2

Review of Literature

This chapter discusses the research work reported in literature in the field of power quality, PQ detection techniques, PQ improvement techniques, distribution static compensator and PQ issues in the utility grid interfaced with RE sources. Identified research gaps are also presented at the end of chapter.

2.1 INTRODUCTION

With the integration of renewable energy sources to the distribution grid to meet out increasing electrical energy demand, it is expected that electrical power systems deliver power supply at high quality to the consumers [Thapar et al., 2004]. Voltage or current abnormalities in power delivery with the RE generation lead to huge losses to the economy of a country [Dugan et al., 1996]. PQ disturbances increase the risk of blackout; especially because of the failure of interdependencies between sub-networks and associated dynamical propagations. To prevent these issues customers are willing to invest in the on-site equipments to ensure higher level of quality supply such as Uninterrupted power supply (*UPS*) and stabilizers even though these are very costly [Flores, 2002]. It shows the importance of power quality towards economic distribution of the energy. Renewable energy integration and smart transmission systems cause problems such as harmonics, flicker, voltage sag/swell, voltage regulation, load unbalancing and deviations in phase as well as frequency. Several solid-state electronic/power-electronic devices have been developed, studied and proposed to the international scientific community with the goal of improving supplied power quality in last two decades [Brenna et al., 2009]. Harmonics and power sinusoids modulated by low frequency signals are also observed in electrical networks due to sudden changes in the operating conditions such as load disturbances, network contingencies, and output of renewable energy sources [Sharon et al., 2008], [Kwan et al., 2012]. This causes increased operational and planning complexity of electricity supply networks which requires increased attention for quality of power supply [Teke et al., 2011]. The PQ events need to be monitored and mitigated to maintain standard of supply and economic operating conditions. In complex and large power systems, during operations, huge amount of measured PQ events data make analysis difficult for monitoring programs. Therefore, a smart tool and methodology is required for detection and classification of this data for clear and smart understanding to the utilities, regulators and customers about the operating requirements under sudden change of operating conditions [Zhang et al., 2011]. In this regard, feature extraction and classification are the most important part of the generalized PQ event classification system where PQ events detection requires the feature extraction from the disturbances. To make analysis more effective, a set of better features should be available to report the disturbance signal efficiently [Brenna et al., 2009]. Thereafter, this set of extracted features can be used for classification process. The detected PQ disturbances are mitigated with the help of mitigation techniques such as filters, UPQC, DSTATCOM etc. The detailed study of the PQ detection methods, PQ mitigation techniques and DSTATCOM will help to design an universal technique for the PQ assessment and mitigation in the distribution network with RE sources.

This chapter presents brief review of literature reported in the field of power quality detection techniques, PQ improvement techniques, DSTATCOM as a tool for power quality improvement and PQ issues in the distribution network with RE sources. At the end of chapter identified research gaps are presented which have been addressed in this work.

2.2 DETECTION OF PQ DISTURBANCES

According to IEEE standard 1159-1995 [Group et al., 1994], the PQ disturbances include a wide range of PQ phenomena namely transient (impulsive and oscillatory), short duration variations (interruption, sag and swell), frequency variations, long duration variations (sustained under voltages and sustained over voltages) and steady state variations (harmonics, notch and flicker) with a time scale which ranges from tens of nanoseconds to steady state. Inigo Monedero *et al.* [Monedero et al., 2007] defined PQ disturbances based on Spanish association for standardization (*UNE*) standard in Spain as given in Table 2.1. IEEE Std. 1459-2010 [Std.1459-2000, 2010] includes definitions for measurement of electric power quantities under sinusoidal, non-sinusoidal, balanced, and unbalanced conditions. In [Alfonso-Gil et al., 2013], authors presented an IEEE Std. 1459 power magnitude measurement system working as part of a PQ improvement structure. The variation of the voltage or current or frequency from normal characteristics can damage or shut down the critical electrical equipments designed for specific purpose. Such variations happen in electrical networks with a great frequency due to a competitive environment and continuous change of power supply [Dugan et al., 1996], [Darrow et al., 2005]. In highly evolved electrical system PQ sensitive demands can be classified as (i) digital economy (such as banking, share market and railways), (ii) continuous process manufacturing industries and (iii) fabrication and essential services. Cost incurred to operate all the above types of loads vary from 3 to 120 per kVA per event [Darrow et al., 2005]. This is huge and greatly affects economic operation of power industries. To mitigate PQ issues, customers are also equipped with some back-up instruments apart from grid supply [Kezunovic and Liao, 2002]. PQ events classifier and reported techniques for PQ detection and classification are detailed in the following subsections. A detailed literature review of PQ recognition techniques is provided by Mahela and Shaik in [Mahela et al., 2015].

Table 2.1 : PQ Disturbances Classification Based on UNE Standard

Type	Disturbance Type		Time	Range	
				Min. value	Max. value
Frequency	Slight Deviation		10s	49.5Hz	50.5Hz
	Severe Deviation			47.0Hz	52.0Hz
Voltage	Average Voltage		10min	0.85Un	1.1Un
	Flicker		-	-	7 %
	Sag	Short	10ms-1s	0.1U	0.9U
		Long	1s-1 min		
		Long-time disturbance	>1min		
	Under voltage	Short	<3min	0.99 U	
		Long	>3min		
	Swell	Temporary Short	10ms-1s	1.1U	1.5kV
		Temporary Long	1s-1min		
		Temporary Long-time	>1min		
		Over voltage	<10ms		6 kV
Harmonics and other information signals	Harmonics		-	THD>8%	
	Information signals		-	Included in other disturbances	

2.2.1 Power Quality Events Classifier

Before 1990s some manual configurations were used for monitoring and managing the quality of power supply due to lack of signal processing and intelligent techniques advancement. The decision was based on the operator/expert intuition to maintain quality within a certain range. As technology evolved, smart signal processing techniques (such as pattern-recognition, data mining, internet-networking and artificial intelligence) with intelligent instruments (such as computers, digital signal processors, mass storage, information and communications) are adopted time to time. A basic block diagram of PQ event classifier is given in Fig. 2.1 [Saxena et al., 2010]. Disturbance signal is passed through the pre-processing unit having two function blocks: segmentation and feature extraction. Extracted features of the disturbances are passed through processing unit for classification. Finally, the post processing unit gives an actual decision regarding the type of disturbance.

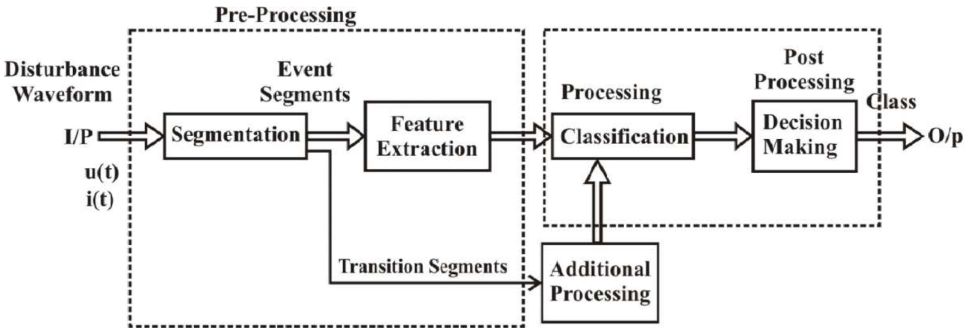

Figure 2.1 : Block diagram of power quality event classifier

(a) Segmentation

Segmentation divides the data sequence into stationary and non-stationary parts [Barros et al., 2012]. Events are the segments in between transition segments. Feature is extracted from the event segments because the signal is stationary and normally contains the information that is unique enough to distinguish among different types of disturbances. To capture the disturbance waveform period, a triggering method is required to get start and end time instant of PQ event [Bollen and Gu, 2006]-[Gunal et al., 2009]. The current methods used for detecting PQ disturbances are based on a point-to-point comparison of adjacent cycle or a point-to-point comparison of the Root mean square (*RMS*) values of the distorted signal with its corresponding pure signal and/or frequency domain transformed data. The recent methods proposed for this purpose are classified as parametric (or model based) and non-parametric (or transform based). The parametric methods include techniques such as Kalman filter (*KF*) and Auto-regressive (*AR*) models while non-parametric techniques include short-time Fourier transform (STFT) and wavelet transform (WT) [Ribeiro et al., 2004].

(b) Feature Extraction

Feature extraction from PQ disturbances is also known as detection of disturbances. The commonly used feature extraction techniques include Fast Fourier transform (*FFT*), short time Fourier transform (STFT), Stockwell transform (*ST*), Hilbert Huang transform (*HHT*), Wavelet transform (WT) and Gabor transform (*GT*). The best known technique for frequency domain analysis is the Fourier transform (FT), where it represents a signal as sum of sinusoidal terms of different frequencies [Karimi et al., 2000]. FT is suitable for stationary signals and extracting spectrum at specific frequencies, however it is unable to resolve any temporary information associated with fluctuations [Axelberg et al., 2007]. One variant of FT, the short time Fourier transform (STFT) divides the signal into small segments where each segment can be assumed to be stationary

[Granados-Lieberman et al., 2011]. In this regard, STFT determines the sinusoidal frequency and phase contents of local sections of signal as they change over time. Also, it extracts several frames of signals to be analysed with a window that moves with time. With a moving window, the relation between the variance of frequency and time can be identified [Dash et al., 2003a]. It is difficult to analyse non-stationary signals with STFT [Gu and Bollen, 2000], however it has been applied to non-stationary signals when operating in a fixed window size [Wright, 1999]. Discrete STFT is used for time-frequency analysis of non-stationary signals. It decomposes the time-varying signals into time-frequency domain components [Jurado and Saenz, 2002]. Discrete Fourier transform (*DFT*) represents the discrete signals that repeat themselves in a periodic fashion from negative to positive infinity whereas fast Fourier transform (FFT) gives exactly same result as the DFT in much less time [Huang et al., 1999]. The S-transform is a time-frequency tool generated by the combination of WT and STFT [Rodriguez et al., 2011]. It produces a time-frequency representation of a time series. It uniquely combines a frequency-dependent resolution that simultaneously localizes the real and imaginary spectra. The basic function for the S-transform is Gaussian modulated co-sinusoids [Dash et al., 2003b]. In case of non-stationary disturbances with noisy data, the S-transform provides patterns that closely resembles the disturbance type and thus requires a simple classification procedure [Lee and Dash, 2003]. The Hilbert Huang transform (HHT), a novel signal processing algorithm was proposed in 1998 by Dr. Huang which consists of two distinct processes [Yang et al., 2010]. The signal to be analysed is decomposed using the Empirical mode decomposition (*EMD*) process into Intrinsic mode function (*IMF*) that have meaningful instantaneous frequencies and amplitudes. The EMD decomposes the signal into IMFs in such a way that the IMFs are sorted from the highest frequency to the lowest frequency. Once the signal is decomposed into IMFs, the Hilbert Transform can then be applied to each IMF giving the instantaneous amplitude and instantaneous frequency versus time curve. This combination of EMD process and Hilbert transform is known as the HHT [Afroni et al., 2013]. The wavelet transform (WT) is a mathematical tool, much like FT, that decomposes a signal into different scales with different levels of resolution by dilating a signal prototype function. The WT is based on a square-integral function and group theory representation. The WT provides a local representation (in both time and frequency) of a given signal. Therefore it is suitable for analysing a signal where time-frequency resolution is needed such as disturbance transition events in power quality [Santoso et al., 1997]. The WT is classified in to discrete wavelet transform (DWT) and Continuous wavelet transform (*CWT*) [Angrisani et al., 1998]. Computational efficiency of major power quality disturbance detection techniques to detect PQ disturbances is given in Table 2.2. The comparison of main PQ disturbance analysis methods is detailed in Table 2.3.

(c) Classification

Extracted features are used to classify the PQ events. Thereafter, the classifier's information is used to make the final decision through post-processing unit [Saxena et al., 2010]. The selection of suitable features of PQ events is extremely important for classification. Features may directly be extracted from the original measurement either from some transformed domain or from the parameters of signal models [Ji et al., 2011]. The artificial intelligent techniques are used to classify the PQ events. A broad definition of artificial intelligence (AI) can be the automation of activities that are associated with human thinking such as decision making, problem solving, learning, perception and reasoning [Ibrahim and Morcos, 2002]. AI techniques such as support vector machine (SVM), NN based techniques, Fuzzy expert system, neuro-fuzzy system, genetic algorithm and Fuzzy logic are the commonly used classification techniques.

Foundation of the Support Vector Machine (SVM) has been developed by Vapnik [Vapnik, 2013], where statistical learning theory being the basis provides a new pattern recognition approach. SVMs are a set of related supervised learning methods used for classification and regression. They belong to family of generalized linear combiners [Khasnobish et al., 2011]. Neural

Table 2.2 : Computational Efficiency of PQ Detection Techniques

Sr. No.	PQ Disturbance	Percentage Efficiency of PQ Detection Techniques			
		HHT [Shukla et al., 2009]	ST [Shukla et al., 2009]	DWT [Masoum et al., 2010b]	FFT [Abdel-Galil et al., 2005]
1	Sag	100	100	98.67	95
2	Swell	100	100	99.33	98
3	Harmonics	95	100	99.33	100
4	Flicker	100	100	98.67	89
5	Notch	100	83	97.33	-
6	Spike	95	77	-	-
7	Transient	98	100	98.67	100
8	(1+3)	98	100	98.18	-
9	(2+3)	89	100	98.18	-
10	(1+7)	-	-	96.36	-
11	(2+7)	-	-	98.18	-

Table 2.3 : Comparison of Main Methods of PQ Disturbances Analysis

Sr. No.	Method	Advantages	Disadvantages
1	STFT	Successfully used for stationary signals where properties of signals do not evolve in time. Simple in implementation	Not suitable for non-stationary signal as it does not track signal dynamics properly due to limitation of fixed window width.
2	HHT	Useful in feature extraction of distorted waveform, generates quadrature signal by which instantaneous amplitude and phase can be easily evaluated	Limited only for narrow band conditions
3	ST	Fully convertible from time domain to 2-D frequency translation domain and then to Fourier frequency domain.	Based on block processing manner, does not satisfy real-time requirement, incorrect measurement of harmonics due to dependency of frequency window width on central frequency
4	WT	Provide local representation in both time and frequency. Therefore, suitable where good time-frequency resolution is required.	Strongly influenced by noise present in the signal, suffering from spectral leakage and picket fence effects
5	GT	It has high signal to noise ratio and good time-frequency resolution	Use limited at high frequencies, computational complexity is directly associated with sampling frequency

networks (NN) represent the promising new generation of information processing systems. They are good at tasks such as pattern matching, classification, function approximation, optimization and data clustering [Khasnobish et al., 2011]. The classification and function approximation capabilities of artificial neural networks (ANN) have been employed in power quality studies, fault, and harmonics source classification. Fuzzy classification system is based on Mamdani type rules to evaluate the information provided by the linguistic variable inputs [Chacon et al., 2007]. Fuzzy logic (*FL*) refers to a logic system that generalizes the classical two-valued logic for reasoning under uncertainty. It is motivated by observing that human reasoning can utilize concepts and knowledge that do not have well defined or sharp boundaries [Yen and Langari, 1999]. Fuzzy expert system (*ES*) is an expert system that uses a collection of fuzzy sets and rules instead of Boolean sets for reasoning about data [Liao and Lee, 2004]. Neuro-fuzzy based methods have advantages of handling any kind of information, manage imprecise, partial and vague or imperfect information. These methods also have advantages to resolve conflicts by collaboration and aggregation, self-learning, self-organizing and self-tuning capabilities. Further, there is no need of prior knowledge of relationship of data, mimic human decision making process and fast computation using fuzzy number operations [Ajil et al., 2010]. Genetic algorithm (*GA*) is a search algorithm based on the mechanics of natural selection and natural genetics. It combines survival of the fittest among string structures with a structured yet randomized information exchange to form a search algorithm with some of the innovative flair of human search [Holland and Goldberg, 1989]. The GA is considered to be an excellent intelligent paradigm for optimization using a multipoint, probabilistic, random and guided search mechanism [Levitin et al., 2000]. The strength and weakness of different AI techniques for power quality disturbance classification are analysed and presented in Table 2.4. The comparison of different power quality disturbances classification methods is provided in Table 2.5.

Table 2.4 : Strength and Weakness of AI Techniques

Sr. No.	Attributes	AI Techniques					
		NN	ANN	SVM	FL	GA	ES
1	Uncertainty tolerance	⋆⋆⋆	⋆⋆⋆	⋆⋆⋆⋆	⋆⋆⋆	⋆⋆⋆	⋆⋆
2	Imprecision tolerance	⋆⋆⋆	⋆⋆⋆	⋆⋆⋆⋆	⋆⋆⋆	⋆⋆⋆	⋆
3	Knowledge representation	⋆	⋆⋆⋆⋆⋆	⋆	⋆⋆⋆	⋆	⋆⋆
4	Adaptability	⋆⋆⋆	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆⋆⋆	⋆
5	Maintainability	⋆⋆⋆	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆⋆	⋆
6	Learning ability	⋆⋆⋆	⋆⋆⋆⋆	⋆⋆⋆⋆	⋆	⋆⋆⋆	⋆
7	Explanation ability	⋆	⋆⋆	⋆	⋆⋆⋆	⋆	⋆⋆⋆
8	Data mining	⋆⋆⋆	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆⋆	⋆
9	Generalised performance	⋆⋆⋆	⋆⋆⋆	⋆⋆⋆⋆⋆	⋆	⋆	⋆

AI Technique with higher number of ⋆ is more preferred for specific purpose

2.2.2 Effect of Noise on PQ Event Classifier

The signals captured by monitoring devices are often accompanied with noise thereby affecting the extraction of important features from the signal. Noise has an adverse effect on the performance of techniques used for PQ events detection, time localization and classification schemes due to the difficulty of separating noise and disturbances [Hua et al., 2007]. The disturbed components of the waveform carries the most important information for detection and classification. When PQ data is decomposed using wavelet transform most of the disturbance components are reflected at higher frequency bands which are also occupied by noise. Therefore, even if the magnitude of noise level present is not very high compared to fundamental component for many PQ disturbances it is comparable to disturbance energy at these bands. Hence, the presence of noise degrades the detection capability of PQ monitoring system [Panigrahi and Sinha, 2006].

Table 2.5 : Comparison of PQ Events Classification Methods

Sr. No.	Method	Advantages	Disadvantages
1	NN	High classification accuracy for mixed PQ disturbances	Less efficient under noisy conditions
2	ANN	High accuracy for real time applications and provides mathematical flexibility	Convergence speed and accuracy depends on the network architecture as well as noise in the signal
3	SVM	Potential to handle large features, provide stable solution to quadratic optimization, high learning processes	Poor classification accuracy when training samples are minimum
4	FL	Accurate in modelling and analysing complex systems,	Training set for every case is fixed, hence not suitable for new disturbances
5	GA	Accurately classify PQ disturbances generated due to dynamic performance of power system and damped sub-harmonic signals	High computational time
6	ES	It can be used with or without limited data	Expensive system, slow in execution, it is difficult to draw conclusion if assumptions and actual situations does not match exactly

2.3 DETECTION OF POWER QUALITY DISTURBANCES WITH RENEWABLE ENERGY SOURCES

Increased consumption of electricity and negative effects of fossil fuels have forced the utilities to use renewable energy sources. These sources are more suitable to environment and capable to cover the deficit in demand of electrical power [Kocatepe et al., 2009]. Among various types of renewable energy (RE) sources, the wind and solar energies have been promoted world-wide as the distributed generation (DG) sources at distribution level in the recent years for generation of electricity. Wind powered electric generation is an ideal energy source due to its infinite sustainability and causes no pollution. Wind energy conversion systems (WECS) are widely used across the globe due to their low cost and high efficiency. The integration of these systems to the utility grid generate variable power and voltage which in turn affects the quality of power supplied to the customers [Kaddah et al., 2016]. Solar photovoltaic (SPV) system based energy has shown very fast development in the whole world recently due to its low operating cost and causes no pollution. The unpredictable characteristics of solar radiations lead to unreliable performance of SPV system in grid connected mode of electric supply. The operational events of SPV systems influence power quality (PQ) of distribution networks. In particular, large current variations during outage and synchronization of SPV system can lead to significant voltage transients [Mohanty et al., 2013].

PQ disturbances such as flicker, harmonics, voltage unbalance, voltage magnitude and voltage variation ratio limit the capacity of wind generation in to the utility grid [Hsu et al., 2015]. Thus, the power quality assessment plays an important role in deciding the levels of RE penetration. The power quality requirements laid by IEC standards include a flicker-emission level <4%, limit for step change in voltage <3%, range of voltage fluctuations <4% and harmonic distortions <5% at point of common coupling (PCC) with wind energy [61400-21, 2006; Saqib and Saleem, 2015]. Power quality disturbances remain within the limits when the wind generators are connected to strong utility grid. In case of weak grids (in terms of its fault level or short circuit strength), these disturbances may exceed limits laid by IEC standards. Therefore, there is a need to perform detailed analysis of PQ events associated with the wind energy penetration into the weak grids. A number of case studies have been reported in literature considering various aspects such as a type of generator, type of wind turbine, designs of grid side and rotor side converters of the doubly-fed induction generator (DFIG), seasonal variations of wind speed. Ray *et al.* [Ray et al., 2012], presented the assessment of power quality disturbances associated with the RE sources in the events of environmental changes by simulation studies. Power quality assessment due to sudden changes of load in the presence of solar photovoltaic (PV) and wind generators has been reported in [Ray et al., 2014]. Detection of the power quality disturbances due to nature of environmental changes such as variation in solar insolation and wind speed of the hybrid power system are reported in [Ray et al., 2013]. Hsu *et al.* [Hsu et al., 2015], presented the detection of PQ disturbances such as steady state voltage variations, reverse power flow, flicker, short circuit current and harmonics associated with a wind power generation system integrated to a practical radial distribution feeder. The power quality study of a wind farm installed in Hatay region has been presented in [Yildiz et al., 2015].

Power quality problems such as harmonics, voltage regulations, reactive power, reverse power flow and power factor limit the capacity of solar photovoltaic (PV) generation into the utility grid [Patra et al., 2016]. A distribution system shows passive characteristics in terms of unidirectional power flows from generating station to loads. Integration of the solar PV generators into the utility network changes this behaviour/characteristics and power might flow backwards if large number of solar PV systems are connected to a feeder. This may lead to increase in voltage at the point of common coupling (PCC) [Alam et al., 2013]. Increased penetration level of solar PV energy into the utility network also affects the power quality such as voltage level, continuity of supply, voltage flicker and total harmonic distortions [Han et al., 2012]. However, the introduction of limited amounts of solar PV generation into the distribution network is beneficial in terms of voltage profile improvement and postpone the investment related to feeder capacity up-gradation [Farhoodnea et al., 2013], [Ray et al., 2012]. With the increasing solar PV penetration level on the same feeder, the power quality disturbances may cause operating problems to the utility grid. Thus, the assessment of power quality plays an important role in deciding the levels of solar PV energy penetration. Power quality events may cause the solar PV inverter to reject the grid. Such rejection may prevent operation of the solar PV generator because the inverter monitors the voltage, frequency and impedance. Deviations outside the range of pre-defined parameters might lead to shut-down [Urbanetz et al., 2012]. Therefore, PQ disturbances need to be monitored and mitigated to maintain the supply as per standards. A number of case studies have been reported in literature considering various aspects such as type of solar PV plates, design of converters of solar PV system, seasonal variations of solar insolation. Rodriguez *et al.* [Ruiz-Rodriguez et al., 2015], investigated the voltage unbalance sensitivity for different sizes of a single-phase SPV with different penetration level in a practical distribution feeder of Spain. This helps the operators to define the optimal limits. The power quality events associated with the design constraints of two different types of inverters used for the integration of solar PV system to the utility grid has been detailed in [Patra et al., 2016]. Silva *et al.* [Silva et al., 2016], investigated the effect of grid connection of solar PV system on the power quality indices (PQI) of a distribution network. PQ disturbances such as long term voltage variations and voltage unbalance have been analysed in detail. A transient model of solar PV system which can be utilized for the power quality studies has been presented in [Patsalides et al., 2016]. Plangklang *et al.* [Plangklang et al., 2016], presented a simulation based study on the measurement of PQ disturbances such as voltage sag, swell, frequency, THD and voltage ripple associated with a rooftop solar PV system integrated to the utility grid of Thailand.

Significant research is reported in the field of power quality issues due to design of converters used for grid integration of solar PV system. However, a small quantum of articles are available on the power quality events due to the operations of solar PV system such as grid synchronization, outage and variations in solar insolation. Power quality assessment of 3-phase grid connected solar PV system with single and dual stage circuits has been presented in [Patra et al., 2016]. Rahmani *et al.* [Rahmani et al., 2015], presented an advanced universal power quality conditioning system and hybrid maximum power point tracking (MPPT) method to interface solar PV systems to the power system network addressing power quality.

2.4 POWER QUALITY IMPROVEMENT

The passive filters, active filters, hybrid filters, unified power quality conditioner (UPQC), static var compensator (SVC), distribution static compensator (DSTATCOM), dynamic voltage restorer (DVR) are widely used terminologies in the area of power quality improvement [Goswami et al., 2011]. These proposed techniques have made it possible to mitigate power quality disturbances in the view point of both utility and consumers. DSTACOM is widely used for power quality improvements. It is basically a voltage source converter based power electronic device [Chidurala et al., 2013]. It helps in minimizing the effects of poor load power factor, load harmonics, unbalanced loads and dc offset in loads. Distributed generation (DG) and Superconducting magnetic energy storage (*SMES*) devices have also been used for PQ mitigation in addition to the above mentioned technologies. The detailed study of PQ improvement techniques has been presented by Mahela and Shaik in [Mahela and Shaik, 2016b].

2.4.1 Power Quality Improvement Using Filters

Filters play an important role in harmonics mitigation, reactive power compensation, load balancing, neutral current compensation, reducing flickers, compensations related to voltage sags and swells [Singh et al., 1999]. The filters are classified into three categories namely passive, active and hybrid filters.

(a) Passive Filters

The passive filters are simplest and most economical counter measure against harmonics related problems in the electrical power supply. These consist of different combinations of inductors and capacitors. The filtering of particular harmonic component from the supply depends on the topology of filter and values of inductance and capacitance used. The various designing techniques reported in the literature include series filter, shunt filter, single tuned filter, double tuned filter, low pass filter, high pass filter, band pass filter, LCL filter, and LLCC filter [Cha and Vu, 2010]. The passive filters have drawbacks such as large size, resonance and tuning problems [Akagi and Fujita, 1995]. The limitations of passive filters have been overcome by the use of Quasi passive filter (*QPF*) proposed in [Mahanty, 2008]. Circuit diagram of the proposed QPF is shown in Fig. 2.2. The QPF comprises of a parallel and series tuned LC tank circuit. It utilises AC capacitor (C) which is realised by two DC capacitors, two diodes and two power semiconductor switches. The parallel tank circuit formed by inductor (L_1) and C is tuned at the fundamental frequency to block the whole line frequency. The shunt passive filter formed by C and inductor (L_2) provides a low impedance path for harmonic frequency currents and tuned at third harmonic. The proposed QPF is effective in overcoming the limitations of shunt passive filters.

(b) Active Filters

The active power filters (APFs) consist of power electronic switching devices and passive energy storage elements such as inductors and capacitors. These are also known as Active power line conditioner (*APLC*), Active power quality conditioners (*APQC*), and instantaneous reactive power compensator (IRPC) [Singh et al., 1999]. The active filters intend to provide compensation

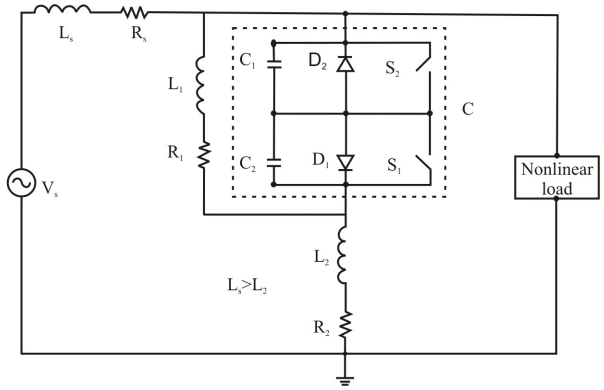

Figure 2.2 : Circuit diagram of quasi passive filter

for voltage harmonics, voltage unbalance to the utilities as well as current harmonics and current imbalance to the consumers. These active power filters provide mitigation of harmonic disturbances of voltage and current, voltage notch, sudden voltage distortion, transient disturbances and power factor improvement effectively in medium power applications [Chaoui et al., 2010], [Paice, 1996]. Depending on the type of load connected to the supply systems, APFs are basically classified in to three configurations namely two-wire (single phase), three-wire (three-phase without neutral), and four-wire (three-phase with neutral) [Mikkili and Panda, 2013]. Depending on the connections with the supply systems, the APF topologies can be classified as series, shunt and combinations of both [P and Mahapatra, 2012]. The combination of series and shunt APFs is known as unified power quality conditioner (UPQC). The current fed type APF is used to meet the harmonic current requirement of nonlinear loads. This type of APFs have the drawbacks of higher losses and requirement of higher values of ac power capacitors. The voltage fed type shunt active filter is used for elimination of current harmonics, reactive power compensation and balancing currents. The series APF connected near the load end using a matching transformer is used to eliminate voltage harmonics. It also helps in balancing the terminal voltage of the load and voltage regulation. It has also been used to reduce negative sequence voltage and voltage regulation in the three-phase systems.

(c) Hybrid Filters

Hybrid filters (HF) are the combinations of passive and active filters. Use of the low cost passive filters along with high performance APFs provide cost effective solution for harmonic compensation and voltage regulation [Wu et al., 2012]. Hybrid filters are classified in to three categories namely single-phase [Vlatkovic et al., 1996], three-phase three-wire [Jintakosonwit et al., 2002], and three-phase four-wire [Barrero et al., 2003]. The single-phase hybrid filters are further classified in to passive-passive [Vlatkovic et al., 1996], passive-active [Rastogi et al., 1995], and active-active [le Roux and Mouton, 2001]. The three-phase three-wire hybrid filters are again classified in to the same categories as passive-passive [Gonzalez and McCall, 1987], passive-active [Cheng et al., 1998], and active-active [Jintakosonwit et al., 2002]. Similarly, three-phase four-wire hybrid filters are also further classified in to passive-passive [Syafrudin et al., 2002], passive-active [Rodriguez et al., 2002], and active-active [Barrero et al., 2003].

2.4.2 Power Quality Improvement Using UPQC

Unified power quality conditioner (UPQC) is a combination of series and shunt active filters aimed to mitigate several power quality disturbances simultaneously [Forghani and Afsharnia, 2007]. It is also known as universal APF. Moran [Moran, 1989], proposed a system in which series and shunt APFs were connected back to back with dc reactor. Fujita *et al.* [Fujita and Akagi, 1998], has proposed back to back topology of series and shunt APFs for the first time and verified with experimental set-up and named it as unified power quality conditioner (UPQC). UPQC is used in distribution system similar to unified power flow controller (UPFC) used in transmission system [Hingorani and Gyugyi, 2000]. UPQC is proved to be successful in mitigating PQ events such as voltage sag, swell, unbalance, harmonics, flicker and for load current problems such as unbalance, neutral current, reactive current, harmonics [Khadkikar, 2012]. The UPQCs are classified based on voltage sag compensation and physical structure. Converter topology based classification includes Current source inverter (*CSI*) [Melín et al., 2010] and Voltage source inverter (*VSI*) [Karanki et al., 2010] based UPQCs. Control strategy plays an important role in the performance of UPQC in PQ mitigation. UPQC control strategy decides the switching instants of power switches as per reference signals. The control methods are available in both time and frequency domains. The three-phase *pq* theory or instantaneous active and reactive power control theory [Akagi et al., 1984] and three-phase *dq*0 transformation or synchronous reference frame theory [Bhattacharya and Divan, 1995] are the commonly used time domain control techniques.

2.4.3 Power Quality Improvement Using FACTS Devices

FACTS technology is based on power electronics devices. It is used to meet the challenges in power industry. Originally, FACTS based devices were implemented in the transmission networks. However, similar possibilities have now been explored for applications in the distribution networks. FACTS have been proved successful in protecting sensitive loads from voltage sag, transients, and damping oscillations [Goswami et al., 2011]. FACTS have been used for mitigation of voltage sag [Milanovic and Zhang, 2010], and harmonics [Haghighat et al., 2003]. Performance of FACTS has been reported in literature for PQ improvement in case of grid connected wind energy systems [Patel et al., 2012] and V2H battery [Sharaf and Khaki, 2011]. A dynamic voltage restorer (DVR) is used for power quality mitigation against voltage sag, swell and harmonics in grid voltage [Babaei and Kangarlu, 2012]. Applications of static compensator (STATCOM) for PQ improvement are reported in [Mohod and Aware, 2010]. A Distribution static synchronous series compensator (*DSSSC*) aimed at mitigating many power quality problems such as voltage sag, swell, flickers and harmonic compensation has been proposed in [Qader, 2015]. Performance of the DSSSC is evaluated using Proportional Integral (PI) and quadratic controllers.

2.4.4 Power Quality Improvement using Distribution Static Compensator

A static synchronous compensator (STATCOM) with a coupling transformer, an inverter, and energy storage device used in distribution system is called DSTATCOM and has configuration as the STATCOM [Naderi et al., 2013]. A DSTATCOM can be used effectively to meet the specifications for utility connection due to its capability of filtering the load currents. This device can be used to cancel the effect of poor load power factor, harmonic currents in loads, unbalanced loads and dc offset in loads. This device can also be used to mitigate voltage sag and voltage flicker effectively. DSTATCOM also proved to be effective for reactive power compensation, voltage regulation, neutral current compensation, harmonic elimination, current harmonic compensation, and balancing of nonlinear as well as linear loads. Mahela and Shaik provided the detailed review of DSTATCOM topologies and control techniques in [Mahela and Shaik, 2015].

(a) Topologies of DSTATCOM

The DSTATCOM topologies can be classified based on the application in Three-phase three-wire (*3P3W*) and Three-phase four-wire (*3P4W*) distribution systems. Further topological classification can be based on the use of transformer for isolation and neutral current compensation, number of switching devices, type of converter, etc. Classification of the DSTATCOM topologies is shown in Fig. 2.3.

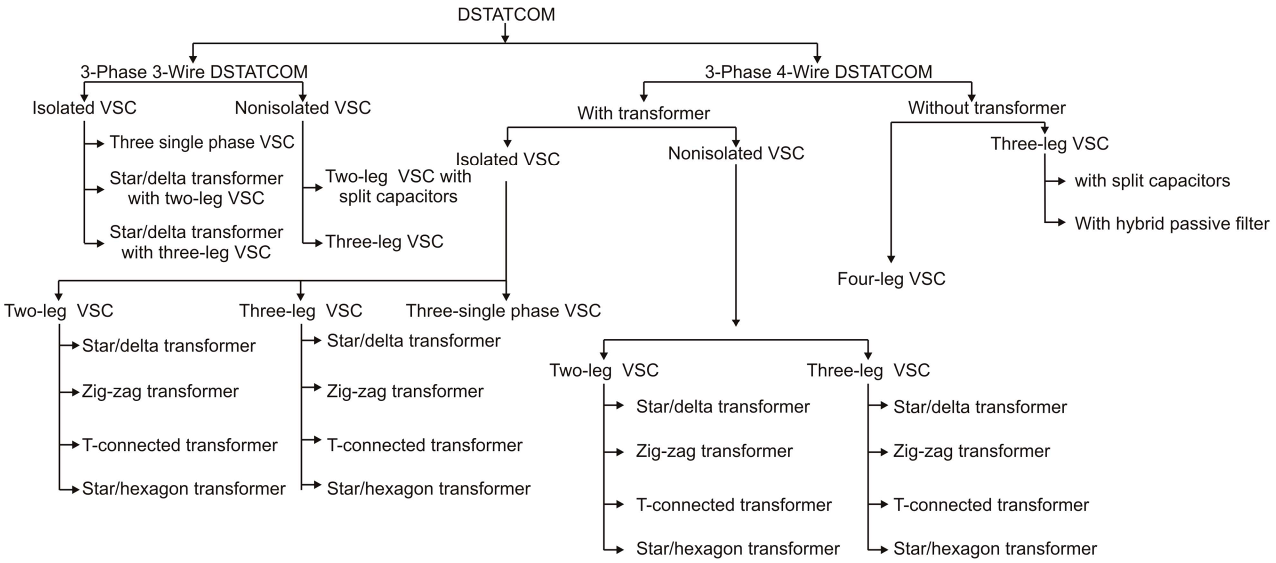

Figure 2.3 : Topological classification of DSTATCOM

Three-phase three-wire DSTATCOMs are used for reactive power compensation, harmonic elimination, PQ improvement and load balancing in 3P3W distribution system. The topologies for three-phase three-wire DSTATCOMs include isolated VSC and nonisolated VSC–based DSTATCOM. A comparative study of isolated and nonisolated VSC–based, 3P3W DSTATCOM topologies is presented in Table 2.6. The numerical data included in the table are just indicative of the approximate values of the elements. However, actual values may be different depending on the specific application.

Table 2.6 : Comparative Study of 3P3W DSTATCOM Topologies

DSTATCOM Topology	Semiconductor devices (In Nos.)	Transformer (type)	Interfacing inductance (mH)	DC bus voltage (V)	Capacitor (μf)	Transformer (kVA)
Isolated three single–phase VSC	12	3 Single-phase units	6	600	1000	2.5
Isolated three–leg VSC	6	Star/delta	2.5	700	1000	7.2
Isolated two–leg VSC	4	Star/delta	7	1400	5000	7.2
Nonisolated three–leg VSC	6	Not required	2.5	700	3000	Nil
Nonisolated two–leg VSC	4	Not required	4.3	1400	6000	Nil

T–connected, zig–zag, and star–hexagon transformers may also be used.

Three–phase four–wire DSTATCOM is used in three–phase four–wire distribution system to filter load current to meet out the specifications for the utility connection [Ananth et al., 2013]. This can be used to cancel the effect of poor load power factor (PF) such that source current has near unity PF, provide harmonic compensation in loads such that source current become sinusoidal, provide compensation for unbalanced loads such that source current become balanced, cancel dc offset in loads and for PQ improvement. The three–phase four–wire DSTATCOM topologies are mainly classified into two categories, with transformers and without transformers. A comparative study of isolated two–leg, three–leg, three single–phase VSCs-based 3P4W DSTATCOM topologies is carried out and presented in Table 2.7. Here, again also the numerical data included in the table are just indicative of approximate values of the elements. However, actual values may be different depending on specific application of the DSTATCOM.

Table 2.7 : Comparison of Isolated VSC Based 3P4W DSTATCOM Topologies

DSTATCOM Topology	Semiconductor devices	Transformer (Type)	Interfacing inductance (mH)	Dc bus voltage (V)	Capacitor (μf)	Transformer (kVA)
Two–leg VSC with star/delta transf.	4	Star/delta	3.3	400	1200	15
Two–leg VSC with T–connected transf.	4	T–connected	2.5	700	7600	12
Two–leg VSC with zig/zag transf.	4	Star/zig–zag	4	400	4000	12
Two–leg VSC with star/hexagon transf.	4	Star/hexagon	3.5	400	6600	12
Three–leg VSC with star/delta transf.	6	Star/delta	1.5	700	5500	32
Three–leg VSC with T–connected transf.	6	T–connected	2.3	400	6600	12
Three–leg VSC with zig/zag transf.	6	Star/zig–zag	2.5	400	2200	12
Three–leg VSC with star/hexagon transf.	6	Star/hexagon	1.5	200	1650	6
Three single–phase VSC	12	3 single–phase units	2.5	300	5000	5

Non–ioslated VSC–based DSTATCOM topologies using no transformer are classified as four–leg and three–leg VSC–based topology. A comparative study of different topologies of non-isolated VSC–based 3P4W DSTATCOM without transformer is provided in Table 2.8. The detailed comments are included to highlight the important aspects of each topology.

Nonisolated two–leg VSC–based 3P4W DSTATCOM topologies use star-delta, T–connected, zig–zag, and star–hexagon transformer. Two–leg VSC with split capacitor is directly connected to the three–phases of the supply system. Three–phases and neutral of the transformer winding are connected to the three–phases and neutral of the supply system respectively forming a paral-

Table 2.8 : Comparison of Nonisolated VSC–Based 3P4W DSTATCOM Topologies without Transformer

Sr. No.	Topology	N_c	N_s	Comments
1	Four–leg VSC	1	8	It uses maximum number of switches and compensate for unbalanced load currents containing dc components in 3P4W system. Fourth–leg is used for compensation of zero sequence component of load currents which need separate reference currents along with an appropriate switching control strategy for their operation. Voltage of dc bus is easier to control.
2	Three–leg VSC split Capacitor	2	6	It can compensate for unbalanced load currents in 3P4W system. The dc component of load current is not compensated. Size of capacitor is large to reduce ripple. The two dc bus capacitors increase size of the DSTATCOM. The zero sequence component of load current injected by the compensator returns at mid–point of the dc capacitor. It uses minimum number of switches.
3	Three–leg VSC with ac capacitors	2	6	It requires two dc storage devices. Voltage across each dc link capacitor is chosen as 1.6 times the peak value of source voltages. The passive capacitor has the capability to supply a part of reactive power required by the load and reduces dc–link voltage as well as switching frequency. The active filter will compensate the balance reactive power and harmonics present in the load.

: In addition to 2 dc capacitors, 3 capacitors are also used on ac side of the converter; N_c: Number of DC capacitors; N_s: Number of power electronic switches

lel arrangement with two–leg VSC [Kasal and Singh, 2008]. A comparative study of nonisolated three–leg and two–leg VSC–based 3P4W DSTATCOM topologies using transformer is provided in Table 2.9. The numerical data included are indicative only and practical values may be different depending on the specific application.

(b) Control techniques of DSTATCOM

Reactive power needed by the load is provided by the DSTATCOM and only real power is supplied by the source such that source current remains at unity PF. Load balancing is achieved by making reference source current balanced. It has real fundamental frequency component of the load current and used to decide switching of the VSC and being extracted by control techniques [Efkarpidis et al., 2014]. Different control strategies reported in literature such as Instantaneous reactive power (*IRP*) theory, Synchronous reference frame (*SRF*) theory, adaline–based control algorithm, PI controller for maintaining dc bus voltage etc. The commonly used control techniques of DSTATCOM include instantaneous reactive power (IRP) theory [Luo et al., 2014]-[Sreenivasarao et al., 2013b], Synchronous reference frame (SRF) theory [Bangarraju et al., 2014]-[Jayaprakash et al., 2012], Symmetrical component (*SC*) theory [Kumar and Singh, 2009], [Zaveri et al., 2012], Average unit power factor (*AUPF*) theory [Kummari et al., 2012], Proportional integral (*PI*) controller[Valderrábano and Ramirez, 2010]-[Liu et al., 2011], Adaline based neural network [Singh et al., 2005], [Singh et al., 2011a], Sliding mode control (*SMC*) [Gupta and Ghosh, 2006], [Gupta et al., 2010]. A comparative study of strength and weakness of different control techniques for performance and PQ improvement capability of DSTATCOM are analysed and presented in Table 2.10.

Table 2.9 : Comparative Study of Nonisolated VSC Based 3P4W DSTATCOM Topologies

DSTATCOM Topology	Semiconductor devices	Transformer (Type)	Interfacing inductance (mH)	Dc bus voltage (V)	Capacitor (μf)	Transformer (kVA)
Two–leg VSC with star/delta transf.	4	Star/delta	2.5	1400	5000	7.2
Two–leg VSC with T–connected transf.	4	T–connected	2	700	3000	5.2
Two–leg VSC with zig/zag transf.	4	Zig–zag	3.5	1400	3200	9
Two–leg VSC with star/hexagon transf.	4	Star/hexagon	2	700	3200	15
Three–leg VSC with star/delta transf.	6	Star/delta	2.5	200	1650	12
Three–leg VSC with T–connected transf.	6	T–connected	2.5	400	1650	5
Three–leg VSC with zig/zag transf.	6	Zig–zag	3.5	200	1650	7.5
Three–leg VSC with star/hexagon transf.	6	Star/hexagon	2.5	432	4000	6

2.4.5 Selection Criteria of PQ Improvement Techniques Based on Applications

The selection of PQ improvement technique which is important decision for application engineers is largely dependent on the application of consumer. The passive filters are the simplest in design and the most economical ones. However, the drawbacks include large size, resonance and tuning issues. Therefore, they are effective in mitigation of low order PQ disturbances. These are used only for general purpose and not used for specific applications. The specific application of active power filters depends on the type of supply and compensation used. The type of compensation used for PQ mitigation includes voltage, current and combination of both voltage and current based compensations. The voltage based compensation is provided using series filters and the current based compensation is provided by shunt active filters. The voltage based compensations include voltage harmonics compensation, flicker reduction, removal of voltage sags, improvement in voltage regulation and voltage balancing. The current based compensation is categorized into reactive power, current harmonics, neutral current and load balancing based compensations. Hybrid filter (*HF*) topology of active series and active/passive shunt filters are most suitable in the applications where the combination of voltage and current based compensation is needed. Potential applications of hybrid filters include AC-motor drives and power supplies. Table 2.11 gives brief summary of proper selection of active and hybrid filters for specific application.

The UPQC is a natural choice for the applications with critical power quality problems. This is effective in the removal of voltage flickers in arc furnace, transients of induction machines, fault

Table 2.10 : Comparison of DSTATCOM Control Techniques.

S.No.	Attributes	Performance of control technique						
		IRP	SRF	SC	AUPF	PI Controller	NN	SMC
1	Reactive power compensation	Partial	Good	Excellent	Excellent	Partial	Good	Excellent
2	Harmonic mitigation	Good	Good	Better	Excellent	Good	Good	Excellent
3	Load balancing	Excellent	Average	Excellent	Good	Good	Excellent	Excellent
4	Source neutral current elimination	Excellent	Good	Good	Good	Average	Good	Good
5	Computational complexity	High	Average	Simpler	High	Average	Simpler	High

Table 2.11 : Selection of Active and Hybrid Filters for Specific Applications

Sr. No.	Specific application	Type of filter			
		Active series filter	Active shunt filter	Hybrid filter of active series and passive shunt	Hybrid filter of active series and active shunt
1	Voltage harmonic compensation	✓		✓	✓
2	Voltage flicker reduction	✓	✓		✓
3	Removing voltage sags	✓	✓	✓	✓
4	Improving voltage regulation	✓	✓	✓	✓
5	Reactive power compensation		✓	✓	✓
6	Current harmonic compensation		✓	✓	✓
7	Neutral current compensation		✓	✓	
8	Improving load balancing		✓		
9	(1+4)	✓			✓
10	(1+2+3+4)	✓			✓
11	(1+4+5+6)			✓	✓
12	(1+5)			✓	✓
13	(5+6)		✓	✓	✓
14	(5+6+7+8)		✓		
15	(5+6+8)		✓		✓
16	(6+8)		✓		
17	(5+7+8)		✓		

ride through in wind farms connected to the weak networks, mitigating the voltage sag/swell, suppressing the load harmonic components under distorted supply conditions, and individual voltage and current based applications. However, the size, rating and cost of UPQC are on higher side. Flexible AC transmission system (*FACTS*) devices can be used for mitigation of power quality by using advancement in control techniques and power semiconductor devices. UPFC is nothing but a technique which combines series and shunt compensators. This technique is proved to be effective for voltage sag compensation, unbalance voltage mitigation, voltage flicker reduction and power flow control. Static synchronous compensator (*STATCOM*) is basically a reactive power compensator which is effective in voltage sag compensation. A DVR can be used for compensation of voltage harmonics, voltage sags, and voltage unbalance. Static VAR compensator (*SVC*) can be used specifically for voltage flicker reduction in the presence of fluctuating loads to reduce the hypo-synchronous oscillations and power line compensation.

(a) Selection considerations for specific application of DSTATCOM

The selection of a suitable DSTATCOM topology and control technique for its use in specific application is an important task for users. The performance of DSTATCOM depends on the control algorithm used for extraction of reference current components. Comparative study of control techniques presented in Table 2.10 is greatly helpful for selection of these techniques for specific application. Kilo volt ampere (*kVA*) rating of the transformer is a major consideration for selection of the transformer for specific application [Singh et al., 2008b]. A comparative study of different ratings of transformers is given in Table 2.12 and advantages and their disadvantages are given in Table 2.13 which will be helpful in selection of transformer based topology of DSTATCOM for particular application. The star/delta transformer is natural choice because it is simple in design and commonly available in market but has disadvantage of higher rating. Zig–zag transformer has the lowest rating followed by T–connected transformer and with highest rating for star/delta and star/hexagon transformers. The converter topological considerations such as 3P3W, 3P4W, isolated and nonisolated, with and without transformer are critical. Comparative study provided in Tables 2.10 and 2.12 to 2.14, is greatly helpful for topological considerations of the DSTATCOM for particular application.

Table 2.12 : Comparison of Transformers Used for Neutral Current Compensation

Type of transformer	Winding voltage (V)	Winding current (A)	kVA	Number of Transformers (Nos)	Space requirement	Is it a standard transformer	Is it induce circulating currents in the secondary winding	Cost of the compensator
Zig–zag	$\frac{V_l}{3} : \frac{V_l}{3}$	$\frac{I}{n}$	$\frac{V_l I_n}{3}$	3	Low	No	No	Low
Star–delta	$\frac{V_l}{\sqrt{3}} : \frac{V_l}{\sqrt{3}}$	$\frac{I}{n}$	$\frac{V_l I_n}{\sqrt{3}}$	3	High	Yes	Yes	High
T–connected	$\frac{V_l}{\sqrt{3}} : \frac{V_l}{2\sqrt{3}} : \frac{V_l}{2\sqrt{3}}$, $\frac{V_l}{2} : \frac{V_l}{2}$	$\frac{I}{n}$	$(\frac{1}{3\sqrt{3}} + \frac{1}{6})V_l I_n$	1 1	Lowest	No	No	Lowest
Star hexagon	$\frac{V_l}{\sqrt{3}} : \frac{V_l}{\sqrt{3}} : \frac{V_l}{\sqrt{3}}$	$\frac{I}{n}$	$\frac{V_l I_n}{\sqrt{3}}$	3	Highest	No	Yes	Highest

V_l: Line-to-line voltage; $\frac{I}{n}$: Neutral current

Table 2.13 : Advantages and Disadvantages of Transformers Used for Neutral Current Compensation

Type of transformer	Advantages	Disadvantages
Zig–zag	It provides passive compensation, rugged, and less complex over the active compensation techniques. It has the advantages of reduction in load unbalance and reducing the neutral current on the source side. It has lowest kVA rating.	Performance of zig–zag transformer is dependent on the location close to the load. Performance of reducing the neutral current on the source side is affected during the conditions of distorted and unbalanced voltages.
Star–Delta	Easily available in market, simple design, less costly. Star connected primary winding offers low impedance path for zero sequence currents. The delta connected secondary winding provides a path for the induced zero sequence currents to circulate	Its compensation characteristics depend on the impedance of the transformer, location, and source voltage. It will not completely compensate for the neutral current. High kVA rating.
T–connected	Transformer is small in floor space, low in height, and with a lower weight than any other types of transformers. It uses two single–phase transformers which make the core economical to build and easy to assemble. It can be regarded as open–circuit for the positive and negative sequence currents, hence current flowing through the transformer is only zero–sequence component.	Ratings of the transformer depend on the amount of load imbalance and harmonic content. Its compensation characteristics depend on the imbalance of the transformer, location, and source voltage. Impedance offered for the zero–sequence current is a function of the zero–sequence impedances of the utility system.
Star–hexagon	Star connected primary winding provides a low impedance path for the zero–sequence harmonic currents and hexagon connected secondary winding provides a path for the induced zero sequence currents. It can reduce zero sequence harmonic current to a large extent.	It will not completely compensate for the zero sequence currents. Its compensation characteristics depends on the impedance of the transformer, location, and source voltage. It has complex design, high cost, and not easily available. It has highest kVA rating.

2.4.6 Techno-Economical Considerations of PQ Improvement Techniques

Passive filters are the traditional filters used as harmonics improvement devices in the distribution network at the load side. They are economical but do not perform satisfactorily in the presence of dynamic nonlinear loads [Seifossadat et al., 2008]. The technical literature on APFs is available since 1971 [Sasaki and Machida, 1971]. APFs are commercially developed since 1990. Modern APFs are capable of compensating upto 25^{th} harmonics dynamically. These filters having power ratings upto 1000-kVA are available commercially. Initially the cost of APFs was quite high but it has come down due to reduction in the cost of its components namely power switching devices and controllers. Hence, the uses of APFs have become economical now a days. The hybrid filters technology has been developed at matured level which not only compensates for nonlinear loads but also provides quality AC power supply to the critical loads. The development in magnetics has caused the reduction in losses, size and cost of these filters. The application of UPQC to improve the power quality has been proposed in mid 1990s [Peng et al., 1990]. Technology to develop UPQC for commercial purposes is available today. However, the overall high cost and complexity imposes limitations in its wide accepted applications for PQ improvement. The FACTS technology which was basically developed for enhancement of transmission capability has attracted the researchers and designers for their use in distribution system for power quality improvement and reactive power compensation. A technical and economical comparison of power quality improvement techniques has been carried out and provided in the Table 2.14.

Table 2.14 : Technical and Economic Comparison of PQ Improvement Techniques

Attributes	PQ improvement technique				
	Passive filter	Active filter	Hybrid filter	DSTATCOM	UPQC
Reactive power compensation	Poor	Good	Good	Excellent	Excellent
Harmonic suppression	Fixed	Adjustable	Fixed	Adjustable	Adjustable
Resonance	May exist	No	No	No	No
Load compensation	Not provided	Not provided	Not provided	Excellent	Good
Power rating of power converter	-	High	Small	Highest	Small
Power converter switches	-	6	4, 6	4, 6, 12	4, 6, 8, 12, 18, 24
Total cost	Lowest	High	Moderate	*High**	*Highest**

*: Cost depends on the number of switches used in the converter

2.5 POWER QUALITY IMPROVEMENT IN UTILITY GRID INTEGRATED WITH RE SOURCES

The distributed generation also helps in improvement of PQ when applied with proper control technique for interfacing converters. Utilization of available additional capacity of interfacing converters and coordination between DG units would also help in the improvement of PQ. A substantial work is reported on PQ improvement using DG in multi unit power plants [Platero et al., 2010] and LV networks [Mienski et al., 2004]. Some more DG based techniques include automated factories with DG combined in heat and power mode [Moreno-Munoz et al., 2010], optimal allocation of DG in distribution network [Borges and Falcao, 2006], small wind farm comprising of both fixed and variable speed wind turbines [Sarkhanloo et al., 2012], and multi-function DG inverter [Singh et al., 2011b]. The utilization of additional available capacity of DG inverters for harmonic and unbalance mitigation has been reported in [Gajanayake et al., 2009]. Utilization of DG interface to mitigate unbalance, harmonics and voltage flicker has been presented by the authors in [Gajanayake et al., 2009].

Implementation of the DSTATCOM, addressing power quality improvement, for specific applications such as isolated wind power generation, residential low voltage network, load compensation, isolated asynchronous generator, standalone solar photovoltaic system and water pumping system has been reported in the literature. However, very less number of articles are available for implementation of DSTATCOM at grid level addressing PQ improvement specifically with renewable energy sources. Ghosh *et al.* [Ghosh and Joshi, 2004], proposed a DSTATCOM with battery energy storage system for voltage regulation in the mini custom power park. The voltage flicker mitigation of electric arc welder has been achieved using DSTATCOM with BESS and reported in [Virulkar and Aware, 2008]. Improvement of load voltage for a constant speed wind energy system supplying the power to inductive load has been achieved with the help of Fuzzy logic based control of DSTATCOM in [Bhattacharjee et al., 2012]. Alka *et al.* [Singh et al., 2012], proposed the DSTATCOM for compensation of linear and non-linear loads in both steady state and dynamic conditions. The self-charging control technique of DSTATCOM for mitigation of voltage sag, swell and momentary interruption has been proposed in [Woo et al., 2001]. Power quality improvement with wind energy system has been presented by the authors in [Yuvaraj et al., 2011]. Implementation of the DSTATCOM using adaptive neural network based control algorithm for harmonic suppression, load balancing and voltage regulation in isolated distributed generation system is presented in [Arya et al., 2014b]. Shahnia *et al.* [Shahnia et al., 2014], described the application of DSTATCOM for circulation of surplus power in distribution network with distributed generation (DG) sources. A DSTATCOM using solar photovoltaic (PV) system in parallel with the dc-link capacitor for reactive power compensation, neutral current compensation, and harmonic reduction is reported in [Kannan and Rengarajan, 2012]. PQ improvement using DSTATCOM with BESS in distribution network due to grid disturbances and wind energy penetration is reported in [Mishra and Ray, 2016]. DSTATCOM for power quality improvement in the islanded mircogrid operation is reported in [Srivatchan et al., 2015].

2.6 IDENTIFIED RESEARCH GAPS

Based on the critical reviews of the articles cited in this chapter it has been observed that following are the main research gaps which needs to be explored. These identified research areas have been considered for the research work presented in this thesis.

- The reported literature only focusses on the disturbances due to design constraints of the converter, turbine and wind generator where wind generator operational part is missing which needs to be investigated. The power quality disturbances associated with the outage of wind generator, grid synchronization of wind generator, islanding of test system from utility grid and wind speed variations needs to be explored. The effect of high wind energy penetration level on the power quality are also to be investigated.

- The research work on the power quality issues related to converters of solar PV systems have been reported significantly. However, a very less number of articles are available on the power quality events in the solar PV integrated power systems due to the system operations such as sudden integration and outage of solar PV generators, and impacts of environmental characteristics on power quality. Hence, the PQ events associated with grid synchronization and outage of solar PV generator as well as due to sudden change in solar insolation are also to be investigated. Effect of high solar energy penetration level on the power quality needs to be investigated.

- The investigation of power quality events associated with the operational part of wind generator, solar PV system and islanding in the hybrid power system is missing which needs to be addressed.

- Power quality improvement techniques are not available for the improvement of PQ disturbances at grid level in the events of outage and grid synchronization of the RE generators.

- Implementation of the DSTATCOM, addressing power quality improvement, for specific applications such as isolated wind power generation, residential low voltage network, load compensation, isolated asynchronous generator and water pumping system has been reported in the literature. However, very less number of articles are available for implementation of DSTATCOM at grid level addressing PQ improvement specifically with wind energy. Hence, there is a need to investigate the possibilities for the implementation of custom power devices such as DSTATCOM at grid level for PQ improvement in the utility grid in the presence of wind energy generation.

- Very less number of articles are available for application of DSTATCOM at grid level specifically addressing PQ improvement in the presence of solar PV system. Reported literature only focuses on the PQ disturbances due to design constraints of converters used for grid integration of solar PV systems and solar PV plates where solar PV operational part is missing. Hence, there is a need to investigate the possibilities for the implementation of DSTATCOM with battery energy storage system (BESS) in three-phase distribution network with solar PV penetration addressing PQ improvements during the solar PV operations such as grid synchronization and outage. Power quality improvement during the event of sudden change in solar insolation is also to be investigated.

- A small quantum of articles are available on the application of DSTATCOM for the improvement of power quality with renewable energy (RE) sources in hybrid power system. Hence, there is a need to investigate the possibilities for the implementation of DSTATCOM with battery energy storage system addressing PQ improvement in the hybrid power system integrated with solar PV system and wind generator. Power quality improvement with operations of wind and solar PV generators such as grid synchronization and outage in the hybrid power system are to be investigated.

2.7 CONCLUSIONS

According to developed review, it can be concluded that commonly used techniques for detection of PQ disturbances are WT, ST, FT and HHT whereas the commonly used classification techniques of PQ events are ANN, SVM, GA, ES, and FS. Comparative study of these techniques will help in selecting particular technique for specific application. The passive filters, APF, Hybrid filters, UPQC and DSTATCOM are commonly used PQ improvement techniques. DSTATCOM is highly effective for improving PQ at distribution voltage level and has advantage of making stable voltage. Users can select the most appropriate technique with required features to suit a particular application. The commonly used DSTATCOM topologies are isolated and nonisolated 3P3W, isolated two–leg and three–leg 3P4W, nonisolated three–leg/two–leg with and without transformer. The commonly used control techniques of DTSTACOM are SRF, IRP, SC, PI controller, SMC, NN, and AUPF. A comparative study presented will help the users in selecting the particular topology and control technique of DSTATCOM that suit for specific application. The techniques reported in the literature for the recognition and mitigation of power quality issues with RE sources in the distribution network are also presented in detail. Based on the proposed review, the research gaps on the topic of PQ issues with the RE sources have been identified. Based on the presented review suitable techniques for the PQ detection and mitigation in the events of islanding, outage and grid synchronization of wind and solar PV systems have been selected.

…