Recent Trends in Power Quality Improvement: Review of the Unified Power Quality Conditioner

Swati Gade[1†], **Rahul Agrawal**[1], and **Ravindra Munje**[2], Non-members

ABSTRACT

The electrical power sector is currently focusing on power quality (PQ) issues and their mitigation. Industrial automation and the use of power electronic converters for the integration of distributed generation create various PQ problems. This necessitates PQ enhancement, which in turn helps to improve the life span of the equipment as well as the reliability of supply for feeding critical loads within the system. This paper presents a comprehensive review of the Unified Power Quality Conditioner (UPQC) and its widespread application in the distribution system. The UPQC belongs to the family of active power filters. It contributes to the alleviation of voltage and current-related PQ issues along with power factor correction and the integration of renewable energy systems in the distribution network. This paper discusses various topologies, compensation methods, control theories, and the technological developments in recent years. More than 160 research papers have summarized the features of UPQC for further applications. Based on the outcomes of the investigation, the future direction of the UPQC is discussed. This paper is expected to play a major role in guiding research scholars in the application of the UPQC.

Keywords: Harmonics, Power Quality, Renewable Energy System, Solar PV, Unified Power Quality Conditioner

LIST OF SYMBOLS

1P2W	Single-Phase Two-Wire
2C	Split Capacitor
3-HB	Three H-Bridge
3P3W	Three-Phase Three-Wire
3P4W	Three-Phase Four-Wire
3L	Three Leg
3L-2C	Three-Leg Split Capacitor
4L	Four Leg
ALO	Ant Lion Optimization
ANFIS	Adaptive Neuro-Fuzzy Inference System
ANN	Artificial Neural Network
APF	Active Power Filters
COA	Cuckoo Optimization Algorithm
CSC	Current Source Converter
CSOGI	Cascaded Second-Order Generalized Integrator
DA	Dragonfly Algorithm
DANF	Digital Adaptive Notch Filter
DE	Differential Evolution
DG	Distributed Generation
DSC	Delayed Signal Cancellation
DSTATCOM	Distribution Static Compensator
DVR	Dynamic Voltage Restorer
FA	Firefly Algorithm
FLC	Fuzzy Logic Controller
GA	Genetic Algorithm
GOA	Grasshopper Optimization Algorithm
GWO	Grey Wolf Optimizer
LPF	Low Pass Filter
LS	Loss Sensitive
MOPSO	Multi-Objective Particle Swarm Optimization
MOWOA	Multi-Objective Whale Optimization Algorithm
MPPT	Maximum Power Point Tracking
PAC	Phase Angle Control
PCC	Point of Common Coupling
PEC	Power Electronic Converter
PI	Proportional Integral
PID	Proportional Integral Derivative
PLL	Phase-Locked Loop
PQ	Power Quality
PSO	Particle Swarm Optimization
RES	Renewable Energy Sources
ROA	Rider Optimization Algorithm
SCA	Sine Cosine Algorithm
SFCL	Superconducting Fault Current Limiter
SOGI	Second-Order Generalized Integrator

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[1]The authors are with the Department of Electrical Engineering, Sandip University, Nashik, India.

[2]The author is with the Department of Electrical Engineering, K. K. Wagh Institute of Engineering Education and Research, Nashik, India.

[†]Corresponding author: swatiagade@gmail.com

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Solar PV	Solar Photovoltaic
SRF	Synchronous Reference Frame
THD	Total Harmonic Distortion
UPFC	Unified Power Flow Controller
UPQC	Unified Power Quality Conditioner
UPQC-D	Distributed UPQC
UPQC-DG	Distributed Generation UPQC
UPQC-I	Interline UPQC
UPQC-L	Left Shunt UPQC
UPQC-MC	Multi-Converter UPQC
UPQC-MD	Modular UPQC
UPQC-ML	Multilevel UPQC
UPQC-R	Right Shunt UPQC
UPQC-P	UPQC Active Power Control
UPQC-Q	UPQC Reactive Power Control
UPQC-S	UPQC Simultaneous Active and Reactive Power Control
UPQC-VA$_{\text{min}}$	UPQC Minimum Volt-Ampere (VA) Loading
$I_{cr,pp}$	Inductor Ripple Current
I_r	Inductor Current Ripple
I_s	Source Current During Normal Conditions
I_{s1}	Source Current During Sag/Swell Conditions
I_{DSTAT}	Per Phase Current Injected by the DSTATCOM
k	Ratio Between Actual Source and Rated Source Voltages
P_{se}	Active Power by the DVR
P_{sh}	Active Power by the DSTATCOM
Q_{se}	Reactive Power Handled by the DVR
Q_{sh}	Reactive Power by the DSTATCOM
S_{se}	VA Loading of the DVR
S_{sh}	VA Loading of the DSTSTACOM
S_{UPQC}	Total VA Loading of the UPQC
V_{dc1}	Lowest Value of the DC-Link Voltage
V_{DVR}	Voltage Injected by the DVR During Sag/Swell Conditions
V_L	Rated Load Voltage
I_L	Rated Load Current
V_{ph}	Per Phase Voltage
V_s	Rated Source Voltage
I_s	Rated Source Current
δ	Power Angle
ϕ	Rated Load Power Factor Angle
γ	Displacement Angle Between the Source and Series-Injected Voltages

1. INTRODUCTION

In the present days, the use of solid-state devices produces power quality (PQ) hitches, such as voltage sag, swell, power surges, notches, spikes, flicker, voltage unbalance, and harmonics in the supply across the load end of the consumers [1–4]. The main objective of any electric power supply system is to provide a continuous sinusoidal voltage of constant magnitude and frequency with balanced sinusoidal currents. On the other hand, all significant and sensitive loads require uninterrupted sinusoidal, balanced voltage of constant magnitude, and frequency. Otherwise, the protection system malfunctions, causing substantial loss of data, time, product quality, and service [1]. To achieve power quality standardization, the International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE) have framed different power quality standards. Table 1 lists these standards and their respective PQ phenomena.

Table 1: *Standards and PQ phenomena.*

PQ Phenomena	Standard	Ref.
Classification of power quality	IEC 61000-2-1: 1990	[5]
	IEC 61000-2-5: 1995	[6]
	IEEE 1159: 1995	[7]
Transients	IEC 816: 1984	[8]
	IEC 61000-2-1: 1990	[5]
	IEEE c62.41: (1991)	[9]
	IEEE 1159: 1995	[7]
Voltage sag/swell and interruption	IEC 61000-2-1: 1990	[5]
	IEEE 1159: 1995	[7]
Harmonics	IEC 61000-2-1: 1990	[5]
	IEC 61000-4-7: 1991	[10]
	IEEE 519: 1992	[11]
Voltage flicker	IEC 61000-4-15: 1997	[12]

The integration of distributed generation (DG) involving windmills, solar plants, fuel cells, etc., is growing considerably. The application of DG has numerous technical, environmental, and economical advantages. However, the integration of DG imposes many challenges on the electric utilities [13]. The controlling of DG mainly depends upon reactive power compensation. Frequent changes to the reactive power consumption of bulk loads can introduce voltage sag and swell into the system. This causes a change in the real power demand of the system, resulting in power fluctuations [14]. Uncompensated reactive power also affects the efficiency of DG system, power factor (PF), and active power capability. The use of a power electronic converter (PEC) for the interconnection of DG to the utility grid ensures the safe functioning of equipment and switching between sources. However, it introduces a wide range of PQ problems such as current and voltage harmonics, voltage sag/swell, voltage and current unbalance, voltage flicker, load reactive power, neutral current, impulse transients, and interruptions [15].

Active power filter (APF) technology is used for compensating voltage-current harmonics, reactive power, reducing flicker, and improving voltage balance in 3-phase AC systems [4, 16–17]. Various

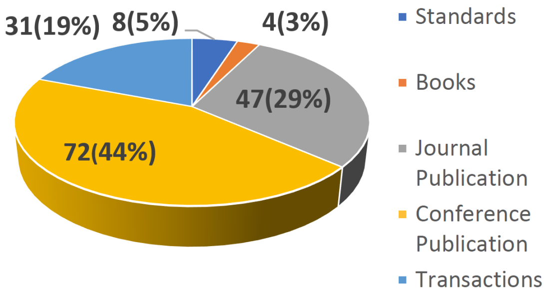

Fig. 1: *Literature reviewed for this article.*

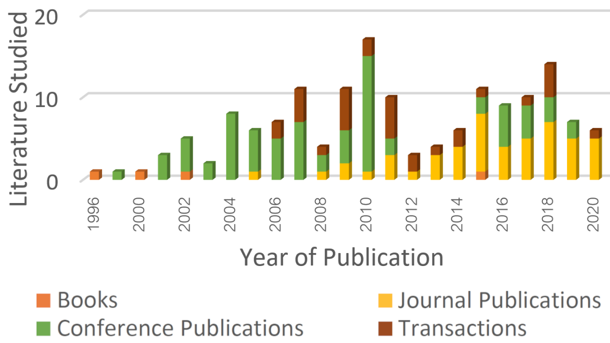

Fig. 2: *Published literature on the UPQC.*

custom power devices such as the dynamic voltage restorer (DVR), distribution static compensator (DSTATCOM), and unified power quality conditioner (UPQC) which belong to the APF family are used to mitigate various PQ problems [3]. This study focuses on the UPQC, which is a combination of both DVR and DSTATCOM. It is considered to be an optimal device for critical and sensitive loads to mitigate both voltage and current-based power quality problems [4, 18–19]. The UPQC consists of two PECs linked to a common DC-link back to back. It is used in the distribution system for simultaneous series and shunt compensation, and should not be confused with the unified power flow controller (UPFC) employed in the transmission system. To balance the shunt/series compensation, UPFC works within a balanced and distortion-free transmission system environment. On the other hand, UPQC must work in an environment with unbalances and distortions created by DC components, voltage harmonics, and current harmonics [20]. The main objective of the UPQC is to reduce the injection of active power through both series and shunt APFs to minimize the circulating active power. Earlier published surveys on active power filters [16], the UPQC for power quality enhancement [20], and the UPQC role in distributed generation [14] provide excellent guidelines for researchers. The researchers in [16] present a survey on the classification of an APF based on its kVA rating and speed of response, circuit configuration, system parameter compensation, and control techniques. Khadkikar [20] provides a review on various topologies, configurations, methods of compensation, and recent developments in the field of UPQC, while [14] presents a survey on the widespread application of DG through various renewable energy systems (RES), PQ problems related to the power electronic interface, and the use of the UPQC to improve PQ and system reliability.

In contrast to these surveys, this paper provides an exhaustive review of topologies, control strategies and algorithms, optimal methods, and applications. In other words, this paper presents a combination of [14], [16], and [20] state-of-the-art publications. For this study, various PQ standards, books, book chapters, IEEE transactions, peer-reviewed journals, and conference proceedings have been examined to identify the various UPQC features and recent technological improvements. Fig. 1 presents details of the previous literature reviewed for this paper.

Fig. 2 shows the year-wise publication of the literature studied. As can be observed from Fig. 2, the UPQC is a popular topic among researchers due to its simultaneous series and shunt compensation features. In past years, researchers have attempted to find various applications and ways of improving UPQC performance.

This paper contributes to the existing literature by providing a detailed discussion on

1. Various UPQC topologies and compensation methods.
2. Time-domain control theories used for controlling the UPQC in various applications.
3. Various algorithms implemented for the optimal design of the UPQC based on kVA rating.
4. UPQC applications for the integration of RES.
5. Various algorithms implemented to determine the optimal location of the UPQC for minimum power loss in the distribution system.

This paper is organized as follows. The different UPQC topologies used in the literature are explained in Section 2. The various control strategies related to the UPQC are highlighted in Section 3. Section 4 covers the optimal designs based on the kVA rating. Section 5 presents the various applications for the UPQC in the integration of a solar PV system in RES, while the optimal location for the UPQC in the distribution system is explained in Section 6. Finally, Section 7 discusses the findings of this study while Section 8 presents the conclusion.

2. UPQC TOPOLOGIES

In the existing UPQC literature, various related topologies have been presented. A basic block diagram for the UPQC is shown in Fig. 3, consisting of a DVR in series, with the DSTATCOM in a shunt position to the AC power supply, shunt coupling inductor, DC-link, and a series injection transformer.

Table 2: *UPQC topologies based on configuration.*

Topology	Description	Ref.
Right Shunt UPQC (UPQC-R)	• A DVR is connected in series with the AC mains and the DSTATCOM near to the load.	[3]
Left Shunt UPQC (UPQC-L)	• A DVR is connected on the load side and DSTATCOM near to the source.	[30,31]
Interline UPQC (UPQC-I)	• A DVR is linked with one of the feeders in series and DSTATCOM is connected in parallel with the second feeder. • It can handle real power flow between two adjacent feeders. • This arrangement only mitigates the current-related PQ problems effectively on the feeder whereas, since the DSTATCOM is connected, the voltage related PQ problems only occur on the feeder to which the DVR is connected.	[32]
Multi-Converter UPQC (UPQC-MC)	• An additional DC Source/VSC is connected to the DC- Link. • It shares real power between two adjacent feeders which are not connected. • It only mitigates the current-related PQ problems effectively on the feeder, whereas, since DSTATCOM is connected, the voltage related PQ problems occur only on the feeder to which the DVR is connected.	[33–35]
Modular UPQC (UPQC-MD) & Multilevel UPQC (UPQC-ML)	• The VSC consists of numerous bridges connected in a cascade. • The DVRs of all cells are connected in parallel while DSTATCOMs are in series to form a UPQC-MD. • Multilevel converters are used for the UPQC-ML in a medium voltage distribution system.	[36–40]
Distributed UPQC (UPQC-D)	• The series transformer neutral of the DVR is utilized as a neutral for the 3P4W load. • The neutral current flowing toward the injecting transformer neutral is compensated by adding the fourth leg of the DSTATCOM to the existing 3P3W UPQC while the voltage of the transformer neutral point is retained at zero.	[41]
Distributed Generators UPQC (UPQC-DG)	• The UPQC is integrated with the DG to the grid. • The DG is connected to the DC-link of UPQC. • Power is supplied to the main grid via the DSTATCOM.	[42–48]

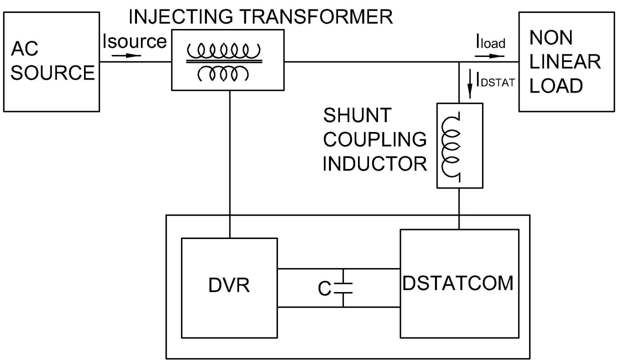

Fig. 3: *UPQC block diagram.*

2.1 UPQC Classification Based on Its Physical Structure

Various UPQC topologies have been proposed by researchers for different applications, and classified based on the converter, configuration of the DVR and DSTATCOM, and the supply system. All types of topologies are discussed in detail in the following subsections.

2.1.1 Converter Based Classification

The UPQC can be connected to the system using the voltage source converter (VSC) or current source converter (CSC). The VSC-based configuration is the most popular, due to its flexible control, high efficiency, and compact size [4]. The CSC-based UPQC is observed in [21–23]. The systematic non-linear control based on the state space variable model is used for controlling the CSC of the UPQC [21]. Kinhal *et al.* [22] considered the CSC-based UPQC in their performance analysis of the neural-network-based UPQC.

2.1.2 Configuration Based Classification

Depending on the connection of the DVR and DSTATCOM, the UPQC can be classified into various categories and used for specific applications. Significant works on various UPQC topologies based on the connection of the DVR and DSTATCOM are presented in Table 2. The right shunt UPQC (UPQC-R) is compact and simple to control. It requires a low rating converter and therefore has become more popular than the left shunt UPQC (UPQC-L) [24–25]. The UPQC utilized for the integration of RES into the main grid is known as UPQC-DG. This UPQC compensates for voltage-current-related PQ problems, maintaining synchronization between RES and the main grid as well as controlling the power generated by RES [14, 26–29]. This UPQC DC-link is fed by the power generated from RES.

According to Table 2, not only can the UPQC be

Table 3: *Classification of the UPQC based on the supply system.*

Topology	Highlighted Aspects	Ref.
Single-Phase Two-Wire (1P2W)	• DVR and DSTATCOM are isolated from each other by a bidirectional DC/DC-isolated converter and a high-frequency transformer. • The power transfer can be controlled by adjusting the voltage phase shift between two inverters.	[63]
Three-Phase Three-Wire (3P3W)	• In high voltage applications, the isolation transformer is used to isolate the DSTATCOM.	[64]
	• Ripple filters are connected across both the DVR and DSTATCOM to reduce the switching ripples of the output.	[22], [29], [65–67]
	• In the case of 3P3W with an additional star–hexagon/T-connected transformer, neutral current mitigation is possible only if the voltages across these transformers are sinusoidal.	[68]
Three-Phase Four-Wire (3P4W)	*Split Capacitor (2C):* • The neutral wire is connected at the mid-point of the capacitor which is at zero potential. • The equal voltage across both capacitors avoids a circulating current. • An additional control loop is added to maintain the DC-bus capacitor voltage regulation.	[69–72]
	Four Leg (4L): • The neutral current load is compensated by an additional leg having two semiconductor switches.	[73–76]
	Three H-Bridge (3-HB): • Three units of single-phase H-bridges are connected to the same DC-bus of the UPQC.	[24], [77–79]
	• Without affecting its compensation capability, the UPQC works with reduced DC-link voltage as well as helping to fulfill the DC-link voltage requirement of the DSTATCOM and DVR.	[80]

used to enhance PQ in the power distribution network but also to integrate the DG into the utility grid such as solar or wind power. Interconnected and islanding are the two operating modes of the UPQC-DG [13]. However, this topology has limitations such as interface issues, complex circuits, and high cost. The modular UPQC (UPQC-MD) and multilevel UPQC (UPQC-ML) are used in high power rating applications. Depending upon the operating voltage, the multilevel UPQC allows numerous H-bridge modules to be connected.

2.1.3 Supply System Based Classification

Based on the supply system, the UPQCs can be classified as single-phase two-wire (1P2W), three-phase three-wire (3P3W), and three-phase four-wire (3P4W). Table 3 further illustrates the work carried out on types of UPQC based on the supply system. Various 1P2W and UPQC topologies are presented in [49], however, two half-bridges (HBs) with eight-switches are the most commonly used [26, 50–51]. In a three-leg (3L) topology with six switches, four switches are used for the DVR and two switches for DSTATCOM. However, in HB topology, two switches are used for the DVR and the remaining two switches for DSTATCOM [52].

In the case of a three-phase supply system, most of the research work has been conducted in a balanced environment using the 3P3W topology of the UPQC [53–60]. However, to mitigate 3P4W system problems such as excessive neutral current, harmonics, reactive power burden, and imbalance, the 3P4W UPQC tends to be implemented [61–62].

The performance of the UPQC depends upon the number of switching devices used for PEC. Therefore, 3L and HB topologies may affect the compensation performance of the UPQC. These topologies can be utilized for economically low power applications. The separate fourth leg used in four-leg (4L) topology controls the neutral current more effectively and therefore gives better performance than the split capacitor (2C) and 3-HB topologies for low to medium power applications. Since 12 switches are required in the 3-HB topology, it is more costly than the other two [81]. However, it is more suitable for medium to high power applications than 2C and 4L topology. In [82], 4L PEC is used for the DSTATCOM while 3L PEC is employed for the DVR with a split DC-link capacitor. In this study, the DC-bus voltage amplitude required for the DVR operation is less than that required for the DSTATCOM operation. Thus, it requires lower DC-bus voltage compared to the two 3L-2C topologies and a reduced number of switches in comparison to the two 4L topologies.

2.2 Classification Based on the Compensation Method

Based on the methods of compensation, the UPQC can be categorized as active power control (UPQC-P), reactive power control (UPQC-Q), simultaneous active and reactive power control (UPQC-S), and minimum volt-ampere (VA) loading (UPQC-VA_{min}). A detailed discussion of each method is presented as follows.

2.2.1 Active Power Control (UPQC-P)

In a UPQC-P, the DSTATCOM performs current-based compensation with a unity PF at the load end, while the DVR performs voltage sag/swell compensation [83–87]. The operation of the UPQC-P during voltage sag in terms of its phasor diagram

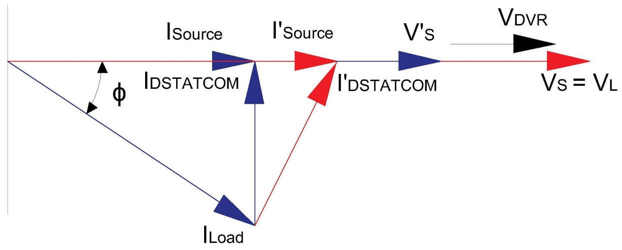

Fig. 4: *Phasor diagram of the UPQC-P for voltage sag.*

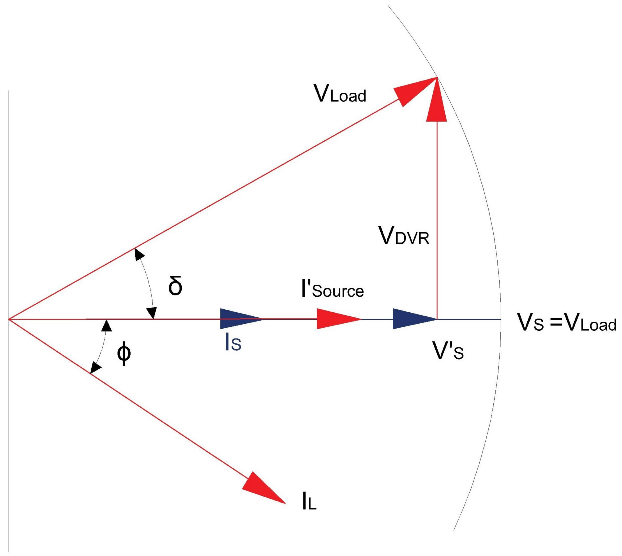

Fig. 5: *Phasor diagram of the UPQC-Q.*

is represented in Fig. 4. It can clearly be observed that the UPQC-P requires only active power since the injected voltage is in phase with the supply current and supply voltage [36, 71].

The UPQC-P integrated with a wind turbine is used to provide active power to the grid as well as for mitigating PQ problems such as deep voltage sag and voltage interruption [25, 55]. The design and dynamic performance of the UPQC-P with solar PV to mitigate PQ problems and supply active power to the grid are explored in [46, 67].

2.2.2 Reactive Power Control (UPQC-Q)

The UPQC-Q requires only reactive power as the injected voltage since it is in quadrature with the supply current and supply voltage as presented in Fig. 5. Voltage sag compensation is achieved by the DVR without taking active power either from the source or PEC [54]. This DVR quadrature voltage injection leads the supply current which requires a large VAR loading of DVR [88–90]. Another limitation of the UPQC-Q is the phase difference between input and output voltage which relates to the severity of voltage sag and therefore it cannot effectively compensate for any kind of voltage drop

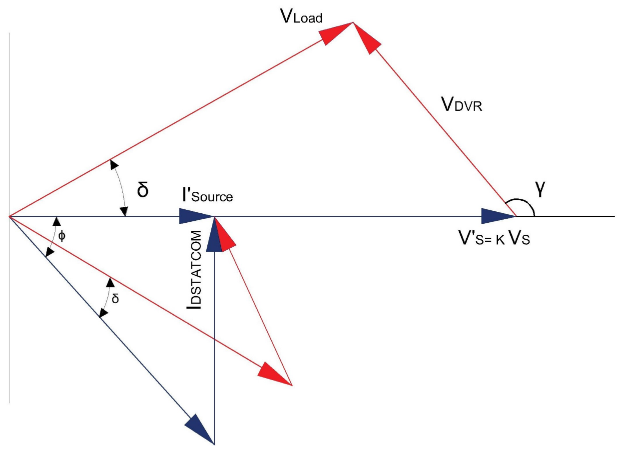

Fig. 6: *Phasor diagram of the UPQC-P for voltage sag.*

[66]. This can be overcome with minimum active power injection. For the compensation of higher magnitude voltage sags and voltage swell, a certain amount of active power is also required to be injected along with reactive power [66, 88]. A higher amount of series injection voltage is required by the UPQC-Q to compensate for the same amount of voltage sag in comparison to the UPQC-P [91].

2.2.3 Simultaneous Active and Reactive Power Control (UPQC-S)

In the UPQC-S, both active and reactive powers are delivered by the DVR and utilized to mitigate voltage sag/swell while load reactive power-sharing is achieved simultaneously by the DSTATCOM [59, 92–93]. The phase angle control (PAC) approach can be used to control the UPQC-S for utilizing the UPQC to its maximum capacity [44, 45]. The operation of the UPQC-S during voltage sag and swell in terms of its phasors is shown in Fig. 6.

Under a supply voltage imbalance, effective operation of both PEC is still possible with equal reactive power-sharing. This is obtained by calculating the proper power angle (δ) [94]. The UPQC- S with solar PV shares the load reactive power requirement through the DVR during steady-state conditions as well as supplying active power to the grid, as illustrated in [95].

2.2.4 Minimum Volt-Ampere (VA) Loading (UPQC-VA$_{\mathrm{min}}$)

In similarity to the UPQC-S, both active and reactive powers are delivered by the DVR in UPQC-VA$_{\mathrm{min}}$, and utilized to compensate for voltage sag/swell. However, this series voltage is added at a definite optimal angle by reference to the supply current [96–97]. The percentage of sag, PF angle, and power/swing angle (δ) decides the VA loading of the UPQC. The DVR is used to compensate for an imbalance in the voltage sag. Voltage injected at an optimal angle regulates it at the load end. Therefore, the DVR requires the minimum active power injection and hence the minimum VA loading of the UPQC [98]. Kolhatkar *et al.* [99] determined the optimum angle using a minimum VA optimization algorithm. The optimum phase angle and corresponding angles of the voltage injection for each case are calculated off-line from the 2D lookup table for percentage sag and PF angle. While in [72], an adaptive neuro-fuzzy inference system (ANFIS) is used to calculate the phase angle online. Kumar *et al.* [98] suggested the particle swarm optimization (PSO) technique for determining the optimum angle. The calculation of the optimum angle by considering the effects of source voltage THD and load current THD distortion is reported in [100]. An investigation into the fast-Fourier transform algorithm to find the optimum angle was carried out by Kisck *et al.* [97].

3. UPQC CONTROL STRATEGIES

Control strategies of UPQC include control theory and the controller used to control UPQC. UPQC mainly consists of two PECs connected in a back-to-back fashion through a common DC-Link. The following subsections provide a detailed study of time-domain control theories used for controlling UPQC and various controllers used for DC-Link control.

3.1 Control Theories

In power electronics, control theory plays a very important role. The behavior, desired operation, and application of the UPQC for a specific system depend upon the control algorithm used. This, in turn, estimates the voltage signals and reference current, which determine the gating pulses of the VSC, to provide the preferred performance. Some of the control methods used by researchers are listed below:

(a) frequency domain theories
(b) time-domain theories
(c) other techniques.

Frequency domain control theories based on the Fourier transform [101], Kalman filter [102], and Wavelet transform [103, 104] are not preferred for real-time control of compensators due to their sluggish and slow responses. They also involve substantial calculations [4]. On the other hand, time-domain theories are the most widely used for control purposes. Instantaneous active-reactive power or *p*-*q* and synchronous reference frame (SRF) or *d*-*q* theories are widely used in time-domain control algorithms. In these algorithms, voltages and current signals in the ABC-frame are transferred to the stationary reference frame (*p*-*q* theory) [105] or synchronously rotating frame (*d*-*q*) [64].

In *p*-*q* theory, instantaneous active and reactive powers are calculated from three-phase load currents and point of common coupling (PCC) voltages. The fundamental and fluctuating components of these powers are separated by using a filter. In most studies, a low pass filter (LPF) is used [74–79]. The referenced three-phase supply currents are estimated using the following expression.

$$\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \sqrt{\frac{3}{2}} \\ -\frac{1}{2} & -\sqrt{\frac{3}{2}} \end{bmatrix} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix} \quad (1)$$

In SRF theory, Park's transformation and reverse Park's transformation are used for the conversion. These signals are synchronized with the PCC voltage using a phase-locked loop (PLL). The fundamental and harmonic components of *d*-*q* axis currents are separated using filters. This theory is mostly used for referencing signal generation. In [44], SRF-based control theory is used to control the UPQC integrated with solar PV while in [88] it is used to control the UPQC-Q with minimum active power injection. It is also used in the comparison of various 3P4W UPQC topologies [68].

The instantaneous power angle (δ) depends upon the variation in the source voltage. Another effective method of UPQC control is the PAC as presented in [92], whereby the instantaneous power angle (δ) is estimated from the extracted instantaneous load active and reactive power as given below

$$\delta = \sin^{-1} \frac{\text{Reactive Power Handled by DVR}}{\text{Load Active Power}} \quad (2)$$

However, this theory can only be implemented in a balanced system. Table 4 shows the time-domain control theories used in the literature.

According to the literature presented in Table 4, it can be clearly observed that under an unbalanced and distorted source voltage environment, performance of the *p*-*q* theory is unsatisfactory compared to SRF theory. The SRF method is superior to *p*-*q* theory for the compensation of reactive power and current harmonics. In the PAC method, the DVR is controlled to share reactive power during voltage sag as well as during steady-state conditions. However, since the reactive power shared by the DVR varies with the voltage sag/swell, power balance can be maintained by controlling the appropriate power angle (δ).

3.2 UPQC Controller

The performance of the UPQC also depends upon the control of the DC-link. A DC-link feedback controller should respond quickly to re-establish the DC-link voltage to a fixed reference value with

Table 4: *Time-domain control theories for the UPQC.*

Control Theory	Highlighted Aspects	Ref.
p-q Theory	• Single-phase *p-q* theory is implemented for load imbalance (3P4W system). • The referenced load voltage extracted for the DVR is utilized as a substitute for actual load voltages to improve performance during distorted or imbalanced source voltages.	[41, 81, 106]
	• Single-phase PLL is used to eliminate the effect of distorted supply voltage on the DSTATCOM performance.	[107]
	• In single-phase *p-q* theory to maintain the DC-link voltage without using a PI-controller, fewer sensors are required.	[108]
	• In the modified *p-q* theory-based control algorithm, the supply current is controlled indirectly.	[105, 109]
	• Variable PAC is used based on the data-driven control technique.	[110]
SRF Theory	• The SRF-based control algorithm is used to control the UPQC in dual compensating mode. • The DVR is controlled as a sinusoidal current source and the DSTATCOM as a voltage source.	[48, 111]
	• The moving average filter (MAF) is used to extract the fundamental component of the d axis load current.	[67]
	• A synchronous double reference PLL frame is used to detect a positive sequence voltage in utility imbalance conditions.	[112]
	• A PLL scheme is presented with less UPQC control using a zero-crossing detection-based line frequency synchronization technique. • This saves the processor time and does not involve extra hardware. • MAF is used to separate the positive sequence component.	[113]
	• The MC-UPQC is controlled using the SRF algorithm, and the second-order LPF for extracting the fundamental component of the d axis load current. • The fuzzy logic controller (FLC) is used to generate the d axis reference current of the DSTATCOM.	[114]
	• A PLL-less SRF control algorithm is used to control solar PV integrated UPQC. • A discrete filter is used for extraction of the fundamental positive sequence (FPS) components of grid voltage.	[115]
Phase Angle Control (PAC) Method	• In the fixed PAC method, the power angle (δ) is maintained constant under all operating conditions, whereas in the variable PAC method, the power angle (δ) is kept variable to allow for voltage fluctuation.	[106]
	• PAC and instantaneous symmetrical component theory-based approaches are used to control the UPQC. • The power angle (δ) is estimated using the simple mathematical approach of "triangle rule of vector addition".	[116]
	• PAC-based SRF with a modified PLL algorithm is used for highly distorted and unbalanced conditions. • The power angle (δ) estimate is based on equal reactive power-sharing, with efficient utilization of both inverters under a supply imbalance.	[76, 94, 117]
	• A PAC for an unbalanced load is presented. • Balanced reactive power shared by the DVR and unbalanced reactive power greater than 50% of the total reactive power is shared by the DSTATCOM.	[118]

the least delay while exceeding it during dynamic conditions. The most widely used DC-link controller is the proportional integral (PI) based controller [59, 66, 83, 119]. The primary requirements of a UPQC controller are quick detection of the disruption, high precision, fast-tracking of the reference signal, and a high dynamic response. However, due to parameter variations and the non-linearity of load disturbance, the conventional controller fails to perform.

This problem is overcome by implementing a fuzzy logic-based PI-controller [17, 120–121], artificial neural network (ANN) based controller [122], the fuzzy- proportional integral derivative (PID) controller [123], and an ANFIS [124]. An ANN-based controller is fast in response and maintains the stability of both converters for wide operating ranges [22]. The optimum value gained by the PI-controller improves system performance. In [125], the FLC along with the ant colony optimization technique is used. In [126], the PSO along with fuzzy based PI control are used to control the solar PV-UPQC. The virus colony search algorithm [127] and flower pollination optimization algorithm [128] are implemented to determine the optimum value of the PI-controller gains to mitigate voltage sag, THD, and improve the power of the hybrid system using the UPQC. A fuzzy-PID controller in the UPQC is used to control the DC-link capacitor voltage since it combines the benefits of the high steady-state accuracy of PID control and good robustness of the fuzzy control [123]. Both fuzzy and neural network systems are incorporated the ANFIS to estimate the referenced DC-link voltage and DC-link voltage regulation [124]. To minimize the UPQC online VA loading, a data-driven control (DDC) technique is developed using the variable PAC method [110]. In [93], the gravitational search algorithm is used to tune the PI-controller gains of the UPQC-S.

4. OPTIMUM UPQC DESIGN BASED ON KVA RATING

The DVR is designed to handle voltage-related PQ problems and otherwise remains ideal in steady-state conditions. Therefore, the DSTATCOM is loaded heavily, increasing the overall size of the UPQC and reducing the reliability of the system. The DSTATCOM plays an important role in maintaining the power system balance in all conditions. The kVA ratings of the DVR and DSTATCOM are dependent upon the load VAR variation and percentage of sag/swell. The kVA rating of the UPQC depends upon the compensation method. A steady-state analysis of the UPQC is given in [86]. The kVA rating issues are discussed in [24]. In [129], an attempt is made to reduce the DC-link voltage, resulting in an overall reduction in the VA rating of the PE converter and switches. To reduce the VA loading of DSTATCOM and the overall VA rating of the UPQC, many researchers have tried to use a DVR to achieve reactive power compensation. A DVR can be used not only to mitigate voltage sag/swell but also to compensate for a certain amount of load reactive power, thereby increasing DVR utilization and reducing the kVA rating of DSTATCOM [96]. The suitable angle at which voltage can be injected by the DVR is pre-calculated. This also reduces power loss in the UPQC [130]. The reactive power shared by the DVR depends upon the power angle (δ). Different techniques for estimating an optimum power angle (δ) have been reported in the literature. For instance, [76] discusses the PSO technique for minimizing the VA loading of the UPQC while considering the effect of source voltage and load current harmonics. In [43], the PAC algorithm is used to reduce the burden on the DSTATCOM by utilizing the DVR for active power injection into the system even during steady-state conditions, thereby helping to improve system reliability. In [131], the optimal size of the UPQC is determined using the following generalized equations. Total VA loading of the UPQC, as a function of the power angle (δ) and ratio between actual and rated source voltages (k), is represented by

$$S_{UPQC}\left(\delta,k\right)=S_{sh}\left(\delta,k\right)+S_{se}\left(\delta,k\right) \quad (3)$$

where VA loadings of the DVR and DSTATCOM in any operating conditions are computed by Eqs. (4) and (5), respectively

$$S_{se}\left(\delta,k\right)=\sqrt{\left[P_{se}\left(\delta,k\right)\right]^2+\left[Q_{se}\left(\delta,k\right)\right]^2} \quad (4)$$

$$S_{sh}\left(\delta,k\right)=\sqrt{\left[P_{sh}\left(\delta,k\right)\right]^2+\left[Q_{sh}\left(\delta,k\right)\right]^2} \quad (5)$$

A novel algorithm is presented to find the least possible VA rating of the UPQC as a function of the corresponding optimal power angle (δ), DVR, DSTATCOM, and series transformer ratings. It is implemented for all operating conditions and UPQC compensation approaches. The interior-point method is used to determine the optimum size for UPQC converters to minimize the overall cost of the UPQC and series transformer [110, 132]. In [133], a two-stage optimization control algorithm based on the variable PAC method is proposed for the optimal design of UPQC. In a two-level algorithm, both the transformer VA rating and capital cost are considered for optimization [134]. In [135], a superconducting fault current limiter (SFCL) is connected to the parallel feeder of the main feeder where the UPQC is connected. The SFCL limits the excessive fault current, resulting in a considerable reduction in the UPQC rating. In [136], a normalized simulated annealing algorithm is compared with the analytical hierarchy process objective optimization to find the optimal solution. The optimization model contains the minimization of VA loading, SFCL conductance, and temperature within the constraints of the referenced voltage load.

5. APPLICATION OF THE UPQC IN RES

Distributed generation (DG) offers a gateway to enhance power system reliability while decreasing the requirement for forthcoming growth. The fast development of PEC technology makes it possible to integrate DG into the main grid through grid-interactive inverters; however, it deteriorates the PQ [137]. This is overcome by using the UPQC to integrate the RES with the main grid. Proper control of the DC-link voltage for the UPQC improves the dynamic performance of the system during disturbances. In [138], a hybrid RES consisting of fuel cell and doubly-fed induction generation-based wind energy systems are integrated with a weak grid using the UPQC. In [137], the UPQC is utilized for the integration of RES with the main grid, employing a PI-controller with FLC. To integrate a wind energy system with improved PQ, the Firefly algorithm is used to optimize the control pulses with a recurrent neural network for training the optimization parameter [139]. In this study, the focus is on applying the UPQC to integrate solar PV with the main grid. In a solar PV integrated UPQC, the array is directly connected to the DC-link of the solar PV-UPQC. The reference voltage for the DC-bus is obtained from the maximum power tracking (MPPT) algorithm. The DSTATCOM of the solar PV-UPQC performs dual functions such as compensating the reactive power while providing active power from the PV array into the grid. The DVR of the SPV-UPQC mitigates the sags and swells. In [140], an attempt is made to optimize the solar PV hosting capacity and energy loss in the distribution system by placing the open UPQC in the proper place. The solar PV-UPQC with a battery can supply power during peak periods. An analysis of the open solar PV-UPQC with and without a battery is presented in [141]. A biogeography-based optimization (BBO) technique for harmonics elimination in a smart grid integrated with solar PV using the UPQC is presented in [18]. The optimum switching angle of the converter eliminates the lower-order harmonics, while the higher-order harmonics are blocked by injecting an equal magnitude and opposite phase of the same order harmonics from the PE converter. In [46], the dynamic performance is presented of a solar PV integrated UPQC-P under varying irradiation, voltage sag, swell, and a step-change in load. The design and performance investigation of a 3P3W solar PV-UPQC is witnessed in [67], whereby the UPQC is designed using the following mathematical expressions.

Voltage magnitude of the DC-link:

$$V_{dc} = \frac{2\sqrt{2} \cdot V_{LL}}{\sqrt{3}m} \tag{6}$$

where V_{LL} is the line voltage of the grid and m is the depth of modulation.

DC-link capacitor rating:

$$C_{dc} = \frac{3 \cdot k \cdot a \cdot V_{ph} \cdot i_{DSTAT} \cdot t}{0.5\,(V_{dc}^2 - V_{dc1}^2)} \tag{7}$$

where a is the overloading factor and t is the time required to attain a steady value after a disturbance.

Interfacing inductor for the DSTATCOM:

$$L_f = \frac{\sqrt{3} \cdot m \cdot V_{dc}}{12 \cdot a \cdot f_{sh} \cdot I_{cr,pp}} \tag{8}$$

Interfacing inductor of the DVR:

$$L_r = \frac{\sqrt{3} \cdot m \cdot V_{dc} \cdot K_{se}}{12 \cdot a \cdot f_{se} \cdot I_r} \tag{9}$$

where f_{se} and f_{sh} are the switching frequencies of the DVR and DSTATCOM, respectively, K_{se} is the transformation ratio of the series transformer.

In [142], a control approach is discussed, based on a second-order generalized integrator (SOGI) and delayed signal cancellation (DSC). Two cascaded SOGI (CSOGI) band-pass filters are used for the extraction of the PCC voltage template to control the DVR. The DSTATCOM control is based on the extraction of the fundamental load current using CSOGI. This method extracts the fundamental component of the load current with better accuracy and improved dynamic performance. A single-phase solar PV-UAPF with UPQC is proposed in [117] to improve the dynamics without affecting the steady-state performance. The performance of the UPQC-S incorporated with solar PV under distorted PCC voltages with a modified *p*-*q* theory-based control algorithm is presented in [95]. A generalized cascaded delay signal cancellation technique is used for the extraction of the fundamental positive sequence components of voltages in the PCC. Integrated solar PV at the DC-link of PV-UPQC-S decreases the load demand on the main supply. In [143], a digital adaptive notch filter (DANF) is used to extract the fundamental active current and grid voltage template. The DANF is a good alternative to the PLL. In [115], a digital filter is used to extract the fundamental positive sequence component of the distorted grid voltage which is used to generate the sine and cosine values necessary for *d*-*q* based control.

6. UPQC LOCATION IN THE DISTRIBUTION NETWORK

The performance of the distributed system in terms of improving voltage stability, voltage regulation, reducing power loss and overall system costs, along with maximizing system reliability, can be achieved by optimal reactive power compensation. The effectiveness of optimal reactive power compensation can be improved by placing the UPQC at the proper location [144].

Based on the size of the UPQC, the optimal location in the radial distribution system can be determined using the differential evolution algorithm [145]. In the three-phase unbalanced distribution network, the Cuckoo optimization algorithm is implemented to allocate the optimal place for the UPQC [146]. In [147], identifying the UPQC location in the radial distribution system is framed as a non-linear single-objective problem to decrease the real power loss and improve the voltage profile of the system. In this regard, the latest technique, i.e., the Ant Lion optimization algorithm is implemented. The multi-objective Whale optimization algorithm can be effectively implemented to determine the optimal location and size of DGs in distribution systems for minimum power loss [148]. The multi-objective Grey Wolf optimizer algorithm based on probabilistic load flow along with the fuzzy method for choosing the best final answer is implemented to find the optimal location and size for the PAC-based UPQC [149]. In [150], the Grasshopper optimization algorithm (GOA) is proposed to find the optimal location and size for the UPQC. The GOA is a novel optimization method for encouraging the movement and immigration of a grasshopper in nature. It contains the global convergence requirement, and also supports the capabilities of local and global searches. A meta-heuristic Firefly algorithm is proposed in [151] to determine the optimal size for the DG in

Table 5: *Optimization techniques for identifying the appropriate location and size of the UPQC.*

Optimization Algorithm	Highlighted Aspects	Ref.
PSO	• Higher loading ability • Can be implemented on non-linear loads • Requires the consideration of various types of modeling	[155]
	• Applicable for use in the science and engineering fields • Requires no mutation and overlapping calculation • Can be implemented on a single-phase load	[156]
Differential Evolution	• Reduced voltage fluctuation enhances speed • Can be implemented on baseloads • Line loading limits need to be considered	[157]
Imperialist Competitive Algorithm (ICA)	• Maintains energy supply continuity • Minimizes consumer discontent • Can be implemented on linear loads • Lower convergence rates • Cannot solve the multi-objective problem	[158]
Firefly Algorithm Differential Evolution	• Cost-effective and easy to apply • Can be implemented on non-linear loads • Requires further observation on power loss	[159]
Multi-Objective PSO (MOPSO)	• Enhances the PV hosting capacity • Reduces energy loss • Can be implemented on linear loads • Requires inspection on various converters	[140]
Moth-Flame Optimization	• DVR voltage is determined using MFO • DVR is utilized for reactive power compensation	[160]
Pareto-based MOPSO	• Increases the peak load shaving • Minimizes the total power loss • Can be implemented on non-linear loads	[161]
Demand Response Programs	• Minimizes power loss • Can be used to identify optimal electricity prices in DRP during peak hours • Consideration is given to responsive loads • Requires frequency control and congestion management	[162]

the power system. The loss-sensitive (LS) method is used to determine the appropriate locations of DG. Accordingly, the LS index is calculated such that the variation in power loss is divided with rises in the generation and rank of buses to recognize the appropriate positions for DG. Optimization models implemented to determine the location of the UPQC must offer more reliability and feedback signals. Some hybrid algorithms have been used to determine the optimal location of the UPQC by focusing on efficiency, system cost, and voltage stability index such as a hybrid algorithm of the genetic algorithm and dragonfly algorithm (DA) known as the genetically modified DA algorithm [152] and crow search mating-based lion algorithm [153]. In [154], a novel rider optimization algorithm (ROA)-modified PSO on a fitness basis is presented for the improvement of PQ by choosing a particular location and size for the UPQC. Accordingly, a steady-state model of UPQC is derived to set the forward/backward sweep load flow with the objective of enhancing voltage and current profiles, while minimizing power loss and the investment costs. Table 5 summarizes the various algorithms used in the literature to determine the optimal location and size for the UPQC in the distribution system.

7. DISCUSSION

The recent research carried out in the field of UPQC to develop new topologies, compensation methods, control theories, and controllers is presented in Fig. 7. It can clearly be observed from Fig. 7 that since the introduction of UPQC for PQ enhancement, researchers have attempted to implement it in various applications with the objective of mitigating PQ problems and integrating RES with the main grid. However, the UPQC is still in the research phase and has not yet been extensively applied. The main reason for this is that the UPQC includes two sets of PE converters and a series transformer. This raises the overall cost dramatically along with production and marketing expenses, etc. The main challenge to the researcher is reducing the VA rating of the UPQC without compromising on performance.

Many studies have been conducted to identify the features of the UPQC for its application in a balanced environment. However, the power system is

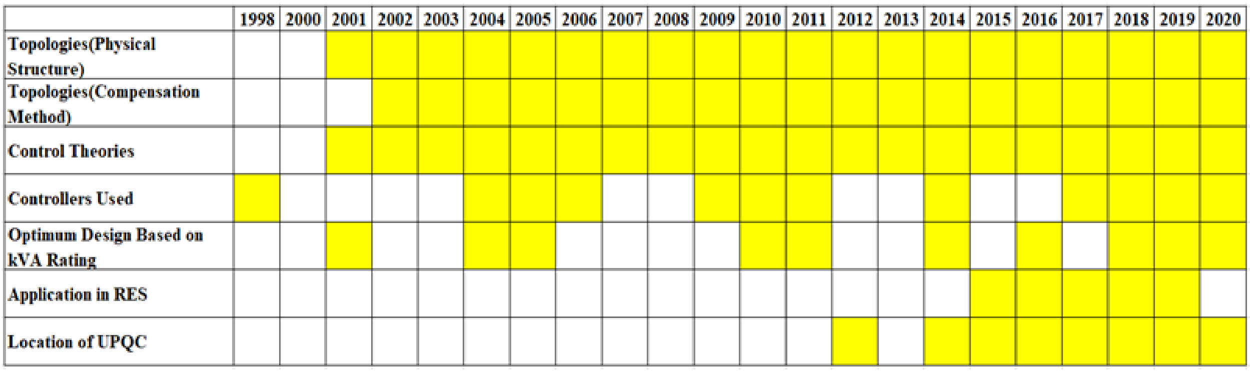

Fig. 7: *UPQC research.*

unbalanced with both single-phase and three-phase loads. The major PQ problems occurring in an unbalanced power system are an excessive neutral current, harmonics, a reactive power burden, etc. According to the published literature in the last five years, it can be observed that researchers are attempting to implement a 3P4W UPQC to overcome these obstacles.

Researchers made a concerted effort to develop an effective and efficient technique to compensate for voltage sag/swell with the introduction of UPQC-P, UPQC-Q and UPQC-S topologies. However, to minimize costs, it is necessary to increase the utilization of both PECs during all operating conditions. According to the recent research articles, it is clear that compensation techniques and design algorithms are being developed for the maximum utilization of both PECs in all operating conditions. The UPQC performance mainly depends on the control algorithm employed. Focusing on the literature involving control theories, it can be determined that time-domain theories are more efficient compared to the frequency domain. The SRF and *p*-*q* theories appear to be more popular among researchers. However, the main drawback of SRF is the presence of the double harmonic component in the d axis current. Using LPF at a very low cut-off frequency helps to improve the performance at the cost of poor dynamics. This can be overcome by implementing MAF or digital filters.

The *p*-*q* theory has been widely used to control the UPQC-DG in the integration of RES. The main advantages of *p*-*q* theory-based control are that it is simple, fast, and does not require a complex computational block such as PLL. However, the performance of *p*-*q* theory is poor in unbalanced grid voltage conditions.

To extract the distorted components of voltage and current, various methods have been applied by researchers such as zero-crossing detection, adaptive notch filtering, least-squares estimation, complex vector filtering, and SOGI-PLL. Among them, the PLL block is widely used and more popular for its simple structure, effectiveness, and overall performance acceptability. However, the precision and rapidity of the PLL declines under extremely unstable and distorted circumstances. With the conventional PLL algorithm, an inaccurate transformation angle is derived which results in undesired reference signal generation. However, with a modified PLL algorithm, a distortion-free transformation angle can be derived, providing proper synchronization of the reference signals with the supply system. Some advanced PLL algorithms are available that perform well in distorted circumstances such as filtering-based approaches, decoupling network-based PLLs, modified loop filter PLLs, etc.

The PAC approach is helpful in the effective utilization of the UPQC since it introduces active and reactive power-sharing features into the distribution system. There are two approaches found in the literature based on PAC, the first use *p*-*q* theory and the second use SRF theory The sensing circuit required in the PAC-based SRF method is less, enabling the controller to operate smoothly under an unbalanced and highly distorted source voltage environment since it includes the estimation of reference load voltage. Whereas the PAC-based *p*-*q* controller requires the magnitude of series-injected voltage and individual phase of the system to be calculated if operated under the same system conditions. Consequently, the increased number of sensors makes the calculation more complex. The PAC-based SRF theory with an advanced PLL algorithm is considered superior in terms of addressing problems associated with the real-time management of voltage, current, and reactive power from the source as well as the load side under highly distorted conditions.

The DC-link voltage control plays a very important role in improving the performance of the UPQC. Therefore, a quick response to maintain the DC-link voltage constant with minimum delay in all operating conditions is the basic requirement of a DC-link controller. The PI-controller is the most widely used in the literature. However, it fails to perform well due to parameter variations and the non-linearity of load disturbance. This can be overcome by implementing advanced controllers such as the fuzzy logic-based PI, fuzzy-PID, ANFIS, and ANN-based. These controllers provide a fast dynamic response and maintain the stability of both PECs in a wide operating range. The tuning of PI-controller gains using any optimization algorithm reduces the complexity involved in determining the controller parameters and gives better performance compared to manual and conventional PI-tuning methods.

By increasing the utilization of DVR for active-reactive power-sharing during steady-state, the overall VA rating of the UPQC can be minimized and system reliability improved. Steady-state analysis and the factors on which the VA rating of the UPQC is dependent are highlighted by many researchers. Active-reactive power shared by the DVR depends upon the power angle (δ). It can be observed that the optimization of the VA loading of the UPQC has rarely been deliberated so far. There is no comprehensive approach for optimizing the rating of a UPQC. It is clear from the existing literature on the implementation of various methods for minimizing the VA loading of the UPQC that power angle (δ) is controlled directly or indirectly. Satisfactory results are obtained in a particular operating condition such as voltage sag. On the other hand, minimum VA ratings of the DVR, DSTATCOM, series transformer, and, thus, the overall UPQC system is independent of minimum VA loading at a certain operating condition. Variation in the individual VA loading of both PECs is not considered during all operating conditions.

From Fig. 7, it can be clearly observed that other than PQ enhancement, using the UPQC for the integration of RES with the main grid has become a more popular field of research in recent years. The UPQC is used to integrate various RES (such as weak wind farms, fuel cells, and solar PV) with the grid to provide clean, green energy for society. In this case, the UPQC can be operated in two modes, i.e., interconnected and islanding, to supply the critical load without interruption. Solar PV-UPQC is efficient in enhancing the PQ of the grid and maintaining the voltage regulation compared to conventional grid-connected PV systems. Although the existing literature reports on the design and operation of solar PV-UPQC, no serious focus has been given to UPQC performance enhancement. Moreover, interfacing issues, complex circuits, high costs, and fast dynamic response are the main challenges to researchers.

The proper location of the UPQC in the distribution network provides the optimal reactive power compensation, resulting in the improved performance of the distributed system in terms of increased efficiency, voltage stability, voltage regulation, a reduction in the VA rating, and overall system costs, with better system reliability. Although there are numerous optimization algorithms, including advanced techniques such as GOA, GWO, Sine Cosine, PSO, hybrid PSO, according to the literature, Ant Lion and multi-objective Whale optimization have been found to be more effective for determining the optimal location and size of DGs for minimum power loss.

According to a review of the recent literature, the scope of future UPQC research should include the following.

1. Application and performance improvement of the UPQC under power system imbalance to mitigate PQ problems such as excessive neutral current, harmonics, reactive power burden, etc.
2. Design and development of advanced PLL algorithms such as MAF-based PLL to improve UPQC performance under normal, abnormal, and harmonically distorted grid conditions.
3. Design and development of an advanced controller with optimization techniques such as the Jaya algorithm to improve the dynamic response and maintain the stability of both PECs over a wide operating range.
4. Determination of the optimum power angle (δ) for maximum UPQC utilization under any operating conditions using advanced optimization algorithms such as Teaching-learning-based optimization (TLBO), Jaya, and Rao.
5. Design and development of an adaptive controller to address all PQ problems and regulate DC-link voltages in the solar PV-UPQC.
6. Determination of the optimal location and size for integrated DGs using the UPQC with the main grid to achieve minimum power loss through advanced optimization techniques.

8. CONCLUSION

This paper presents a review of the UPQC-based topologies, their compensation, control theories, and optimal location in the distribution system. The need for DG continues to increase at a rapid rate, while fast-growing PEC technology makes it possible to integrate DG with a grid. The UPQC is capable of compensating for all types of supply voltage and load current PQ problems along with the integration of RES with the main grid. Comparing all the topologies, it can be concluded that the UPQC-DG, UPQC-MC, and UPQC-ML play very important roles in the power system for integrating RES with the grid. From the rigorous study of various control theories, it is clear that the performance of the UPQC depends on control methods, but complexity of the control approach presents a significant challenge. It can be observed that the PAC-based SRF approach of the UPQC helps to maximize DVR utilization by reactive power-sharing while mitigating sag/swell. This results in a rating reduction for the DSTATCOM without affecting the overall UPQC rating. This paper presents relevant information on the UPQC and may act as a potential data source for research scholars, manufacturers, and electrical utilities working in the field of power system research.

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Swati Gade received her B.E. and M.E. degrees in Electrical Engineering from the Pune University, India, in 2003 and 2007 respectively. Currently, she is an assistant professor in the Department of Electrical Engineering at Sandip Institute of Engineering and Management, Nashik, India. Also, she is Research Scholar at Sandip University Nashik, India. She has published about 6 national and international journal and conference papers. Her research interest covers power systems, application of optimization techniques in power system, and power quality. She is a life member of ISTE, IE(i), and IAENGE (H.K.).

Rahul Agrawal received his B.E. Degree in Electrical Engineering from JIT Khargone, India in 2001, and M.E. in Power Electronics from SGSITS Indore, India in 2008, and Ph.D. from Maulana Azad National Institute of Technology Bhopal, India in 2017. Presently, he is an Associate Professor with the Department of Electrical and Electronics Engineering, Sandip University, Nashik, Maharashtra, India. He has 19 years of teaching experience. He has published 20 papers in national and international conferences & journals. His current research interests are in the areas of application of optimization technique in power system, power electronics, and FACTS devices. He is a life member of ISTE, India.

Ravindra Munje received his B.E. degree in Electrical from Mumbai University, India in 2005, M.E. degree in Electrical (control systems) from Pune University, India in 2009, and Ph.D. Degree in Electrical from Swami Ramanand Teerth Marathwada University, Nanded, India in 2015. He was a Post-Doctoral Fellow with Shanghai Jiao Tong University, Shanghai, China from June 2017 to May 2019.

Currently, he is a Professor at the Electrical Engineering Department, K. K. Wagh Institute of Engineering Education and Research, Nashik, India. He has written a book and about 50 refereed papers. His research interests include modeling and the control of large-scale systems using sliding mode, multirate output feedback, power quality analysis using AI techniques.

Dr. Munje received the Promising Engineer Award in 2016, Outstanding Researcher Award in 2018 and Best Faculty Award in 2019.