Enhancing Electric Power Quality Using UPQC: A Comprehensive Overview

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***Abstract*—This paper presents a comprehensive review on the unified power quality conditioner (UPQC) to enhance the electric power quality at distribution levels. This is intended to present a broad overview on the different possible UPQC system configurations for single-phase (two-wire) and three-phase (three-wire and four-wire) networks, different compensation approaches, 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, UPQC-Q, UPQC-R, UPQC-S, and UPQC-VA$_{\min}$. More than 150 papers on the topic are rigorously studied and meticulously classified to form these acronyms and are discussed in the paper.**

***Index Terms*—Active power filter (APF), harmonic compensation, power quality, reactive power compensation, unified power quality conditioner (UPQC), voltage sag and swell compensation.**

I. 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 well discussed [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]. APFs have made it possible to mitigate some of the major power quality problems effectively. Extensive and well-documented surveys on the APF technologies covering several aspects are provided in [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.

This paper is intended to provide a comprehensive review on the topic of UPQC. Over 150 publications [8]–[168] are critically reviewed to classify them in different categories. It is noticed that more than half of the papers on UPQC have been reported in the last five years, which indeed suggest the rapid interest in utilizing UPQC to improve the quality of power at the distribution level. These research papers are broadly classified into two major groups based on 1) physical structure of the UPQC [7]–[168] and 2) method used to compensate sag/dip in the source voltage [143]–[168]. It is noticed that several interesting topologies/configurations can be realized to form a UPQC system [19], [23], [39], [40], [78], [88], [108], [147]. 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. These acronyms are very useful to give a broad overview on the research aspect under consideration. Therefore, this paper aims at developing an acronymic list to cover different UPQC aspects. In all 12 acronyms are identified, alphabetically, UPQC-D, UPQC-DG, UPQC-I, UPQC-L, UPQC-MC, UPQC-MD, UPQC-ML, UPQC-P, UPQC-Q, UPQC-R, UPQC-S, and UPQC-VA$_{\min}$. Besides this, this paper also discusses the most significant control strategies/approaches/concepts that are utilized to control the UPQC.

II. UPQC—STATE OF THE ART

There are two important types of APF, namely, shunt APF and series APF [8]–[10]. The shunt APF is the most promising to tackle the current-related problems, whereas, the series APF is the most suitable to overcome the voltage-related problems. Since the modern distribution system demands a better quality of voltage being supplied and current drawn, installation of these APFs has great scope in actual practical implementation. However, installing two separate devices to compensate voltage- and current-related power quality problems, independently, may not be a cost effective solution. Moran [11] described a system configuration in which both series and shunt APFs were connected back to back with a common dc reactor. The topology was addressed as line voltage regulator/conditioner. The back-to-back inverter system configuration truly came into attention when Fujita and Akagi [14] proved the practical application of this topology with 20 kVA experimental results. They named this device as unified power quality conditioner (UPQC), and since then the name UPQC has been popularly used by majority of the researchers [15], [18], [20]–[26], [28], [29], [31]–[67], [69]–[79], [81]–[145], [147]–[168]. The back-to-back inverter topology

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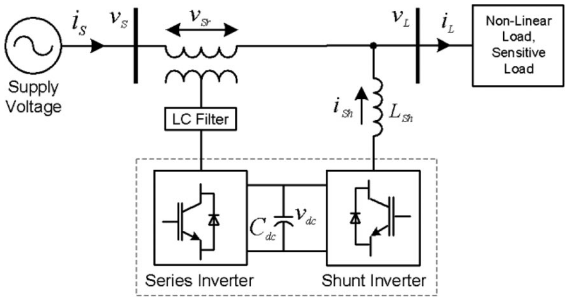

Fig. 1. UPQC general block diagram representation.

has been also addressed as series–parallel converter [12], unified APF (UAPF) [13], universal active power line conditioner [16], [27], universal power quality conditioning system (UPQS) [19], load compensation active conditioner [30], [57], universal active filter [146], and so forth.

In construction, a UPQC is similar to a unified power flow controller (UPFC) [5]. Both UPQC and UPFC employ two voltage source inverters (VSIs) that are connected to a common dc energy storage element. A UPFC is employed in power transmission system whereas UPQC is employed in a power distribution system, to perform the shunt and series compensation simultaneously. However, a UPFC only needs to provide balance shunt and/or series compensation, since a power transmission system generally operates under a balanced and distortion free environment. On the other hand, a power distribution system may contain dc components, distortion, and unbalance both in voltages and currents. Therefore, a UPQC should operate under this environment while performing shunt and/or series compensation.

The main purpose of a UPQC is to compensate for supply voltage power quality issues, such as, sags, swells, unbalance, flicker, harmonics, and for load current power quality problems, such as, harmonics, unbalance, reactive current, and neutral current. Fig. 1 shows a single-line representation of the UPQC system configuration. The key components of this system are as follows.

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

In principle, UPQC is an integration of shunt and series APFs with a common self-supporting dc bus. The shunt inverter in UPQC is controlled in current control mode such that it delivers a current which is equal to the set value of the reference current as governed by the UPQC control algorithm. Additionally, the shunt inverter plays an important role in achieving required performance from a UPQC system by maintaining the dc bus voltage at a set reference value. In order to cancel the harmonics generated by a nonlinear load, the shunt inverter should inject a current as governed by following equation:

$$i_{\mathrm{Sh}}(\omega t) = i_S^*(\omega t) - i_L(\omega t) \tag{1}$$

where $i_{\mathrm{Sh}}(\omega t)$, $i_S^*(\omega t)$, and $i_L(\omega t)$ represent the shunt inverter current, reference source current, and load current, respectively.

Similarly, the series inverter of UPQC is controlled in voltage control mode such that it generates a voltage and injects in series with line to achieve a sinusoidal, free from distortion and at the desired magnitude voltage at the load terminal. The basic operation of a series inverter of UPQC can be represented by the following equation:

$$v_{\mathrm{Sr}}(\omega t) = v_L^*(\omega t) - v_S(\omega t) \tag{2}$$

where $v_{\mathrm{Sr}}(\omega t)$, $v_L^*(\omega t)$, and $v_S(\omega t)$ represent the series inverter injected voltage, reference load voltage, and actual source voltage, respectively. In the case of a voltage sag condition, v_{Sr} will represent the difference between the reference load voltage and reduced supply voltage, i.e., the injected voltage by the series inverter to maintain voltage at the load terminal at reference value. In all the reference papers on UPQC, the shunt inverter is operated as controlled current source and the series inverter as controlled voltage source except [112] in which the operation of series and shunt inverters is interchanged.

The UPQC system modeling aspects are discussed in [12], [18], [22], [52], [74], [97], [104], [106], [143], [151], [156]. The three-phase system in *abc* frame is transferred into synchronous *dqo* frame. The system is then represented in state-space formulation [12], [22], [52], [74], [106], [151]. It is observed that the system is nonlinear on its states as well as on its outputs [73]. In [18], a UPQC mathematical model is realized using switching functions. A small signal model for the UPQC system is developed in [97] and [154]. Rong *et al.* [104] have shown that the UPQC system can be modeled as a typical switched linear system. However, 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. The authors in [52], [74], [104], and [154] discuss the UPQC system modeling in detail.

The control of dc-link voltage plays an important role in achieving the desired UPQC performance. During the system dynamic conditions, for example, 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. The

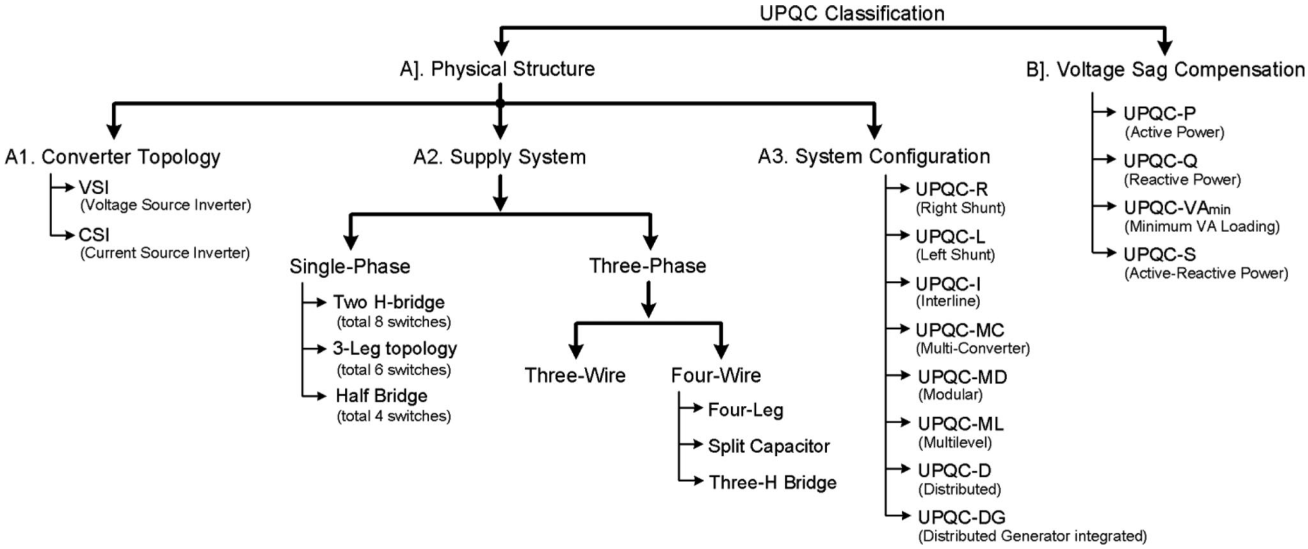

Fig. 2. Pictorial view for the classification of UPQC.

proportional–integral (PI)-regulator-based dc-link voltage controller is simple to implement and hence widely used by the researches [12]–[14], [16]–[20], [22], [23], [26]–[33], [36], [38], [40], [42], [46]–[48], [50], [54], [56], [60], [61], [64], [67], [68], [75]–[77], [81]–[84], [88]–[90], [92], [94], [95], [100], [103]–[105], [108], [109], [111]–[114], [116], [117], [119], [122], [124], [126]–[128], [130]–[135], [137]–[139], [143], [145]–[155], [157]–[164], [167], [168]. To overcome the slow response time of PI-controller-based approach, researchers have developed several alternative ways, for example, a fuzzy-logic-based PI controller [15], [65], fuzzy-PID controller [101], artificial-neural-network (ANN)-based controller [65], [136], linear quadratic regulator with an integral action controller [74], optimized controller [80], PIλDμ controller [91], unified dc voltage compensator [97], and so on.

III. UPQC CLASSIFICATION

In this section, the classification of UPQC is given. Fig. 2 shows a pictorial view for the classification of UPQC. The UPQC is classified in two main groups: 1) based on the physical structure and 2) on the voltage sag compensation approach used. Former type is considered as voltage sag compensation is one of the important functionalities of UPQC.

A. 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 this section.

1) Classification Based on the Converter Topology: In a UPQC, both shunt and series inverters share a common dc link. The shunt inverter is responsible to regulate this self-supporting dc link at a set reference value. The UPQC may be developed using a pulsewidth modulated (PWM) current source inverter (CSI) [9]–[11], [115] that shares a common energy storage inductor L_{dc} to form the dc link. A voltage blocking diode connected in series with insulated gate bipolar transistor is required to realize this topology Fig. 3 shows single-line representation of a CSI-based UPQC system configuration. The dc current in the inductor is regulated such that the average input power is equal to the average output power plus the power losses in the UPQC. The CSI-based UPQC topology is not popular because of higher losses, cost, and the fact that it cannot be used in multilevel configurations.

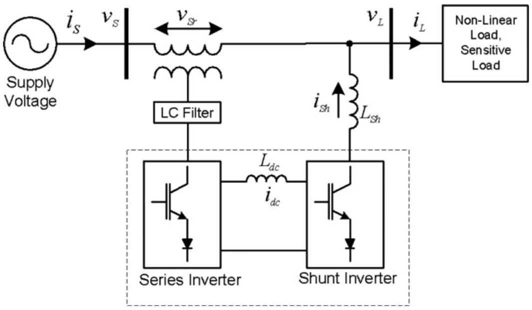

Fig. 3. CSI-based UPQC system configuration.

The second topology, a most common and popular converter topology for UPQC, consists of PWM VSI that shares a common energy storage capacitor C_{dc}. Fig. 1 depicts single-line representation of a VSI-based UPQC system configuration. Almost all the reported work on the UPQC dominantly uses the VSI-based topology [12], [114]–[168]. The advantages offered by VSI topology over CSI include lighter in weight, no need of blocking diodes, cheaper, capability of multilevel operation, and flexible overall control.

2) Classification Based on the Supply System: The ac loads or equipments on the power system can be broadly divided into single-phase and three-phase, supplied by single-phase (two-wire) or three-phase (three-wire or four-wire) source of power.

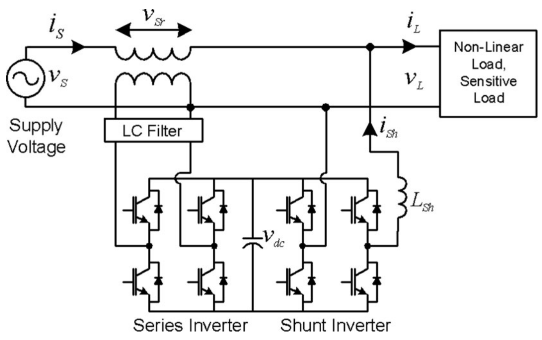

Fig. 4. 1P2W UPQC: two H-bridge configuration (eight switches).

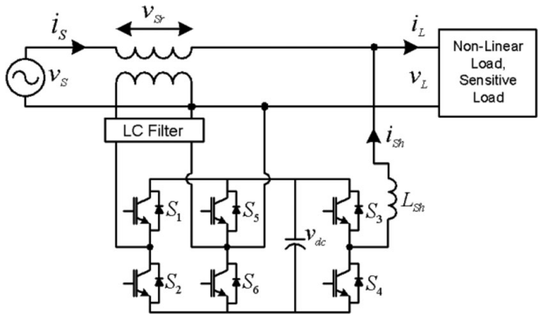

Fig. 5. 1P2W UPQC: three-leg configuration (six switches).

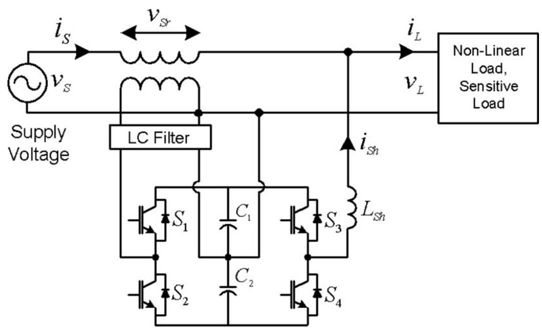

Fig. 6. 1P2W UPQC: half-bridge configuration (four switches).

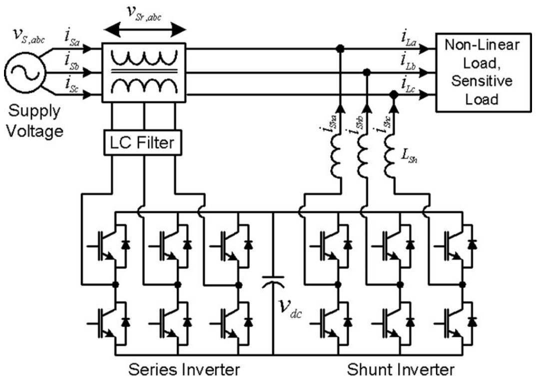

Fig. 7. 3P3W UPQC.

To mitigate the power quality problems in these systems, different UPQC configurations are possible and are classified based on the type of the supply system. The voltage-related power quality problems are similar for both single- and three-phase systems except an additional voltage unbalance compensation needed in the case of a three-phase system. For a single-phase system, the load reactive current and current harmonics are the major issues. In the case of three-phase three-wire (3P3W) system, one needs to consider current unbalance apart from reactive and harmonics current. Furthermore, the three-phase four-wire (3P4W) system requires an additional neutral current compensation loop.

Fig. 4 shows the most popular UPQC system configuration to compensate the power quality problems in single-phase two-wire (1P2W) supply system consisting of two H-bridge inverters (total eight semiconductor switches) [11], [23], [37], [40], [41], [53], [55], [64], [76], [79], [86], [104], [107], [145], [146], [150], [155], [156], [163]. It represents the VSI-based 1P2W UPQC topology. A CSI-based topology can also be realized for 1P2W UPQC, as given in [11]. Nasiri and Emadi introduced two additional reduced part configurations for single-phase UPQC [40], namely, three-leg single-phase UPQC (total six semiconductor switches) shown in Fig. 5 and half-bridge single-phase UPQC (total four semiconductor switches) shown in Fig. 6. These topologies can be considered for low-cost low-power applications. In a three-leg topology, the series inverter consists of switches S1 and S2 (leg one), whereas, switches S3 and S4 are for shunt inverter (leg two). The third leg, switches S5 and S6, is common for both the series and shunt inverters. The half-bridge topology consists of one leg each for shunt and series inverters. The reduced switching devices may affect the compensation performance of UPQC. The half-bridge topology-based UPQC system can be found in [57], [83], [106], [150], [156]. Zhang *et al.* [93] have considered a bidirectional two H-bridge dc/dc-isolated converter topology to isolate UPQC shunt and series inverters from each other. The two inverters can be connected with each other using a high-frequency transformer. Like bidirectional-isolated dc/dc converter, the power transfer between two inverters can be controlled by adjusting voltage phase shift between them.

Several nonlinear loads, such as, adjustable speed drives fed from 3P3W, current regulator, frequency converters, arc welding machines, and arc furnace, impose combinations of previously listed power quality problems. A 3P3W VSI-based UPQC is depicted in Fig. 7. It is the most widely studied UPQC system configuration [12]–[15], [17]–[20], [22], [24], [26], [29], [32]–[34], [36], [38], [39], [42], [44]–[50], [52], [54], [56], [59]–[61], [63], [65], [67], [68], [71], [72], [74], [75], [80], [84], [87], [91], [92], [94]–[100], [103], [109], [112], [113], [115], [117], [119], [120], [124], [127], [131]–[139], [141], [143], [148], [149], [151]–[153], [158], [161], [167], [168]. Apart from the three-phase loads, many industrial plants often consist of combined loads, such as, a variety of single-phase loads and three-phase loads, supplied by 3P4W source. The presence of fourth wire, the neutral conductor, causes an excessive neutral current flow and, thus, demands additional compensation requirement. To mitigate the neutral current in 3P4W system, various shunt inverter configurations have been attempted, namely, two split capacitor (2C) [16], [30], [70], [82], [89], [114], [118], [154], [166], four-leg (4L) [51], [108], [122], [135] and three H-bridge (3HB) [21], [43], [49], [126].

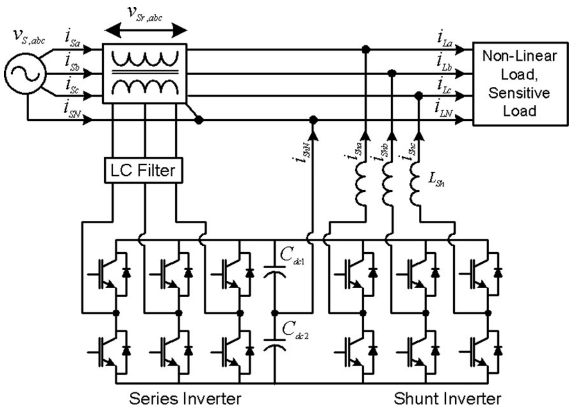

Fig. 8. 3P4W UPQC based on 2C shunt inverter topology.

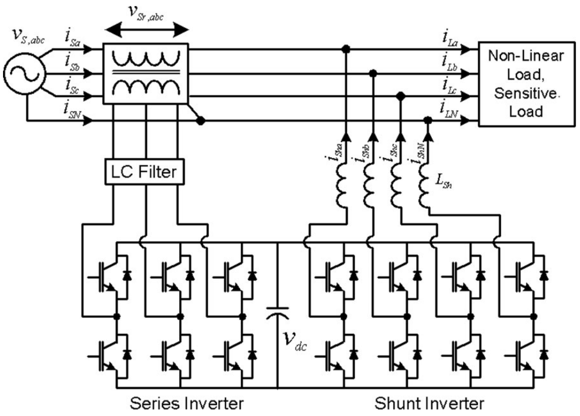

Fig. 9. 3P4W UPQC based on 4L shunt inverter topology.

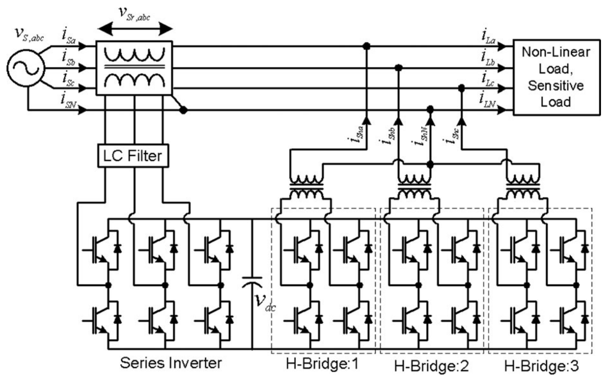

Fig. 10. 3P4W UPQC based on 3HB shunt inverter topology.

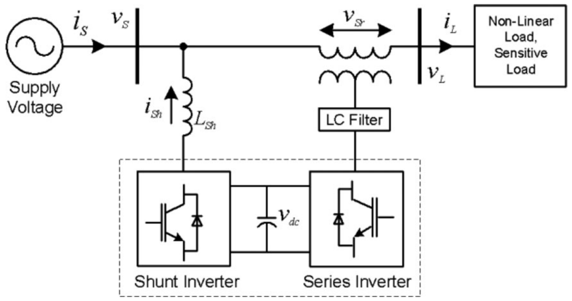

Fig. 11. UPQC-L system configuration.

Figs. 8–10 show the 3P4W UPQC configurations based on 2C, 4L, and 3HB topologies. The 2C topology consists of two split capacitors on the dc side. The midpoint of the capacitor, expected to be at zero potential, is used as connection point for the fourth wire. In 2C topology, it is important to maintain equal voltages across both the capacitors to avoid the flow of circulating current. This requires an additional control loop for dc bus capacitor voltage regulation in 2C topology.

In 4L topology, as depicted in Fig. 9, an additional leg (two semiconductor switches) is used to compensate the load neutral current. The 4L topology may offer better control over neutral current due to the dedicated fourth leg. The 3HB topology uses three units of single-phase H-bridge inverters connected to the same dc bus of the UPQC. Fig. 10 shows a UPQC system configuration where the shunt inverter consists of 3H-bridges. In [49], the series inverter is configured as 3HB while the shunt inverter is realized as 2C to compensate the neutral current. Similarly, 3HB configuration for series inverter for 3P3W UPQC system is given [21], [25]. A superconducting magnetic energy storage is integrated with 3HB series-inverter-based 3P3W UPQC system in [126]. Furthermore, a configuration where both shunt and series inverters are realized as 3HB units (total 24 semiconductor switches) is also possible [43], [78], [129]. A comparative study, using 2C, 4L, and 3HB topologies for shunt active filters given in [169] is equally applicable for the shunt part of UPQC system. For high-voltage applications, for the reduction in UPQC system voltage requirement by a factor of 1.732 [169], the 3HB topology may be considered. However, such a configuration would increase the total number of semiconductor devices, UPQC system losses, overall size, and the cost of the system. As given in [135], the neutral current compensation topology consisting of 3P3W UPQC and an additional star–hexagon/T-connected transformer to circulate the zero sequence current component may also be considered.

3) Classification Based on the UPQC Configuration: This section gives an overview on the different UPQC configurations.

1) Right and Left Shunt UPQC (UPQC-R and UPQC-L): Since the UPQC has two back-to-back connected inverters, it can be classified based on the placement of shunt inverter with respect to series inverter. The shunt inverter can be located either on the right (thus the name right shunt UPQC (UPQC-R)) [7]–[20], [22], [23], [25], [26], [28]–[40], [42], [44]–[56], [58]–[84], [86]–[97], [99]–[127], [129]–[144], [153]–[168] or left (hence the name left shunt UPQC (UPQC-L)) [7], [21], [24], [27], [41], [43], [57], [85], [98], [128], [145], [152] side of the series inverter.

Figs. 1 and 3–10 represent UPQC-R system configuration, while Fig. 11 shows UPQC-L configuration. Among two configurations, the UPQC-R is the most commonly used. In UPQC-R, the current(s) that flow through series transformer is(are) mostly sinusoidal irrespective to the nature of load current on the system (provided that the shunt inverter compensate current harmonics, reactive current, unbalance, etc., effectively). Thus, UPQC-R gives a better overall UPQC performance compare to UPQC-L. The UPQC-L structure is sometimes used in special cases, for

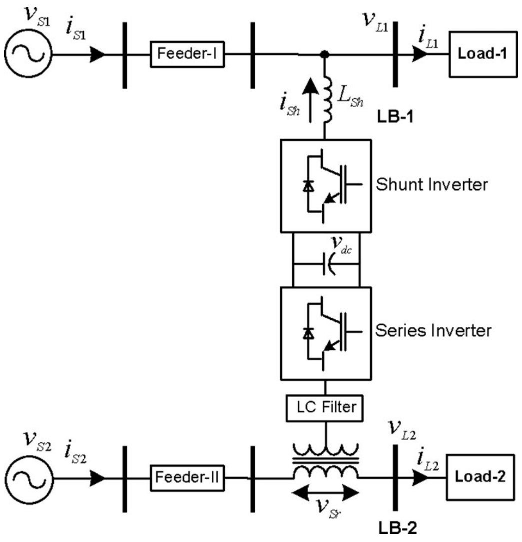

Fig. 12. UPQC-I system configuration.

example, to avoid the interference between the shunt inverter and passive filters.

2) Interline UPQC (UPQC-I): Fig. 12 depicts an interesting UPQC system configuration, suggested by Jindal *et al.* [78], where the two inverters of the UPQC are connected between two distribution feeders named as interline UPQC (UPQC-I). One of the inverters is connected in series with one of the feeders while the other inverter in shunt with second feeder. With such a configuration, the simultaneous regulation of both the feeder voltages can be achieved. Furthermore, the UPQC-I can control and manage the flow of real power between the two feeders. This configuration, however, has certain limitations and can be used for special cases. The current-related problems (such as harmonics and unbalance) could be effectively compensated only on the feeder in which the inverter is connected in shunt. Alternatively, the harmonics in the voltages can only be adequately mitigated in the series-inverter-connected feeder.

3) Multiconverter UPQC (UPQC-MC): Researchers have explored the possibilities for improving the system performance by considering additional third converter unit to support the dc bus [17], [19], [62], [66]. To further enhance the system performance, the use of storage battery or super capacitor can be used as discussed in [17] and [66]. The third converter can be connected in different ways, for example, in parallel with the same feeder [17], [19], [62], [66] or in series/parallel with the adjacent feeder [105]. Graovac *et al.* [19] addressed this configuration as UPQS. Wong *et al.* [17] have named this configuration as DS-UniCon (distribution system unified conditioner), whereas, Mohammadi *et al.* [105] called this configuration as MC-UPQC (Multiconverter UPQC). In MC-UPQC, the third converter is connected in series with the adjacent feeder. Similar to UPQC-I, the MC-UPQC can be connected between two different feeders. In this paper, the configuration in which three converters are utilized to realize the UPQC system is termed as multiconverter UPQC (UPQC-MC). Fig. 13 shows a pictorial view of UPQC-MC.

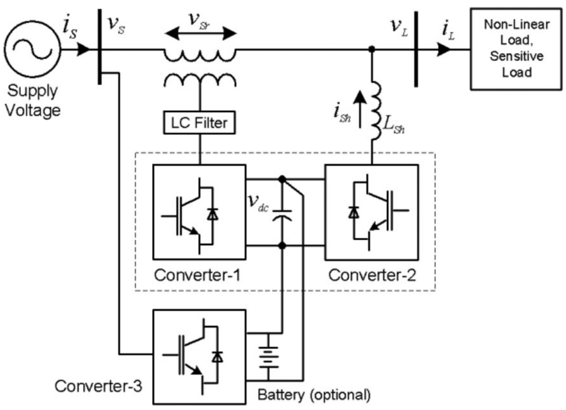

Fig. 13. UPQC-MC system configuration.

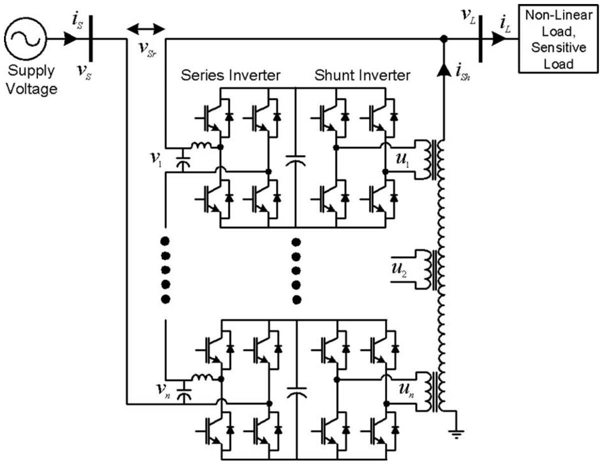

Fig. 14. UPQC-MD system configuration.

4) Modular UPQC (UPQC-MD): A modular UPQC configuration (named in this paper as UPQC-MD) introduced by Han *et al.* is illustrated in Fig. 14 [147]. This configuration is realized by using several H-bridge modules similar as connecting several single-phase UPQCs (eight semiconductor switches) in cascade in each phase.

In [128] and [147], the H-bridge modules for shunt part of UPQC are connected in series through a multiwinding transformer, while the H-bridges in the series part are directly connected in series and inserted in the distribution line without a series injection transformer. In [88], [110], and [128], the series inverter H-bridges are connected in parallel and inserted in the line through series transformers. As the number of modules increase, the voltage handled by each individual H-bridge would reduce, and thus, it can be useful in the medium voltage application to achieve higher power levels. A double cascade H-bridge UPQC-MD would require four H-bridges (16 semiconductor switches) for each of the phases, i.e., 48 semiconductor switches for a three-phase system.

5) Multilevel UPQC (UPQC-ML): Rubilar *et al.* have realized a multilevel UPQC based on a three-level neutral point clamped (NPC) topology [88]. In this paper, this configuration is addressed as UPQC-ML. Fig. 15 shows a UPQC-ML system configuration. A three-level topology requires double

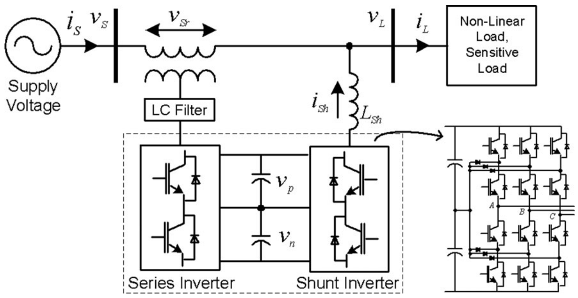

Fig. 15. UPQC-ML system configuration.

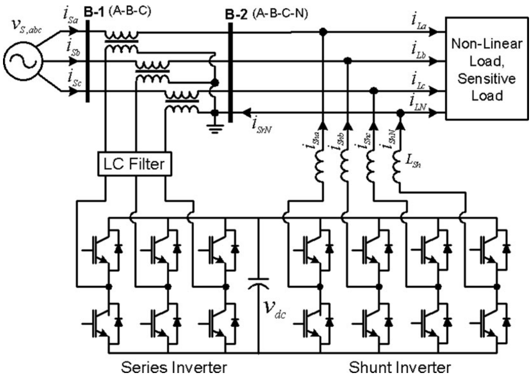

Fig. 16. UPQC-D system configuration.

semiconductor devices (24) as that of the two-level UPQC system. Similar to UPQC-MD, the UPQC-ML can be considered as an alternative option to achieve higher power levels. Based on the requirements, the UPQC-ML can be realized in several levels such as 3-level, 5-level, 7-level and so on.

6) 3P3W-to-3P4W Distributed UPQC (UPQC-D): A 3P4W distribution system is generally realized by providing a neutral conductor along with the three power lines from substation or by utilizing a delta–star transformer at the distribution level. A new topology for 3P4W UPQC-based distribution system is proposed in [108]. With this topology, it is possible to extend the UPQC-based 3P3W system to a 3P4W system, here referred as 3P3W to 3P4W distributed UPQC, the UPQC-D. The system configuration of UPQC-D is given in Fig. 16. The neutral of series transformer, used in the series part of UPQC, is considered as a neutral for 3P4W system. Thus, even if the power supplied by utility is 3P3W, an easy expansion to 3P4W system can be achieved in UPQC-based applications. A fourth leg is added to the existing 3P3W UPQC to compensate the neutral current flowing toward transformer neutral point and it can ensure zero current flow toward the neutral point. Thus, the transformer neutral point can be maintained at virtual zero potential.

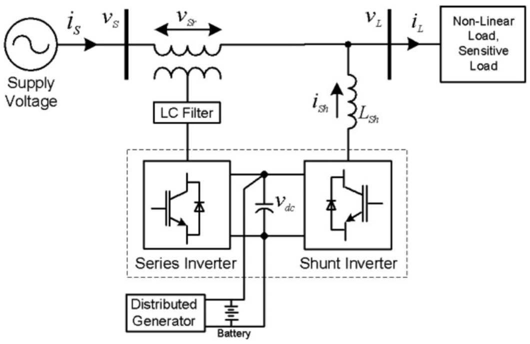

Fig. 17. UPQC-DG system configuration.

7) Distributed Generators Integrated With UPQC (UPQC-DG): Solar and wind energies are emerging as alternate sources of electricity. The UPQC can be integrated with one or several distributed generation (DG) systems [39], [63], [86], [98], [152]. The system configuration, thus, achieved is referred as UPQC-DG and is illustrated in Fig. 17. As shown, the output of DG system is connected to dc bus of the UPQC. The DG power can be regulated and managed through UPQC to supply to the loads connected to the PCC in addition to the voltage and current power quality problem compensation. Additionally, a battery can be connected to the dc bus, such that the excess DG generated power can be stored and used as backup. In the event of voltage interruption, the UPQC-DG system gives additional benefit by providing the power to the load (uninterruptible power supply operation). Furthermore, the DG power can be transferred in an interconnected mode (power to the gird and loads) or islanding mode (power to the specific loads) and so on.

So far, several interesting UPQC system configurations are brought to the attention. Some of these configurations may impose limitations, interface issues, increase overall circuit complexity, and cost. These aspects need to be addressed adequately for practical viability of these configurations. Nevertheless, these topologies give alternative options to realize the UPQC-based system configuration in several ways.

B. 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.

1) Active Power Control (UPQC-P): In this method, active power is used to mitigate the voltage sag and hence the name UPQC-P (P for active/real power). In principle, to compensate the voltage sag, an in-phase voltage component is injected in the series with line through a series inverter [143]–[156]. This in-phase component is equal to reduced voltage magnitude from the desired load voltage value. In order to achieve the effective sag compensation, the shunt inverter of UPQC draws the necessary active power required by the series inverter plus the losses associated with UPQC. Due to this, an increased source current magnitude during voltage sag compensation in UPQC-P method can be observed.

2) Reactive Power Control (UPQC-Q): The voltage sag can also be mitigated by injective reactive power through a series inverter of UPQC [157]–[159], [161], [167]. In such a case, it is called as UPQC-Q (Q for reactive power). The concept is to inject a quadrature voltage through the series inverter of UPQC such that the vector sum of source voltage and the injected voltage equals the required rated voltage at the load bus terminal. The shunt inverter of UPQC necessarily maintains a unity power factor operation at the source side. Therefore, by injecting the series inverter voltage in quadrature with the source voltage, the need of active power to compensate the sag on the system is eliminated. However, the resultant voltage, thus, achieved gives phase angle shift with respect to the source voltage. To compensate an equal percentage of sag, the UPQC-Q requires larger magnitude of series injection voltage than the UPQC-P. This increases the required rating of series inverter in UPQC-Q applications. Furthermore, the UPQC-Q cannot mitigate the swell on the system. Among the aforementioned discussed two approaches, the UPQC-P is the most commonly used method for voltage sag compensation in UPQC applications.

3) Minimum Volt-Ampere (VA) Loading (UPQC-VA$_{\min}$): Recently, there has been an attempt to minimize the UPQC VA loading during voltage sag compensation [160]–[167]. Instead of injecting the series voltage in quadrature or in-phase, in this method, it is injected at a certain optimal angle with respect to the source current. This method to compensate the voltage sag using UPQC is abbreviated as UPQC-VA$_{\min}$. Beside the series voltage injection, the current drawn by the shunt inverter (to maintain dc bus and overall power balance) needs to be taken into account while determining the minimum VA loading of UPQC. In [165], a comparison on VA loading to mitigate voltage sag using UPQC-P, UPQC-Q, and UPQC-VA$_{\min}$ methods is carried out.

4) Simultaneous Active and Reactive Power Control (UPQC-S): This approach is similar to UPQC-VA$_{\min}$, where the series inverter delivers both active and reactive power. Unlike the UPQC-VA$_{\min}$, in this method, the efforts are made to utilize the available series inverter VA loading to its maximum value. The series inverter of UPQC is controlled to perform simultaneous voltage sag/swell compensation and load reactive power sharing with the shunt inverter. Since, the series inverter of UPQC in this case delivers both active and reactive powers, it is given the name UPQC-S (S for complex power) [168]. The control of UPQC as UPQC-S involves several control loops and, thus, appears relatively complex to employ. However, it can easily be implemented when controlled digitally using a DSP [168].

Lately discussed two approaches, UPQC-VA$_{\min}$ and UPQC-S, suggest the new era for research and development in the subject of power quality enhancement using UPQC where attempts are being made to use the series inverter of UPQC optimally. Furthermore, the concepts like UPQC-I, UPQC-MC, UPQC-MD, UPQC-ML, UPQC-D, and UPQC-DG provide interesting features that can be considered in futuristic UPQC applications.

IV. UPQC ACRONYMS

In the previous section, 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-VA$_{\min}$, are listed in Table I. These acronyms could be useful to highlight the key features of UPQC in an application more concisely.

TABLE I
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

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-VA$_{\min}$, or UPQC-S approaches. Based on the aforementioned discussed classifications, there are more than 50 possibilities in which a UPQC can be categorized.

V. CONTROL TECHNIQUES FOR UPQC

Control strategy plays the most significant role in any power electronics based system. 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. There are several control strategies/algorithm/techniques available in the existing literature those have successfully applied to UPQC systems. 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. Control methods for UPQC in the time domain are based on instantaneous derivation of compensating commands in the form of either voltage or current signals. There are a large number of control methods in the time domain. Few are briefly discussed here.

Two most widely used time-domain control techniques for UPQC are the instantaneous active and reactive power or three-phase *pq* theory [170] and synchronous reference frame method or three-phase *dq* theory [171]. 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. 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. The UPQC controller based on three-phase *pq* can be found in [14], [16], [17], [27], [32], [52], [98], [104], [109], [113], [114], and [126], while *dq* method based controller can be found in [12], [18], [19], [22], [25], [26], [33], [45], [47], [68], [75], [81], [84], [88], [89], [95], [105], [111], [112], [114], [117], [121], [128], [135], [143], [152], [153], [158], [161], and [167]. 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* theory. The UPQC controller based on this modified *pqr* theory can be found in [49], [63], [70], [82], [116], [131], and [147]. 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 [172], [173] including single-phase UPQC systems [37], [55], [79], [94], [107], [108], [130].

A simple controller scheme for UPQC, called as unit vector template generation (UVTG), is given in [46]. The method uses a phase-locked loop (PLL) to generate unit vector template(s) for single-/three-phase system. The experimental evaluation of UVTG-based single-phase system is given in [155]. On the other hand, Khoor and Machmoum [54] have given an analogical method for current and voltage perturbation detection. This method does not need a frequency synchronizer, such as PLL. Ghosh *et al.* [41] have used a pole shift control technique for UPQC. It is a discrete-time control technique in which the closed-loop poles are chosen by radially shifting the open-loop poles toward the origin. One cycle control (OCC) of switching converters concept based controller is developed for the UPQC in [51] and [76]. The OCC controller generally uses an integrator with reset feature to force the controlled variables to meet the control goal in each switching cycle. The OCC has the advantages of fast response and high precision [51]. Authors in [94] 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 [94]. 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 Zhang *et al.* [125]. The MPC can handle multivariable control problem and has relatively simple online computations. Li *et al.* [62] have suggested a $H\infty$-based model matching control to track the inverter output waveforms for effective and robust control of UPQC. Furthermore, Kwan *et al.* [106] have given a model-based solution via $H\infty$ loop shaping for UPQC. The UPQC is modeled as a multi-input multioutput system to deal with the coupling effect between the series and shunt inverters. Additionally, Kalman filter can be integrated to extract the harmonics in supply voltage/load current [59], [106], [125]. Kamran and Habetler [12] have put forward a technique based on deadbeat control in which the UPQC inverter combination is treated as a single unit [12], [22]. The overall system can be modeled as a single multi-input, multioutput system. This results in improved control performance over the separately controlled converters and/or reduced interconverter energy storage. The system can have fast dynamic response and high steady-state accuracy. A nonlinear control law based on linearization via exact feedback theory is described for UPQC in [151] and [141]. A sliding mode controller with a constant frequency scheme is utilized to control the series inverter of UPQC in [162]. Particle swarm optimization technique has also been utilized to develop the controller for UPQC [99], [129], [165]. Furthermore, an ANN technique can also handle the multi-input multioutput control system effectively. Thus, the ANN technique can be utilized to develop the controller for the UPQC to compensate different voltage and/or current related problems [34], [50], [65], [68], [69], [136],]. A feedforward ANN scheme is reported by Banaei and Hosseini [68] to separate the harmonics contents in the nonlinear load. In [34] and [69], a Levenberg–Marquardt backpropagation ANN technique is used for UPQC. 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 multiresolution analysis, the wavelet transform can represent a time-varying signal in terms of frequency component. Elnady *et al.* [24], Forghani *et al.* [77], and Karthikeyan *et al.* [133] have applied the wavelet transformation technique to control UPQC.

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 [25], [31]–[33], [43], [72]. A special attention on compensating the problem of voltage flicker [14], [31], [45], [46], [144], [155] and/or voltage unbalance [81], [117], [144], [166] can be noticed. The UPQC could be the most effective power quality conditioner to solve the flicker problems caused by an arc furnace load [14], [31],] [45], [47]. The one approach could be based on *dq* theory [45] or by using symmetrical component theory [31]. The latter is more effective because the arc furnace produces flicker in the positive-sequence voltage and unbalance in the three phase voltages. Furthermore, for a fast and precise detection of positive-sequence voltage under unbalanced source voltages, a PLL supported by synchronous double frame method is suggested by Rodriguez *et al*. [29]. Moreover, the UPQC could be useful to enhance the fault ride through the wind farm connected to a weak ride and/or to enhance the overall performance of a wind farm [71], [85], [102], [153], or even the transient performance of induction motors type of load [100].

The kVA rating issues [21], [102], [113], [148], protection issues [26], [120], reliability analysis [28], etc., are also studied for optimized design of UPQC. Faranda and Valade [35] have given a procedure to calculate the UPQC operating losses. In [127], authors have used fault current limiter to reduce the UPQC rating particularly by limiting the excessive current during the event of a fault. Finally, it is found that throughout the development phases of UPQC, researchers have given equal importance to evaluate the control algorithm and overall UPQC system performance by experimental investigation [11], [14], [22], [23], [26], [33], [40], [42], [51], [52], [56], [57], [60], [63], [75], [80], [81], [89], [94], [97], [107], [109], [114], [116]–[118], [120], [129], [143]–[145], [147], [150], [155]–[157], [159], [161], [163], [164], [167], [168]. A 250-kVA UPQC system is developed at the Centre for the Development of Advanced Computing (C-DAC), Thiruvananthapuram, India [75]. Additional significant UPQC prototypes and testing at higher power ratings: 20 [14], [42], [63], 15 [145], [164], 12 [117], 10 kVA [89], [114], and so on.

VI. TECHNICAL AND ECONOMICAL CONSIDERATION

Technical literature on the APFs can be found since early 1970s [9]. However, the use of UPQC to enhance electric power system quality is reported since mid 1990s [11]. Among the various power quality enhancement devices, STATCOM and few others are commercially available [9], [174]–[178]. At the time of writing this paper, no commercial UPQC product was available in the market. A 250-kVA prototype developed at C-DAC, Thiruvananthapuram, India [75], is the most viable reported prototype. The technology to develop commercial UPQC system is available today; however, the overall cost and complexity of such a system still imposes some limitations.

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) [179]–[181]. In terms of power quality, the excessive feeder voltage rise due to reverse power flow from DG system and power system stability is of significant importance. Moreover, most of the DG systems utilize power electronic converters as interfacing device to deliver the generated power to the grid. The switching operation of these systems is contributing as increased harmonic levels both in the grid voltages and currents [182]–[184]. The aforementioned 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. Among these configurations, UPQC-DG could be the most interesting topology for a renewable-energy-based power system. This configuration can offer multifunctional options, namely, active power delivery from DG system to grid (normal DG operation), voltage- and current-related power quality compensation (UPQC operation), and uninterruptible power supply operation. Commercial products have started to appear in the market to increase the renewable energy system connectivity by compensating some of these problems [185], [186]. As the penetration levels of DG system on the existing power system continue to increase, the utilization of active compensating technologies (such as, flexible ac transmission system devices and APFs) is expected to increase gradually.

VII. CONCLUSION

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. An effort is made to categorize interesting features of the UPQC by organizing an acronymic list. These acronyms could be used to clearly identify particular application, utilization, configuration, and/or characteristic of the UPQC system under study. It is desirable that this review on UPQC will serve as a useful reference guide to the researchers working in the area of power quality enhancement utilizing APFs.

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