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A Review on Development in Unified Power Quality Conditioner

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Abstract: - Power quality issues such as voltage sags, swells, harmonics, and interruptions are significant concerns in modern electrical networks, affecting the reliability and efficiency of power supply to consumers. These issues can lead to equipment malfunction, increased downtime, and financial losses for industries. To mitigate these challenges, Unified Power Quality Conditioner (UPQC) technology has emerged as a crucial solution. UPQC is designed to address multiple power quality problems simultaneously. By integrating series and shunt active power filters, UPQC can regulate voltage, mitigate harmonics, and balance reactive power in real-time. This comprehensive approach not only improves the quality of power delivered to end-users but also enhances the stability and efficiency of the entire electrical grid. Recent advancements in UPQC technology have focused on enhancing its power structure, control systems, and application-specific adaptations. Innovations include modular designs to accommodate distributed generation (DG) systems, microgrids (MC), and other renewable energy sources. Advanced control algorithms ensure precise management of power flow, responding swiftly to dynamic changes in the grid conditions. These developments make UPQC systems versatile and adaptable, capable of meeting the specific needs of different industrial and residential applications. In this paper, a comprehensive literature review of Unified Power Quality Conditioner (UPQC) is presented, focusing on several key aspects: classification, control techniques, reduced switch configurations, and controllers utilized for UPQC operation.

Keywords: Unified Power Quality Conditioner (UPQC), Power Quality Issues, Power Quality.

I. INTRODUCTION

Nowadays to reduce the carbon footprint the uses of efficient loads and the concept of smart city picked up the pace. Moreover, the use of renewable sources and electric vehicle also increased numerously to reduce the consumption of fossil fuels. As per the Bloomberg New Energy Finance (BNEF) report, currently the contribution of electric vehicle compares to total vehicle is 3%, it can be increased to 10% by 2025, with that number rising to 28% in 2025 and 58% in 2040. The prediction of the use of different electric vehicle is also shown in fig.1. Consequently, it will increase the need of more charging stations to accommodate the requirement of charging. Additionally, the concept of smart city relies on the need of smart grid and smart homes. It substantially increased the use of non-linear load to make system more efficient and reliable.

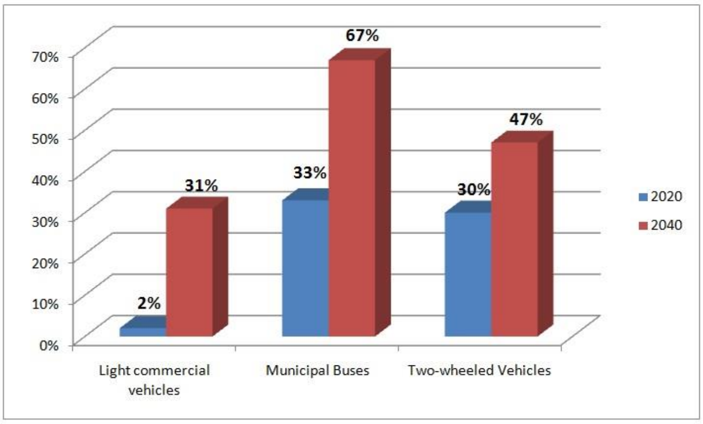

Fig.1. Prediction of percentage Electric vehicles on road compare to total vehicles

However, the use of non-linear load creates the power quality (PQ) problems, which affects the sensitive non-linear load connected to the grid. Additionally, the frequency of faults also increases due to complex grid structure, which creates interruption to sensitive loads. To mitigate such power quality issues, the different

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custom power devices are used. The current and voltage related power quality issues can be mitigate using shunt and series active filters respectively. However, installing individual custom power devices may not be cost effective to compensate all the problems. In 1998, Fujita and Akagi introduced Unified Power Quality Conditioner (UPQC) for simultaneous compensation of voltage and current related disturbances and reactive power compensation [3]. UPQC has series and shunt compensation capabilities to compensate voltage and current harmonics, voltage disturbances and reactive power. The recent development in UPQC adds the benefit to compensate/supply the active power with all the power quality related compensation [39] and even during voltage interruptions. UPQC-DG and open-UPQC are capable to supply the active power to the load during voltage interruptions and all power quality related compensations [37, 46].

II. Basic structure and Principle of operation

The basic structure of UPQC is shown in fig.2. Series APF and shunt APF are connected back-to-back with common self-supporting DC-link to solve all the voltage and current related power quality problems [3, 6]. In recent times, UPQC is widely used because it is cost effective and compact in size. Additionally, simultaneous control of voltage and current is possible. It can also be used in distributed generation system in which output of DG system connected to DC bus of the UPQC [6-8].

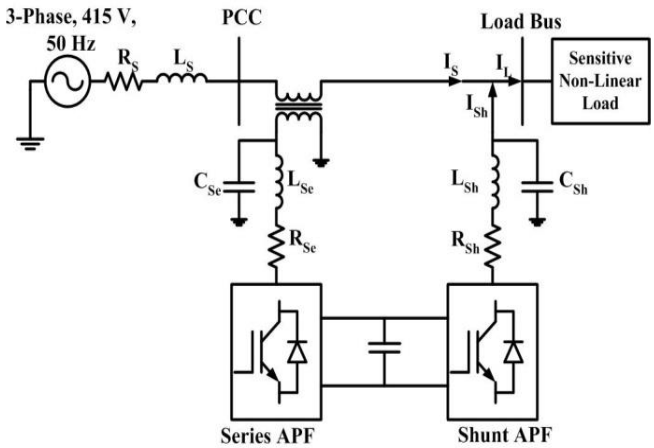

Fig.2. Structure of Unified Power Quality Conditioner [3]

In addition to compensate voltage and current power quality problems, DG power can also be supplied to load through UPQC [6]. DG based UPQC can be used in islanding mode or interconnected mode depending on the voltage interruption event. This makes UPQC more superior than other FACTS devices to eliminate all power quality related problems.

In UPQC, the series APF and shunt APF are connected back-to-back with self-supporting common DC link. The series APF is connected in series of AC lines though series injection transformer. Where, shunt APF is connected across the PCC or sensitive nonlinear load. The main objective of series APF is to compensate the voltage flicker, voltage imbalance, voltage harmonics and regulate the voltage at point of common coupling. The shunt APF is connected to remove the current harmonics, reactive power compensation and balance the load current. Moreover, it also regulates the DC link voltage between both the active filters. As PWM techniques are used to control both the APFs, they require LC ripple filters to eliminate the switching ripples. The purpose of UPQC is to compensate the voltage related issues, such as, voltage sags/swells, flickers, unbalance, voltage harmonics and current related issues such as current harmonics, neutral current, reactive power compensation to maintain voltage regulation at PCC along with sinusoidal source current with unity power factor.

Recent advancements in Unified Power Quality Conditioner (UPQC) technology have introduced several innovative variations. These include UPQCs with reduced switches, which aim to lower costs and complexity while maintaining effectiveness in improving power quality. Additionally, developments like the Open-UPQC suggest more accessible and modular designs for easier integration into power systems. Another notable trend is the integration of distributed generation sources with UPQCs, allowing them to not only enhance power quality but also supply active power, thereby improving overall efficiency and grid stability. These advancements reflect ongoing efforts to enhance the performance and versatility of UPQCs in modern electrical distribution systems.

III. Classification of UPQC

UPQC can be classified based on supply system, type of converter, number of switches, system configuration and voltage sag compensation. The classification of the UPQC with mentioned criterion are shown in fig. 3.

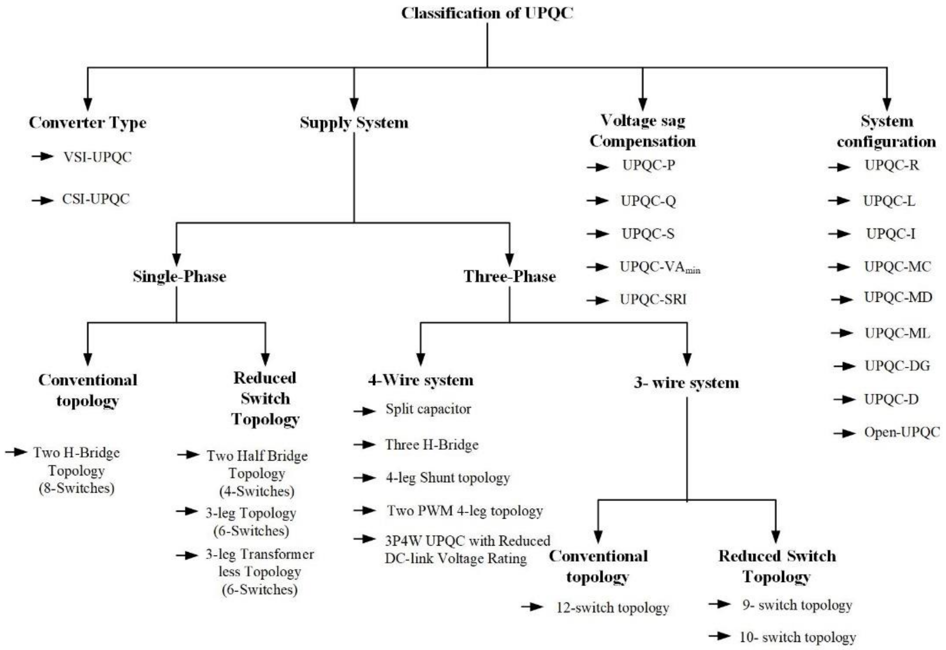

Fig. 3. Classification of UPQC

A. Classification based on type of converter

In UPQC two converters are connected back-to-back with common DC-link reactor. The converters are either Voltage source inverter (VSI) or Current source inverter (CSI). In VSI based topology, shunt and series converter shares common DC link capacitor [3]. Where in CSI based topology, the converters share common energy storage inductor [7].

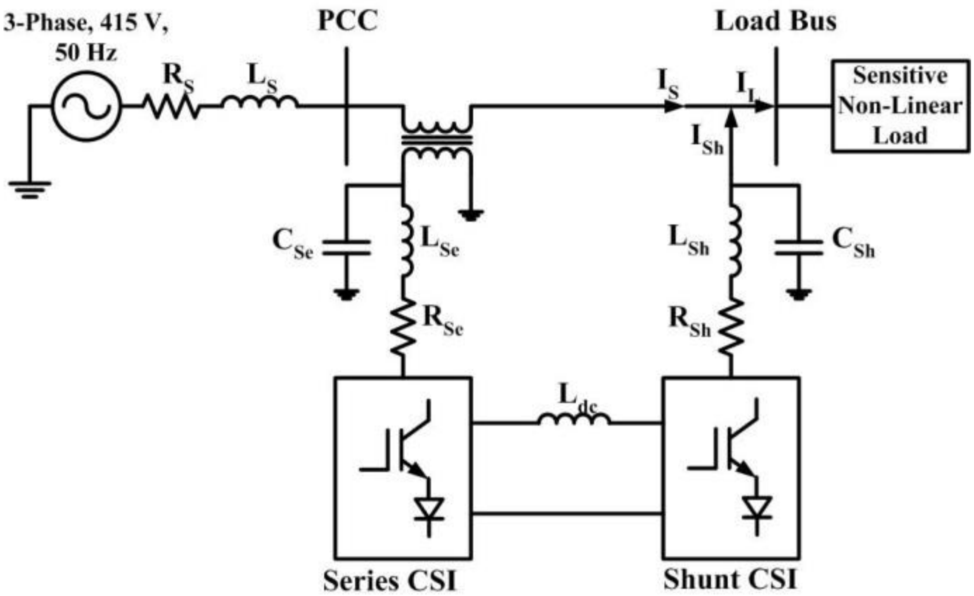

Fig.4. CSI based UPQC configuration [7]

The CSI based topology is realized by connecting voltage blocking diode in series with IGBT, as shown in fig.4. The CSI based UPQC is not preferred as it has higher power losses, higher cost, bulky and requires additional voltage blocking diode compares to VSI topology. The VSI based topology is shown in fig.2; this topology includes two converters are connected back-to-back through self-supporting common DC link capacitor. The DC link voltage is regulated by shunt converter. It is more popular compare to CSI as it is cheaper, light in weight, no need of voltage blocking diodes, Flexible control and adaptability for multilevel operation.

B. Classification based on supply system:

The different supply system is available according to the consumers need. The supply system is mainly classified into two parts, single phase (2-wire) and three phase (3-wire and 4-wire). Similarly, UPQC can also be classified based on the supply system. The current/voltage harmonics and reactive power compensation is common problem in all the supply system. Where, unbalanced voltage compensation is required in three phase (3-wire and 4-wire) system. In case of 3-phase, 4-wire system, the additional neutral current compensation is required. The reduced switch topologies are also proposed by some researchers, which are cost effective, but it may also affect the compensation performance.

1) Single phase (2-wire) UPQC:

The conventional topology of 1P2W system is shown in fig.5, where two H-bridge inverters are connected in series and shunt to 1-phase 2-wire supply system [7,8]. This configuration is popular due to its flexible control. The CSI based topology can also be realized in 1P2W system.

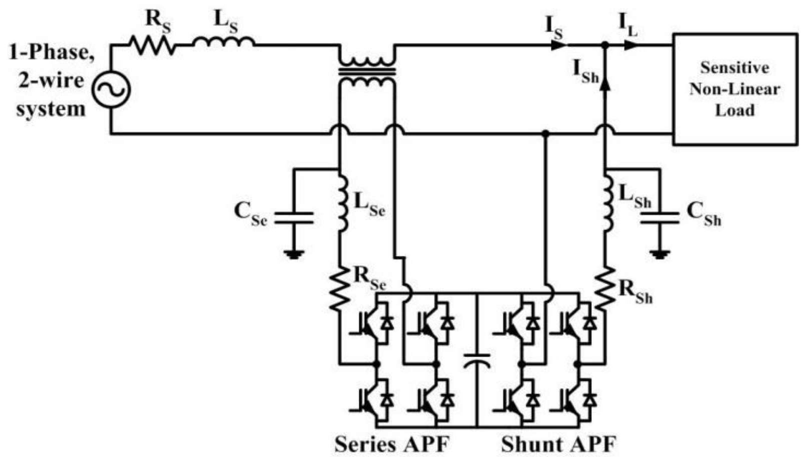

Fig. 5. Two H-bridge topology (8-Switches) [62]

The two half-bridge UPQC topology is also possible with reduced number of switches (4-switches) shown in fig.6. In two half-bridge topology, one each leg is used for series and shunt inverters and requires split capacitor DC link [9].

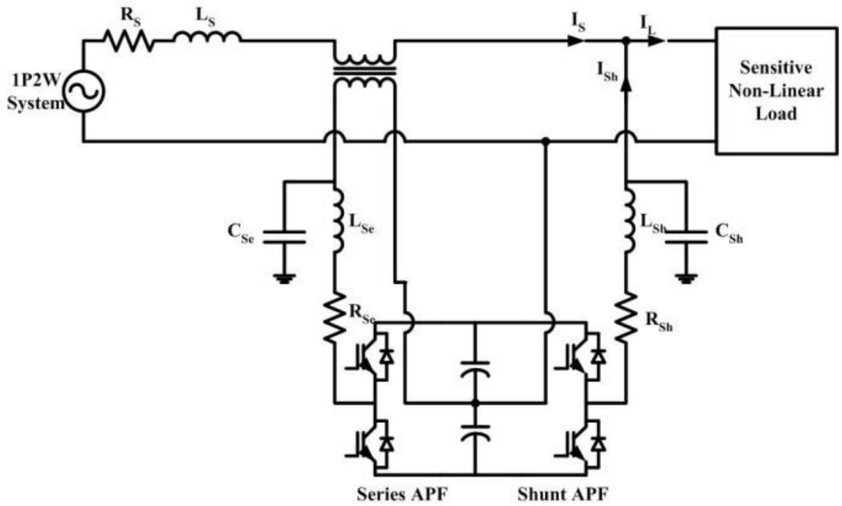

Fig. 6. Two Half-bridge topology (4-Switches) [9]

The 6-switch topology shown in fig.7 has total 3-leg; leg-1 is used for series inverter, leg-3 is used for shunt inverter and leg-2 is commonly used for series and shunt inverter [10].

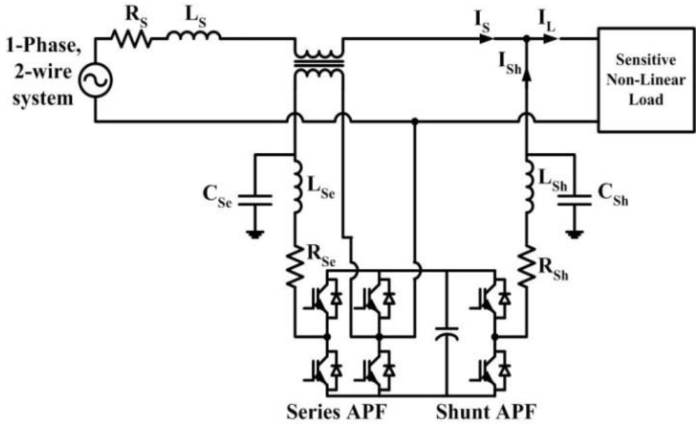

Fig.7. 3-leg topology (6-Switches) [10]

The Transformer less UPQC shown in fig.8 is also preferable choice for low-power low-cost applications as it does not require transformer and requires only 6-switches [24]. However, it requires bulky dc-link capacitor to provide sufficient voltage sag/swell ride through capacity. The modified TL-UPQC with distinct features is shown in fig.9. It has one capacitor and inductor connected in DC-link [25]. The inductor is used to eliminate the high frequency switching harmonics and capacitor is used to mitigate the power difference between input and output side. As a result, a stable dc-link current is obtained without using the bulky passive elements. Therefore, this topology has high power density. Additionally, it does not have circulating current issue.

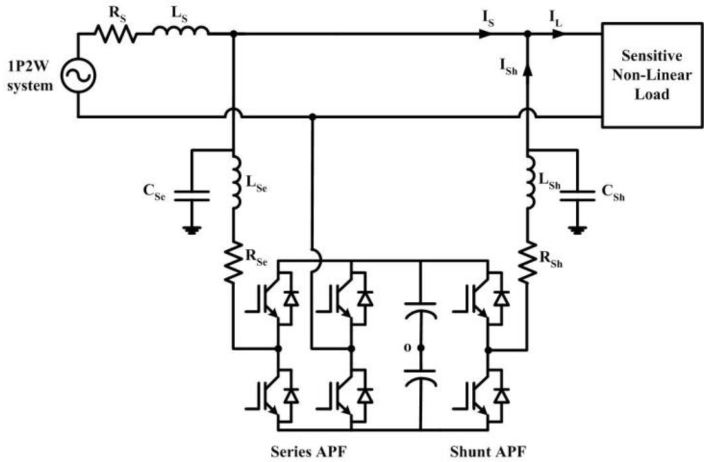

Fig.8. Transformer-less UPQC Configuration [24]

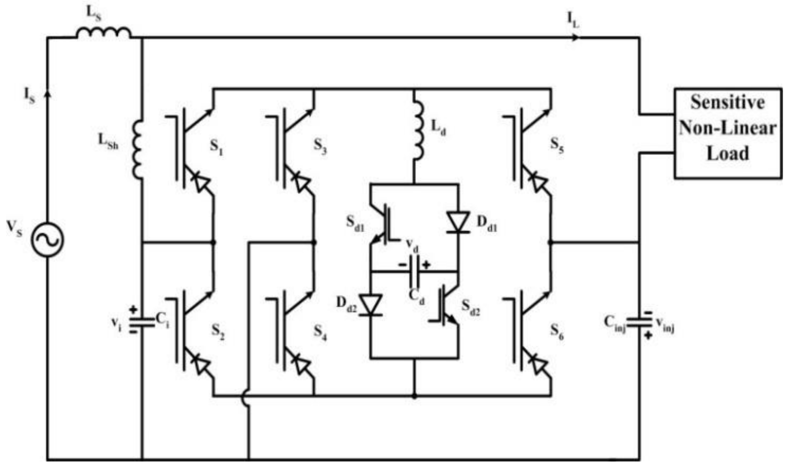

Fig. 9. Modified Transformer-less UPQC Configuration [25]

2) Three phase (3-wire) UPQC:

Some of electrical load, such as Electric drives, cyclo-converters, arc furnaces, arc welding machine are operated on 3P3W system. The commonly used 3-phase, 3-wire VSI based UPQC is shown in fig.10 [11-16]. The 12-switch topology has two 3-phase VSI connected back-to-back with common DC-link. It has excellent capability to eliminate the grid disturbances.

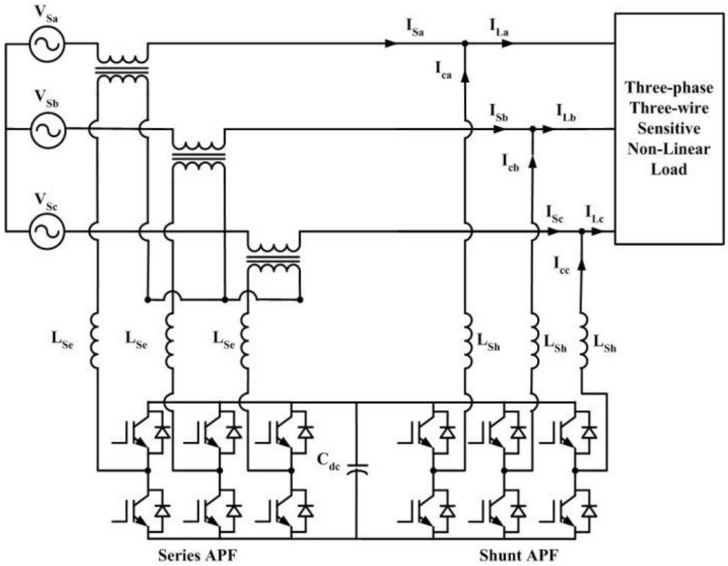

Fig.10 Three-phase, Three-wire UPQC topology [13]

The 9-Switch topology shown in fig.11, is proposed by L. Zhang, P. C. Loh, and F. Gao has capacity to eliminate the grid disturbances with reduced number of switches [17]. However, it required higher current rating of the switches and all the switches are in operation irrespective of the compensation mode. The 10-switch topology is also shown in fig.12; it has all the merits of conventional 12-switch topology and requires low VA rating of switches [18].

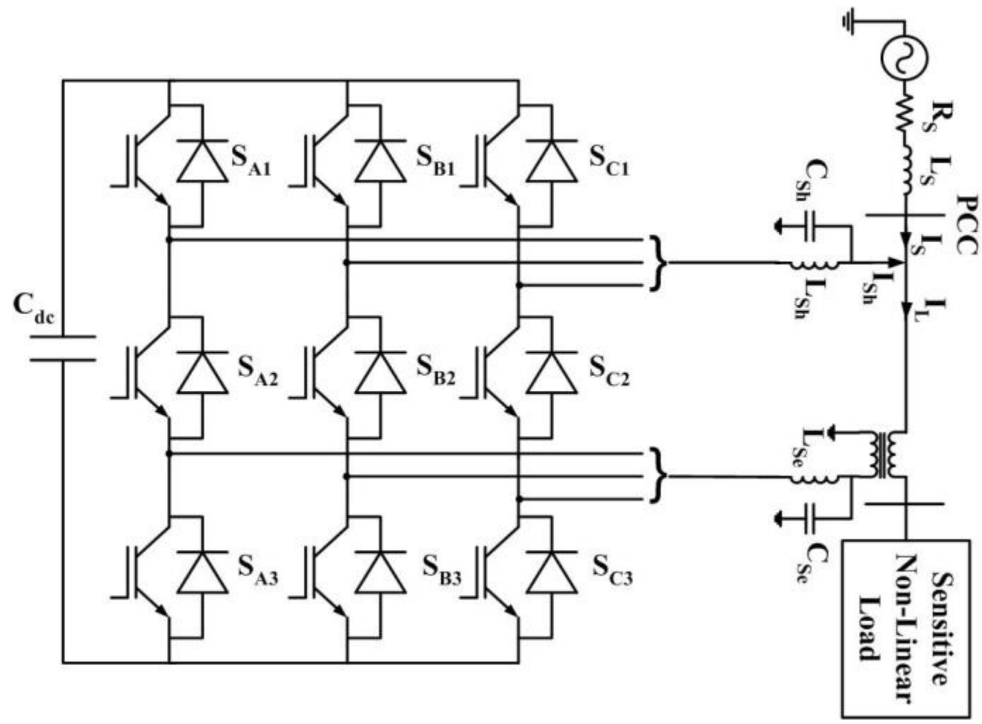

Fig.11. 3P3W, 9-Switch topology [17]

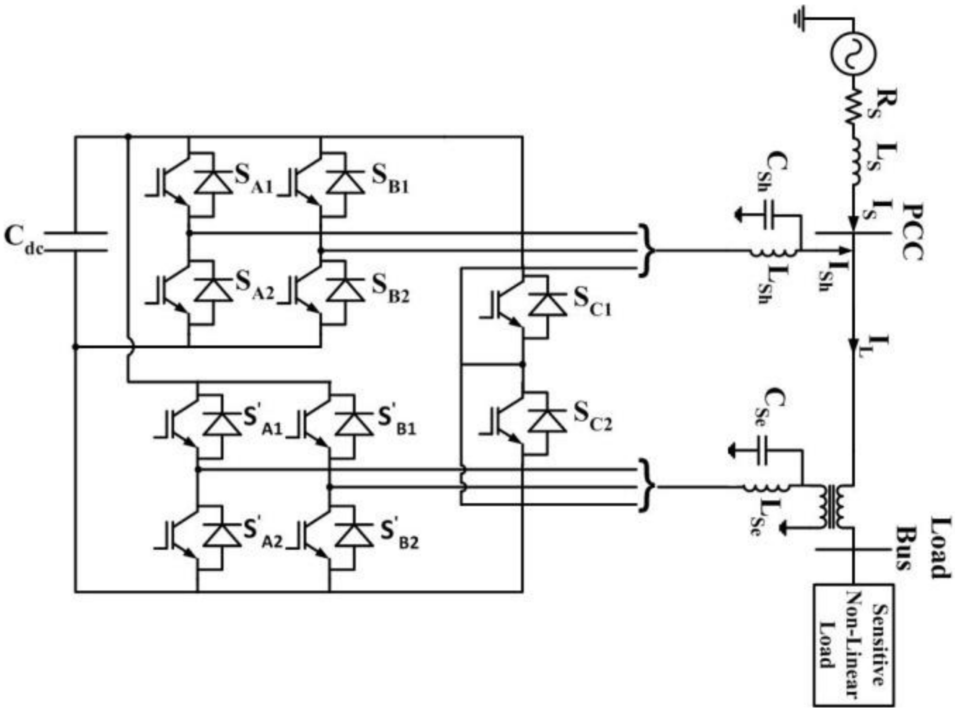

Fig.12. 3P3W, 10-switch topology [18]

3) Three phase (4-wire) UPQC:

A large number of domestic load as well as the 3-phase load may be supplied with 3-phase, 4-wire system. This load may create power quality problems such as, large neutral current, voltage/current harmonics, reactive power burden and unbalance in the system. To compensate these problems various configuration has been reported. The 4-leg shunt inverter topology shown in fig.13, it has 4-leg in shunt inverter, one additional leg is provided to control the neutral current of 3P4W system [21].

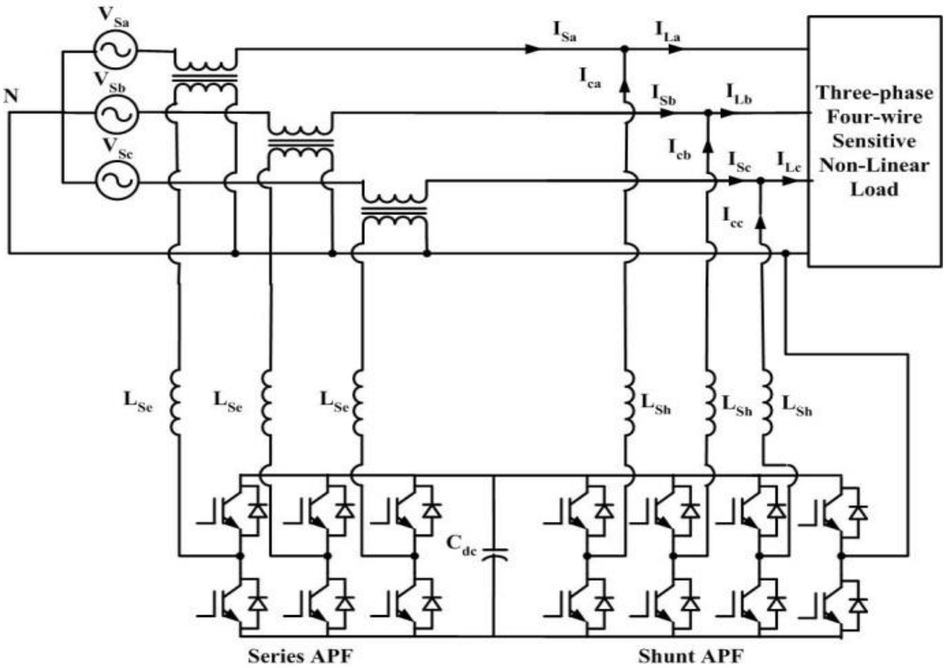

Fig.13. 3P4W, 4-leg shunt inverter topology [21]

The split capacitor DC-link topology is shown in fig.14, in this topology neutral wire is connected to Mid-point of the DC-link [22-23]. Both the capacitor voltage should be maintained to avoid the circulating current. However, it requires higher DC voltage. The modified topology with reduced DC link voltage is shown in fig. 15. It gives same performance as 4-leg shunt topology and split-capacitor topology with reduced DC-link voltage [27]. Fig.16 shows the Three H-bridge shunt inverter topology. It requires total 18-switches and requires additional star connected transformer in shunt inverter. This makes system complex, costlier and bulky compare to other configurations [23].

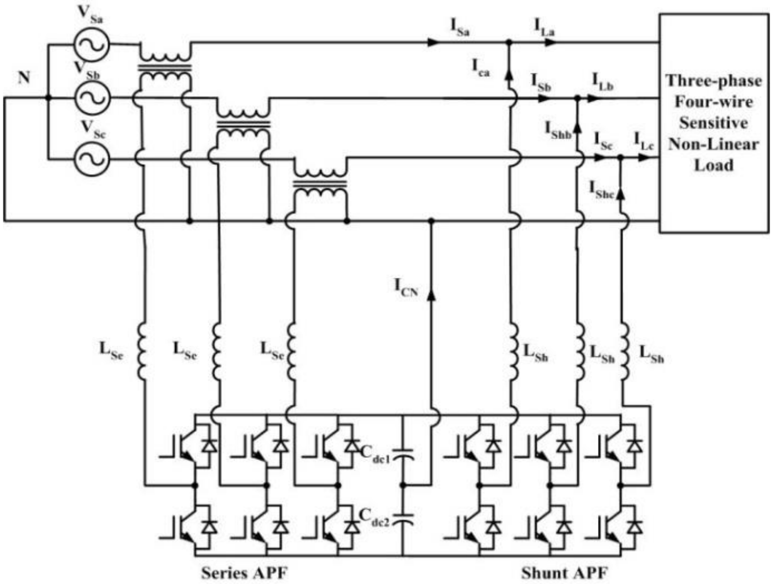

Fig.14. 3P4W Split capacitor topology [22]

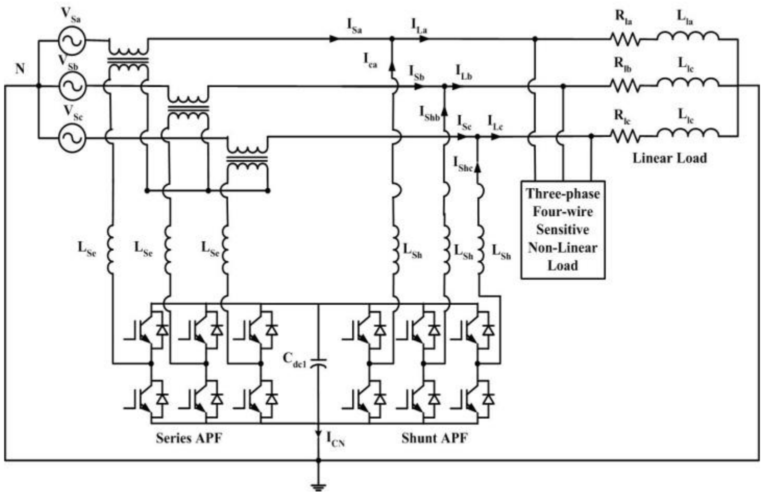

Fig. 15. 3P4W Modified 6-leg UPQC without Split capacitor [27]

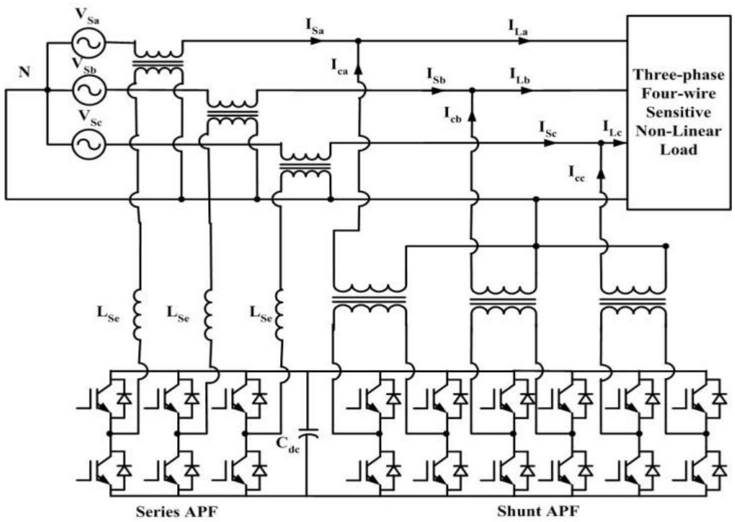

Fig.16. 3P4W, 3 H-Bridge shunt inverter topology [23]

The 4-Leg PWM converter-based topology shown in fig.17. though it uses greater number of switches, it offers certain advantage compare to other topologies such as, it requires lower DC-link voltage to operate, it does not require an additional loop to compensate DC-link voltage unbalances. Additionally, the fourth leg allows better for neutral current compensation and it also operate as UPS application during grid fault condition by connecting battery back-up at DC-link [26].

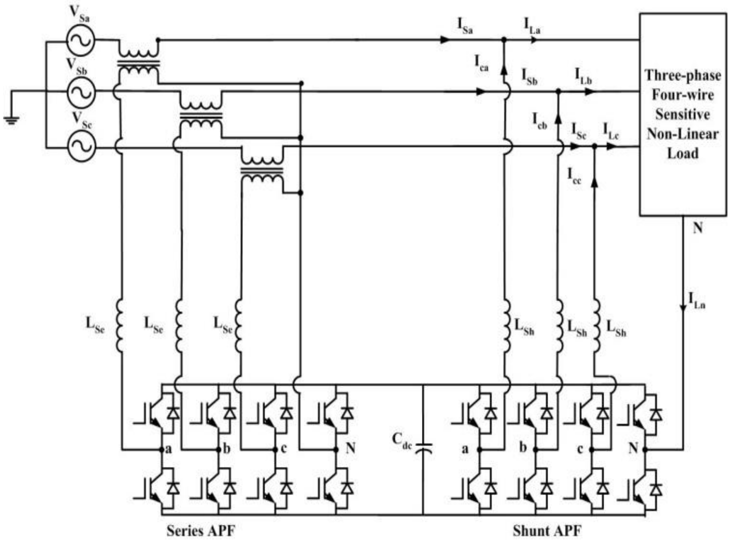

Fig.17. 3P4W topology with two PWM 4-leg converters [26]

C. Classification based on system configuration:

The different configurations of UPQC are available based on the application and physical structure.

1) Right shunt (UPQC-R) and Left shunt UPQC (UPQC-L):

In UPQC, the two VSIs are connected back-to-back with common DC link capacitor. The UPQC can be classified based on the location of Shunt connected inverter with respect to the series inverter. If the shunt connected inverter is left to the series connected inverter than the configuration is known as UPQC-L [28] and if shunt connected inverter is either side of series inverter than it is called UPQC-R [10-11].

2) Interline UPQC (UPQC-I):

In Interline UPQC shown in fig. 18, the UPQC is connected between two different feeders. The UPQC-I compensate voltage related distortion from both the feeders. Additionally, it will also control the flow of active power between two feeders. The limitation of interline UPQC is current compensation is only achieved on feeder on which shunt inverter is connected [29-30]. The UPQC-I with four VSC and multilevel configuration is also proposed to eliminate the limitation of UPQC-I [33]. In this topology simultaneous compensation of voltage and current of both the feeders can be achieved.

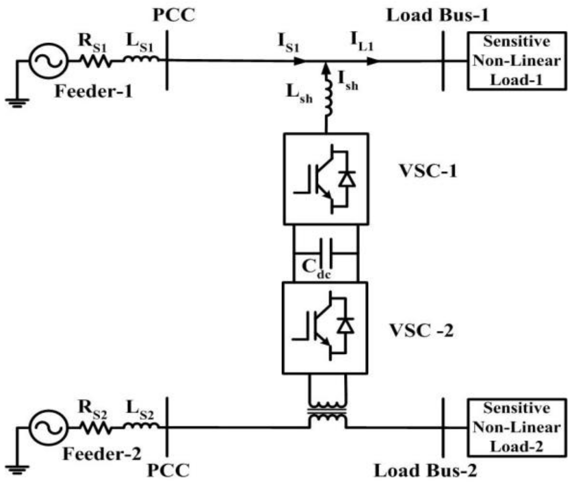

Fig.18. UPQC-I Configuration [29]

3) Modular UPQC (UPQC-MD):

In UPQC-MD shown in fig.19, the several H-bridges are connected in cascaded based on the load voltage. The series part of UPQC-MD is directly connected between PCC and non-linear load without injection transformer. Where, shunt part of this configuration is connected through multi-winding transformer. It is useful for higher voltage application. In this topology the numbers of modules are selected in such way that it will be fully utilized [30-31].

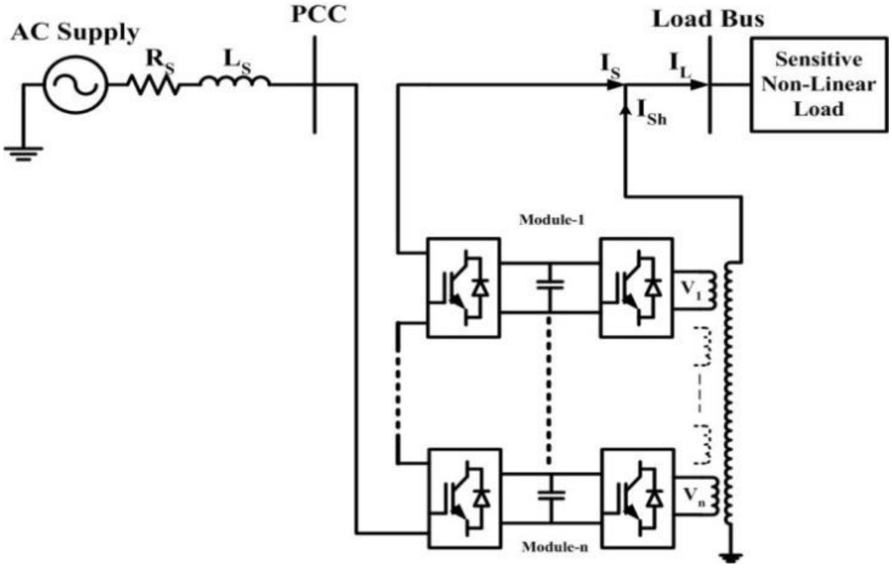

Fig.19. UPQC-MD Configuration [30]

4) Multi-converter UPQC (UPQC-MC):

In UPQC-MC, one shunt and two or more series inverters are present. The UPQC-MC is shown in fig.20. The series APF 1&2 are compensating voltage related disturbances of their respective feeders. Whereas, Shunt APF compensate the current related problems of feeder-1 and regulates the DC-link voltage. Additionally, it also supplies to feeder-1 through Shunt inverter during supply interruption on feeder-1 [32].

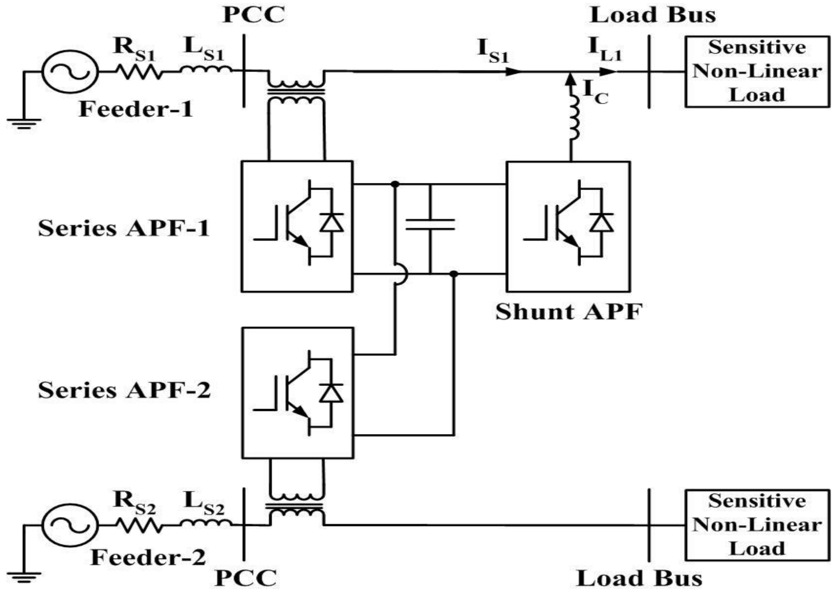

Fig.20. UPQC-MC Configuration [32]

5) Multilevel UPQC (UPQC-ML):

To achieve higher power level UPQC-ML is used, where different multilevel inverter topologies are used to get higher levels. A three level NPC based UPQC-ML is proposed by Rubilar is shown in fig.21. The UPQC-ML play vital role where different non-linear loads are operated on higher voltage levels [34].

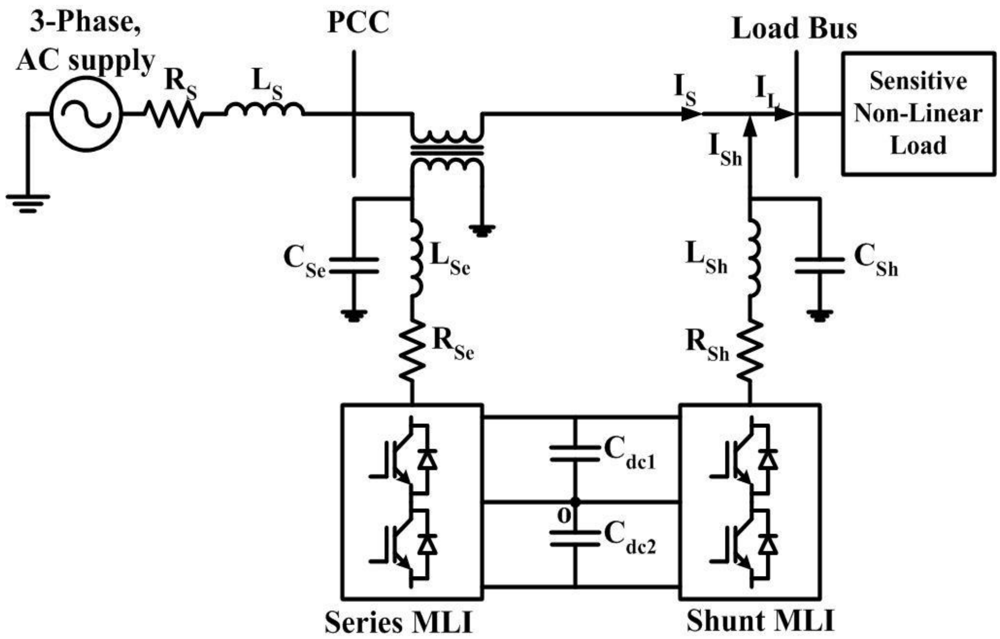

Fig.21. UPQC-ML Configuration [34]

6) Distributed UPQC (UPQC-D):

The Novel structure for 3P3W to 3P4W distribution system by utilizing UPQC was proposed by Khadikikar V, shown in fig.22. The common terminal of the transformers used in series part is considered as the neutral wire for 3P4W system. To compensate the neutral current, fourth leg is added in shunt inverter [19].

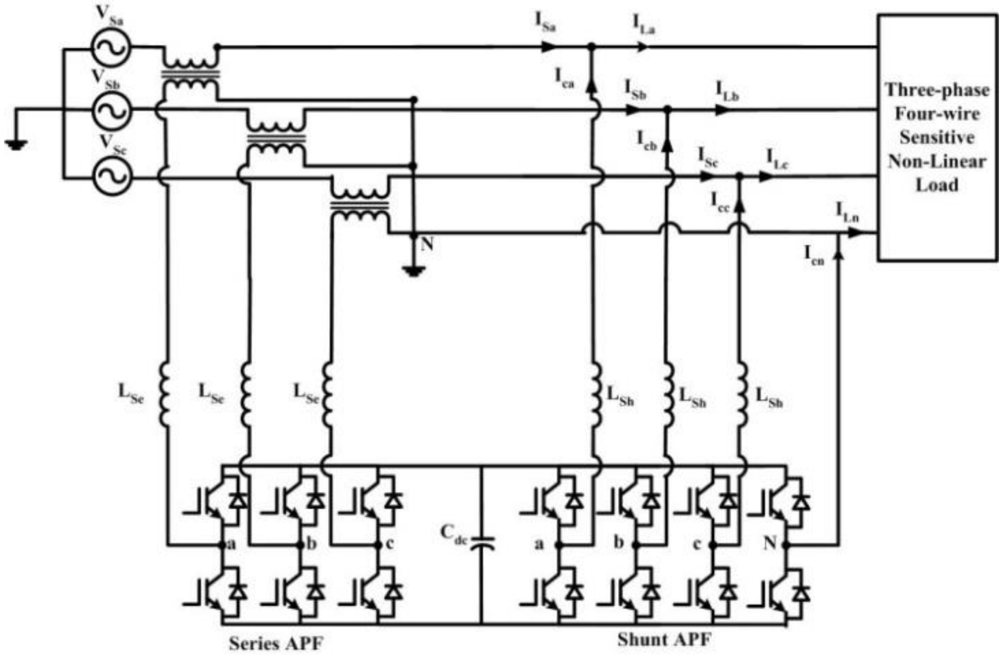

Fig.22. UPQC-D Configuration [19]

7) Distributed Generators Integrated with UPQC (UPQC-DG):

In UPQC-DG shown in fig.23, the output of the distributed generation system is connected to DC link of the UPQC. The UPQC is used to compensate power quality problems of the system, additionally it also regulates the power generated by DG system and supply it to the loads connected at Point of common coupling (PCC). The battery is also connected to DC-link to store the excess power generated by DG system. The PV and Fuel cell (FC) based UPQC-DG is reported by several authors [35-42]. Recently the PV-UPQC and PV-B-UPQC has also been developed which is capable to supply the active power during off-grid and on grid condition based on the availability of the solar power [39, 41].

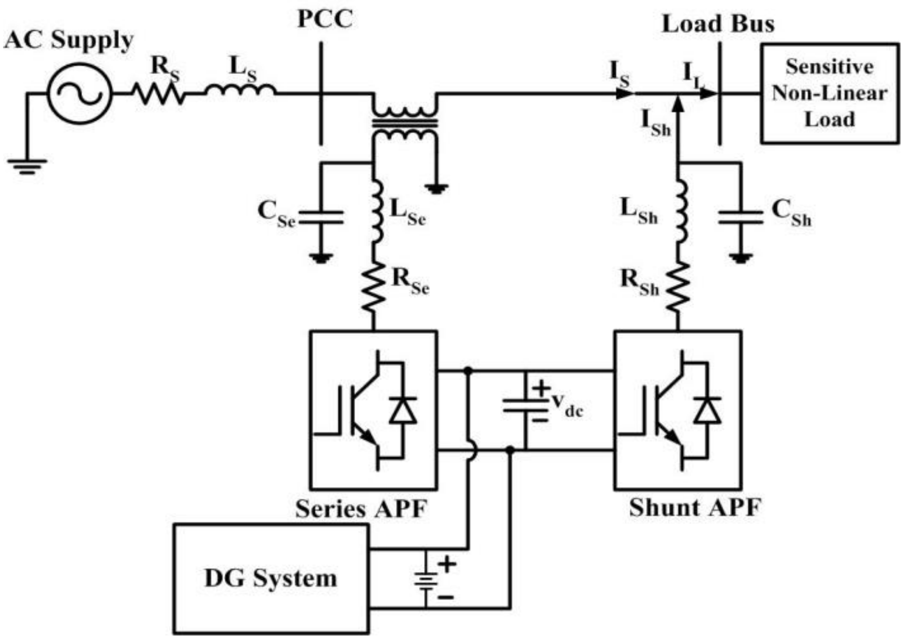

Fig.23. UPQC-DG Configuration [38]

8) Open-UPQC:

For field application, OPEN-UPQC has more flexible modularity than conventional UPQC. OPEN-UPQC consists of two controlled PWM shunt and series inverters with separate DC-link, shown in fig.24 [43, 46]. Series inverter compensates the voltage related disturbances caused by fault on transmission system and shunt inverter compensates the current disturbances caused by non-linear load.

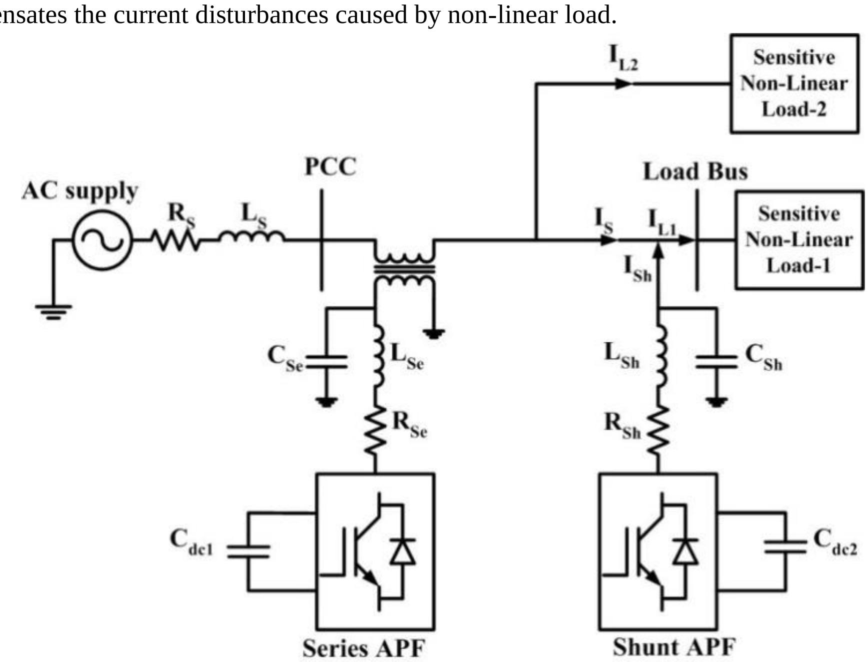

Fig.24. Open-UPQC Configuration

The series APF compensates voltage disturbances and protects sensitive loads 1&2 against voltage sag/swell. Where, Shunt APF operates as a controlled current source and compensate current related disturbances in Load-1. Open-UPQC can reduce the most common disturbance for all the consumers that are connected to supply through series APF. It also offers additional improved power quality to the consumers using shunt APF [43-46].

The detailed comparison of various UPQC topologies is shown in the above below, encompassing critical aspects including total switch count, effectiveness in addressing different power quality issues, and the capability to supply active power under both off-grid and on-grid conditions.

Table.1 Comparison of different topologies

Type of supply system	**UPQC Topology**	**Number of Switches**	**Harmonic current compensation**	**Reactive power compensation**	**Sag/Swell mitigation**	**Active Power supply**
1-Phase, Two-wire	Two H-bridge	8	Y	Y	Y	N
	Two half bridge	4	Y	Y	Y	N
	3-leg topology	6	Y	Y	Y	N
	3-leg transformer less topology	6	Y	Y	Y	N
	Modified Transformer less topology	8-switches, 2-diodes	Y	Y	Y	N
3-Phase, Three-wire	12-switch topology	12	Y	Y	Y	N
	10-switch topology	10	Y	Y	Y	N
	9-switch topology	9	Y	Y	Y	N
	PV-UPQC	13, 1 diode	Y	Y	Y	Y
	PV-B-UPQC	15, 1 diode	Y	Y	Y	Y
3-Phase, Four-wire	Split capacitor topology	12	Y	Y	Y	N
	Modified 6-leg UPQC without split capacitor topology	12	Y	Y	Y	N
	Three H-bridge shunt inverter topology	18	Y	Y	Y	N
	4-leg shunt inverter topology	14	Y	Y	Y	N
	Two PWM 4-leg converter topology	16	Y	Y	Y	N
	UPQC-FC	14	Y	Y	Y	Y

D. Classification based on voltage sag compensation approach

In this section the UPQC is classified based on the voltage sag compensation approach. There are different methods available to compensate the voltage sag.

1) Active power control (UPQC-P):

In this topology, the reduced voltage of desired voltage is injected to line through series injection transformer. V_{S1} and I_{S1} are the supply voltage and supply current without the compensation. The injected voltage V_{inj} is in phase with supply current/supply voltage and needs active power as shown in fig. 25(a). The shunt inverter of UPQC draws the necessary active power from the supply mains that required by the series inverter plus the losses associated with UPQC. Due to this, the source current magnitude is increased during voltage sag compensation in UPQC-P, which is I_{S2} in the above phasor diagram. similarly, the voltage swell can also be compensate using UPQC-P shown in fig. 25(b).

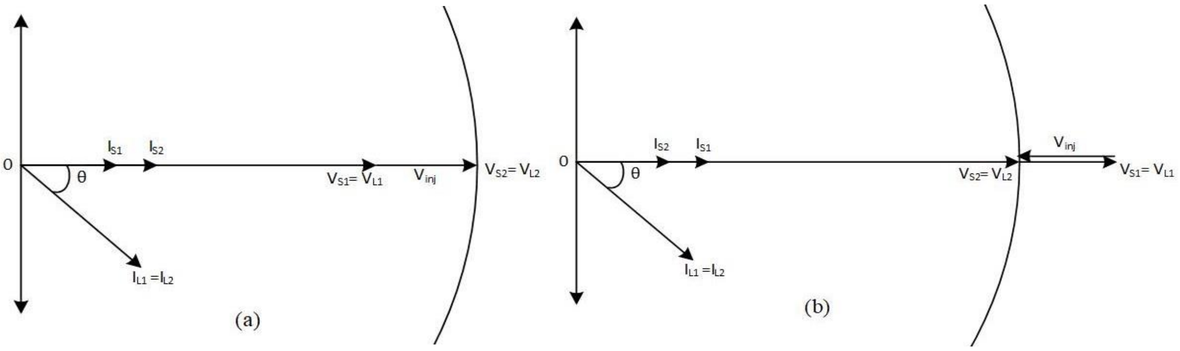

Fig. 25. Phasor diagram of a UPQC-P for voltage sag and swell compensation.

2) Reactive power control (UPQC-Q):

In this topology, the reduced voltage of desired magnitude is injected to line through series injection transformer. The series inverter injects the voltage in quadrature with the supply current as shown in fig. 26(a). However, it requires high series voltage to compensate small voltage sag. To compensate the voltage sag, it only needs reactive power from the series inverter without injecting active power [47]. Since the series inverter of the UPQC only injects only reactive power, this type of UPQC is also known as UPQC-Q. When the supply voltage has no deficiency $V_S = V_{S1} = V_{L1}$ and the series injected voltage V_{inj} requirement is zero. This state is represented by adding suffix '1' to all the voltage and current quantities. To maintain the unity power factor the shunt inverter drawn the $-I_{C1}$ current, which is opposite to the load reactive current. As a result, load always draws in-phase current from the supply.

During voltage sag condition, series inverter injects V_{inj} in quadrature with supply voltage to maintain the load voltage constant. This state is represented by adding suffix '2' to all the voltage and current quantities. During this state the current drawn by the load is I_{L2} and shunt inverter injects current $-I_{C2}$ such that only active current component is drawn from the supply and source current I_{S2} is in-phase with the V_{S2}.

The voltage swell cannot be compensated using UPQC-Q as shown in fig. 26(b) as the voltage injected by the series inverter does not intersect with the rated voltage locus.

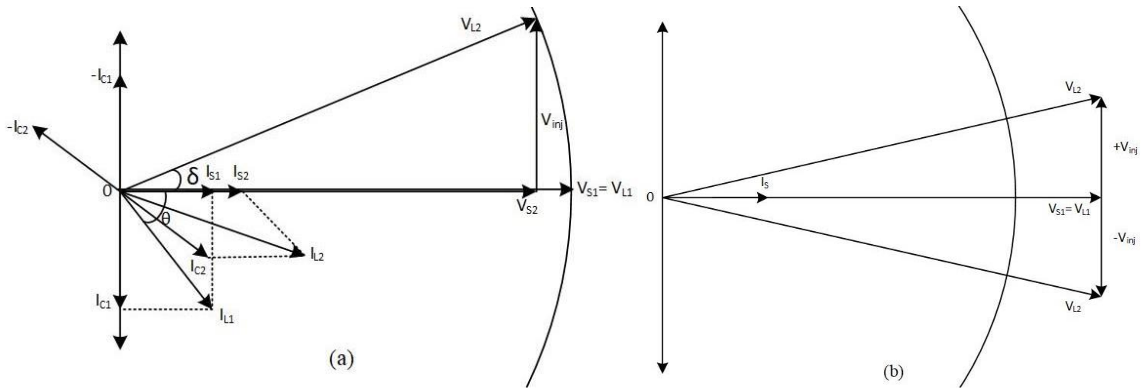

Fig.26. Phasor diagram of a UPQC-Q for voltage sag and swell compensation.

3) Simultaneous Active and Reactive power control (UPQC-S):

In this topology, the series inverter injects a voltage in series with the supply voltage at a calculated phase angle. It requires both active and reactive power to inject series voltage. In this topology the VA rating of series inverter is fully utilized [38, 48]. The series inverter injects a series voltage between AC mains and the load end at predetermined phase angle with PCC voltage and requires both active and reactive power through the series inverter with minimum VA rating of both series and shunt inverter as shown in fig. 27.

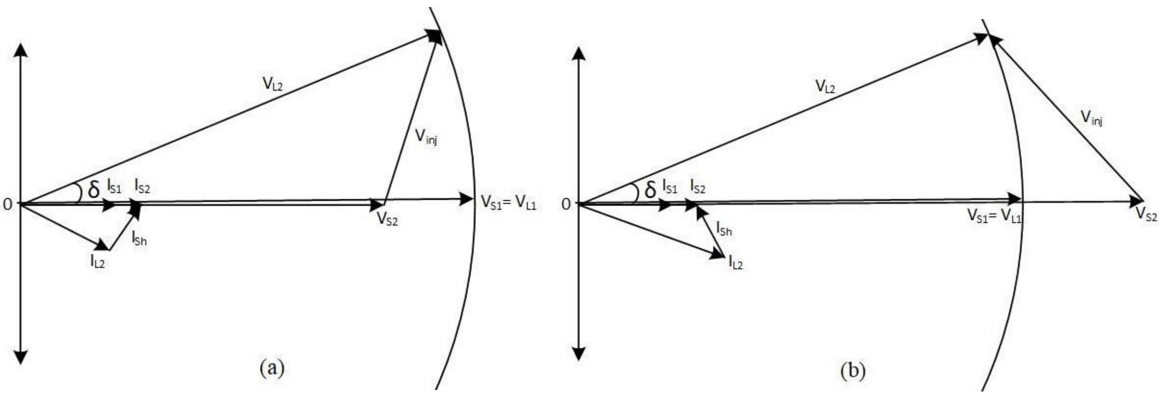

Fig. 27. Phasor diagram of a UPQC-S for voltage sag and swell compensation.

4) Minimum Volt-ampere (VA) loading (UPQC-VAmin):

It is similar to UPQC-S topology; however, in this topology the sharing of reactive power is done such that it reduces the rating of shunt and series inverter. It requires proper coordination between series and shunt inverter for supplying reactive power [49-52].

5) Simultaneous Reactive power Injection (UPQC-SRI):

This strategy for voltage sag compensation, which is based on the optimization of current-carrying utilization. This strategy uses both the series and shunt converters to inject reactive power for compensating voltage sag, and calculates the voltage injecting angle based on the minimization of current-carrying [63].

IV. Control Techniques of UPQC

Control techniques are crucial for UPQC performance, as they address various power quality issues. The control algorithm determines the references needed to achieve the desired voltage and current on the load side. Various control strategies have been proposed, falling into two categories: frequency domain and time domain techniques. Frequency domain techniques are less preferred due to their need for extensive iterations and slower response compared to time domain techniques. Time domain methods, on the other hand, derive the reference compensating voltage and current based on feedback signals, offering more efficient performance [53].

A. Frequency domain control techniques:

There are various control techniques available in the frequency domain. The Fourier analysis of distorted signals is used to separate harmonic components and generate compensating signals. In real-time implementation, this requires more time for calculation and results in a time delay in the compensating signal. The Fourier series theory, Fast Fourier Transform theory, Discrete Fourier Transform theory, Recursive Discrete Fourier Transform theory, Wavelet Transform theory, Kalman filter-based control algorithms, Stockwell transformation theory, and Hilbert-Huang transformation theory are used to generate compensating signals in frequency domain methods [53].

B. Time domain control techniques:

In time domain methods, the instantaneous compensating commands in terms of voltage and current are derived from distorted voltage or current signals. Various time domain analysis techniques are available, including Instantaneous Reactive Power Theory (PQ theory), Synchronous Reference Frame Theory (DQ theory), Power Balance Theory, Instantaneous Symmetrical Component Theory, Unit Template Vector Generation, Neural Network Algorithms, PI Controller-Based Algorithms, Power Angle Control (PAC), and Enhanced Phase-Locked Loop-Based Control Algorithms [53]. A combination of various control strategies is also used to improve system performance. Non-linear sliding mode control is combined with Synchronous Reference Frame Theory to generate rapid and stable reference signals for series and shunt converters. Ahmet T. used an enhanced phase-locked loop with a nonlinear adaptive filter to compensate for the effects of voltage sag/swell and to eliminate load current harmonics under distorted supply conditions [44].

The conventional PI controller, combined with supply voltage feed-forward in the d–q reference frame, has been proposed to tackle voltage sags. However, due to the presence of negative sequence current in unbalanced conditions, the conventional PI controller is not able to track the reference signal. To mitigate unbalanced voltage sags, two PI controllers in positive and negative d–q reference frames, a proportional–resonant (PR) controller [55], or an H∞ controller in the stationary frame [54] have been developed. However, the unbalancing of grid voltage is not only due to voltage sags but can also be caused by distorted non-linear loads. To compensate for unbalanced voltage sag problems, Proportional Resonant controllers and resonant controllers for the series inverter, and PI and 3-vector PI controllers for the shunt inverter, are used [12].

V. CONTROLLER USED IN HARDWARE IMPLEMENTATION

Various controllers are used to manage the series and shunt Active Power Filters (APF) of UPQC to achieve higher efficiency, faster response times, and improved control. Among researchers, digital signal processors (DSP) and FPGA controllers are popular choices due to their enhanced performance capabilities. DSP models such as TMS320F2812 [51], TMS320C33 [3, 16], TMS320C6713 [30], and TMS320F28335 [13, 25], [58-61] are commonly employed to implement control algorithms for UPQCs. Many studies have documented the use of these digital controllers for UPQC control strategies. Additionally, digital signal processors like dSPACE DS1103 [8, 21, 39, 56], dSPACE DS1104 [5, 46, 55], and dSPACE MicrolabBox [36, 38, 41] are widely recognized for their effectiveness in UPQC control applications. In some studies, control algorithms are implemented on real-time hardware-in-loop (CHIL) platforms, utilizing OPAL-RT 5600 and dSPACE MicroLabBox. These platforms enable the construction of physical UPQC models and power system models, incorporating sources, transmission lines, distribution lines, and various loads within the real-time digital simulation environment of the OPAL-RT 5600 [57]. This capability facilitates real-time performance verification of the systems.

VI. CONCLUSION

This comprehensive review of UPQC for power quality improvement in distribution systems highlights critical advancements and emerging trends. The latest UPQC topologies address power quality issues in modern electrical networks, particularly in distributed generation and micro-grid environments. The growing deployment of UPQC in these contexts underscores its importance in maintaining stable and efficient power delivery. Advanced controllers are crucial for implementing control algorithms in UPQC systems. By listing these controllers, this review provides a valuable resource for researchers and practitioners selecting suitable control strategies. The diverse range of UPQC topologies and control algorithms reported in the literature demonstrates ongoing efforts to enhance system performance and effectively tackle power quality challenges.

Despite significant progress, there remain areas for further exploration, such as UPQC-ML, UPQC-DG, UPQC-MD, and Open-UPQC configurations. UPQC-ML (Multi-Level UPQC) can offer improved performance in handling complex power quality issues, while UPQC-DG (Distributed Generation integrated UPQC) focuses on integrating renewable energy sources into the grid. UPQC-MD (Modular Design UPQC) emphasizes scalability and flexibility, suitable for various applications from residential systems to industrial setups. Open-UPQC represents an innovative approach to enhancing interoperability and adaptability within smart grid infrastructures.

In conclusion, this review underscores the vital role of UPQC in modern power systems and highlights ongoing advancements in its topologies and control strategies. By addressing current challenges and exploring emerging opportunities, researchers and practitioners can continue to develop more efficient and effective solutions for power quality improvement, supporting the reliable and sustainable operation of future electrical grids.

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