Mitigation of Power Quality Problems Using Custom Power Devices: A Review

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Abstract

Electrical power quality (EPQ) in distribution systems is a critical issue for commercial, industrial and residential applications. The new concept of advanced power electronic based Custom Power Devices (CPDs) mainly distributed static synchronous compensator (D-STATCOM), dynamic voltage restorer (DVR) and unified power quality conditioner (UPQC) have been developed due to lacking the performance of traditional compensating devices to minimize power quality disturbances. This paper presents a comprehensive review on D-STATCOM, DVR and UPQC to solve the electrical power quality problems of the distribution networks. This is intended to present a broad overview of the various possible DSTATCOM, DVR and UPQC configurations for single-phase (two wire) and three-phase (three-wire and four-wire) networks and control strategies for the compensation of various power quality disturbances. Apart from this, comprehensive explanation, comparison, and discussion on D-STATCOM, DVR, and UPQC are presented. This paper is aimed to explore a broad prospective on the status of D-STATCOMs, DVRs, and UPQCs to researchers, engineers and the community dealing with the power quality enhancement. A classified list of some latest research publications on the topic is also appended for a quick reference.

***Keywords**: power quality, voltage sag, voltage swell, distributed static compensator, voltage source inverter, Z-source inverter, current source inverter, DVR, UPQC*

1. Introduction

Nowadays electrical power quality is a very important issue in the electrical distribution system. It has been always a challenging task to maintain the power quality within acceptable levels [1-11]. In general, power quality disturbances that affect the voltage and current wave-forms quality are imbalances, harmonics, flickers, voltage sags and swells [12-17]. PQ problems can lead to poor power quality which may occur because of increased losses, undesirable and abnormal nature of equipment, problem of interference etc [18-21].

To develop dynamic, flexible and adjustable solution to the electrical power quality disturbances, passive L-C filters [22-24], active power filters (APFs) [25-29], hybrid filters [30] and custom power devices (CPDs) [31-36] are used from time to time.

This paper focuses on a DSTATCOM, DVR and UPQC type compensating custom power devices. The CPDs mainly DSTATCOMs, DVRs and UPQCs are the APF family members connected in shunt, series and a combination of shunt and series to achieve superior control over different power quality disturbances simultaneously.

This paper is intended to present a comprehensive survey of previous research on DSTATCOM, DVR and UPQC type custom power devices for power quality enhancement in power distribution network. Over 200 publications [11-218] are seriously reviewed to classify them in different categories.

The D-STATOM, DVR and UPQC type custom power device are categorized based on the (1) type of converter topology (voltage source converter and current source converter); (2) supply system (single-phase two-wire, three-phase three-wire and four-wire).

Therefore, this paper is presented as follows: The state of the art of D-STATCOM, DVR and UPQC are presented in section 2, section 3 illustrates the classification of custom power devices (D-STATCOM, DVR and UPQC). Section 4 describes the control methodologies and approaches including the derivation of reference signal and current/voltage control techniques. Section 5, latest trends and technical consideration on CPDs are discussed; finally, section 6 discusses the conclusion part of the paper.

2. DSTATCOM, DVR and UPQC: State Of The Art

Electrical power quality (EPQ) problems are an issue that is becoming increasingly important to all levels of usage such as industrial, commercial and utilities. The power quality issues include short-term events such as voltage sags, swells or even transients with duration of less than a few seconds. Power system harmonic and flicker issues also fall into the category of power quality (PQ), even though these issues tend to occur much longer intervals than sags and transients [11]. Table 1 shows the various power quality problems and their causes. The authors [12-16] discussed voltage sag and its characteristics in detail. M.R.Alam et al. [17] proposed an algorithm for detection; classification and characterization of voltage sag and swell in electricity networks, using three-phase voltage ellipse parameters. The proposed method employs the instantaneous magnitude of three-phase voltage signals in three axes, which are separated from each other by 120⁰.

From time to time different efforts have been carried out to provide an active and flexible solution to mitigate power quality disturbances. Before the advent of active filters, passive filters based on inductors and capacitors [22-24] were used and still used in many power transmission and distribution applications, but it has various disadvantages such as instability, fixed compensation, resonance with supply as well as loads and utility.

To overcome these drawbacks active power filters (APFs) have been used [25-29]. However, they are costly options for power quality enhancement because their ratings are sometimes very close to full load (up to 80%) in typical applications.

To face the power quality problems and increase the reliability, an advanced power electronic based devices have launched over last decades. These power electronic based devices are called Custom power devices (CPDs) [31-36]. N.G.Hingorani [7] introduced the concept of custom power. Custom power solution can be network reconfiguration type or compensation type as shown in Figure1. In this paper, a comprehensive review of compensating type is presented [9]. The compensating custom power devices are used for active filtering, load balancing, voltage regulating (sag/swell), harmonic elimination and power factor correction. These devices are either connected in shunt or in series or a combination of both and also called D-STATCOM, DVR and UPQC.

D-STATCOM: D-STATCOM is the most important solid state shunt connected CPD. It has been widely used to precisely regulate system voltage, improve voltage profile, reduce voltage harmonics, reduce transient voltage disturbances and load compensation. D-STATCOM controller can be constructed based on both voltage source inverter topology and current source inverter (CSI) topology [11], [20], [37], [38] as shown in Figure 1. In practice, CSI topology is not used for D-STATCOM because higher losses on the DC reactor of CSI compared to the DC capacitor of VSI [39]. The authors [40], [41] proposed reverse blocking insulated gate bipolar transistor has eradicated the need for the series diode and making CSI a good alternative. The principal of generating instantaneous active and reactive powers by D-STATCOM is shown in Figure 2. In Figure 2, voltages and currents are represented with instantaneous space vectors obtained using a power invariant Clarks transformation. Figure 3 are presented in three cases: the general one, for reactive power equal to zero and for active power equal to zero. Form the Figure 3 it is clear that by generating an appropriate AC voltage it is possible to generate arbitrary instantaneous vectors of both active and reactive power. [11] The authors in [37], [42-44], [45-47] discuss the various aspects such as modeling, design and simulation for reactive power compensation, unbalanced and harmonic compensation and voltage regulation (sag/swell). In [9], [48], a D-STATCOM model is used for feasibility and validating the design. K.R. Padiyar [10], H. Fugita et al. [49], Arya et al. [50] discussed D-STATCOM for voltage regulation in detail.
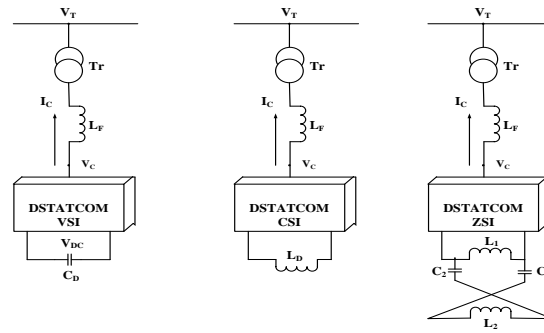
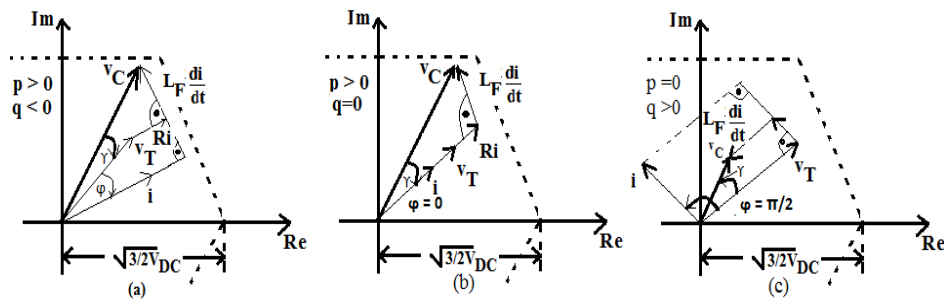Figure 1. Schematic Diagram of VSI, CSI and ZSI based DSTATCOM

Figure 2. Operating Principle of DSTATCOM (a) General Case (b) Reactive Power Zero and (c) Active Power Zero

DVR: A dynamic voltage restorer (DVR) is a power electronic (PE) converter-based CPD, which can protect sensitive loads from all supply-side disturbances other than outages. It is connected in series with a distribution feeder as shown in Figure. 3 and also is capable of generating or absorbing real and reactive power at its AC terminals. The basic principle of a DVR is simple: by inserting a voltage of the required magnitude and frequency, the DVR can restore the load-side voltage up to the desired amplitude and waveform even when the source voltage is either unbalanced or distorted [11]. A typical location in the distribution system and the operating of the DVR is shown in Figure.3. The different aspects such as modeling, design and simulation for harmonic elimination, voltage flicker suspension [9], voltage sag and swell mitigation are reported in [51-54]. A.K.Jindal et al. [55] highlighted dynamic voltage restorer for voltage regulation function.
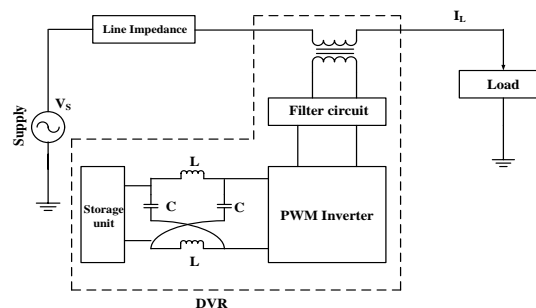

Figure 3. Basic Structure of DVR

UPQC: For enhancing power quality in the system and protecting sensitive loads a universal solution can use by an integration of the series-parallel active power filters called UPQC as depicted in Figure 4.UPQC is a flexible device that can compensate almost all types

of PQ disturbances related to voltage and current simultaneously. Shunt active power filter is the most promising to tackle the current-related problems such as current harmonics, current unbalance, reactive current whereas, the series APF is the most suitable to overcome the voltage-related problems such as voltage harmonics, voltage unbalance, voltage flicker, voltage sag and swell.

In operating principal, UPQC is a union of shunt and series APFs with two VSI-based common self-supporting DC bus. The shunt APF is controlled in a current controlled mode such that it produces a current that is equal to the set of the reference current as produced by the control algorithm of UPQC.
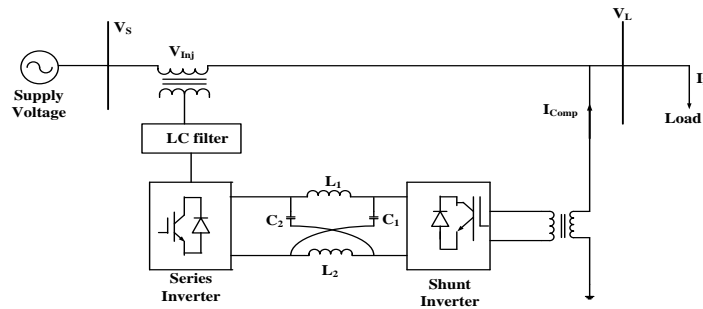

Figure 4. Schematic Diagram of UPQC

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

where $i_{sh}(\omega t)$, $i_S^*(\omega t)$, $i_L(wt)$ represents the shunt APF current, reference source current and load current. Shunt active power filter should inject a current to eliminate the harmonics produced by a nonlinear load.
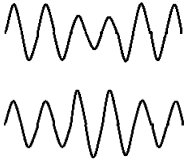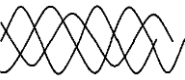
The series active power filter is controlled in voltage control mode such that it generates a voltage and injects in series with line to achieve a sinusoidal and distortion free voltage at the load terminal. In the case of voltage sag (VS) condition, series APF should inject a voltage to maintain the load voltage.

$$V_{SC}(\omega t) = V_L^*(\omega t) - V_S(\omega t) \tag{2}$$

where $V_{SC}(\omega t)$, $V_L^*(\omega t)$, $V_S(\omega t)$ represents the series APF voltage, reference load voltage and source voltage. The system modeling aspects of the UPQC are reported in [56-63]. In [64], a mathematical modeling and design of a versatile UPQC are discussed clearly. A.Ghosh et al. [65] discussed the application of UPQC for voltage regulation in critical loads.

Table 1. Some Effects of Power Quality Problems for the Different Voltage Events

Broad Classification	Specific Classification	Typical Characteristics		Disturbance	Consequence
		Duration	Magnitude		
1. Transients	1.1 Impulsive	50 ns- 1ms	< 6 kV		Insulation failure. Reduced Lifetime of transformers and motors
	1.2 Oscillatory	5 μs-0.3 ms	0 – 4 pu		
2.Short duration variations	2.1. Interruption	10 ms – 3 min	< 1%		Disconnection.
	2.2. Sag	10 ms – 1 min	1 - 90%		Disconnection of sensitive loads. Fail functions.

	2.3. Swell	10 ms – 1 min	110 - 180%		Disconnection of equipment may harm equipment with inadequate design margins
3. Long duration variations	3.1 Under Voltage	> 1 min	80-90%		Disconnection of sensitive loads. Fail functions. Disconnection of equipment may harm equipment with inadequate design margins
	3.2 Over Voltage	> 1 min	160-120%		
4. Curve distortion	4.1 Harmonics	Stationary	0- 20%		Extended heating. Fail function of electronic equipment
5. Voltage Unbalance	___	Stationary	0.5 - 2%		Voltage quality for overloaded phase. Over load and noise from 3-phase equipment.
6.Voltage Fluctuation	___	Intermittent	0.2 - 7%		Ageing of insulation. Fail function. flicker

3. Classification of Custom Power Devices (D-STATCOM, DVR AND UPQC)

In this section, classification of compensating type custom power devices is given. As shown in Figure.5, a pictorial view for the classification of custom power devices. The custom power devices are mainly classified in two main categories: (1) based on converter topology and (2) based on supply system.
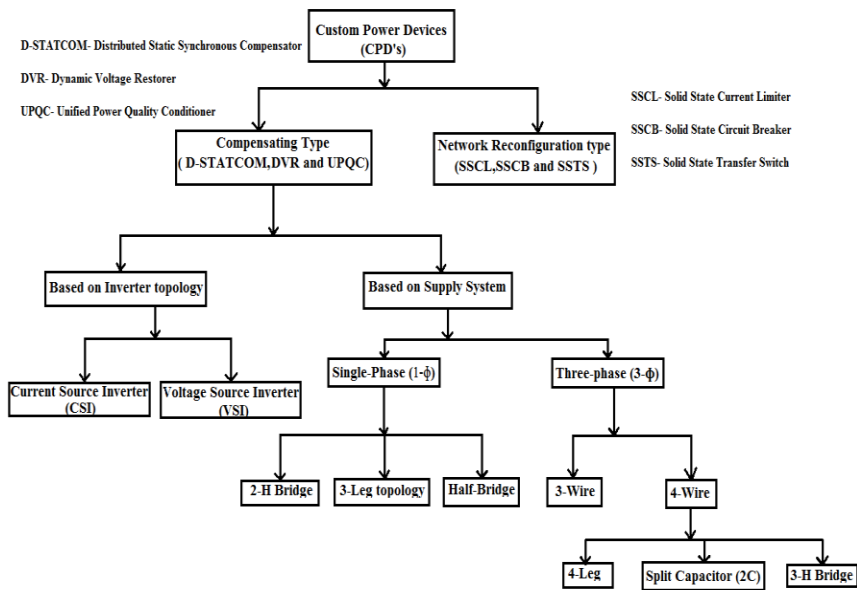

Figure 5. Classifications of CPDs

3.1. Based on Converter Topology

This D-STATCOM, DVR and UPQC type custom power devices can be constructed based on voltage source inverter (VSI) topology, current source inverter (CSI) topology [11] and Z-source inverter topologies.

Figure 6 (a-c) depicts single-line representation of a CSI based D-STATCOM, DVR and UPQC system configuration [18], [20], [21]. The D-STATCOM, DVR and UPQC may be constructed using a pulse width modulated (PWM) current source inverter (CSI) [27], [28], [37-41], [66-70] which uses an inductor LDC as a common energy storage to form the DC link. In practice, D-STATCOM, DVR and UPQC based on current source inverter are not used due to high cost, higher losses, [20], [39], and also it cannot find its application in multilevel configurations. The second topology is based on VSI, which is the most common and popular inverter topology can be used in D-STATCOM, DVR and UPQC system configurations [9], [20-26], [29- 36], [42-65], [70-218].
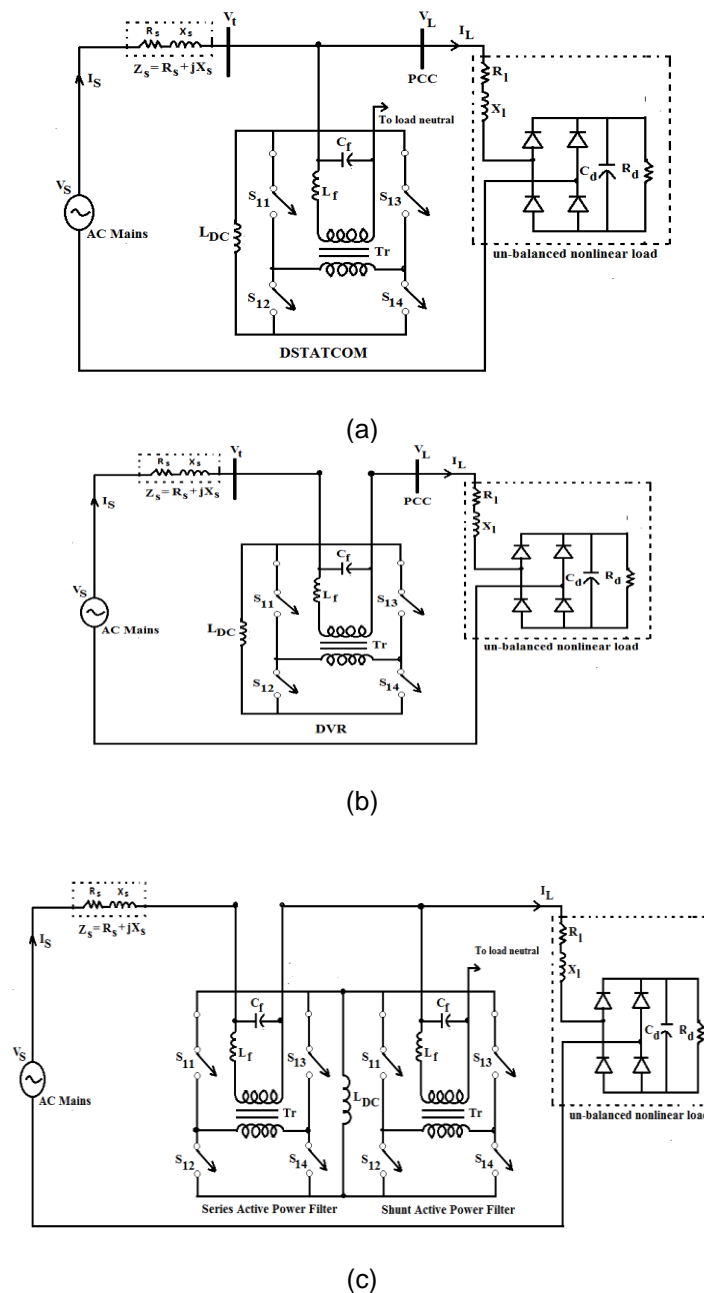
(a)

(b)

(c)

Figure 6. CSI-Based (a) DSTATCOM (b) DVR and (c) UPQC

Figure 7(a-c) shows the configurations of D-STATCOM, DVR and UPQC based on voltage source inverter (VSI) and Figure 8(a-c) shows the Z-source inverter based configurations.

The VSI-based topology has the advantages over CSI-based topology include cheaper, flexible overall control, no need of blocking diodes and capable of multilevel operation [18]. A.Ghosh et al. [9] explained a CSI is usually more reliable and fault tolerant than a VSC because the large series inductor limits the rate of rise of current in the event of a fault. However, CSIs have higher losses because of the need to store energy by circulating current in the inductors which are lossier than capacitive energy storage. Since capacitors are more efficient, smaller and less expensive than inductors, VSIs are most commonly used in D-STATCOM, DVR and UPQC system configurations.
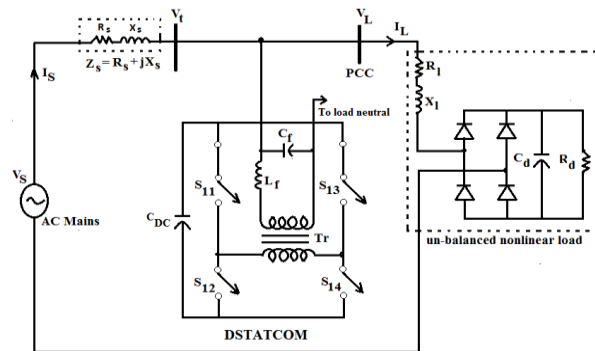
(a)
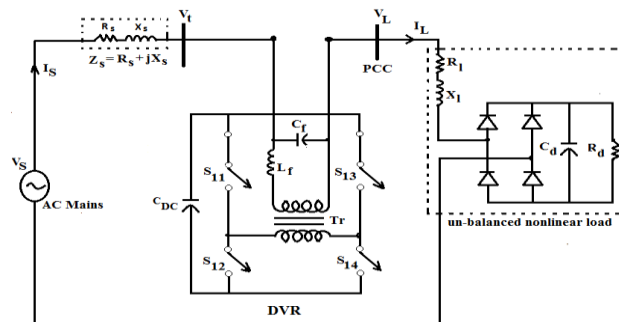
(b)
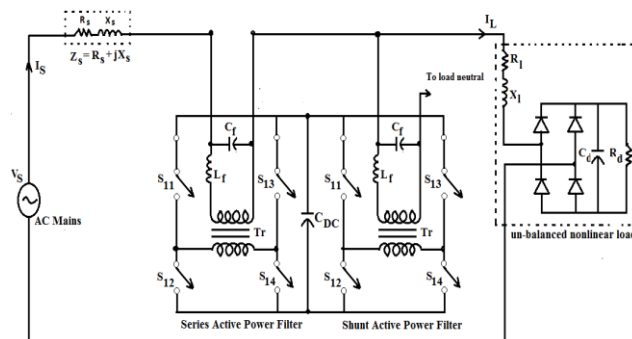
(c)

Figure 7. VSI-Based (a) DSTATCOM (b) DVR and (c) UPQC
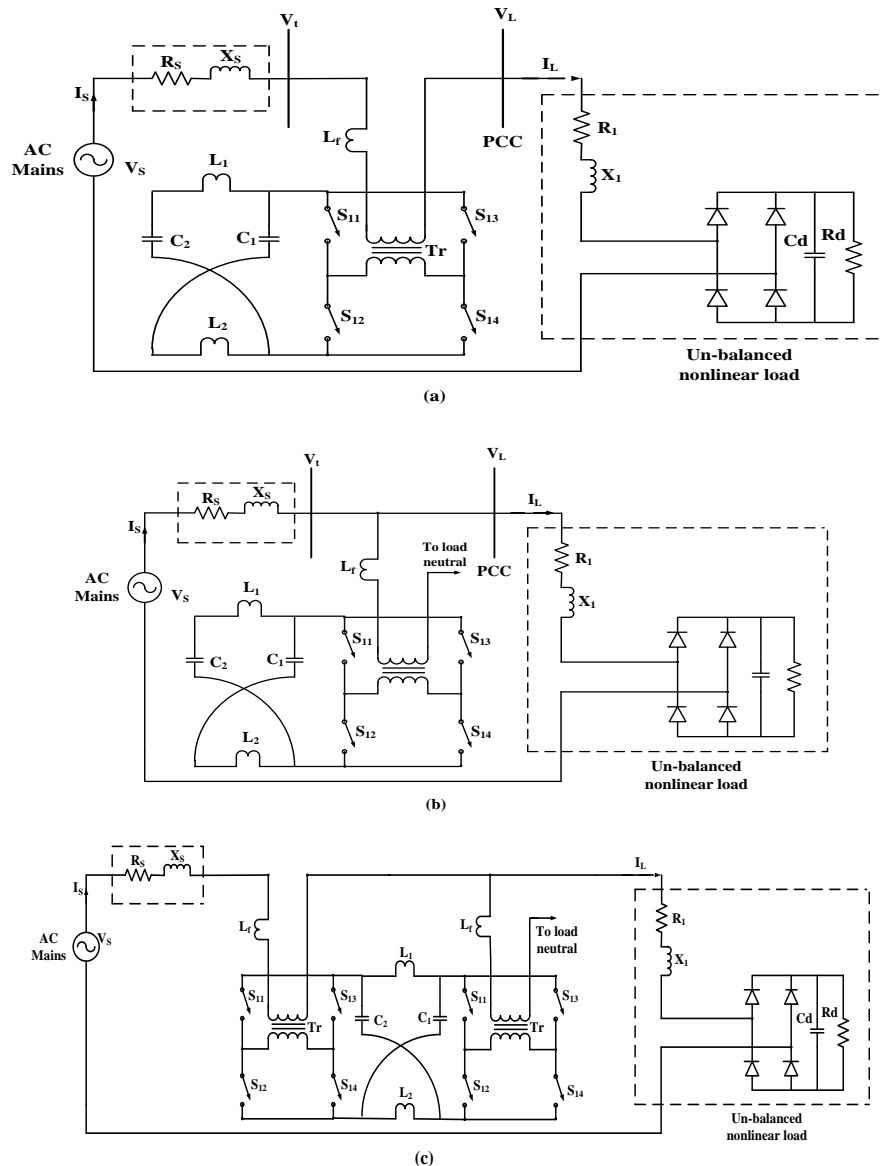
Figure 8. ZSI-Based (a) DVR (b) DSTATCOM and (c) UPQC

3.2. Based On Supply System

To mitigate the power quality disturbances in power distribution system different D-STATCOM, DVR and UPQC configurations are introduced and they can be divided based on the type of the supply system topology. In general, AC supplies or loads on the power system can be mainly classified into single-phase two-wire (1p2w) and three-phase three-wire (3p3w) and four-wire (3p4w) source. The supply voltage related power quality problems have similar characteristics for single-phase and three-phase systems. In addition, three-phase systems need voltage unbalance compensation capability to provide enhanced power quality (PQ). The load current harmonics and reactive current are the major limitations for a single-phase system. For the case of three-phase three-wire (3p3w), one must need to consider current unbalance apart from the reactive and harmonics current.

3.2.1. Single-phase two wire (1p2w) compensating devices

Single-phase two-wire (1p2w) systems are used in all three modes as shunt (D-STATCOM) [71-74], series DVR [75-83] and a union of both as UPQC [84-101].

Figure 9 (a-c) shows the most popular DSTATCOM, DVR and UPQC configurations consist of two H-bridge inverters [72-74], [83], [84], [86- 97], [99], [101] in single-phase two-wire (1p2w) system to compensate the power quality (PQ) issues by injecting current in case of D-STATCOM, voltage in case of DVR and both in the case of UPQC of the electrical power distribution system.

Figure 10(a-c) shows the most commonly used D-STATCOM, DVR and UPQC configuration to consists of 3-leg inverters [102] in single-phase two-wire (1p2w) system to mitigate the power quality (PQ) disturbances by injecting current, voltage and both current and voltage.

Figure 11(a-c) depicts the most popularly use D-STATCOM, DVR and UPQC system configuration which consists of half-bridge inverters [85], [98], [100], [103] in single-phase two-wire (1p2w) system to compensate the power quality (PQ) problems by injecting current in case of D-STATCOM, voltage in case of DVR and both in the case of UPQC of the electrical power distribution system.

(a)

(b)

(c)
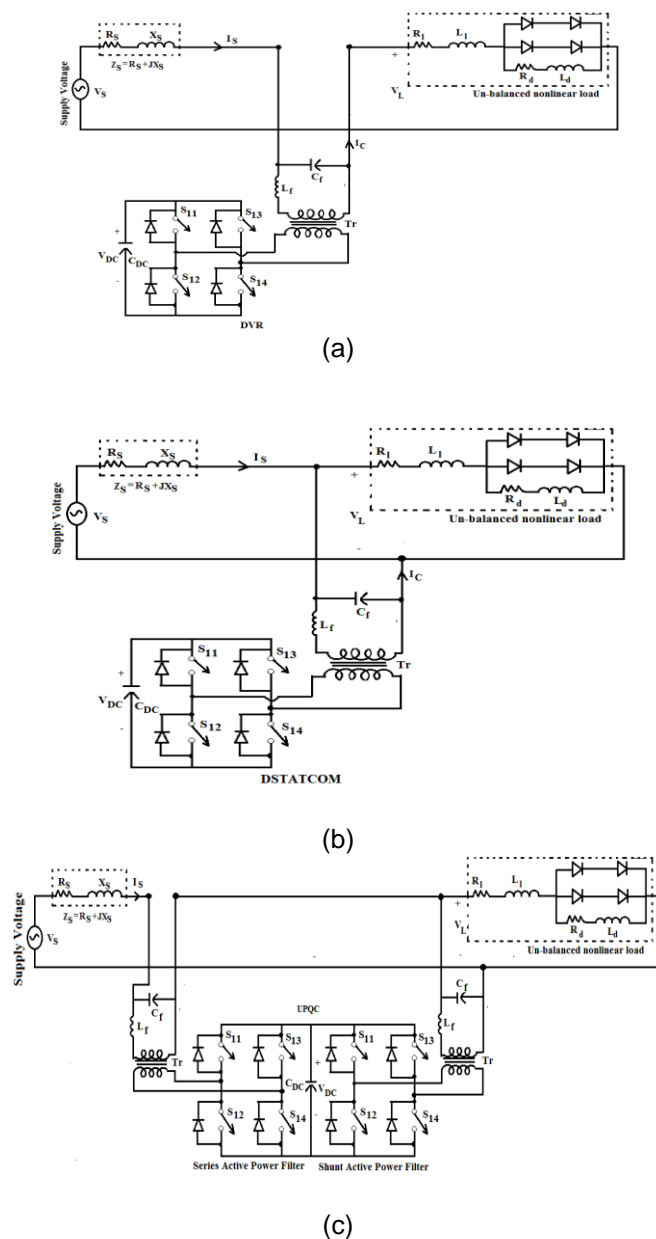
Figure 9. Two H-bridge (a) DVR (b) DSTATCOM and (c) UPQC
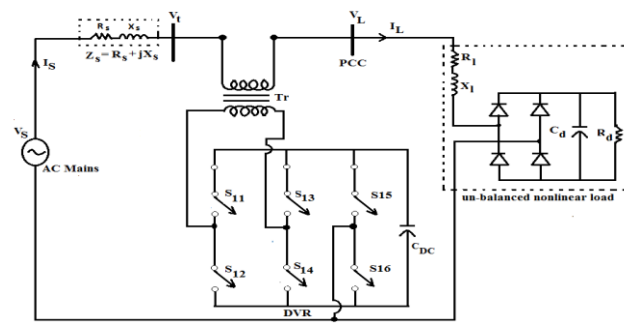
(a)
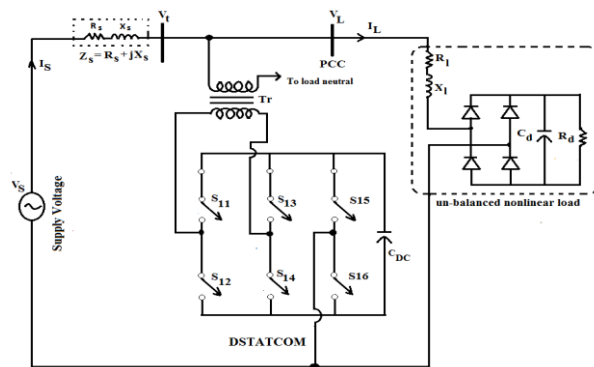
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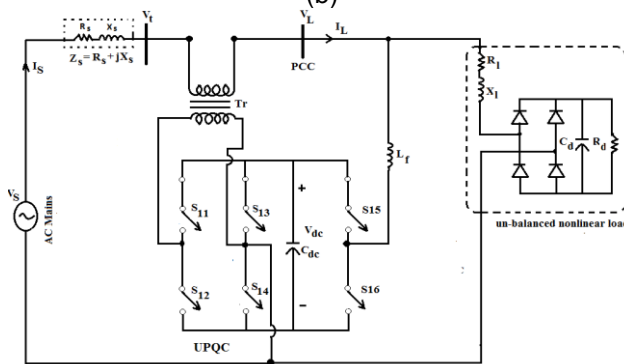
(c)

Figure 10. 3-Leg (a) DVR (b) D-STATCOM and (c) UPQC
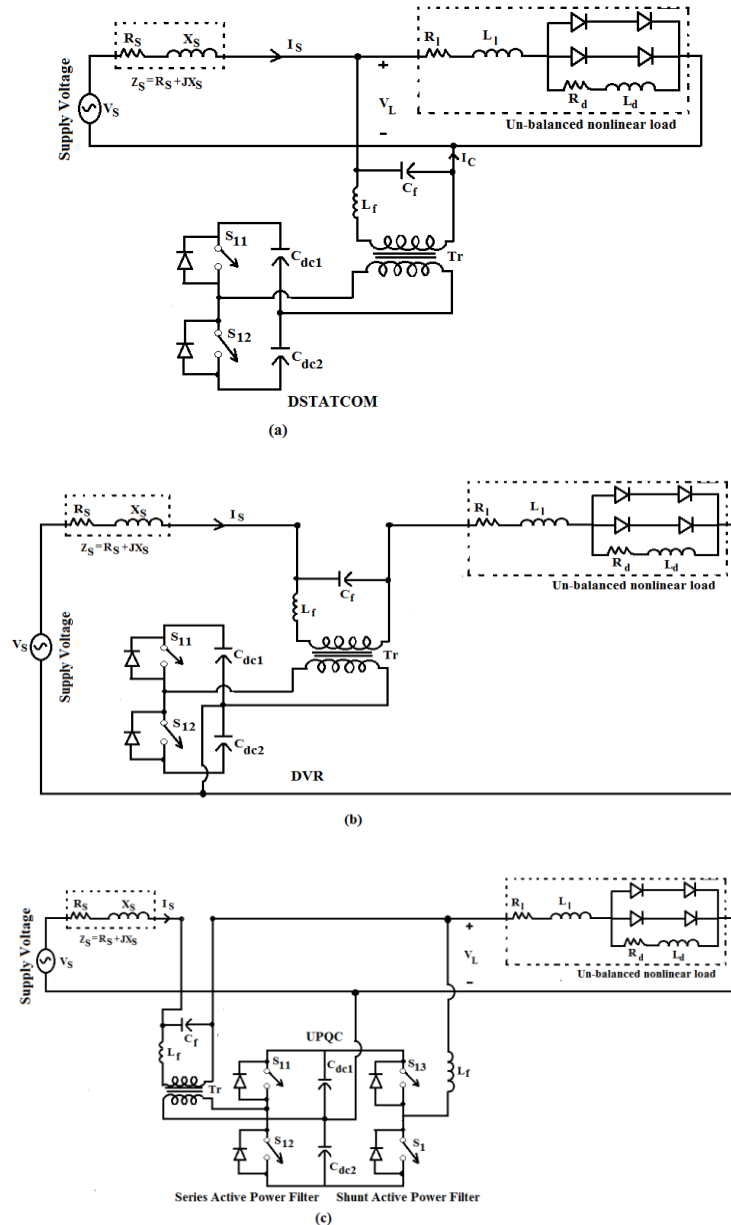
Figure 11. Half-Bridge (a) DSTATCOM (b) DVR and (c) UPQC

3.2.2. Three-phase three wire (3P3W) Compensating devices

Three-phase three-wire (3p3w) nonlinear loads such as adjustable speed drives (ADSs), frequency converter, current regulator, arc welding drives/machines and arc furnace causes several power quality (PQ) problems such as voltage sag, swell, harmonics etc. . Most widely preferred and suitable three-phase three wire (3p3w) voltage source converter (VSC)-based D-STATCOM , DVR and UPQC network configurations are shown in Figure 12 (a-c) and are widely reported in literature [56-60], [70],[104-118], [119-130], [131-179].

(a)

(b)

(c)
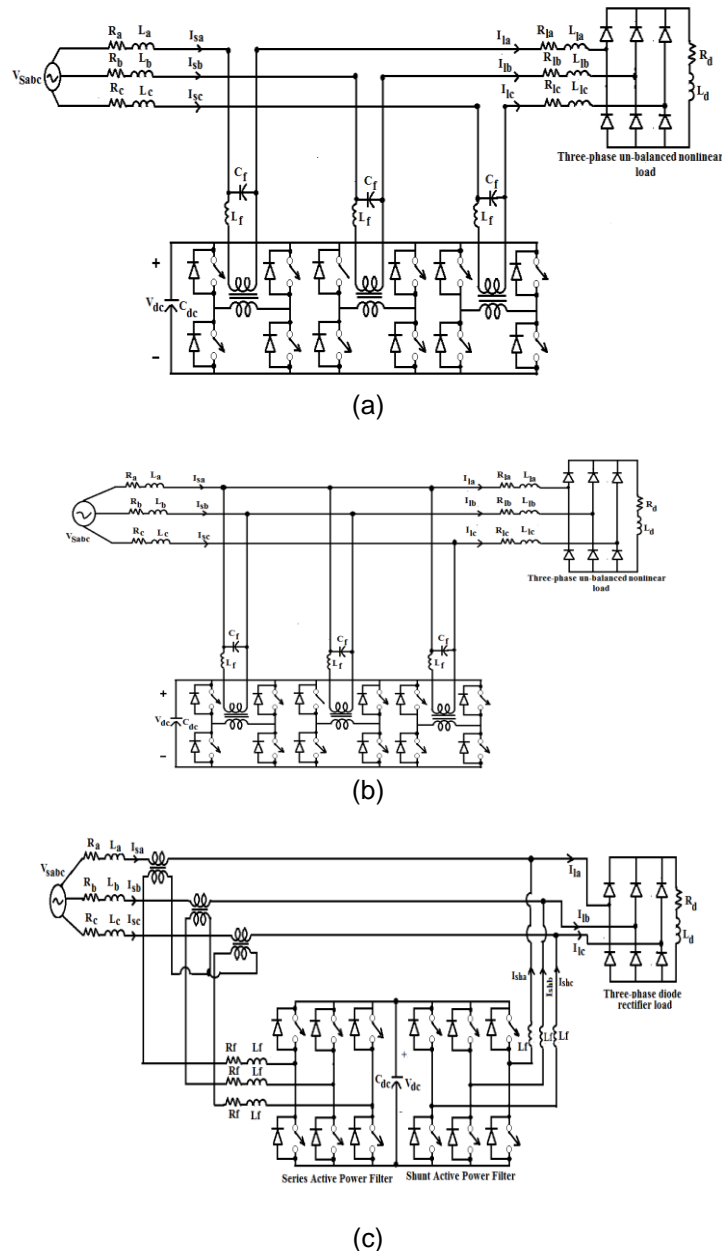
Figure 12. Three-phase Three-Wire (a) DVR (b) DSTATCOM and (c) UPQC

3.2.3. Three-phase four-wire (3p4w) compensating devices

A large number of single-phase (1-φ) loads may be supplied from three-phase (3-φ) mains with a neutral conductor. They cause excessive neutral current, harmonics and reactive power burden. To reduce the neutral current in a three-phase four-wire (3p4w) system [180-183], various D-STATCOM, DVR and UPQC configurations have been applied, mainly two split capacitor (2C), four-leg (4L) and three H-bridge (3HB) configurations. The first one uses three H-bridge voltage source converters (VSCs) and these H-bridges are connected through isolation transformers. The split capacitor topology and four-leg topologies are looking similar. The fundamental difference between these two topologies is the number of power semiconductor devices and the connection of the neutral wire.

3.2.3.1. Three H-bridge topology

Figure 13 a-c shows the three-phase four-wire (3p4w) D-STATCOM, DVR and UPQC system configuration based on three H-bridge (3HB) topologies in three-phase four wire distribution system and are reported in [65],[184-193]. Three H-bridge (3HB) topology consists of three single-phase (1-ϕ) H-bridge (full bridge) voltage source inverter (VSI) tied with a common self supporting DC bus [194]. The main advantage of this topology is the control can be done either as a three-phase (3-ϕ) unit or three separate single-phase (1-ϕ) units. The maximum voltage that appears across each H-bridge is the single phase voltage and not the three-phase voltage as in the case of capacitor midpoint or four-leg topology.

(a)

(b)

(c)
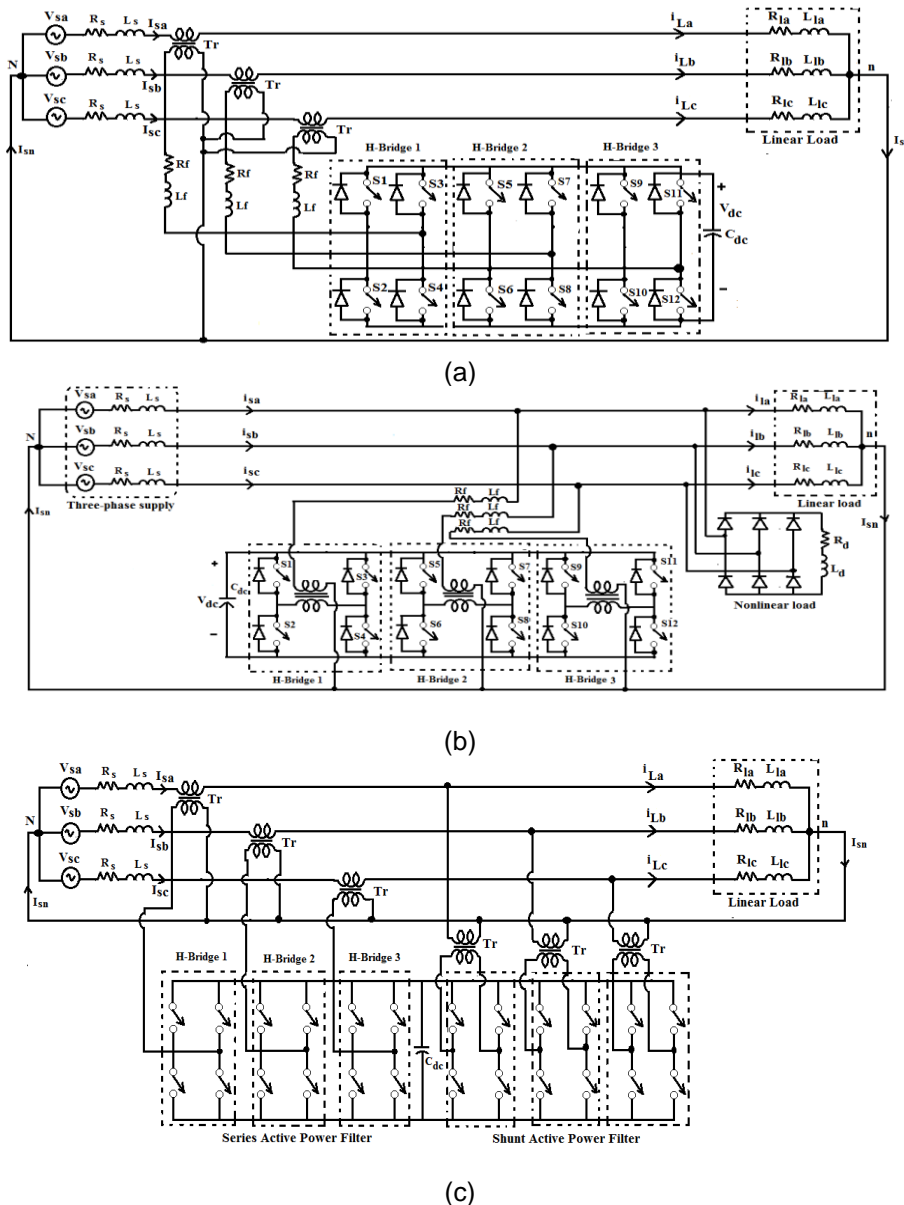
Figure 13. Three-Phase Four-Wire Three H-bridge (a) DVR (b) DSTATCOM and (c) UPQC

3.2.3.2. Three-phase four-wire split capacitor (2C) topology

The split capacitor topology uses the standard three-phase traditional inverter where the DC capacitor is split and the neutral wire is directly connected to the electrical mid-point of the capacitors through an inductance. The capacitors midpoint allows load neutral current to flow

through one of the DC capacitors Cd-1, Cd-2 and return to the AC neutral wire. Figure 14 (a-c) shows the 3p4w D-STATCOM, DVR and UPQC system configuration based on split capacitor topology [195-208]. In this topology, the voltage unbalance between the capacitors is one of the series problems [18], [20], [209]. This is due to the direct flow of neutral current through one of the capacitors (Cd-1, Cd-2), causes voltage variations among them. There are two possible ways to balance the capacitors: (1) by adjusting the switching of the inverter [209], but this approach requires additional control circuitry and (2) by using additional power electronic switching circuitry, but this approach increases the cost.

(a)

(b)

(c)
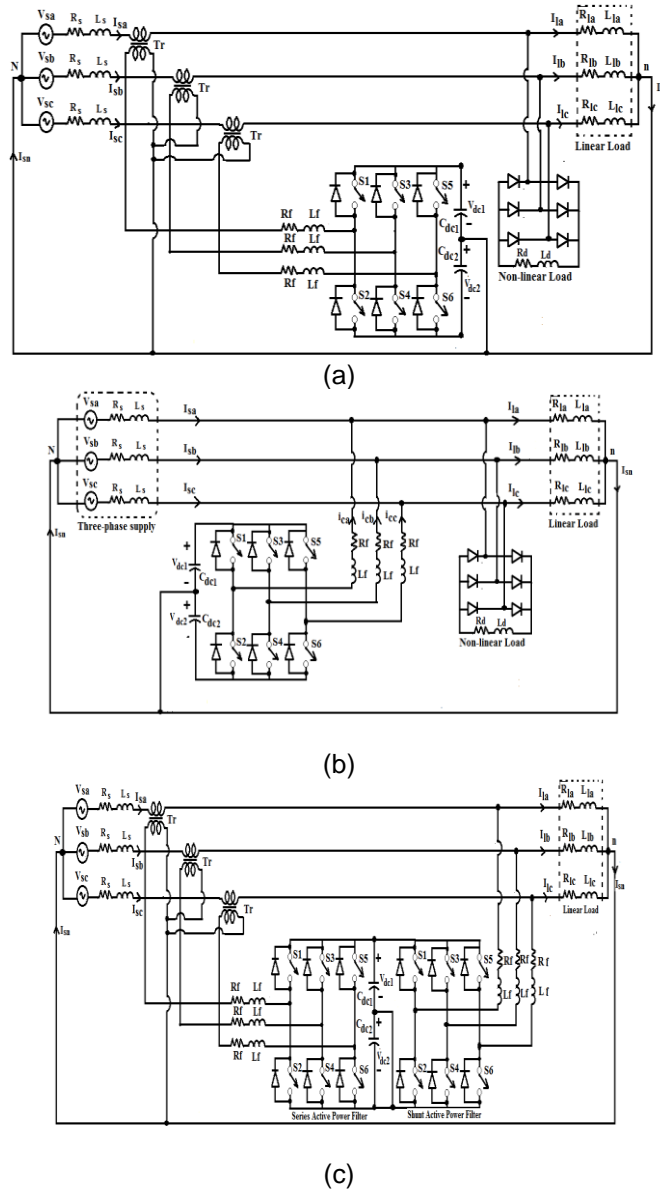
Figure 14. Three-phase Four-Wire Split Capacitor (a) DVR (b) DSTATCOM and (c) UPQC

3.2.3.3. Three-phase four-wire (3p4w) four-leg (4L) topology

Figure 15 a-c shows the 3p4w D-STATCOM, DVR and UPQC system configuration based on three phase four-wire (3p4w) four-leg (4-L) topology. For elimination of high neutral currents the 4-leg topology used in 3P4W systems [27], [210-218].Having a higher number of switching devices this topology outweighed the split capacitor topology by number for factors [27], [209]: (a) Better controllability: In 4- leg topology only one DC-bus voltage needs to be

regulated. This importantly simplifies the control circuitry with better controllability [27]. (b) Lower DC voltage and current requirement: This topology requires a lower DC-bus voltage and current with it. (c) Higher order harmonics in DC side current: In this topology, the DC side current has only higher order harmonics and will not contribute to significant ripple on the DC-bus voltage.

(a)

(b)

(c)
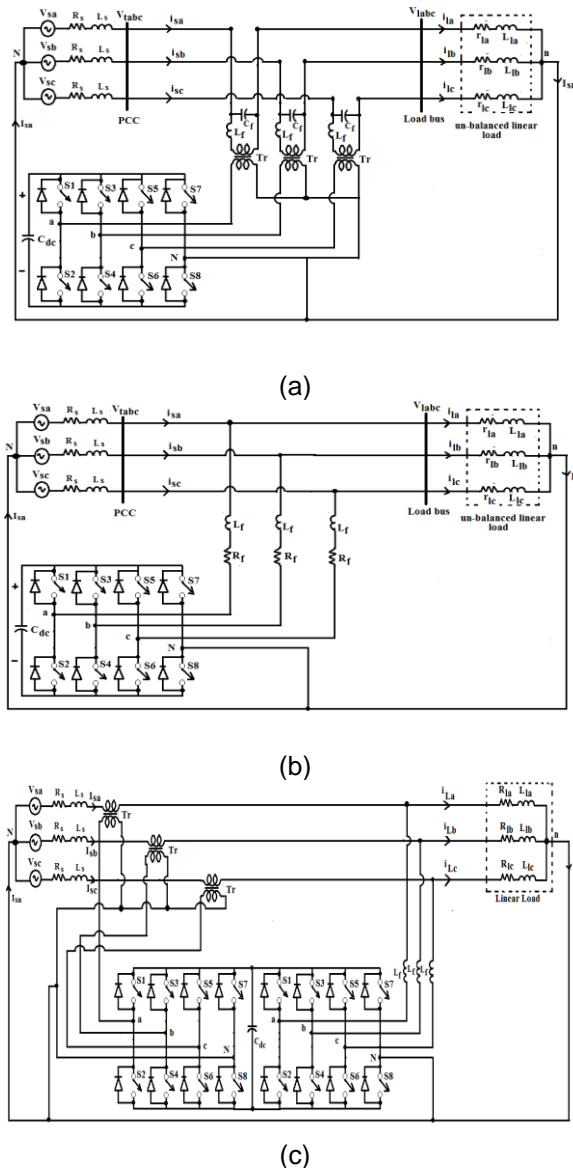
Figure 15. Three-Phase Four-Wire Four-Leg (4L) (a) DVR (b) DSTATCOM and (c) UPQC

4. Control Techniques for Custom Power Devices (D-STATCOM, DVR and UPQC)

The election of strategy control is essential to get the desired compensation aim. Control technique is the heart of the D-STATCOM, DVR and UPQC devices. It plays the most important role in overall performance in any power electronics based system. The control of custom power devices (DSTATCOM, DVR and UPQC) is realized in three stages. In the first stage, the necessary current and voltage signals are sensed to gather accurate system information. In the second stage compensating signals in terms of current and voltage levels are produced based on different control methods and DSTATCOM, DVR and UPQC configurations. In the third stage of control, the gating signals for the solid state devices of the compensating devices are derived either in the open loop or closed loop. The open and closed loop schemes are used only for lower order systems. For second and higher order systems sliding mode

control, linear quadratic regulator (LQR), pole-shift control, deadbeat control, and Kalman filter are used. Recently, for improving the dynamic and steady state performance of the devices, the complex algorithms like fuzzy logic [46], [82], [108], [115], [125], [161], [163], neural networks and genetic are implemented with the help of microprocessor and microcontroller

4.1. Derivation of Reference Signal
Generation of reference signals either in terms of voltage, current and both are important part of custom power devices (D-STATCOM, DVR and UPQC) for their control, transient as well as steady-state performance. The performance of the D-STATCOM, DVR and UPQC are strictly depends on its reference signal production technique. In general, control strategies to generate compensation or reference signals are based on frequency domain and time domain correction techniques [9] as shown in figure 16. In addition, to these control methods for power electronic based compensating type custom power devices (D-STATCOM, DVR and UPQC) can also be categorized on the basis of linear and nonlinear, classical and modern, hard and soft computing, online and off-line, but for the sake of brevity, they are not discussed here.
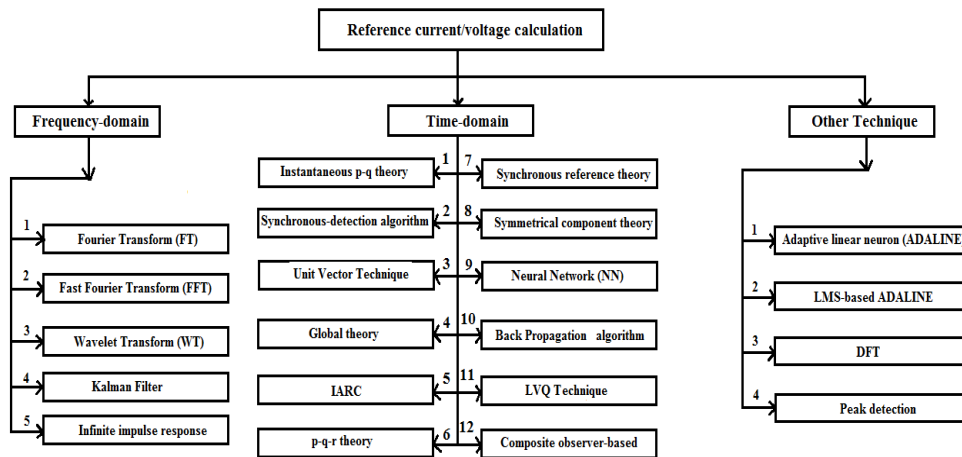
Figure 16. Reference Signal Derivation

4.1.1. Compensation in Frequency-Domain Technique
The most commonly used model in the frequency-domain (FD) [9] is a balanced three-phase (3ϕ) system at fundamental and harmonic frequency and single-phase (1-ϕ) system. They are mainly divided into Fourier transform, Wavelet transform, infinite impulse response and Kalman filter.

4.1.1.1. Fourier Transform (FT)
One of old techniques used in analysis of non-sinusoidal signals is Fourier transform. Fourier analysis has been used for power quality assessment for a long period. It permits mapping of signals from time domain to frequency domain and vice-versa by decomposing the signals into several frequency components. Application of Discrete FT and fast Fourier transform (FFT) are very useful to overcome some of the disadvantages of the earlier one [18], [20], [21], [27], [28]. In custom power devices (D-STATCOM, DVR, and UPQC) FFT is used to extract the harmonic components from the harmonic polluted signals. Due to excessive computation in online application, FFT has high response time.

4.1.1.2. Wavelet Transform (WT)
Fourier transform fails in the analysis of transients owing to the non-sinusoidal property, Wavelet transforms (WT) helps us in such cases. Wavelet transform analysis [18], [20], [21] has been suggested as a new tool for measurement and monitoring power quality problems both in

absence and presence of transients [5], [9], [11], [18], [20],[21],[53],[133],[218]. Fourier transform or Wavelet transform is a cumbersome computation and results in a large response time. Hence, this makes it difficult for real –time application with dynamically varying loads [21].

4.1.1.3. Kalman Filtering method

For detection and analysis of voltage events (voltage sag and swell) in distribution system Kalman filter have been used. The Kalman filtering method gives the information on both magnitude and phase angle of the supply voltage during the voltage sag and swell events and the point-on-wave where the voltage events begin unlike the RMS method [18], [20], [81], [98], [121], [145], [212].

4.1.2. Compensation in Time-Domain (TD) Technique

Control methods for D-STATCOM, DVR and UPQC in the time-domain are based on instantaneous derivation of compensating commands in the form of either voltage, current or both voltage and current signals. There are a large number of control methods in time-domain. Few are briefly discussed here.

4.1.2.1. Instantaneous Reactive Power Theory (p-q Theory)

Akagi introduced the first version of the instantaneous reactive power theory in English. It is also known as p-q theory for three-phase (3-φ) circuits. However, it is only become known worldwide after their second publication (1984). This theory is based on a coordinate's transformation from a-b-c (or 1-2-3) axes to new α-β-0 axes. The aim of p-q control strategy is to find an effective strategy to compensate nonlinear loads using active power filters. Initially it was applied to balanced three-phase three-wire systems (3p3w) and then it was extended to unbalanced four-wire systems [18], [20], [21], [56], [61], [71], [92], [110], [116], [131], [133], [134], [136], [144], [146], [159], [161], [165], [167], [173], [180-183], [187], [188], [190], [202], [203], [213], [216].

4.1.2.2. Synchronous detection theory (SDT)

The synchronous detection algorithm is very similar to the instantaneous reactive power algorithm and relies in the fact that three-phase currents are balanced. The mean power is calculated and equally divided between the three phases. In synchronization process, the signals are synchronized with respect to the phase voltage for each phase. Implementation of this technique is very easy, but it suffers voltage harmonics [20], [27], [28], [133], [202].

4.1.2.3. Cross-vector theory (CVT)

In cross-vector theory (CVT) Clarks (α-β-0) transformation does not necessarily required because, it directly calculates the instantaneous powers in the a-b-c coordinates. Cross-vector theory (CVT) defines one instantaneous real power and three instantaneous imaginary powers by scalar/vector product of the voltage and the current space vectors in a three-phase four wire system. The sum of the instantaneous real and imaginary powers is equal to the instantaneous apparent power and this power is used to maintain the power conversion [20], [181], [182].

4.1.2.4. Global theory (GT)

This theory does not need any kind of reference frame transformation because the reference compensation currents are directly determined in the a-b-c reference frame. Therefore, this theory gives less complexity in realizing the control circuit of the D-STATCOM, DVR and UPQC. Using this theory D-STATCOM, DVR and UPQC are able to compensate reactive power, suppress harmonics and neutral currents of the distorted and unbalanced load without supplying and consuming active power [20], [182], [183].

4.1.2.5. Vectorial theory (VT)

Vectorial theory uses the same power variables as the original instantaneous imaginary power in phase coordinates. This method also does not need any kind of coordinate transformation. The current vector is divided into three components. The first one is collinear with respect the modified voltage vector and it transports the instantaneous active power. The second one is collinear with respect to the zero sequence voltage vector, and it transport the

instantaneous zero-sequence power and third one is normal with respect to the modified and zero-sequence voltage vectors and it transports the instantaneous reactive power [20], [180], [182].

4.1.2.6. p-q-r theory

The instantaneous reactive power theory (IRPT) bear disadvantages of not compensating the load under distorted and unbalanced point of common coupling (PCC) voltages. To overcome these limitations the original p-q theory has been modified and generally known as p-q-r theory. The D-STATCOM, DVR and UPQC controllers based on this modified p-q-r theory can be found in [18], [20], [21],[113],[119], [180- 182],[188],[192], [205]

4.1.2.7 Synchronous Reference Frame (SRF) Theory

The synchronous reference frame (SRF) theory is developed in time-domain based reference current/voltage generation technique. The SRFT is performing the operation in steady-state or transient state as well as for generic voltage and current and capable of controlling the active power filters in real time system [15] , [18], [20], [21], [27], [28], [51], [54], [57], [58], [76], [77], [82], [104], [106], [111], [115], [120], [121], [125], [127], [128], [130],[131], [133], [134], [137], [141], [142], [150], [153], [155], [160], [167], [177], [178], [179], [180], [182], [187], [189], [190], [195], [204], [203], [207], [213],[214], [217], [218], [219]. One of the important characteristics of this theory is the simplicity of calculation because it involves only algebraic calculation. The undesired AC components are eliminated using low pass filters. The controller mainly deals with DC quantities so the system is stable, but causes a time-delay in filtering the DC quantities.

4.1.2.8. Instantaneous symmetrical component (ISC) theory

A symmetrical component theory is generally a choice in the D-STATCOM, DVR, and UPQC applications to extract the fundamental positive-sequence component when the systems supply voltages are unbalanced and distorted. The ISC theory based control algorithm is capable of providing perfect compensation of any kind of unbalance and harmonics in the load [18], [20]. [21], [65], [105], [109], [126], [136], [137], [182], [184], [188], [195-199], [201], [213].

4.1.2.9 Neural Network (NN) based theory

Neural network (NN) technique can handle efficiently the multi-input multi-out control system. Thus, the artificial neural network technique can be utilized to develop the controller for the D-STATCOM, DVR and UPQC to compensate different voltage and current related power quality problems [53] [68] [108], [115], [138], [150], [220].

4.1.2.10. Back Propagation (BP) based theory

Back propagation control algorithm is used to identification of user faces, industrial processes, data analysis, mapping data, control of power quality improvement custom power devices (D-STATCOM, DVR and UPQC). Bhim Singh et al. [118] proposed a BP algorithm is implemented in three-phase shunt connected power quality improvement device known as D-STATCOM. Due to more numbers of learning steps, the training process is slow, but after the training of samples, BP technique generates very fast trained output response [20], [118].

4.1.2.11. Learning vector quantization (LVQ) based theory

Learning vector quantization (LVQ) technique [59], [181] is used to determine the structure of classifier by minimizing the bounds of the trained error and generalization error.

4.1.3. Other algorithms

To determine the current and voltage compensating signals there are numerous optimizations and estimated techniques such as adaptive linear neuron (ADALINE), LMS-based ADALINE, differential evolution, **Fortescue** decomposition with recursive DFT, and peak detection can be used.

4.2. Current/Voltage Control Techniques

Generation of suitable gating signal is the most important part of D-STATCOM's, DVR's and UPQC's control technique and has a high influence on the compensation performance [39]. Figure 17 shows the classification of current/voltage control techniques. The current/voltage

control techniques often categorized as feed-forward (open-loop), feed-back (closed-loop) and second and higher order systems.
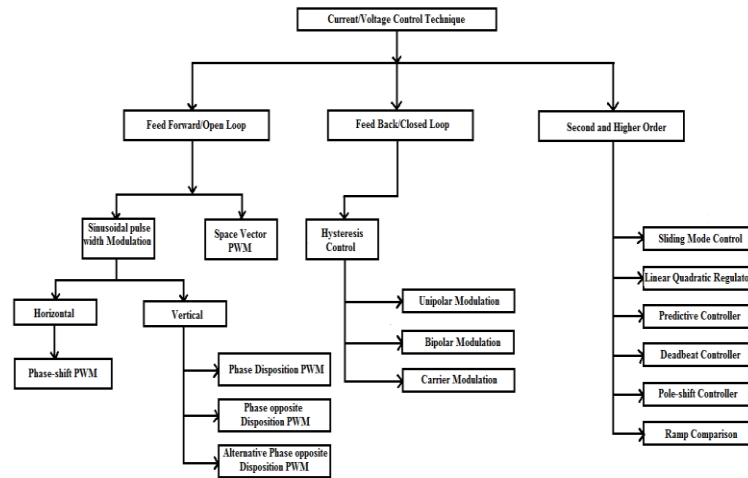

Figure 17. Classifications of Current/Voltage Control Techniques

4.2.1. Feed forward (Open-loop) methods
The feed forward method is divided into sinusoidal pulse width modulation (SPWM) and space vector pulse width modulation (SV-PWM) methods.

4.2.1.1. Sinusoidal pulse width modulation (SPWM) method
The most popular form of pulse width modulation (PWM) synthesis is the sinusoidal pulse width modulation (S-PWM) [20], [47], [77], [80-82], [107], [111], [112], [117], [125], [126], [130], [203], [205], [207]. In an S-PWM scheme the modulating signal is sinusoidal and carrier signal is a triangular wave. The magnitude of these two signals is compared to generate firing pulses which in turn is used to control the inverter. To increase the performance of multilevel inverter based D-STATCOM, DVR and UPQC the multicarrier S-PWM control methods are generally used. The multicarrier S-PWM can be categorized according to vertical and horizontal carrier signals typically being triangular wave forms as shown in figure 17. The vertical multicarrier S-PWM techniques can be sub-categorized as (a) Phase- Disposition pulse width modulation (PD-PWM): Phase-disposition pulse width modulation (PD-PWM) technique employs a (m-1) number of carriers which are all in phase accordingly. All eight carrier waves are in phase with each other in nine-level converter [20], [110]. (b) Phase opposition Disposition pulse width modulation (POD-PWM): Phase opposition disposition pulse width modulation (POD-PWM) technique employs an (m-1) number of carriers which are all in-phase above and below the zero reference. All eight carrier waves are phase-shifted by 180º between the ones above and below zero reference in nine-level converter [20], [110]. (c) Alternative Phase Opposite Disposition pulse width modulation (APOD-PWM): This technique requires each of (m-1) carrier waveform for an m-level phase waveform to be phase displaced from each other by 180º' alternatively [20], [110]. The horizontal multi-carrier SPWM is identified as phase-shifted (PS) control techniques. This technique employs a (m-1) number of carriers, phase-shifted by 90º accordingly. All eight carrier waves are phase-shifted by 90º in nine-level converter.

4.2.1.2. Space vector pulse width modulation (SV-PWM) method
Space vector pulse width modulation (SV-PWM) is one of the popular PWM techniques used in multilevel inverters and best among all the PWM methods. In this method eight different switching combinations are possible for a three-phase three-leg (3-L) inverter based D-STATCOM, DVR and UPQC . Six active vectors (V1-V6) form the axes of a hexagon among these eight switching vectors and feed electric power to the load. Two-adjacent zero vectors

(V0-V7) are located at the origin and do not feed any power to the load [20], [27], [43], [83], [84], [70], [114], [127], [131], [202], [205], [214].

4.2.2. Feed-back (Closed-loop) methods

Most custom power devices like D-STATCOM, DVR and UPQC are operated in closed loop fashion in which they either track a specific current reference or a voltage reference or both. The hysteresis controller or bang-bang controller is the most common form of tracking control for lower order closed loop systems.

4.2.2.1 Hysteresis controller

The method of controlling a voltage source inverter (SVI) so that an output current/voltage is generated which follows a reference current/voltage waveform, known as hysteresis current/voltage control. In hysteresis current control, limit bands are set on either side of a signal representing the desired output voltage waveform. The sign reference signal wave of desired magnitude and frequency compared with the actual signal. When the signal cross the prescribed hysteresis upper limit, upper switch is turned OFF and the lower switch is turned ON. Similarly when the signal cross the prescribed lower limit, the lower switch is turned OFF and the upper switch is turned ON. Hysteresis control technique is widely used in the D-STATCOM, DVR and UPQC applications because of its ease of implementation, fast dynamic response and inherent peak current-limiting capability [20], [28], [56], [58], [59], [65],[72], [76], [86], [94], [159] [161], [165], [169], [171], [175], [183], [184], [185], [186], [187], [188], [198], [200], [201], [211], [217].

4.2.3 Second and higher order systems

First order systems are readily stabilized by proportional controllers, even when the gain approaches infinity, while many resonant systems become unstable under high proportional control.

4.2.3.1 Sliding mode controller (SMC)

Sliding mode controller (SMC) can be alleviated the need for accurate mathematical models [20], [27], [73], [94], [133]. This controller does not need accurate mathematical model, but requires knowledge of parameter variations to ensure stability. As the power electronic based custom power devices such as DSTATCOM, DVR and UPQC converters are highly variable structured, sliding mode control offers several advantages such as stability even for large supply and load variations, robustness, good dynamic response and simple implementation.

4.2.3.2 Linear quadratic regulator (LQR)

Linear quadratic regulator (LQR) consists of the two weighting matrices one Q and R whose value set by hit and trail method until satisfactory steady-state response with minimum settling time is achieved. Due to presence of wide gain margin (GM) (-60º to + ∞) and phase margin (PM) (-60º to +60º) the linear quadratic regulator control ensures the stability of closed system with robustness feature. Another important feature of the LQR is that it can tolerate the input non-linearity [20], [59], [185].

4.2.3.3 Predictive and Deadbeat controller

Predictive and deadbeat method predicts the current error vector on the basis of the actual/present error and the load parameters (R, L, C) at the beginning of each modulation period. The voltage to be generated by pulse width modulation during the next modulation period is determined to minimize the forecast error [20].

4.2.3.4 Constant switching frequency predictive algorithm

In this technique, the predictive algorithm calculates the voltage vector signals once every sampling period. This will force the current vector according to it's signal. The main disadvantage of this algorithm is that it does not guarantee the inverter peak current limit [20].

4.2.3.5 Deadbeat controllers

When the choice of the voltage vector is made in order to null the error at the end of the sample period, the predictive controller is called a deadbeat controller [20], [58], [94], [133].

4.2.3.6 Pole-shift controller

This controller produces a variable switching frequency control action and designed in such a way that the desired reference voltage, current and both are tracked accurately. This type of pole-shift control can only be used when the systems state space model is well known. For simplicity, a single phase distribution system is considered for all the system studies, but it can easily be extended to a three-phase distribution system [9], [20], [187].

5. Technical and Economical Consideration

The use of D-STATCOM, DVR and UPQC type CPD's to improve electrical power quality is reported since mid 1990s [34]. CPD's mainly D-STATCOM, DVR and UPQC have been developed with high performance, more functionalities and low costs. To reduced rating and enhance performance of CPD's efforts have been made for optimize the control, energy saving, reduced parts, reduced switching losses, minimum power injection, and selective harmonic elimination. The control techniques applied to DSTATCOM's, DVR's and UPQC's will play most important role to alleviate/mitigate the PQ problems. So optimizing the control techniques and executing multifunctional control are the main research trend. The CPD's provide maximum amount of real power to the load is a deciding factor in determining the capability of the device. The selection of D-STATCOM, DVR and UPQC structure for practical applications is most significant task for scientists and engineers. The main design considerations for proper selection of CPDs are: manufacturing cost level, current and voltage distortion level, dv/dt stress level, power rating and output voltage level.

6. Conclusion

A comprehensive review and discussion on the D-STATCOMs DVRs and UPQC's to enhance the electrical power quality at utility grid has been reported in this paper. The extensive review and classification of topologies\configurations and control techniques of compensating type CPDs provide compensating solution to different PQ disturbances. With the required features, customers can select a particular compensating device (D-STATCOM, DVR and UPQC). This exhaustive review on DSTATCOM, DVR and UPQC will be useful reference guide to the users, manufacturers and researchers working in the field of PQ improvement using CPDs.

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