1
Introduction

1.1 POWER QUALITY

Recently, the power quality has become a relevant concern for utilities and customers to identify the cause of disturbances for protection of the equipments [Khokhar et al., 2015]. Power quality problem (PQ) is defined as any problem manifested in voltage, current, or frequency deviations that results in failure or misoperation of customer equipments [Dugan et al., 2004]. To evaluate the possibility of measuring and quantifying the performance of power system, the International electro technical commision (*IEC*) defines PQ in the standard IEC 61000-4-30 [Electromagnetic Compatibility (EMC), 2003] as: Characteristics of electricity at a given point on an electrical system, evaluated against a set of reference technical parameters. The Institute of electrical and electronics engineers (*IEEE*) standard 1100 [IEE, 1992] defines power quality as: The concept of powering and grounding sensitive equipments in a matter that is suitable to the operation of that equipment. Power quality covers a wide variety of steady-state and transient electromagnetic phenomenon such as voltage sag, swell, momentary interruption, harmonics, oscillatory transient, impulsive transient, notch, spike, flicker and unbalance [Biswal et al., 2012]. Simultaneous occurrence of two or more such disturbances is called a complex PQ disturbance. The power quality disturbances in a voltage waveform are shown in Fig. 1.1. Power quality (*PQ*) disturbances related to both current and voltage such as poor voltage regulation, high harmonics current burden, load balancing, poor Power factor (*PF*), excessive neutral current, voltage flicker, sag, swell, momentary interruption, notch and spike degrade the quality of electrical power [Mishra et al., 2008]. The commonly observed power quality disturbances with their parameters are provided in Table 1.1. PQ disturbances are due to the widely spread use of computers and data processing loads, energy efficient lamps, variable speed drives, solid state switching devices, non-linear loads, power electronically switched loads, data processing equipments, industrial plant rectifiers and inverters as well as power system faults. The use of microprocessor based controllers and devices in large number of complicated industrial processes also affect power quality [Uyar et al., 2009]. Further, the penetration of renewable energy (RE) into the electrical network also affects the quality of power [Fu et al., 2012]. Operations of RE sources such as outage, synchronization and islanding also affect the quality of power supplied. Power quality problem might cause damage or incorrect operation of equipments installed in the grid as well as end user equipments [Rampinelli et al., 2015]. The presence of poor power quality may cause overheating of lines, mal-operation of protective equipments, computer data loss, inaccurate metering, premature ageing of equipment and appliances, motor failures, interference with communication systems and reduced efficiency of appliances [Masoum et al., 2010a]. The sources and causes of PQ disturbances must be known before initiating appropriate mitigation action. This requires the fast and reliable detection, localization, classification and monitoring of such disturbances.

1.2 RENEWABLE ENERGY SOURCES

Renewable energy (*RE*) sources such as wind and solar PV power are very good solution to provide alternative energy to overcome the global energy problem. Further, the development in grid integration technologies, for these resources during the last decade, has increased the use of RE sources [Tsengenes and Adamidis, 2011]. Research work proposed in this thesis is focussed

Table 1.1 : PQ Disturbances in Power System

S. No.	Category	Typical spectral content	Typical duration	Typical voltage magnitude
1.0	Transients			
1.1	Impulsive transients			
1.1.1	Nanosecond	5-ns rise	<50 ns	
1.1.2	Microsecond	1 μs rise	50 ns-1 ms	
1.1.2	Millisecond	0.1 μs rise	>1 ms	
1.2	Oscillatory transient			
1.2.1	Low frequency	<5 kHz	0.3-50 ms	0-4 pu
1.2.2	Medium frequency	5-500 kHz	20 μs	0-8 pu
1.2.3	High frequency	0.5-5 MHz	5 μs	0-4 pu
2.0	Short duration variations			
2.1	Instantaneous			
2.1.1	Interruption		0.5-30 cycles	<0.1 pu
2.1.2	Sag (dip)		0.5-30 cycles	0.1-0.9 pu
2.1.3	Swell		0.5-30 cycles	1.1-1.8 pu
2.2	Momentary			
2.1.1	Interruption		30 cycles-3 s	<0.1 pu
2.1.2	Sag (dip)		30 cycles-3 s	0.1-0.9 pu
2.1.3	Swell		30 cycles-3 s	1.1-1.4 pu
2.3	Temporary			
2.1.1	Interruption		3 s-1 min	<0.1 pu
2.1.2	Sag (dip)		3 s-1 min	0.1-0.9 pu
2.1.3	Swell		3 s-1 min	1.1-1.2 pu
3.0	Long duration variations			
3.1	Interruption, sustained		>1min	0.0 pu
3.2	Under voltages		>1 min	0.8-0.9 pu
3.3	Over voltages		>1 min	1.1-1.2 pu
4.0	Voltage unbalance		Steady state	0.5-2%
5.0	Waveform distortion			
5.1	DC offset		Steady state	0-0.1%
5.2	Harmonics	$0-100^{th}$ harmonic	Steady state	0-20%
5.3	Interharmonics	0-6 kHz	Steady state	0-2%
5.4	Notching		Steady state	
5.5	Noise	Broadband	Steady state	0-1%
6.0	Voltage fluctuations	<25 Hz	Intermittent	0.1-7%
7.0	Power frequency variations		<10 s	

on the detection and mitigation of power quality disturbances in the presence of wind and solar energy in the utility grid. Hence, wind power generation and solar PV system are briefly described in the following subsections.

1.2.1 Wind Energy Conversion System

Recently wind power generation has been noted as the most growing technology with developments in megawatts capacity wind turbines, power electronics and large power generators [Jain et al., 2015]. Wind energy conversion system (*WECS*) has become widely used RE source in

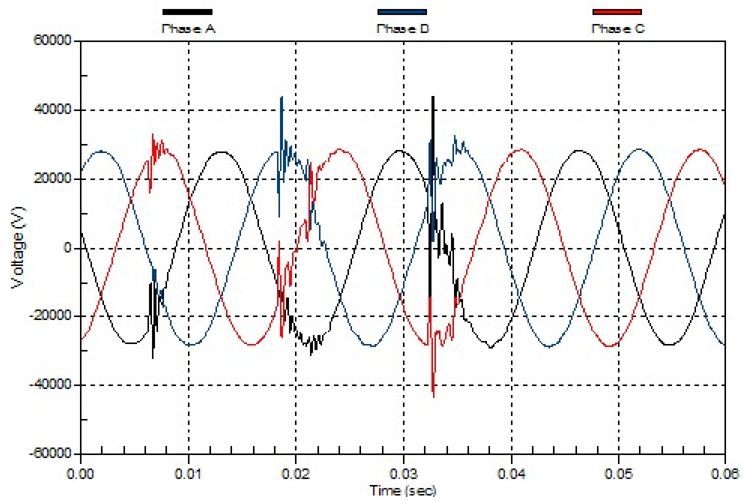

Figure 1.1 : Power quality disturbances in voltage waveform

many countries for generating green, clean and sustainable electrical power due to their low cost and high efficiency. Wind power can reduce power losses, improve voltage profile, defer or eliminate system upgrades, reduce on-peak operating costs and mitigate environmental pollution [Wei et al., 2013]. Currently the cumulative global installation of WECS has exceeded 280 Giga watt (*GW*) [Islam et al., 2014] and by the end of 2020, the installed capacity is expected to be around 1900 GW [Shahbazi et al., 2011]. Development of power electronic converters and high performance controllers make it possible to integrate large wind power generation to the utility grid [Ramirez et al., 2012]. However, the intermittent and uncertain nature of wind power prevents the wind power plants to be controlled in the same way as conventional bulk units [Delfino et al., 2012]. A detailed review of various aspects of wind energy conversion system has been provided by Mahela and Shaik in [Mahela and Shaik, 2016a].

A wind energy conversion system converts kinetic energy of the wind into mechanical energy by means of wind turbine rotor blades which is converted to electrical power by generator and is being fed to the utility grid through power electronic converters [Alaboudy et al., 2013]. The wind plant collector design working group of IEEE divides WECSs based on electric generator, utilised Power electronic converter (*PEC*), behaviour during disturbances and speed [Saleh et al., 2014]. However, manufacturers classify as WECS with and without PEC. The WECS without PEC is mostly based on Squirrel-cage induction generator (*SCIG*) and operated in direct connection to the host grid as shown in Fig. 1.2. A capacitor is used to supply the reactive power. Design optimisation of directly grid-connected permanent magnet synchronous generator based WECS without PEC has been reported in [Potgieter and Kamper, 2015]. A typical WECS with PEC based on Doubly-fed induction generator (*DFIG*) is shown in Fig. 1.3. It has mechanical parts such as aerodynamic system with rotor blades and drive train system, electrical parts which include generator and power electronic converters, control circuitry for control of crowbar, pitch angle, generator torque, power optimisation, frequency, converter etc. [Tourou and Sourkounis, 2014; Bertašienė and Azzopardi, 2015]. Behaviour of the WECS can be defined by wind speed, the mechanical speed of shaft, converter parameters and current injected into the grid [Urtasun et al., 2013]. A DFIG based WECS with PEC has been used in the proposed study due its wide applications in the wind power plants.

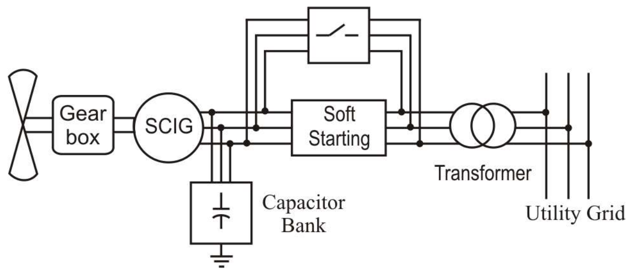

Figure 1.2 : Wind energy conversion system without PEC

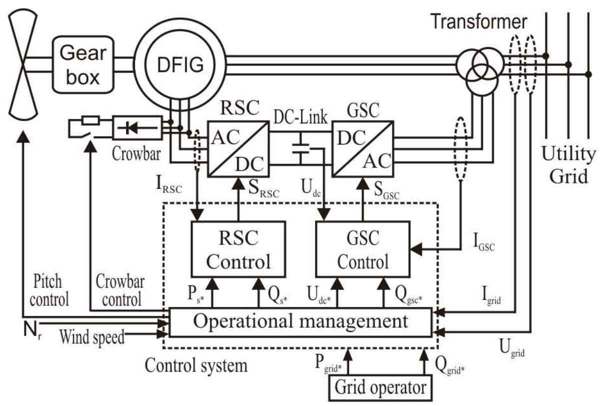

Figure 1.3 : DFIG based wind energy conversion system with PEC

1.2.2 Solar PV System

Solar Photovoltaics (*PV*) system has also become a promising RE source due to its capability of generating electricity in a very clean, quiet, and reliable way. The PV systems are solar energy supply systems, which either supply power directly to an electrical gazette in its stand alone mode or feed energy into the utility electricity grid in its grid-connected mode [Libo et al., 2007]. Grid-connected solar PV (*GCPV*) systems include Building integrated PV (*BIPV*) systems and terrestrial PV (TPV) systems. Terrestrial PV (*TPV*) systems include plants in desert, tide, and saline-alkali land [Widén et al., 2010]. The major elements of a grid-connected solar PV system are shown in Fig. 1.4. A detailed review of solar PV technologies has been provided by Mahela and Shaik in [Mahela and Shaik, 2017]. The unbalance in three-phase currents fed to the supply system by solar PV system depends on unbalancing on three phases of the grid connected solar PV system [Chicco et al., 2014]-[Mishra et al., 2018].

A solar cell consists of a p-n junction fabricated in a thin layer of semiconductor like a p-n junction diode. Its operational characteristics are also same as p-n junction diode and depend on the solar radiations as well as surface temperature [Kuo et al., 2013]. An electrical equivalent circuit of a solar cell can be represented by a single or double diode model [xian Lun et al., 2015]. Although the double-diode model is more accurate under certain operating conditions, the single diode equivalent model has simplicity with sufficient accuracy [Uoya and Koizumi, 2015], and allows for the development of explicit models [Psarros et al., 2015]. The output power from a single PV cell is relatively small. The required voltage and power is produced by grouping the PV cells in series and parallel forming the modules. Modules are combined to form PV panels. These panels are connected together to build up the entire PV array and any desired current-voltage charac-

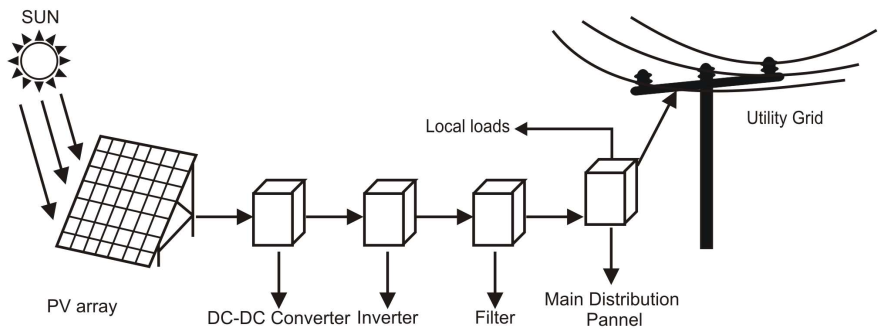

Figure 1.4 : Grid-connected solar PV system

teristics could be generated [Koutroulis and Blaabjerg, 2012; Manna et al., 2014]. As the cost of PV panels production is continuously decreasing due to advances in the material and PV array fabrication technology, it is expected that the solar bulk power generation will be competitive with other forms of RE sources [Mancilla-David et al., 2012]. A filter consisting of inductance and capacitance is used between inverter and the grid. The filter is designed to reduce higher-order harmonics introduced due to PWM modulation of the DC/AC converter [Zanasi and Cuoghi, 2011]. The solar power generation has the problem of low conversion efficiency of the solar cells, and the output power of PV array is dependent on irradiation and temperature. Therefore, Maximum power point tracking (*MPPT*) circuitry should be used for utilization of the PV array at full efficiency [Zhou and Sun, 2015]. The solar PV systems have relatively low voltage output characteristics and demand high step-up voltage gain for grid integration. This is achieved by the use of high efficient DC-DC converters for such practical applications [Al-Saffar and Ismail, 2015]. These converters are able to interface different level inputs and combine their advantages to feed the different level of outputs for solar PV applications [Rehman et al., 2015]. The inverter converts Direct current (*DC*) power to Alternating current (*AC*) power through a solid state switching action used to feed energy generated by a solar PV generator into the utility grid. High efficiency of these converters is a major requirement [Engel et al., 2009]. Solution to control the power injected into the grid are essential for effectiveness of the system. In the real and reactive power control system, the real power output reference is a function of the incident solar irradiance and temperature of the pn diode junction. Reactive power output reference is selected based on the system rating and adopted voltage regulation scheme [Ajala and Sauer, 2014]. Analysis of optimal photovoltaic (PV) array and inverter sizes for a grid-connected solar PV system in Saudi Arabia is presented in [Ramli et al., 2015]. A single-stage solar inverter using hybrid active filter with power quality improvement is proposed in [Mariappan et al., 2014]. A control structure based on Proportional resonant (*PR*) controller for grid-connected solar PV using LCL filter with zero steady-state error and selective harmonic compensation is proposed by the authors in [Zue and Chandra, 2006].

1.2.3 RE Sources Based Hybrid Power System

To meet out the growing demand of energy, the solar PV systems and wind energy conversion system are integrated to the existing power networks to form the hybrid grids. A modern day renewable energy sources based hybrid power system is shown in Fig. 1.5. This network is supplying power to the consumers, the centralized generating stations and RE sources are integrated to the system and the data communications technology is deployed for fast data transfer for the purpose of operation. The major RE sources integrated to existing utility network to form hybrid power system include wind energy, solar photovoltaic (PV) system and fuel cell. The proposed study is carried out using IEEE-13 bus test system modified by integrating wind and solar energy to form hybrid power system network.

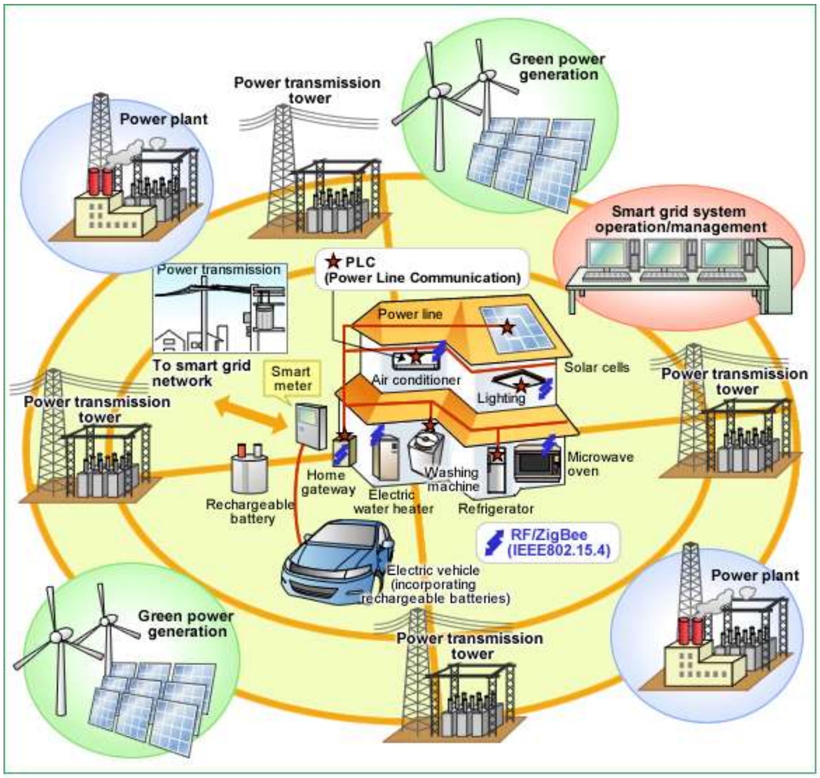

Figure 1.5 : Renewable energy sources integrated hybrid power system

1.3 POWER QUALITY EVENTS IN THE UTILITY GRID WITH RE SOURCES

Integration of the RE sources into the utility grid presents technical challenges in terms of high penetration level of the RE sources into the utility grid. These systems influences the power quality, degrade system reliability, affects grid stability and cause over voltages and safety issues [Adhikari et al., 2013]. Increase in the penetration level of Distributed generation (*DG*) sources like wind, solar, and fuel cell into the utility grid increases the power quality problem [Somayajula and Crow, 2014]. The environmental characteristics such as change in solar insolation and wind speed variations largely affects the voltage signals in the hybrid power system creating power quality disturbances like voltage sag and swell. Further, the increased penetration level of RE sources also deteriorates power quality [Demirdelen et al., 2017]. Power quality disturbances limit the penetration level of RE sources into the utility grid. It imposes severe impacts at the time of outage and grid synchronization of the RE sources. This has motivated to work on the detection and mitigation of power quality disturbances associated with the grid integrated RE sources so as to achieve the high penetration level of RE into the utility grid to meet out the increasing demand of electrical power.

Integration of wind energy into the existing distribution and transmission networks presents technical challenges in terms of stability, voltage regulation, reliability, protection and PQ problems. Harmonic distortions, voltage unbalance, voltage sag, voltage swell, notch, momentary interruption and flicker are detected as power quality disturbances associated with wind energy penetration [Abrantes, 2012]. Power quality issues associated with this energy are determined on the basis of measurements and standards laid by the IEC standard, IEC-61400 [Mohod and Aware, 2010]. Harmonics is one of the PQ disturbance which affect the performance of DFIG based wind generators the most [Xu et al., 2015]. A large number of inverters are connected to the utility network due to the increasing penetration of solar PV systems which affect 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. This can also postpone the investment related to the feeder capacity up-gradation [Farhoodnea et al., 2013; Ray et al., 2012]. Power quality events may cause the 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]. A brief description of the power quality detection and mitigation techniques reported in the literature which are found to be effective for power quality detection and mitigation in the RE sources based utility network is provided in the following subsections.

1.3.1 Recognition of Power Quality Disturbances

Power system is deterministic in nature due to the well defined characteristics of the generators, transmission lines, transformers, protection equipments and end use customers equipments. However, there are events in the power system such as power quality disturbances, islanding, outage and grid synchronization of RE sources which are not deterministic in nature. The term outage indicates a sudden unexpected disconnection of renewable energy generators from the utility grid network. The sudden disconnection may be due to short circuit fault on the generator. It may be due to the faulty event in the utility grid network. It may also be due to manual tripping of the wind and solar PV generators from the utility grid for the purpose of maintenance, management of frequency and any other operational reason. Hence, outage indicates only type of switching event of opening the circuit breaker used to integrate RE generators to the utility grid. Islanding indicates the scenario of power system operation in which a part of the utility grid is disconnected from rest of the network where renewable energy sources tries to meet out local demand of power in isolated part of the utility network. The soft computing techniques are most suitable to investigate these events. The detection of operational events such as islanding, outage and synchronization of RE sources will help to take mitigation action for the power quality disturbances associated with these events. Digital signal processing and artificial intelligent techniques have been used for the effective recognition of PQ disturbances even in the presence of RE sources. The frequency-time domain algorithms are needed for detection and classification of PQ disturbances because these methods have benefits compared to the frequency domain algorithms such multi-resolution capability, variable window size, precise localization of PQ disturbances, effective in analysing both stationary and non-stationary signals [Medina et al., 2013]-[Ramos and Serra, 2009]. The Fourier transform (*FT*) and Short time Fourier transform (*STFT*) have been used for power quality recognition without much success and efficiency. STFT does not track the power quality signal dynamics due to the fixed window size limitation [Biswal et al., 2012]. Wavelet transform (*WT*) provides a local representation of signal in both time and frequency. It provides short window at high frequency and long window at low frequency that closely monitors the nature of non-stationary signal. The WT is suitable for analysing the signal where time-frequency resolution is needed such as disturbance transition events in power quality disturbances [Santoso et al., 1996]. However, its capabilities are significantly degraded under noisy environment [Rodriguez et al., 2012]. The Stockwell transform has the ability to accurately detect the PQ disturbances even in the noisy environment. The *S*-transform is a spectral localization technique that combines the elements of both WT and STFT. It is based on a moving and scalable localizing Gaussian window having characteristics superior to both WT and STFT. The Gaussian window dilates and translates providing frequency dependent resolution [Dash et al., 2003b]. An algorithm based on Discrete wavelet transform (*DWT*) and wavelet networks for recognition of single stage and combined PQ disturbances has been presented in [Masoum et al., 2010a]. Classification of the PQ disturbances is a pattern recognition problem.

Artificial intelligent (*AI*) techniques such as support vector machine (SVM), Neural network (*NN*) based techniques, Fuzzy expert system, neuro-fuzzy system, genetic algorithm and Fuzzy logic are the commonly used classification techniques. A technique for recognition of the single stage and multiple PQ disturbances using *S*-transform based Artificial neural network (*ANN*) classifier and decision tree is proposed in [Kumar et al., 2015]. The artificial intelligent techniques such as neural network [Uyar et al., 2009], ANN [Kumar et al., 2015], Probabilistic neural network (*PNN*) [Mishra et al., 2008], Fuzzy C-means (*FCM*) clustering and adaptive Particle swarm optimization (*PSO*) [Biswal et al., 2009], Support vector machine (*SVM*) [Lin et al., 2008], rule based decision tree [Zhang et al., 2011], and binary feature matrix method [Nguyen and Liao, 2009] have been reported in literature for classification of PQ disturbances. These signal processing techniques have been utilised for the recognition of PQ events associated with the RE sources based power system. The flow diagram showing the necessary steps for the evaluation of PQ disturbances in the utility grid is shown in Fig. 1.6.

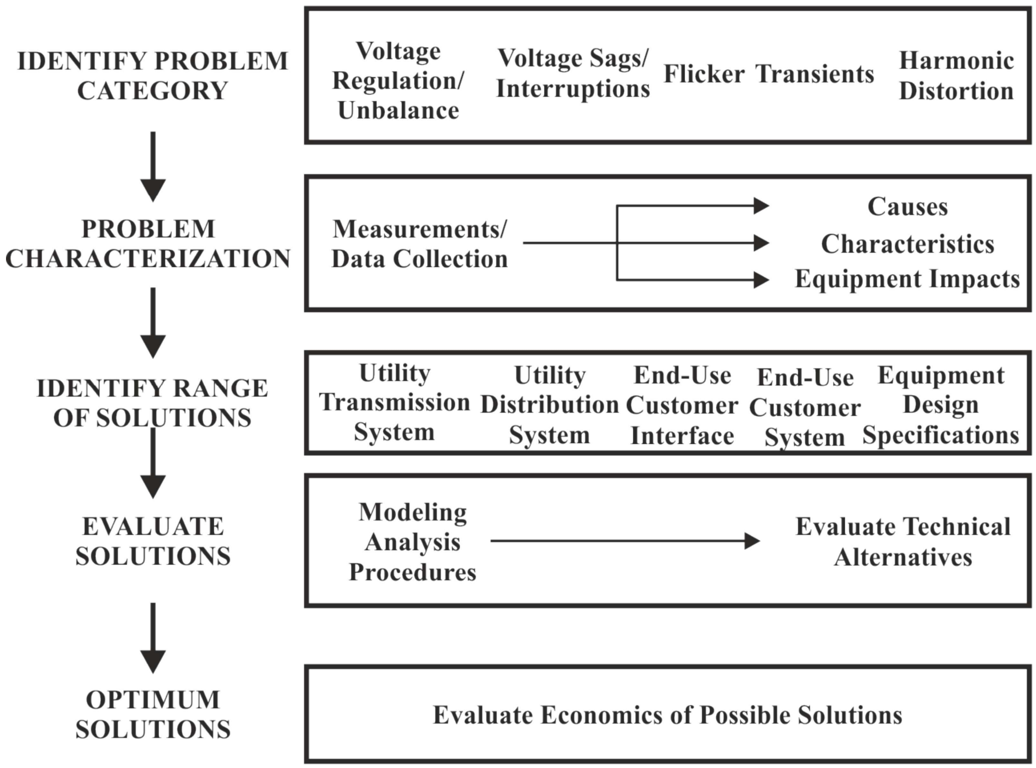

Figure 1.6 : Flow diagram for evaluation of PQ disturbances

Islanding is a scenario in which utility grid is disconnected in the event of network disturbances where RE sources tries to meet out local demand of power. This leads to PQ problems and may cause serious damage to RE sources if utility power is wrongly restored. This requires early detection of event to provide anti-islanding protections. Islanding detection methods are classified into active and passive types. Passive methods are based on selection of appropriate threshold. Reported passive methods are based on total harmonic distortions (THD) and voltage unbalance which have their own demerits. A method for detection of islanding and PQ disturbances in distributed generation based hybrid power system has been proposed in [Ray et al., 2011]. Hsu *et al.* [Hsu et al., 2015] investigated the impacts of a large wind power generation system on the distribution system. The classification of islanding and PQ disturbances in grid connected DG sources based hybrid power system using modular PNN and SVM has been proposed by the authors in [Mohanty et al., 2013]. Heideri *et al.* [Heidari et al., 2013], proposed a method for islanding detection based on the analysis of transient state signals in the hybrid power system with DG penetration.

Classification of PQ disturbances using decision tree and chemotactic differential evolution based fuzzy clustering has been reported in [Biswal et al., 2012]. Based on the merits and demerits of the PQ recognition techniques as discussed above, the *S*-transform, Fuzzy C-means clustering and rule-based decision are selected as the tools for the detection and classification of PQ disturbances and operational events. A brief overview of these techniques with their merits is provided in the following subsections.

(a) Stockwell Transform

The Stockwell transform (ST) is conceptually a hybrid of short-time Fourier analysis and wavelet analysis containing elements of both but falling in different category. It was proposed in 1996 by R. G. Stockwell. The *S*-transform performs MRA of a time varying signal while retaining the absolute phase of each frequency. It uses window whose width varies inversely with frequency. This gives high time resolution at high frequency and high frequency resolution at low frequency [Ray et al., 2012]. Since most of the PQ disturbances are non-stationary in nature, the *S*-transform can effectively be applied to extract the features. The *S*-transform is an invertible time-frequency spectral localization technique that combines elements of the WT and STFT. Output of the *S*-transform is a complex matrix of size $n \times m$ called *S*-matrix. Rows and columns of the *S*-matrix corresponds to frequency and time respectively. Each column represents frequency components present in the signal at a particular time. Each row represents the magnitude of a particular frequency with time in terms of samples from 0 to $N-1$. From the *S*-matrix important information in terms of magnitude, frequency and phase can be extracted. Magnitude contour is locus of the maximum values of *S*-matrix at a particular time. To calculate phase from *S*-matrix, the regions of maximum amplitude are determined and corresponding phase at these points is calculated. Frequency content of signal is also derived from the *S*-matrix and presented as frequency contour [Panigrahi et al., 2009].

The *S*-Transform of a function $h(t)$ is defined as CWT with a specific mother wavelet multiplied by phase factor

$$S(\tau,d) = W(\tau,d)e^{i2\pi f\tau} \tag{1.1}$$

where mother wavelet is defined as

$$w(t,f) = \frac{|f|}{\sqrt{2\pi}}e^{-\frac{t^2f^2}{2}}e^{-i2\pi ft} \tag{1.2}$$

Final form of the continuous *S*-transform is given by the relation

$$S(\tau,f) = \int_{-\infty}^{\infty} h(t)\frac{|f|}{\sqrt{2\pi}}e^{-\frac{(\tau-t)^2f^2}{2}}e^{-i2\pi ft}dt \tag{1.3}$$

Width of the Gaussian window depends on the frequency and given as

$$\sigma(f) = T = \frac{k}{|f|} \tag{1.4}$$

where T is time period. Choice of unity for constant k makes the Gaussian window narrowest in time domain. By taking advantages of the fast Fourier transform (FFT) and convolution theorem, the discrete form of the *S*-transform can be calculated. PQ signal $h(t)$ can be sampled in to a discrete time series $h(kT)$, where T is the sampling time interval and $k = 0,1,...,N-1$. The discrete Fourier transform is given by

$$H\left[\frac{n}{NT}\right] = \frac{1}{N}\sum_{k=0}^{N-1} h[kT]e^{-\frac{i2\pi nk}{N}} \tag{1.5}$$

where $n = 0, 1, ..., N-1$. The discrete S-transform is projection of the vector defined by time series $h[kt]$ onto a spanning set of vectors. Elements of the S-transform are not independent and spanning vectors are not orthogonal. Each basis vector of Fourier transform is divided into N localized vectors by an element-by-element product with N shifted Gaussians such that sum of these N localized vectors is original basis vector [Stockwell et al., 1996]. The S-transform of discrete time series $h[kT]$ for $n \neq 0$ is given by (letting f $\rightarrow n/NT$ and $\tau \rightarrow jT$) [Mishra et al., 2008]

$$S\left[jT, \frac{n}{NT}\right] = \sum_{m=0}^{N-1} H\left[\frac{m+n}{NT}\right] e^{-\frac{2\pi^2 m^2}{n^2}} e^{\frac{i2\pi mj}{N}} \tag{1.6}$$

and for $n = 0$ voice, it is equal to constant defined by

$$S[jT, 0] = \frac{1}{N} \sum_{m=0}^{N-1} h\left[\frac{m}{NT}\right] \tag{1.7}$$

where j, m, and $n = 0, 1, ..., N-1$.

S-Matrix

Output of the S-transform is a complex matrix of size $n \times m$ called S-matrix. It is represented by following mathematical relation

$$S(\tau, f) = A(\tau, f) e^{-i\varphi(\tau, f)} \tag{1.8}$$

where $A(\tau, f)$ is amplitude and $\varphi(\tau, f)$ is phase. Rows and columns of the S-matrix corresponds to frequency and time respectively. Each column represents frequency components present in the signal at a particular time. Each row represents magnitude of a particular frequency with time in terms of samples from 0 to $N-1$. From the S-matrix important information in terms of magnitude, frequency and phase can be extracted. Magnitude contour is the locus of maximum value of the S-matrix at a particular time. To calculate phase from S-matrix, regions of the maximum amplitude are determined and corresponding phase at these points is calculated. Frequency content of the signal is also derived from the S-matrix and presented as frequency contour [Panigrahi et al., 2009]. Using equation (3.6), the Stockwell transform amplitude (STA) matrix used to analyse PQ disturbances is obtained by $|S[jT, n/NT]|$ and phase is given as

$$\varphi = tan^{-1} \left\{ \frac{imag(S[jT, \frac{n}{NT}])}{real(S[jT, \frac{n}{NT}])} \right\} \tag{1.9}$$

The S-transform has following advantages over other transforms:

(i) This provides high time and frequency resolution. It has a good frequency localization, superior frequency resolution at low frequencies and high time resolution at high frequencies.

(ii) The combination of STFT features with the advantages of wavelet function in S-transform makes it as an ideal feature extraction algorithm to analyze the non-stationary signals like power quality.

(iii) It combines the frequency dependent resolution of the time-frequency, phase and absolutely referenced local phase information.

(iv) It can effectively be applied to the general complex valued time series data.

(v) Phase information given by the S-transform is always referenced to time t = 0. This is in contrast to a wavelet approach, where phase of the wavelet transform is relative to centre (in time) of the analysing wavelet.

(vi) It provides fast computation and easy interpretation.

(vii) It preserves the phase information, uses a linear frequency scale and can be easily inverted to recover Fourier domain of a signal.

(viii) This transform is capable of obtaining reasonably accurate amplitude and phase spectrum of analysed signal even in the presence of high level of noise.

(b) Fuzzy C-Means Clustering

Features extracted from the S-transform based plots and S-matrix are utilized for the clustering of signals of various events. Features are given as input to the FCM algorithm. Fuzzy C-means clustering is a standard clustering algorithm that groups the data points in multidimensional space into a specific number of clusters according to similarity with the help of membership. Each data point belongs to more than one cluster and value of membership reflects closeness of the data point to clusters. Data points which are nearer to one cluster than other clusters are made more important for this cluster and at same time more insignificant for other clusters. For each cluster centre, summation of the values of its clustering membership to all data points in the data space is assumed to be equal to one. Since membership value is non-negative, for each cluster centre, the clustering membership can be regarded as probability that the centre will cluster data points [Biswal et al., 2009]. Fuzzy C-means (FCM) clustering technique is a multiple-clustering technique initially proposed by Dunn and then generalized by Bezdek in 1981 [Huang et al., 2013]. It is based on optimization of the basic c-means objective function, or some modification of it. Objective function is given by the following relation

$$J_m = \sum_{i=1}^{N}\sum_{j=1}^{C} u_{ij}^{m}||x_i - c_j||^2 \tag{1.10}$$

where m is number of clusters, u_{ij} is degree of membership of x_i in cluster j, x_i is i_{th} element of n-dimensional measured data, and c_j is n-dimensional centre of cluster. FCM is able to determine, and in turn, iteratively update the membership values of a data point with pre-defined number of clusters. Thus, a data point can be member of all clusters with corresponding membership values [Biswal et al., 2012]. Fuzzy C-means clustering technique has following advantages over other clustering techniques:

(i) Among various clustering methods (i.e., Ward's method, artificial neural networks, co-clustering etc.), Fuzzy C-means clustering has a kind of uniqueness. In this clustering, samples belong to every cluster with a corresponding membership value. Thus, concept of the similarities and break points decide easily and more precisely that a sample should be inside or outside of a cluster. Due to this quantified concept of similarity, clustering of the variables is effective and easier.

(ii) It uses minimum number of fuzzy rules.

(iii) FCM is relatively insensitive to initializations, it is commonly known to be vulnerable to outliers.

(iii) Minimum computational complexity which is further reduced with the use of interval-valued fuzzy set.

(iv) FCM clustering algorithm produces more appropriate results while determining the class boundaries because it may accounts for uncertainties.

(c) Rule-Based Decision Tree

Decision tree is a decision support tool which uses a binary tree like graph to reveal the hidden relationship between inputs and outputs. It was developed by Breiman in 1980 and firstly introduced in the field of power system by Wehenkel in 1989 [Chen et al., 2009]. Rule-based decision tree (*RBDT*) represents the decision based on rules driven from the data. A set of distorted signal data extracted from the ST matrix are used for decision rules. Decision tree (*DT*) follows the decisions in the form of tree from root node down to a leaf node. Leaf node contains the response [Rodriguez et al., 2012].

1.3.2 Power Quality Improvement

Power quality improvement technologies have been developed at matured level which make use of current-based compensation for nonlinear loads and voltage-based compensation for improving the quality of AC power supply at grid level. This helps in eliminating the voltage sags, swells, harmonics, notches, flickers, spikes, glitches and voltage unbalance. These technologies also provide voltage regulation. The initial stage of developments includes the passive filters which provide cost effective solution of power quality problems with simplest design [Jayaraman et al., 2013]. Performance of these passive filters is largely affected by the source impedance. The passive filters also have the disadvantages of filter overloading, excessive harmonic currents flow in the filters, parallel and series resonances which amplifies the harmonic currents on source side [Farahat and Zobah, 2004]. The second stage of developments makes use of the active power filters (APF) which are basically current source inverter and voltage source inverter based devices. Active power filters are the combination of power electronic switching devices and passive energy storage elements (capacitors and inductors) [Chellammal et al., 2012]. Active power filter (*APF*) is effective to overcome the limitations of passive filters. The APF technologies provide compensation for harmonics, reactive power, and neutral currents. The third stage of developments includes hybrid filters (HF) which provide better option for PQ improvement in terms of cost effectiveness. The revolution in the HF technology was due to the development of Metal-oxide semiconductor field effect transistor (*MOSFET*), Insulated gate bipolar transistor (*IGBT*) and evolution of microelectronics [Hosseini et al., 2009]. The fourth stage of technological developments uses unified power quality conditioner (UPQC). The UPQC is an integration of shunt and series APFs with a common self-supporting dc bus. Shunt inverter in the UPQC works in the current controlled mode whereas the series inverter works in the voltage controlled mode. This enables UPQC to provide compensation for power quality issues and non-linear load currents [Khadkikar, 2012]. In the recent years FACTS devices are employed for the power quality improvements. These are power-electronics switching devices in combination with storage and passive elements (inductors and capacitors) which control network parameters thereby mitigating for PQ disturbances. This group of controllers known as custom power devices and include devices such as Unified power quality conditioner (*UPQC*), Dynamic voltage restorer (*DVR*), and Distribution static compensator (*DSTATCOM*) are used for improving the quality of electrical power [Jayaprakash et al., 2008]. Distribution static compensator is found to be effective for improvement of PQ disturbances in the distribution utility network. Hence, it is selected for the mitigation of PQ disturbances in the presented work. The principle of operation and applications of DSTATCOM are detailed in the following subsections.

(a) Principle of Operation of DSTATCOM

A typical DSTATCOM connected to the Point of common coupling (*PCC*) in distribution system having unbalanced and nonlinear loads is shown in Fig. 1.7. The main function of DSTATCOM is to supply reactive power (as per requirement) to the system in order to regulate the voltage at PCC. Active power can also be supplied if a storage battery or fly wheel is available on dc–side of the DSTATCOM [Iyer et al., 2005]-[Eldery et al., 2007]. Equivalent circuit of the DSTATCOM as shown in Fig. 1.8 is represented by a controlled voltage source (V_{VR}) in series with transformer impedance Z_{VR}. The voltage V_{VR} can be regulated to control voltage (V_k) of the bus k. Fig. 1.9, represents phasor diagram related to the DSTATCOM operation under both lagging and leading power factor modes.

(a) Major Components of DSTATCOM

The various components of DSTATCOM include voltage source converter (VSC), dc bus capacitor, transformer and ripple filter as shown in Fig. 1.10. The VSC converts a dc voltage into a three–phase ac voltage and synchronized with PCC through a tie reactor and capacitor. The transformer is used to match the inverter output to the line voltage [Hussain and Subbaramiah, 2013]-[Singh et al., 2014a].

Voltage source converter (*VSC*) allows bidirectional power flow and realized using devices

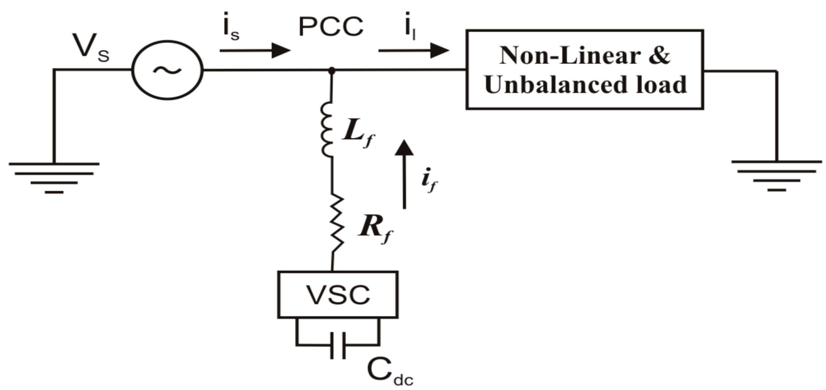

Figure 1.7 : Single–line diagram of the DSTATCOM

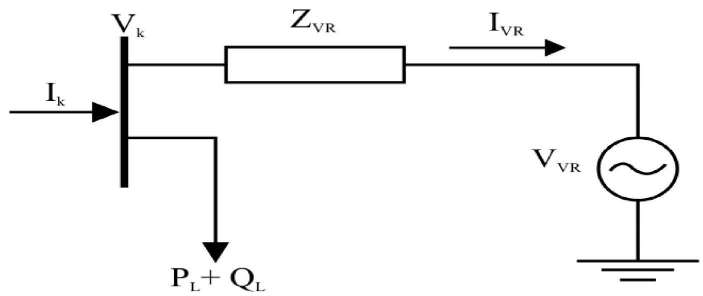

Figure 1.8 : Equivalent circuit of the DSTATCOM

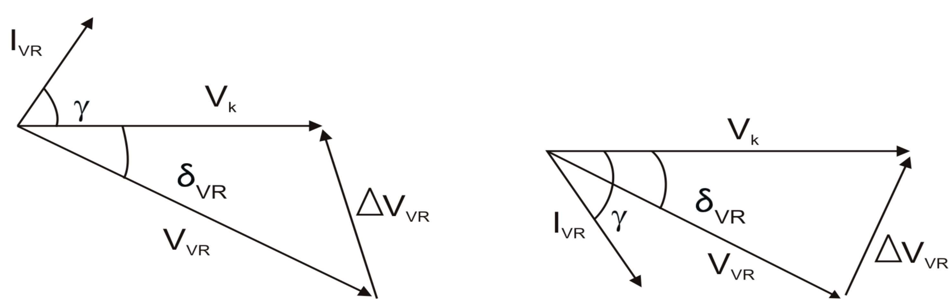

Figure 1.9 : Phasor diagram of DSTATCOM (a) Lagging operation and (b) Leading operation

such as insulated gate bipolar transistors (IGBT) and metal oxide semiconductor field effect transistors (MOSFET). Switching of these devices is based on Pulse width modulation (*PWM*) technique [Freitas et al., 2005]-[Bahramirad et al., 2013]. In addition to switching devices, VSC also has components like dc bus capacitor and interfacing inductor [Chilipi et al., 2014]-[Hande et al., 2014]. The minimum dc bus voltage should be greater than twice the peak value of the phase voltage of the system. The value of dc capacitor depends on the instantaneous energy available to the DSTATCOM during transients. The dc bus capacitor may also be used with two split sections having equal or unequal values [Srikanthan and Mishra, 2010]-[Yutaka Ota et al., 2015]. The transformer is used for neutral current compensation. Its effectiveness for compensating the neutral current depends on the system impedance and location of the compensator [Sreenivasarao et al., 2013a]-[Gupta et al.,

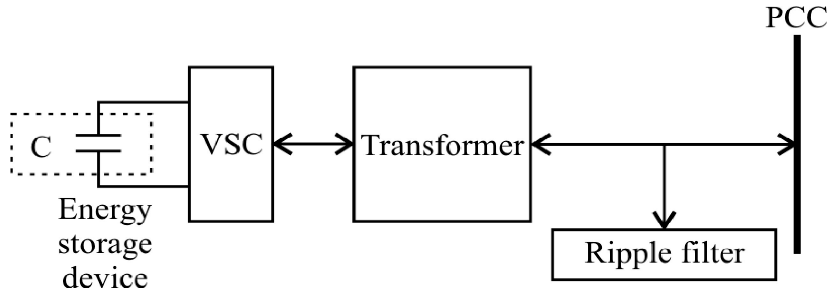

Figure 1.10 : Block diagram of the DSTATCOM

2007]. Transformers are used either in nonisolated condition for compensating the neutral current only or for providing isolation of the VSC along with neutral current compensation. The transformer topologies commonly used with DSTATCOM are zig-zag, star/delta, T-connected, and star/hexagon [Sreenivasarao et al., 2012]. A first–order high–pass filter tuned at half the switching frequency is used to filter the high–frequency noise from voltage at the PCC [Rohilla and Pal, 2013]. It consists of a series resistance R_f in series with the capacitor C_f [Arya and Singh, 2013] and known as ripple filter. Time constant of the filter should be very small compared to the fundamental time period (T). For reducing ripple in compensating currents, the tuned values of interfacing inductors are connected at the ac output of VSC [Singh and Arya, 2014]. AC inductance (L_f) of VSC depends on the current ripple $i_{cr,p-p}$, switching frequency f_s, and dc bus voltage V_{dc} [Singh et al., 2005].

(b) Applications of DSTATCOM

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. DSTATCOM injects current into the system at PCC which helps in achieving harmonic filtering, power factor correction, neutral current compensation and load balancing. Potential applications of DSTATCOM such as reactive power compensation in single–phase operation of microgrid [Majumder, 2013], voltage support strategy in Low voltage (*LV*) networks [Mokhtari et al., 2013], a dynamic hybrid Volt-ampere reactive (*VAR*) compensator along with Thyristor switched capacitor (*TSC*) in distribution system [Shuai et al., 2009], system impact study [Xu et al., 2013], reduction of photovoltaic power fluctuations [Yan et al., 2014], enhancement of solar PV penetration in distribution system [Chen et al., 2013], and mitigation of voltage sag/swell/flicker [Elnady and Salama, 2005] are reported in literature. A small quantum of articles are available on the application of DSTATCOM for the improvement of power quality with RE sources. Shahnia *et al.* [Shahnia et al., 2014], described the application of DSTATCOM for circulation of surplus power in distribution network with DG sources. A DSTATCOM using solar 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 Battery energy storage system (*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].

1.4 OBJECTIVE OF THE THESIS

The above mentioned facts indicate the seriousness of the power quality issues with increased penetration level of the renewable energy in the utility grid. The major problem is that the events such as islanding, outage and synchronization raises the PQ problem with increased penetration level of RE energy. Therefore, it is of paramount importance to investigate the PQ disturbances associated with these events and initiate the appropriate mitigation action so as to reduce their effects considerably. Further, very less number of articles are available for implementation of DSTATCOM at grid level addressing PQ improvement specifically with renewable energy sources. Hence, following are the main objectives of the research work presented in this thesis.

- Detection of the operational events such as islanding, outage and grid synchronization of the RE generators in the presence of various types of the RE sources in the utility grid.
- Recognition of 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. The effect of high wind energy penetration level on the power quality is also to be investigated.
- Investigation of PQ events associated with grid synchronization and outage of solar PV generator as well as with sudden change in solar insolation. The effect of high solar energy penetration level on the power quality is also to be explored.
- To detect the PQ disturbances associated with the operational events such as islanding, outage and grid synchronization of RE sources in the hybrid power system.
- Improvement of the power quality disturbances in the utility grid during the events of grid disturbances, outage and grid synchronization of the RE generators.
- Design and implementation of the DSTATCOM at grid level for PQ improvement in the utility grid in the presence of RE sources. To achieve the PQ improvement in the events of solar PV and wind generator operations such as grid synchronization and outage. Power quality improvement during the event of sudden change in solar insolation and wind speed variations needs to be investigated. The PQ improvement in the hybrid power system is also to be achieved.

1.5 CONTRIBUTIONS OF THE THESIS

The above mentioned sections have described the importance of detection and mitigation of the PQ events in the utility network integrated with the RE sources. Hence, power quality events associated with distribution network integrated with RE sources are analysed with different case studies. Mitigation of the PQ disturbances in the utility grid with different RE sources are achieved during various operating scenarios. Contributions of the work presented in this thesis are detailed in the following subsections.

1.5.1 Recognition of Standard PQ Disturbances

The standard PQ disturbances are generated using mathematical models as per IEEE-1159 standard. Complex PQ disturbances are generated by various combinations of these single stage PQ disturbances. A method based on multi-resolution analysis of the Stockwell's transform and decision tree initalized FCM clustering has been proposed for the recognition of power quality disturbances. The proposed algorithm has also been tested in the presence of the noise. It has been established that this technique is effective for the recognition of PQ disturbances with high efficiency even in the presence of noise. Performance of this technique has been compared with the rule-based decision tree algorithm. The complex power quality disturbances have been recognised successfully using the Stockwell's transform based decision tree algorithm.

1.5.2 Recognition of PQ Disturbances Associated with the Renewable Energy Penetration in the Distribution Utility Network

The *S*-transform based technique is used for recognition of PQ events associated with operations of wind generator and solar PV system integrated to single bus utility grid using experimental set-ups. To establish effectiveness of the algorithm, a detailed study is performed using IEEE-13 bus test system modified by integrating wind and solar PV systems. Power quality disturbances associated with wind generator operations such as outage, grid synchronization, islanding of test system from the utility grid and wind speed variations have been investigated. The algorithm is also used to investigate effects of increased wind energy penetration on the power quality. The proposed technique is also used for detection of PQ disturbances associated with grid integration of solar PV system. PQ events associated with grid synchronization and outage of solar PV generator as well as due to sudden change in solar insolation have been investigated. The PQ events associated with high solar energy penetration have also been investigated using proposed algorithm. The PQ disturbances have also been investigated in DG sources based hybrid power system during the events of islanding, outage of RE generators and grid synchronization of RE generators. Further, the detection of islanding and operational events utilizing *S*-transform based multi-resolution of negative sequence component of voltage is a contribution to the earlier studies.

1.5.3 Power Quality Improvement Using DSTATCOM in Distribution System with RE Penetration

This part of work proposes implementation of DSTATCOM with battery energy storage system in the three phase balanced distribution network addressing PQ issues. Synchronous reference frame theory based control algorithm is used for the control of DSTATCOM. The power quality improvement during disturbances in the grid due to feeder tripping, feeder re-closing, load switching, voltage sags and swells have been investigated. Power quality events with wind energy operations such as outage of wind generator, grid synchronization of wind generator and wind speed variations have also been investigated. Proposed DSTATCOM with BESS is also implemented 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 has also been investigated. Finally, the proposed DSTATCOM with battery energy storage system is also used for PQ improvement in the hybrid power system integrated with solar PV system and wind generator. Power quality improvement with the operations of wind and solar PV generators such as grid synchronization and outage have been investigated.

List of Publications

International Journal Publications

Following papers are published/under review in SCI indexed international journals.

Review Articles

1. Om Prakash Mahela and Abdul Gafoor Shaik, Comprehensive overview of grid interfaced solar photovoltaic systems, *Renewable and Sustainable Energy Reviews (Elsevier)*, Vol. 68, Part 1, pp. 316-332, February 2017.

2. Om Prakash Mahela and Abdul Gafoor Shaik, Topological aspects of power quality improvement techniques: A comprehensive overview, *Renewable and Sustainable Energy Reviews (Elsevier)*, Vol. 58, pp. 1129-1142, May 2016.

3. Om Prakash Mahela and Abdul Gafoor Shaik, Comprehensive overview of grid interfaced wind energy generation systems, *Renewable and Sustainable Energy Reviews (Elsevier)*, Vol. 57, pp. 260-281, May 2016.

4. Om Prakash Mahela and Abdul Gafoor Shaik, A review of distribution static compensator, *Renewable and Sustainable Energy Reviews (Elsevier)*, Vol. 50, pp. 531-546, October 2015.

5. Om Prakash Mahela, Abdul Gafoor Shaik and Neeraj Gupta, A critical review of detection and

classification of power quality events, *Renewable and Sustainable Energy Reviews (Elsevier)*, Vol. 41, pp. 495-505, January 2015.

Research Articles

6. Abdul Gafoor Shaik and Om Prakash Mahela, Power quality assessment and event detection in hybrid power system, *Electric Power System Research (Elsevier)*, Vol. 121, pp. 26-44, 2018.
7. Om Prakash Mahela and Abdul Gafoor Shaik, Recognition of power quality disturbances using S-Transform based ruled decision tree and Fuzzy c-means clustering classifiers, *Applied Soft Computing (Elsevier)*, Vol. 59, pp. 243-257, 2017.
8. Om Prakash Mahela and Abdul Gafoor Shaik, Power quality recognition in distribution system with solar energy penetration using S-Transform and Fuzzy c-means clustering, *Renewable Energy (Elsevier)*, Vol. 106, pp. 37-51, 2017.
9. Om Prakash Mahela and Abdul Gafoor Shaik, Power quality improvement in distribution network using DSTATCOM with battery energy storage system, *International Journal of Electrical Power and Energy Systems (Elsevier)*, Vol. 83, pp. 229-240, 2016.
10. Om Prakash Mahela and Abdul Gafoor Shaik, Experimental investigation of power quality disturbances associated with solar energy penetration into utility grid using Stockwell transform, *IET Renewable Power Generation*, Under Revision, Paper ID: RPG-2018-5374, 2018.
11. Om Prakash Mahela and Abdul Gafoor Shaik, Recognition of complex power quality disturbances using S-transform based ruled decision tree, *Journal of Signal Processing Systems (Springer)*, Under Revision, VLSI-D-16-00644.
12. Om Prakash Mahela and Abdul Gafoor Shaik, Recognition of power quality disturbances using *S*-transform and rule-based decision tree, *IEEE Transactions on Industry Applications*, Under Review, Paper ID: 2017-IACC-0680, pp. 1-8, 2017.
13. Om Prakash Mahela and Abdul Gafoor Shaik, Power quality assessment in utility grid with wind energy penetration, *IET Signal Processing*, Under Review, Paper ID: SPR-2017-0094, 2017.
14. Om Prakash Mahela and Abdul Gafoor Shaik, Power quality recognition in distribution system with wind energy penetration using S-Transform and Fuzzy c-means clustering, *Renewable Energy (Elsevier)*, RENE-D-17-00347, 2017.

International Conference Proceedings

Following papers are published in IEEE international conference proceedings.

1. Om Prakash Mahela and Abdul Gafoor Shaik, Power quality detection in distribution system with wind energy penetration using discrete wavelet transform, In: 2^{nd} *IEEE International Conference on Advances in Computing and Communication Engineering (ICACCE-2015)*, Dehradun, India, May 1-2, 2015.
2. Om Prakash Mahela and Abdul Gafoor Shaik, Detection of power quality disturbances associated with grid integration of 100 kW solar PV plant, In: *1st IEEE Uttar Pradesh Conference-International Conference on Energy Economics and Environment (ICEEE 2015)*, Noida, India, March 27-28, 2015.
3. Om Prakash Mahela and Abdul Gafoor Shaik, Recognition of power quality disturbances using S-transform and rule-based decision tree, In: *2016 IEEE First International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES 2016)*, New Delhi, India, July 4-6, pp. 1-6, 2016.
4. Om Prakash Mahela and Abdul Gafoor Shaik, Recognition of power quality disturbances using S-Transform and Fuzzy c-means clustering, In: *IEEE International Conference and Utility Exhibition on Co-generation, small power plants and district energy (ICUE 2016)* , BITEC, Bang Na, Bangkok, Thailand, September 14-16, 2016.
5. Ashwin Venkatraman, Kandarpa Sai Paduru, Om Prakash Mahela, and Abdul Gafoor Shaik, Experimental investigation of power quality disturbances associated with grid integrated wind energy system, *IEEE International Conference on Advanced Computing and Communication Systems (ICACCS 2017*

Coimbatore, Tamilnadu, India, January 4-6, 2017.

1.6 THESIS OUTLINE

This thesis is organized into seven chapters as follows.

Chapter 1: This chapter provides an overview of power quality, RE sources, hybrid power system, PQ assessment and mitigation in distribution network with RE penetration, *S*-Transform, Fuzzy c-means clustering, rule based decision tree, objective of thesis, main contribution of thesis and organization of the thesis.

Chapter 2: This chapter presents extensive literature review of the research work reported in the field of power quality issues with grid integrated renewable energy sources, power quality detection and mitigation techniques and distribution static compensator. Identified research gaps are presented at the end of this chapter.

Chapter 3: This chapter presents the proposed Stockwell transform based algorithm for the recognition of power quality disturbances. The results of Stockwell transform based decision tree and decision tree initialized FCM clustering applied to the standard PQ disturbances are presented in detail. Detection and classification of complex PQ disturbances using *S*-transform based decision tree have also been presented in this chapter.

Chapter 4: This chapter details the experimental study of power quality assessment in the utility grid interfaced with wind generator and solar PV system.

Chapter 5: In this chapter the detailed simulation study with real time testing of results for assessment of the power quality disturbances in the utility grid interfaced with wind generator and solar PV system using an IEEE-13 bus test system is presented. Results related to wind speed variations, change in solar insolation, various operating events such as outage, synchronization and islanding are presented in detail.

Chapter 6: This chapter presents power quality improvement technique in the presence of grid disturbances, wind energy penetration and solar energy penetration using DSTATCOM with battery energy storage system with control provided by the synchronous reference frame theory.

Chapter 7: Summary of the presented work, concluding remarks and closing comments on the work are discussed in this chapter.

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