having power electronic switches cause DC offset and it results in even harmonics, additional heating in the equipment (which reduces their life), and saturation of transformer core.

3. Mitigation of Power quality issues

Various techniques used to mitigate power quality issues are listed below.

- Capacitor banks
- Harmonic filters
- High power quality equipment design FACTS devices and
- Custom power devices

Capacitor banks of optimal size are placed at an optimal place for load compensation. Three types of harmonic filters viz. active [1], [17], [18], [19], passive [1], [4], [13], and hybrid [10] can be used to remove harmonics. Various FACTS devices like STATCOM, SSSC, UPFC, and IPFC can be used in transmission lines [1], [5], [6], [7], and [8].

4. Introduction to UPQC

As said earlier, UPQC is a conjunction of DVR and DSTAT-COM. In some literature, UPQC is shown as a conjunction of shunt and series APF. The single line representation of UPQC is demonstrated in fig.1.

UPQC system consists of two inverters (Series and shunt inverter), series injection transformers, DC link capacitor, shunt coupling filter Lsh, ripple filter and LC filter (which works as a low pass filter).

The shunt inverter deals with all load current related problems like reactive current, harmonics, unbalance, and neutral current. It also maintains a constant voltage across the DC link to its reference value. The function of shunt inverter is to provide reactive power compensation along with neutral current compensation, load balancing, elimination of harmonics.

It is placed across the consumer load and operated in current control mode to fed current at Point of Common Coupling (PCC), so pure sinusoidal current of the desired magnitude can flow through the load.

The function of the series inverter is to keep load end voltage insensitive to the source end voltage problems. It is operated in voltage control mode to inject voltagein serieswith the line to achieve a distortion-free sinusoidal voltage of the desired magnitude at the load terminal.

Till now the construction and working principle of UPQC is briefed. [1], [9], [10], [20] also discusses about working principle of UPQC. Mathematical modelling of UPQC is given in [21], [22], [23], and [24].

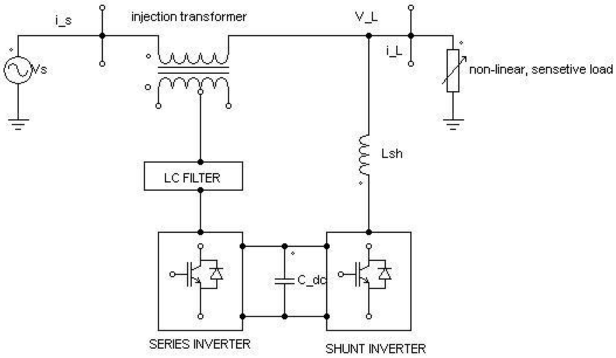


Figure 1 single line representation of UPQC

5. Assortment of UPQC

Fig.2 shows a depictive view of the classification of UPQC. UPQC can be sorted depending on 1) Physical structure 2) Voltage sag compensation technique [10].

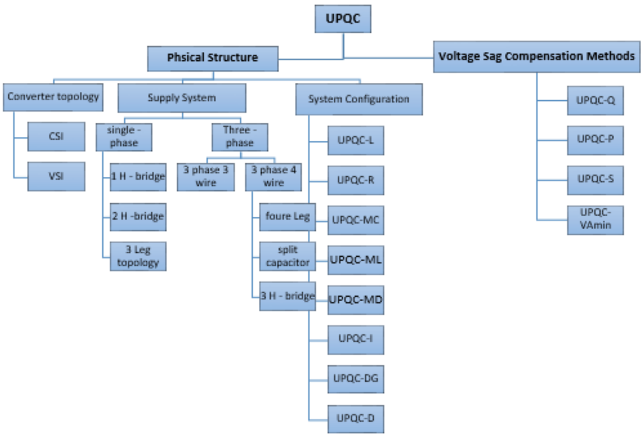


Figure 2: Classification of UPQC

5.1 Depending on the basis of The Physical Structure

Converter topology, type of the supply system, and system configuration are the key parameters that make further classification of UPQC based on the physical structure.

5.1.1 Based on the Converter Topology

Either of converter topologies from Voltage source inverter (VSI) and Current source inverter (CSI) can be employed in UPQC. Fig.3 shows the configuration of UPQC based on CSI and fig.1 shows VSI based UPQC. In UPQC consisting of CSI, an inductor is used as a common energy storage element (to form DC link) via which both the converters are connected [25], [26]. A combination of IGBT and voltage blocking diode is required to realize this topology. Demerits of this topology are higher costs and losses. It can't be utilized in multilevel vesiculation. Capacitor (C_{dc}) is used as a common energy storage element in UPQC having VSI and it is shared by both the converters. This configuration is mostly used because it is cheaper, lighter in weight, there is no need for blocking diodes, it provides flexible overall control, and the capability of multilevel operation.

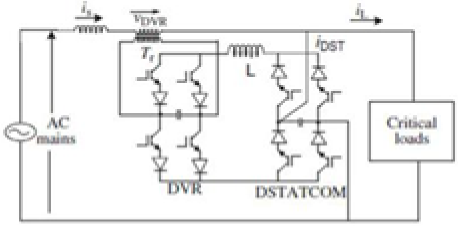


Figure 3: UPQC with CSI [1]

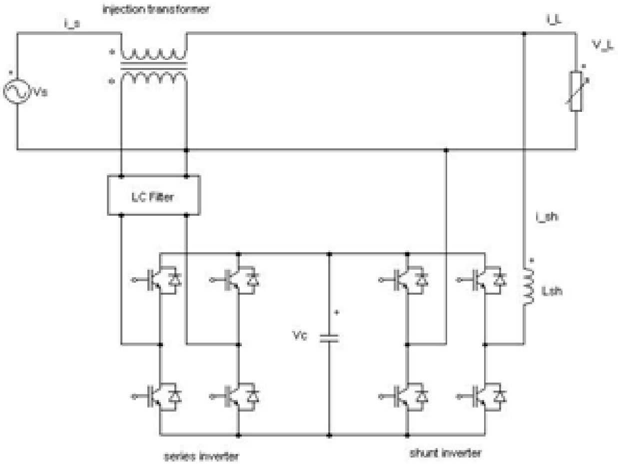


Figure 4: Single-phase UPQC with 2 H-bridge

5.1.2 Based on the Supply System

There are three ways to supply power in the distribution system. Therefore UPQC has three different configurations. 1) Single-phase (1P2W) 2) Three-phase three-wire (3P3W) 3) Three-phase four-wire (3P4W). By comparing these configurations, it has been concluded that in the three-phase arrangement an additional volt-age unbalance compensation is required, which isn't required in a single-phase arrangement. The main concern in a single-phase layout is the load reactive current and current harmonics. In the 3P3W system, current unbalance apart from reactive and harmonic current has to be considered. While an additional neutral current compensation loop is required in the 3P4W system.

1P2W UPQC may have 3 kinds of configuration viz. two Half-bridge (8 switches), one Half-bridge (4 switches), or 3 legs (4 switches). Some non-linear loads like adjustable speed drive (ASD), arc furnace, arc welding machines, frequency converters require a 3P3W system, and thus, the 3P3W layout of UPQC is used. Many industrial plants require a 3P4W supply system and an excessive current flow due to the presence of this 4th wire (neutral conductor), which demands an additional control loop for compensation. To overcome this problem, three different layouts of shunt inverter can be used, which are 4 leg, 3 H-bridge, and 2 capacitor layout. Figure 4,5,and 6 shows the above-discussed configurations of UPQC based on the supply system.

5.1.3 Based on System Configuration

Table-1 shows a list of different kinds of UPQC based on system configuration [1], [10].UPQC-L and UPQC-R can be recognized from the position of the series and shunt inverter. As the name suggests, the shunt inverter is placed on the right side of the series inverter (refer fig.1 to 6) in UPQC-R. While shunt inverter is on the left side of the series inverter in UPQC-L. The performance of UPQC-R is better than UPQC-L because the current flowing via the series injection transformer is sinusoidal irrespective of the type of load current. UPQC-L configuration can be in some particular cases e.g. to avoid intervention between the shunt inverter and passive filters.

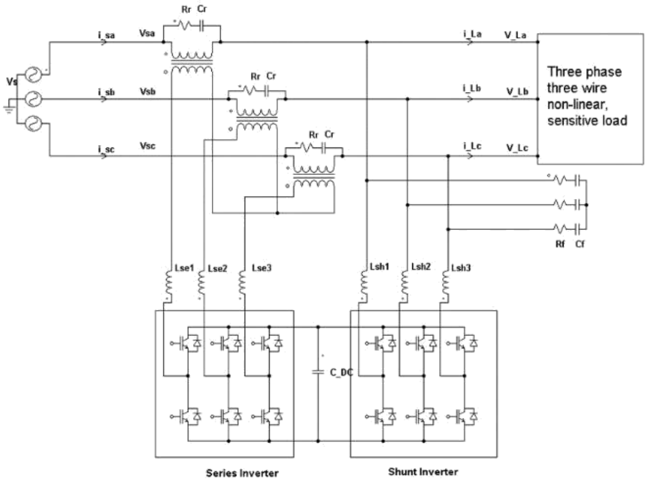


Figure 5: 3P3W UPQC: 2 Full Bridge topology

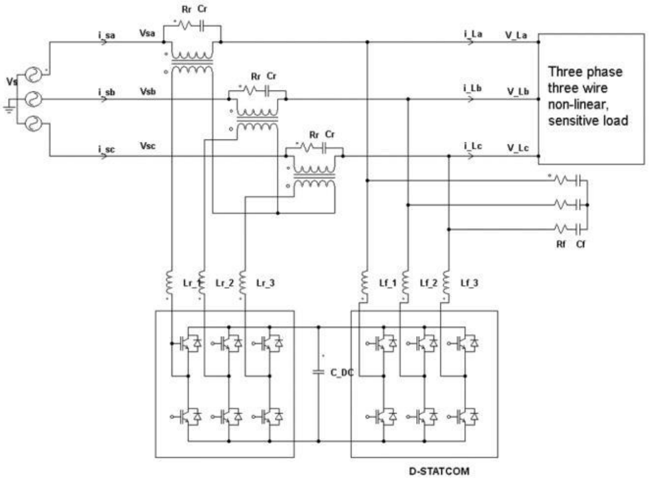


Figure 6: Three-phase four-wire UPQC

Table 1: Various UPQC configuration

UPQC-L	Left shunt UPQC
UPQC-R	Right shunt UPQC
UPQC-D	3P3W to 3P4W distributed UPQC
UPQC-DG	Distributed generator integrated with UPQC
UPQC-I	Interline UPQC
UPQC-MC	Multi-Converter UPQC
UPQC-MD	Modular UPQC
UPQC-ML	Multi-Level UPQC

In UPQC-I [27] shunt inverter is united with one distribution feeder and series inverter with another feeder. In such a way real power flow and voltage regulation of both the feeders can be maintained simultaneously.

UPQC-MC [28], is used to enhance the outcome of UPQC by adding a third converter in the DC bus. It is named as Distribution System Unified Conditioner (DS-UniCon) by Wong et al. [28].

UPQC-MD was acquainted by Han et al. [29]. It can be realized by connecting several H-Bridge. It has the advantage that it can be used for high power levels.

UPQC-ML is an alternative of UPQC-MD for high power level applications. According to the need of different levels (3, 5, 7, and so on), the number of inverter gets vary.

UPQC-D is a conversion of 3P3W UPQC to 3P4W UPQC. Neutral of series injection transformer of UPQC is taken as neutral of system. So, even if the supply from the source side is 3P3W, a 3P4W system can be obtained easily by the UPQC application. A four-leg shunt inverter is required to compensate for the neutral current flowing towards the neutral point of the series transformer.

UPQC-DG is constituted with a distributed generation system. In such a configuration, the DC bus of UPQC is connected with the outcome of the DG system. So, power supplied to the load at PCC by the DG system can be regulated by UPQC in addition to current and voltage power quality compensation. Interaction of wind system with the grid using UPQC is shown in [30]. PV-UPQC is discussed in [31].

5.2 Depending On Voltage Compensation Techniques

There are four techniques used for voltage compensation using UPQC and UPQC is named on the essence of these methods.

5.2.1 UPQC-Q: In this approach, compensation of voltage sag is done by injecting reactive power and that’s why it is called UPQC-Q. Injected Voltage by the series inverter is perpendicular to the system voltage and thus, the need for active power becomes zero. The vector sum of injected voltage and source voltage must be matched with the load terminal voltage. Unity power factor is maintained by the shunt inverter at the source side. A demerit point is that it doesn’t compensate for the voltage swell conditions. [1], [32], [33] discusses about the UPQC-Q.

5.2.2 UPQC-P: The basic idea of UPQC-P is to feed active power in the system to compensate voltage sag conditions. The voltage injected by series inverter has zero phase shift with the system voltage. This in-phase component increases or decreases the voltage of PCC to the desired voltage magnitude. The demand for active power is satisfied by the shunt inverter. The total active power drawn by the shunt inverter from the source is the summation of the losses allied with UPQC and the mandatory active power by the series inverter. This increases the source current magnitude during voltage sag compensation. UPQC-Q needs more voltage of series injection as compared to UPQC-P. This increases the rating of the series inverter of UPQC-Q and thus, UPQC-P is widely used to overcome both voltage sag and swell conditions. [1], [21], [24], [34] has discussed about UPQC-P.

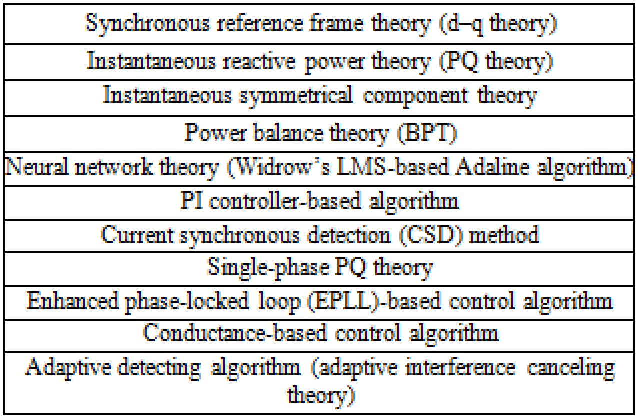
5.2.3UPQC-S: Its series inverter delivers both active and reactive power and thus it is known as UPQC-S. Series inverter delivers the voltage at a particular angle with the source voltage. In this approach, attempts are made to bring the maximum capacity of the series inverter. UPQC-S can be utilized in both sag and swell conditions. Various control loops make the system more complex because it involves monitoring of active as well as reactive power. It is discussed briefly in [1], [35].

5.2.4UPQC-VAmin: The principle of this is similar to UPQC-S. But here efforts are made to minimize the VA rating of UPQC. Current drawn by shunt inverter is also considered during VA rating calculations [36].

6. Different Control techniques for UPQC

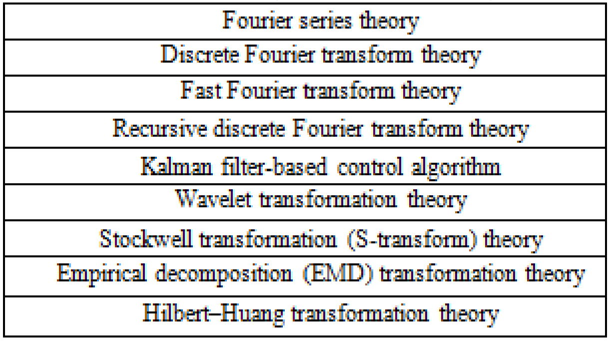
From the working principle of UPQC, we come to know that switching signals given to the switches of the inverter are generated by correlating the actual system signal (voltage and current) with the reference signal (which can be generated by many techniques/algorithms). Mainly, there are two algorithms 1) Time-domain algorithm 2) Frequency domain algorithm. Table-2 and Table-3 below show the various time domain and frequency domain algorithms. Frequency domain control algorithms are very sluggish, slow, and require very high computational time. So, time-domain algorithms are widely applied to control the seriesand shunt inverter in UPQC. In time-domain algorithms, dq theory and PQ theory are more famous. In recent times, researchers have also moved toward metaheuristic techniques (ANN, FUZZY algorithms). In [37] dq theory is explained very well. dq theory-based PI controller is discussed in [21], [32], [36], [38], [39], and fuzzy controller in [40], [41].

Table 2: Time-domain control algorithm



Synchronous reference frame theory (d–q theory)
Instantaneous reactive power theory (PQ theory)
Instantaneous symmetrical component theory
Power balance theory (BPT)
Neural network theory (Widrow's LMS-based Adaline algorithm)
PI controller-based algorithm
Current synchronous detection (CSD) method
Single-phase PQ theory
Enhanced phase-locked loop (EPLL)-based control algorithm
Conductance-based control algorithm
Adaptive detecting algorithm (adaptive interference canceling theory)

Table 3 – Frequency-domain control algorithm



Fourier series theory
Discrete Fourier transform theory
Fast Fourier transform theory
Recursive discrete Fourier transform theory
Kalman filter-based control algorithm
Wavelet transformation theory
Stockwell transformation (S-transform) theory
Empirical decomposition (EMD) transformation theory
Hilbert–Huang transformation theory

Refer [19] to understand the PQ theory. Based on the PQ theory, PI controller is covered in [20], [28], [29], [42], [43] and FUZZY controller in [40], [44]. The Concept of Power angle control (PAC) of UPQC has been developed to magnify the use of series inverter [35], [45]. Using this algorithm gross rating of shunt inverter can be minimized. A simple controller scheme named Unit Vector Template Generation (UVTG) is used in [46] to generate the reference signal for UPQC with the help of Phase Locked Loop (PLL).

In nowadays design of the controller using Fuzzy Logic is in trend. [17], [40], [41], [44], [46], [47] had used Fuzzy logic, to design the controller of UPQC. [30] Has designed UPQC, controlled by Fuzzy to make a grid-connected wind farm system.

As we know, the ANN technique can bear multiple input multiple output system strongly. SO, the ANN controller is developed in [34], [40], [46], [48], [47], and [49] to overcome the voltage and current concern power quality problems. A feed forward ANN controller is reported by [34]. Lovenberg-

Marquardt back-propagation technique is used in [50] and [51]. In [47], [48], [49] UPQC is designed with PI, FUZZY, and ANN controller and their performance are compared.

7. Conclusion

This work represents an absolute overview of UPQC to enhance the quality of power in the distribution network. From the working principle of UPQC, we come to know that it is more beneficial to use UPQC at distribution level instead of passive filters or alone use of series or shunt active power filter. This paper starts by describing different power quality issues. A short description of the devices used to mitigate these issues at transmission and distribution level is given. UPQC's working principle and comprehensive classification are discussed. Various strategies used for the control of UPQC, recent research in them, and newly developed UPQC are narrated. This work will be helpful as a reference for the researchers wishing to work in the area of power quality improvement at the distribution level using UPQC.

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