Chapter 1

Introduction

1.1 General

Renewable energy resources are intermittent in nature and have very less controllability. The wide variation in power output within small time frames may result in grid instability. The inclusion of significant number of wind energy sources in existing power system raises several challenges, like difficulty in integration with the network system, power quality degradation, system stability, maintaining synchronisation, system operation. These challenges were overlooked in earlier phase of integration of wind energy sources. However, with increasing number of shares from wind power, it started affecting the grid and it has now become imperative to address issues related with wind power integration. The majority of wind turbine generators are induction machines and operate asynchronously with respect to the grid and their speed continuously changes with change in wind speed. So, the reactive power demand also changes. There are several issues which impact the stability of system negatively. Some of these are enlisted here.

1. Location of the wind farm in the power system
2. Impact of different technologies of wind turbine generator systems
3. Impacts of wind intermittent and variability
4. Reactive power control and voltage control
5. Impacts of wind farm control strategies

6. Inertial response with wind

7. Wind probability density distribution

There will be major impact of wind variability on system stability and it requires necessary attention, before it reaches to critical level. The major concerns are discussed here in brief.

- Voltage stability: With high wind power penetration, the contribution from WTG become significant. So, a slight variation in wind speed causes large power imbalance and cause wide variation is system voltage. There will be a period of low voltage (brownout) followed by no-voltage (blackout). This situation may also arise under different conditions, like occurance of fault on the system, tripping of Transmission line / Generators etc. Under such conditions, WTG gets disconnected from the system And reconnect when the fault is cleared and transients die out. Also, beyond the cut-in and cut-out speed, WTGs are disconnected from the grid and left idle. The WTGs are connected back when wind speed return to operating range. With large presence of WTGs in the system, frequent disconnection and reconnection affect the voltage stability significantly. Due to gradual increase in wind power share, it is important to know, how the steady state voltage stability gets affected?. Also, it is required to quantify its impact.

- Impacts of wind farms on Power Quality / Harmonic Stability: The majority of new generation turbines are power electronic based and operates at very high switching frequency. It cause current harmonics injection and voltage distortion. Weak system produces large harmonic voltage drop, even with small harmonic current. The power quality problems with small turbines are more imperious than large turbines. However, large number of wind farms affect the power quality severely. There are also some frequencies at which harmonic impedance become so high that, it may over-dominate the fundamental voltage and result in very high overvoltage. Also, with rapid variation in wind power cause voltage fluctuation, widely known as Flicker. It may damage sensitive equipment / devices and also cause stress on the eyes. If power quality gets affected severely, it may affect the stability of wind turbines and hence power system.

- Small Signal Stability: With continuously changing wind power, the power system parameters keep on changing continuously. The change in parameters depends on the magnitude of change in wind power and wind power share. Even small change in some parameters, like voltage and grid strength, can make WTG unstable, which may affect the system stability. Also, small signal stability is a necessary but not sufficient condition to ensure transient stability. A small signal system unstable system cannot survive large signal or transient condition. So, the small signal stability of WTG is necessary to ensure system stability.

- Transient Stability: Besides fault on system, there are many conditions, which may cause transients in power system like disconnection and reconnection of lines, transformer charging, switching surge, sudden change in active / reactive power. The response of different types of WTGs are varied in nature. The behaviour of WTGs will become deciding factor in maintaining transient stability of grid with higher penetration of wind power.

In this work mainly three aspects, Steady State Voltage Stability, Harmonic Stability and Small Signal Stability, are covered. To understand various issues and proposed solutions, available literatures on related topics are studied. These are discussed here.

1.2 State of Art

Wind turbine generator systems completely differ from the conventional grid connected synchronous generators, which is traditionally used in power plants. Due to their different characteristics, these generating systems interact differently with the power system as compared to synchronous generators. The penetration level of wind power determines the interaction of generation and network elements [2, 3]. In the analysis of wind generation-system interaction, local impact and system wide impact are studied separately. In Local Impact, the affected area is restricted to a particular region, farm or wind turbine. This impact can be caused by any specific wind turbine or wind farm. Local impacts can be summarized as change in the load flow, effect on protection scheme, fault current level, harmonic resonance, rating of the protective gears and variation in node voltages. Unlikely local impact, system wide impact can be seen on the relatively larger area of the system. It is the consequence of increased penetration of the wind power in the system and cannot be attributed to individual wind turbine. The system wide impact can be summarized as the dynamic stability, frequency control, system balancing, voltage controllability, reactive power control, economic dispatch of the power generation unit, and requirement of ancillary services.

The grid behaviour is largely determined by the generating system, network and load connected to the system. Load primarily consists of the passive elements and the motor load. The passive elements doesn′t affect much to the grid, but directly connected motive loads have significant effect on the system [4]. In this paper, a detailed analysis on impact of large scale penetration of wind power on voltage stability and transient stability has been given. A fault is created on major transmission lines and the dynamic behaviour of voltage is noted to determine, whether, voltage remains in acceptable range or not. Also, the effect of SVC has been examined on the stability.

The effect of wind turbine on power system can be done accurately only with proper model of wind turbine. Several researchers have made efforts to investigate whether the existing models are suffice to achieve study objectives. If not, then is it possible to use with some adaptation? Mostly, the constant / fixed speed turbines are used. These models are quasi-static. Quasi-static models are developed with certain assumptions like magnetic saturation is overlooked, sinusoidal flux distribution is assumed, the losses of stator and rotor are neglected and the sum of rotor and stator current is assumed to zero. These assumptions not only reduce the accuracy, but also neglect the dynamic nature of the relationship between mechanical torque and wind speed.

The basic structure of wind power generation has been given in [4]. There are five sub-models included in this structure. First is the wind speed model. The output of wind speed model is fed to the rotor model. The rotor model along with the shaft model decides the mechanical output power. Whereas, the combination of generator model and the grid model decides the rotational speed of the turbine. The final output parameters are voltage, frequency, active power and reactive power. The details of each sub-model are available in the literatures [5, 6]. The behaviour of wind farm may get affected by the connection with interconnected grid. The behaviour is basically determined by the point at which the wind farm is connected. The two important factors, which determines the behavior, are the amount of wind power fed at that point and the strength of the network.

Inclusion of wind generation technologies in power system reduces the stiffness of the system due to low inertia of WTG and this cause comparatively larger frequency variation. Also, the output impedance of WTG generator is higher as compared to the conventional Synchronous Generator, so the equivalent impedance seen by the transmission line will be higher. Due to this, low voltage condition may be more pronounced. This makes it necessary to study static response under overload and low voltage conditions. Add on to this, the system operator puts several requirements to evacuate wind power under various operating conditions including low and high voltages. The overload study is carried out using load flow study, PQ analysis and QV analysis under normal and abnormal conditions. Though, modern wind turbines are built with inherent voltage and reactive power control; still they are not self-sufficient to prevent the voltage instability and voltage collapse. The majority of wind generators are induction machine. The main problem with induction machine is an increase in reactive power with a reduction in the system voltage. This will iteratively reduce the system voltage further. If the generator is equipped with capacitor bank, for reactive power compensation, it′s output also decreases with reduction in terminal voltage, which further reduces the voltage. This makes the system unstable and may collapse ultimately. This behaviour can be studied well using P-V analysis and Q-V analysis technique.

If Wind Farm facilities include induction generators, it deteriorates the low voltage condition. On the other, wind farm with power electronic based converter technology (without ride through capability) doesnt support fault and trips under fault condition. Under both the cases, the system stability will be worsen as compared to the conventional grid response. To study the behaviour of wind turbine and the system, a time domain simulation needs to be carried out, which requires detail modelling of the power system components like AVR, Exciter, PSS, Synchronous Generator, FACTS devices, protection system, accurate wind turbine with control systems etc

The grid strength has predominant effect on the performance of wind turbine generator. The strength of the grid is defined as the ratio of short circuit power to the actual power fed to grid (MVA_{SC}/MVA_{rated}). Short Circuit Ratio (SCR) of 25 is considered as an excellent for desired performance. In several studies it is demonstrated that, the minimum SCR has to be 10. Though, it is accepted in the range of 5 to 10, under certain circumstances. But, it is not acceptable below 5. Dynamic voltage stability has been mainly related with the reactive power variation. However, when a wind farm is installed in a network with low X/R ratio (between 2 to 3) or a network with underground cables, active power variation can also be a major cause of instability and requires due attention.

Voltage performance refers to achieving desired voltages within a specified operating range. While the improvement in voltage performance indicates increased system robustness, however, it is not a true measure of the power systems stability. In systems stability assessment, a Power-Voltage (PV) curve can be used as an indicator of voltage stability [7].
Load Flow has been a useful method for assessment of voltage stability and voltage stability margin of transmission system. However, there are several limitations of this method, when variable generation sources like wind is involved. This method works deterministically on single operating point, which will not help in finding the true impact of wind variability. Reference [8] suggested new method called Time Series Power Flow [TSPF] to handle such problem. Probabilistic Load Flow [PLF] has been applied for long time to solve the stochastic non-linear problem. In [9, 10], assessment of the system reliability with high penetration level has been done. The transmission line sufficiency is examined in [11]. In [12] and [13], probabilistic load model has been examined together with wind source. As compared to PLF, TSPF simulation deterministically models the power system and capture it′s response for worst case. Time Series Power Flow has been successfully applied to determine the overload condition [14] and to model variable resources; such as Solar PV and Gas Fired micro CHP co-generation [15]. TSPF is a sequential simulation that examines the past data history of Random Variable (RV). Based on the worst cases in the time series, the deterministic data set has been prepared. This helps in maintaining the correlation between wind power and load, which can be seen throughout the year. It is also necessary to maintain the load-generation balance and it is ascertained by changing the output power of conventional generating units as per the economic merit order.

This method also considers the online unit during the period of simulation, forced outage rates and availability of the units. By formulizing power flow with unit commitment and economic dispatch, this method produces the realistic result of the steady state voltage analysis with wind energy sources.

Inclusion of uncommitted wind generating units in the system will displace the conventional active power sources, accompanied by reduction in reactive power sources. Such changes may force the available power sources to hit their limits [16]. Due to such displacement, there will be a shift in reactive power generation from outgoing unit to the remaining online units. Such alternative reactive power sources may not be available near to the load and will change the power flow and voltage profile of the network, particularly of weaker part of the network. To restore the stability limit, it requires the loading reduction options such as network reconfiguration and load shedding, which are not cost effective [17]. To meet such contingencies, a constrained optimal power flow is required for long term wind generation planning to avoid unscheduled wind capacity allocation, which requires costly remedies in short term perspective, such as uneconomical power system operation. Constrained based optimal power flow has been given in [18, 19]. In [18], security constrained optimization is solved considering static and voltage stability constrain. Also, preventive and corrective actions are separated, using Benders decomposition, based on normal and post contingency stressed condition. In [20], author has proposed reactive power reserve based optimization. The violation of voltage stability margin constraint are identified using continuation power flow. Then, minimum reactive power required to maintain the voltage stability margin constrain has been evaluated and used as an input to OPF problem, which optimize the preventive control requirement. In [21] and [19], two sets of variables are used to solve optimal power flow, considering the normal and critical operating points. Two sets of variables are linked with the loadability margin. In [22], a voltage stability constrained optimization is solved for minimization of re-dispatching of power from conventional units, considering ramping limits of load and generation units. The author of [23] has proposed a method of OPF in which the wind generation is sequentially increased to attain the targeted wind power and unit commitment is also updated accordingly. In [24] Optimization based on DC power flow has been proposed for optimal wind capacity allocation, considering the transmission cost function. In reference [25], the generation expansion due to addition of wind capacity is associated with transmission expansion problem and solved by Benders decomposition.

Voltage Stability Margin can be improved by allocating optimal generation capacity in distribution systems [26] and in transmission systems [12], but as per reference [27], none of the method has taken into consideration, the optimal wind capacity allocation in unit commitment. This is the value addition done by authors in work [27]. In this work, multi operating conditions based Voltage Stability Constrained Optimal Power Flow (VSCOPF) has been proposed. In this method, wind capacity allocation has been done through optimal sizing and siting of wind capacity to enhance the voltage stability margin. Unit commitment puts the limit on the online available capacity. Allocation of power generation to wind sources can change the unit commitment in the system. For each level of wind power capacity, the available online capacity of conventional unit may change. If the active power resource is made offline, the reactive power capacity also gets reduced. A reduction in available reactive power capacity will deteriorate the voltage stability margin. Also with the change in unit commitment, the relative distance of source and sink of reactive power may also get changed, which will significantly affect the voltage support, especially in the weaker part of the network. The closeness of active power to the load improves the loadability margin of the system. The wind capacity allocation as per the procedure given in this document lessen the ill effects of the wind power integration on the loadability margin and may also enhance it. In this method, the voltage stability margin is evaluated at two points, normal and stressed. The two points are related by the load increase factor. First, the voltage stability margin has been found out at the normal operating point. After that, the same normal operating point is stressed by increasing the load at one load bus or several load buses. The stability margin is then found out under stressed condition. Then, stressed condition is reversed and again the system is stressed by some other load increase. This process is repeated for all identified operating conditions. So, for every operating condition, there will be a normal operating point and number of stressed operating points.

In reference [28], a simple voltage stability analysis method is proposed using static Thevenin′s equivalent circuit to represent electrical network. For a fixed value of Thevenin′s voltage and reactance, a P-V curve analysis can be carried out to find out the voltage collapse point and the stability margin. This method calculates the Thevenin′s voltage and reactance using the measured data from PMUs and the SCADA system at a wind hub on medium voltage transmission line. The Thevenin′s equivalent parameters are used to calculate the maximum power transfer capability of wind hub, limited by the voltage stability constraint. The load is connected to a source with fixed internal voltage (E^{th}) and fixed internal source reactance (X^{th}), which is also named as the Thevenin′s equivalent circuit. Now, the active and reactive power at the load bus is increased in a step wise manner and the decrease in the terminal voltage (V) is observed. The basic assumption in this method is the value of E^{th} and X^{th} remains constant. Now, various values of X^{th} is selected and for each value of X^{th}, the corresponding E^{th} is found out for various P, Q and V. The value of X^{th} for which the E^{th} remains constant or does not change much is selected to represent the Thevenin′s equivalent circuit. From such value of E^{th} and X^{th}, the terminal voltage V is calculated (V_{cal}) and compared with measured voltage (V_{meas}) for the model validation purpose.

Distributed Generation (DG) like Wind or Solar in a distribution system can affect the power and current flow in the network. As the node voltages are strongly related with the power flow, it may also get affected. So, prior to connecting DG to distribution system, a voltage profile must be examined to check whether it will comply with utility requirement or not, with inclusion of DG. At a distribution level, there are number of parameters or factors that may affect the voltage profiles; therefore assessment requires detailed model of distribution system. Also, the uncertainties like daily load variation, stochastic DG power variation, network changes or reconfiguration, and the operation of control devices should be taken in to consideration. In [29], a new probabilistic methodology has been proposed to evaluate voltage reliably. The proposed algorithm handles the above mentioned uncertainties and some additional factors like location of DG, power factor settings, the characteristics of DG etc. In this paper, it has been recognised that the different DG models like Constant Power Factor Model, Constant Reactive Power Model, and Constant Voltage model will have different evaluation results (voltage profile of distribution network). In addition to the load and generation variability, the network configuration also affect the results. The network configuration with significant effect on voltage profile is identified and should be avoided. Considering all the uncertainty, the probabilistic load flow problem is formulated and results are evaluated under different operating conditions.

Power System operation is full of uncertainties and many uncertainties may have a potential to hamper the system stability. Not only load variation, but load parameters variation also affect the voltage stability. In [30], voltage stability considering only load variation has been discussed. In this work, the load variation is assumed normal and follow the Gaussian distribution. First, the load flow problem has been formulated and eigenvalues of Jacobian under uncertain load parameter has been obtained. The critical eigenvalue determines the stability of the power system. By varying load parameters, complete distribution of the eigenvalues has been obtained. The ratio of critical eigenvalues to the total eigenvalues gives the probability of system instability. So, this method shows the probabilistic stability of the system. Larger the variation in load parameters, higher will be uncertainty in stability evaluation. In this paper, a case studies on three different test systems are carried out to illustrate the effect of load uncertainty on stability margin. The proposed method is validated using 10,000 sample Monte Carlo Simulation.

In reference [31], the static voltage stability has been carried out using Point Estimation Method [PEM]. The stochastic distributed generation (DG) with their probability distribution function (PDF) has been considered. In the start of the procedure, first several data points are selected using PEM, which replaces the PDF of random variables. Then, on each sample points, the critical voltage stability has been calculated using Continuation Power Flow (CPF) method. Finally, Cornish Fischer expansion is used to estimate the PDF. The proposed method has been tested on IEEE 33 bus. The results are finally compared with Monte Carlo Simulation to prove its usability. According to this literature, the proposed method offers better accuracy and efficiency.

Traditionally, voltage stability has been carried out using power flow method. The load at the specified bus or buses are increased in a step wise manner. As the load increases towards its loadability limit, the Jacobian slowly becomes poorly conditioned and convergence time increases. Finally it fails to converge before reaching the limit; the Jacobian becomes singular at this point. To alleviate singularity problem, Continuation Power Flow method is used. In this method, one continuation parameter is added which increases the dimension of Jacobian by 1. In [32], a new method is proposed, which directly eliminates the singularity problem and also reduces the Jacobian size by 1. A new bus called AQ bus is introduced. On this bus, voltage angle and reactive power are specified. For steady state voltage analysis, the bus angle is varied to change the power transfer to the load, instead of specifying load power itself. For an AQ bus, the power flow problem consists of only reactive power equation. Thus formulated Jacobian matrix remains non-singular at the critical point.

Stability of a power system is a complex function of load bus voltage magnitude (V), active power supplied to the load (P) and reactive power injection or absorption (Q). P-V curves show the relationship between voltage (V) and transmitted power, whereas Q-V curves reveal the relationship between reactive power injection (Q) and voltage (V). Voltage stability characteristics can be established by computing P-V and Q-V characteristics. Both the curves provide different but complementary information. PV curve exhibits the load margin when load and generation is varied in a specified manner. On the other side, Q-V curves quantifie the strength of the system voltage with respect to the reactive power support to the system. These curves are obtained by running number of power flows. The conventional power flow fails to converge at operating point near the loadability limit. The P-V and Q-V curve also be plotted by the continuation method [33]. In reference [34], probabilistic analysis of voltage stability with renewable energy sources has been given. To find out the voltage stability, PV and QV curves are used. Each generator in the system is modelled by normal distribution function. For each dispatch sample, a load flow is executed, which provides active load margin λ_p and λ_q. If there is no solution exist, then the load is decreased to bring the system in a feasible state. In this paper, probabilistic risk of voltage collapse has been evaluated, considering the uncertainty of distributed energy sources. The main aim of this work is to study the different generating scenarios and evaluating the load margin with respect to the base case. This paper contributes by giving some vital information. Using this methodology, the participation of generators in voltage collapse mechanism can be determined. The relationship between reactive power support and system load margin can also be explored. It also gives the probabilistic risk of voltage collapse at each operating point. Add on to these, it calculates the probability of enlarging the system load margin as a function of different operating points.

If distributed generator is connected to distribution system, it will have multiple benefits like line loss reduction, voltage profile improvement, system reliability improvement [35, 36, 37]. But, it also introduce several problems [38], which are the limiting factors for integration of large amounts of DG into the system. For system level planning, both location and rating of the DG are vital optimization parameters. Various techniques and methods are reported in literatures for solving such problems. In [38, 39, 40, 41, 42, 43, 44, 45, 46, 47], meta-heuristic based optimization techniques have been applied. Whereas, in [48], Lagrange based approach is adopted. In [40], two different techniques have been applied to solve the location problem and rating problem. With the help of clustering method, the location problem has been attempted and Tabu Search method has been used to find out the rating of the DG and reactive power source. However, the Genetic Algorithm is a better approach to solve sizing and sitting problem [41, 42, 43, 44, 45]. The advantage of this method is that, the two problems can be solved together with one method only. Simple analysis with one DG of fixed rating is presented in [41]. Though, multiple DG has greater economical and technical benefits. Loss Sensitivity index and Voltage Sensitivity based clustering method is found in [47] for the placement of multiple DGs. In all above methods, the number of nodes are not made an optimization parameter. It is either assumed or pre-set, prior to compute their rating. This can be improved using different method like iterative genetic algorithm [49], Fuzzy Logic based Genetic Algorithm [50]. Continuation Power Flow based determination of voltage stability of nodes in distribution system with application of DG has been given in [51]. In case of radial distribution system (RDS), the Newton Raphson method and its derivatives are not found suitable, as they become ill conditioned near the unstable point. This is due to the high value of R/X and non-dominance of diagonal element of Jacobian matrix. By capitalizing this characteristics of RDS, Voltage Collapse Instability (VCI) has been proposed in [52]. In this work the weak nodes are first identified by VCI and then selected for appropriate DG and improved VCI, post-DG placement, has been demonstrated. As per this work, the margin to voltage collapse can substantially improve with local generation support, using DG. WTGs of different design and technology are available, which can be used as a DG. Particularly, with Squirrel Cage Induction Generator (SCIG), voltage problem becomes complex, because power output is a function of slip and terminal voltage. Also, it requires high amount of reactive power to magnetize the induction machine. In [53] and [54], authors have proposed Star Delta switching to reduce the reactive power consumption. This will in turn improve the node voltage at which the DG is connected. Though, this type of WTG is not attractive, as it requires special type of winding design and should have specific number of rotor and stator slots. In [55], the improvement has been suggested in SCIG by incorporating capacitor along with the Star Delta switching. The capacitors are connected to achieve the near unity power factor. This method provides better performance and also reduce reactive power demand from grid, thus improves the node voltage.

In [56], SCIG with Star Delta Switching and Capacitor has been considered as a DG to connect at the low VCI margin bus. The change in VCI has been observed with change in wind condition as well as with Star and Delta configuration. With the increased penetration of DG in distribution system, the power flow in the distribution system and transmission system will be altered very frequently. As a consequence of this, the stability of the system (angel stability, voltage stability and frequency stability) will be affected [57, 58, 59, 60, 61]. Any system is considered in the state of instability when the concerned parameter or state progressively moves away from the prescribed limit and becomes uncontrollable [7, 62]. In this work VCI has been used to evaluate the voltage stability. VCI method is better in comparison to CPF method, as it does not require multiple iteration to find out the stability margin [52].

Voltage stability has been studied for short term and for a long term. Short term voltage stability can be studied using system dynamics and time domain simulation, whereas, steady state analysis technique is commonly used for long term voltage stability. One obvious question comes to mind is how steady state techniques can be used for a dynamic phenomenon of voltage stability? The argument against this is that the steady state analysis has been used to identify the absence of long term equilibrium point post contingency [63]. Voltage Collapse associated with the long term has also been analysed by linearization of system equations [64]. For short term analysis, the number of variables and their dispersion have been assumed to remain low. But as the time horizon increases, the no of variables and their excursion limit becomes more uncertain, this has been the reason for adopting probabilistic analysis methods for long term stability evaluation.

The maximum load, a system can bear has been used to compute the various indices of voltage stability. The maximum loadability is related with the bifurcation point. There are two major bifurcation, one is saddle node bifurcation and another is limit induced bifurcation. The saddle node bifurcation is related with the point, where the system state matrix attains singularity. The limit induced bifurcation appears when generators reach their reactive power limit and will not be in a position to support system voltage by injecting additional power and ultimately lose control.

The correlation between wind power and load, which can be seen throughout the year, has been very important from stability point of view. It helps in maintaining the load-generation balance and it is ascertained by changing the output power of conventional generating units as per the economic merit order. This method is based on load-wind correlation, also it considers the online unit during the period of simulation, forced outage rates and availability of the units. By formulizing power flow with unit commitment and economic dispatch, the realistic results of the steady state voltage analysis of transmission line with wind energy sources can be produced.

Monte Carlo Simulation has been widely used to model the uncertainty and complexities associated with the system. It has also been applied effectively for voltage stability study [65, 66]. However, the computational cost associated with MCS makes it infeasible for problems with large number of variables. There has been various alternative methods suggested, concentrating on the reduction of computational load without much compromising the accuracy limit. Point Estimation based method is one of them [67]. There are few variants of the point estimation method. Two point estimation method approximates the moments of output variable with only two probability concentration of input variables. The number of data points or concentration or order of the point estimation increases for non-normal distribution. It has been demonstrated that for normal distribution two datapoints are enough. According to central limit theorem, the uncertain parameters should be statistically independent to apply PEM method. Reference [68] proposed new method called Affine Arithmetic (AA) based method, which negates all such limitations. This novel approach computes PV curve with improved accuracy while still reducing computational efforts as compared to MCS. This method accurately calculates the bounds of the PV curve considering the uncertainties of operating conditions. AA method is independent of PDF of associated with uncertain variables. In AA method, uncertainty is modelled as interval with no prior assumptions about their probabilities. According to the traditional methods like MCS, the uncertainties should be independent and there number also should be sufficiently large. But in AA method, the uncertainties need not be necessarily independent; in fact the interdependence is explicitly modelled. This paper has major three contributions. First, PDF of uncertain variables are not required, unlike some other methods, where the PDF needs to be assumed. This characteristics is very important with renewable energy sources, which are intermittent in nature. Second, this method has upper hand in computational efforts required and accuracy of the results. Finally, this method is able to compute full PV curve and associated loadabilities. The results thus obtained are compared with the MCS results. AA is a numerical technique for analysis, where interested variables are represented in the form of uncertainties or approximation errors. In [69], AA techniques is proposed to solve power flow problem considering randomness in load and generation. In this work, the power flow equations are initially solved without the limits. In the case of violation, the bus or buses are treated as PQ buses, as it is done in standard power flow method and then affine form of voltages and angles is applied again for computation. In [68], a modified approach is adopted to take in to account generator reactive power limit. Reactive power limits in terms of noise is introduced to avoid switching from PV to PQ bus.

DG placement considerably affects the operation of distribution network. Inappropriately placed DG increases capital cost, operational cost and network losses. On the flip side, optimal placement of DG helps keep the voltage profile under specified limit, reduce power flow, reduce network losses, enhance power quality and improve reliability of system. The intent of optimal DG placement is to connect DG of appropriate size and at a suitable site without violating various constraints like network constraint, DG operation constraint. DG placement is a complex non-linear mixed integer optimization problem. For such problems, heuristic methods have been applied for a long to solve such problems. In [70], ordinal method is proposed for optimal placement of DG. In [71], mixed integer non-linear programming has been adopted for hybrid electricity market. Placement of DG based on sensitivity test and placement on heuristic curve fitting is proposed in [72]. A multi-objective, loading maximization and profit maximization, DG placement using Fuzzy Genetic Algorithm based approach is given in [73]. In [74], particle swarm optimization has been used to consider variable load model. Some uncertainty such as future load patternn load growth and future penetration of renewable generation makes the problem complex [75]. A combination of GA- Max-Min Fuzzy has been adopted in [76] to solve multi-objective problem. Uncertainties associated with load and generation can be very well dealt with fuzzy numbers and non-dominated GA along with Max-Min to solve the optimization problem. GA along with decision tree has been applied to solve placement and power quality issue under uncertainty in [77]. Uncertainties can also be handled with MCS in conjunction with GA [78, 79]. An optimization model considering reactive power capacity of DG has been developed in [80]. Load uncertainties in optimization has been handled with Cuckoo search [81] and artificial neural network [82]. In [83], Point Estimation Method along with Genetic Algorithm based approach has been proposed. This is known as Probabilistic Power Flow GA (PPF-GA) based approach. In this method, the PPF part has been solved by Point Estimation Method (PEM). The uncertainties considered in this problem are distribution system load growth, renewable energy growth, fuel cost, and electricity prizes. The proposed method has been tested on IEEE-33 bus system considering several scenarios. The results are compared with GA-MCS method. The proposed method has been found seven times faster with almost same accuracy.

In a rural area, there is a possibility of connecting multiple type of DG to the distribution system. Appropriate allocation of DG units in the existing system has vital role in improvement of systems performance. Each DG unit has associated uncertainty, which is different than other units. To consider all the possible uncertainties from all DG is a complex problem. Such problem has been addressed in [84]. A method has been proposed for optimal allocation of different type of renewable distributed generation units in the distribution system to minimize the annual energy loss. This method uses a probabilistic Generation Load Model which is combined with the all the operating conditions of the renewable distributed generation units with their respective probabilities. Hence, this problem becomes deterministic planning problem. It is solved with Mixed Integer Non Linear Programming (MINLP) with an objective of reducing systems annual energy loss. The problem is bounded by various constraints like allowable voltage limits, the capacity of existing feeders, limits on maximum allowable penetration of DG and discrete sizes of available DG units. The proposed method has been applied to typical rural distribution system with different operating scenarios and possible combination of all DG units.

Considerable reduction in the annual energy loss has been shown with all the scenarios. The same problem can also be solved with different approach. Reference [85, 86] have used Hereford Ranch algorithm to minimize the system losses considering total DG power from all the units. Whereas, [87] has presented an iterative technique to place DG sub-optimally. Similarly, [88, 47] have also used iterative method for proper allocation of DG capacity in the distribution system. They have used voltage sensitivity and loss sensitivity to select the best site for placing DG units in the distribution system. In [89], an iterative technique based on power flow has been proposed to include new generation capacity into the existing network, using fault level constraint by considering breakers fault handling capacity. In [90], penetration level has been optimized by analysing the effect of penetration level on the annual energy loss. A multi-objective function has been formulated for sizing of DG and integrating them in to the existing network in work [45]. In [91], an analytical technique has been presented for optimal allocation of DG units in a radial distribution system to minimize power losses. The proposed technique considered different types of load profile with time varying loads and intermittent DG output, while taking into account technical constraints, such as voltage profile and feeder capacity limits. The DG optimization with constraint of protection of distribution system has been solved with GA application in [92]. While, [93, 94] have followed heuristic approach based on the decision theory. In work [95], discrete time steady state analysis havef been carried out for maximizing the connection through OPF technique.

The DG capacity allocation in the system has been studied in the different literature with different objectives. A heuristic approach for multiple load levels and electricity market fluctuations has been proposed in [96] for cost benefit analysis, to minimize capital investment for DG integration. The cost of system expansion for DG inclusion has been minimized over a planning period using optimization model in [97]. Effect of increased penetration of different DG sources on system losses has been analysed in [90], whereas, in [98] an analytical approach has been developed for energy loss minimization by placing DG optimally in the distribution system. Genetic Algorithm (GA) has been proposed in [43] for network loss minimization considering various constraints like network reliability, voltage stability and limit on DG penetration. Voltage stability problem with DG has been iteratively solved in [51]. The capital investment puts bar on the inclusion of DG sources in the existing system. Identification of location candidates for DG has been carried out in [99] to defer investment in system expansion. A comprehensive structure for distribution system planning for inclusion of DG is presented in [71]. In this work the cost of system and upgrades are minimized using sequential two stage optimization method. Ordinal Optimization (OO) has been preferred to reduce computational burden. In [70] also, ordinal optimization has been used to maximize benefits and reduce losses. In [100], Binary Particle Swarm Optimization has been proposed for allocation of biomass based DG for optimization of initial cost. Most of the work in this domain has considered only reactive power from conventional sources. The reactive power from DG sources has totally been neglected. In fact, the reactive power from DG sources can help reduce the power loss and improve the voltage profile across the system. The inattention of reactive power capability of DG, not only results in improper allocation of DG units, but also increases the investment significantly. The DG capacity allocation in distribution system is a stochastic problem with discrete decision variables bounded by various constraints. The inclusion of reactive power capability along with it′s limit will further increase the complexity of the problem. Also, it is difficult to satisfy the planning criteria with single optimal solution, so the complete spectrum of solution with associated probabilities have to be worked out. In reference [80], the variability of DG have been considered for both, active and reactive power, with their limits. In this work, the DG sources location are selected near to the load centres to realise the effectiveness of DG. This has been seen as a cost effective solution for improvement of reliability, voltage profile and energy saving. In the proposed method, the reactive power limit of various DG Solar, Wind and Biomass are included in the planning model together with the uncertainties like load demand, wind speed, solar radiation. Then, Mixed Integer Non Linear Programming (MINLP) problem has been formulated. The objective function has been formed to minimize total cost with optimal allocation of various DGs. The problem is solved with PSO and OO to obtain the optimal and sub-optimal solution. The proposed algorithm has been applied on various test system and results are presented in the work.

Volatile power injection in the grid affects the load margin. Saddle node bifurcation and other similar method increase the load and generation in prefixed direction to observe the nearness to the instability. Loading margin remains near about constant with the level of load. But, with dispersed generation or large renewable generation, the loading margin changes even with the load level remains same. In such case, loading margin has to be considered as stochastic variable. This can help in interpretation of probabilistic load margin. In [101], a Stochastic Response Surface Method (SRSM) has been proposed to assess the probabilistic load margin with minimum number of samples. Monte Carlo Simulation has been, though, straight forward in implementation of uncertain problem; the computation time has been limiting factor. Like several other methods, this method has been developed to overcome the drawback of MCS with large number of variables. SRSM significantly reduce the computational burden. This method has been applied to approximate uncertainties in outputs as a series expansion of random variables. Adequate samples from the input surface have been passed to the system model and output surface has been generated. The method is related to deterministic response surface methodology.

System security has been strongly associated with the voltage stability and it is of prime importance for effective planning and continuous operation of power system; particularly, post-contingency. In a conventional power system, corrective actions are taken to bring system to normal state post contingency, by governing the system into new and more stable equilibrium condition, such as change in network configuration [102, 103]. The preventive actions are also worked out pre-contingency. Several works has been found on formulation and optimization of control technique for voltage stability improvement and maximization of stability margin [104, 105]. In the deregulated market with wide spread penetration of dispersed renewable sources, more aggressive actions and evaluation of new techniques are required. Traditional control methods like transformer tap changing and injection of reactive power may not be enough with change in the system operation.

Power sector has been undergoing major revolutionary change because of market deregulation and allowance of renewable sources in transmission and distribution system. The competitiveness has increased tremendously. Also, the renewable generations are widely accepted as must run plants, which are facing no minimum or maximum technical constraints. So, every operator will inject available power in to the grid for profit maximization without observing restraint. This can push the power system to operate closer to the stability limits [106]. To safeguard the system, continuous monitoring of system parameters is required. The major responsibility is laying with independent system operator (ISO) to institute an impartial and fair transmission services in an open market structure, to provide secure and reliable power system [107]. The ISO should take appropriate and timely actions to cope with the instability related symptoms. However, optimal voltage regulation under deregulated market condition has been considered as challenging task. The main cause of voltage stability is insufficient support of reactive power under heavy load condition. The reactive power management has also been an important task from voltage stability view point. To ensure the availability of reactive power sources, an effective scheme of reactive power management has been required. Two kinds of reactive power pricing structure have been proposed in [108], with the consideration of generators reactive power capability limit. Several other cost based reactive power pricing has also been proposed and discussed in various literatures. In [109], a reactive power support optimization has been proposed with the consideration of voltage collapse margin. In this work, the relation of cost and price of reactive power has been established and also the cost of voltage instability is integrated in the optimal power flow problem. Based on optimal power flow, an optimized reactive power reserve management has been proposed in [110] to improve voltage stability. In order to utilize the maximum capacity of reactive power capability during high power demand and voltage emergencies, a detailed model of Wind Turbine Generator is required. However, the voltage instability cannot be addressed alone with reactive power injection and voltage control. In this condition, generation reschedule should be attempted to change the power flow in stressed part of network and thus improve voltage stability. Generation rescheduling has been gaining importance as an effective way to improve various stability problems. A sensitivity analysis based on structured preserving energy margin has been presented in [111] to determine the rescheduling of generation capacity to stabilize power system under transient condition. In [112], a new strategy has been proposed to improve the power transfer capacity based by appropriate rescheduling of generation, constrained by small signal stability. In [113], a multi-sensitivity based approach has been proposed. In this method, a generation rescheduling has been attempted to change the system operating condition to ascertain voltage security margin above the minimum value. As the deregulation of power industries has been gaining momentum, the concern about the performance of voltage stability has also been growing. It can be achieved by generation rescheduling and contract-transaction adjustments in an optimal and transparent manner. In [107], generator rescheduling based on system security has been proposed in the deregulated power system, but without consideration of voltage stability. A new optimal dispatch method has been proposed in [114] for a deregulated market, in which, bilateral contracts and pool generation are assumed to be co-exist. A fair and effective scheme for pool generation rescheduling and contract transactions adjustment has been proposed in order to achieve adequate voltage stability margin (VSM). A linear optimisation method with an objective of minimization of the social benefit loss because of generation rescheduling and transaction curtailment has been formulated with consideration of the functional operating constraints and VSM requirements with respect to normal condition and contingencies. It is then solved by a linear programming technique. Since, the pattern of load is difficult to predict in new market environment, the system loadability has been computed using locally closest bifurcation and used as the VSM in the proposed method. The effectiveness of the proposed method has been verified using a modified 39-bus New England test system. A study on the effects of post-contingency corrective capability of the system on social benefit loss and voltage stability performance is also presented.

In the recent year, majority of wind turbine connected to the grid are DFIG based variable speed wind turbine [115]. This type of wind turbine usually disconnects itself on detection of fault to prevent the generator from damage. To overcome this, recently the crow-bar circuit has been introduced in the rotor circuit, which gets activated under the fault condition to keep voltage under limit. This can be acceptable with relatively insubstantial amount of penetration of wind generators. As the penetration increases, more and more turbine will be connected to the grid and grid requires them to remain connected under fault condition to ride through the faults and contribute to the system stability during post-fault period. Majority of grid codes across the world mandates wind generator should remain intact with the grid during the fault condition. There are several other factors which makes control of grid fault ride through difficult and it has been a major challenge for DFIG developers and manufacturers.

There are various approaches found on DFIG control in various literatures. In [116], a minor current control loop in rotor side converter is proposed and the optimization of control parameters has been carried out to effectively control the rotor current. The use of crowbar and its effectiveness is evaluated in [117]. The difficulty of controlling ride through during symmetrical fault condition has been explained in [118]. It has been expected that, fast switching device can control the fault current with good time response like in HVDC systems [119, 118]. However, this seems straight forward, but cannot be applied directly to the DFIG. Several changes are required in the protection philosophy to handle the fault ride through. One of the idea proposed was to limit the rotor current with rotor converter and protection is operated on the impedance rather than the over current. But it didnt work well. There are cases reported, where DFIG experienced a high voltage and resulted in damage of rotor converter. In [120], the analysis of fault ride through has been carried out and presented the ability and limitations of DFIG to control the grid fault ride through. The major difficulty is the electromagnetic force induced in the rotor circuit due to negative and zero sequence component of the stator flux linkage and also the rotor speed. Based on the investigation, a control method has been proposed to increase the probability of successful fault ride through with the given current and voltage capacity of converters. It has been shown that, the fault current depends not only on the voltage applied on the rotor side, but, on the internal state of the machine as well. The proposed control design is based on the internal state of the machine. The time domain simulation as well as practical experiment with various fault condition has been carried out and results are presented in the paper. Then, the operating region for successful ride through has been defined for each fault type in terms of fault severity and the pre-fault condition of the machine.

In [121], a methodology has been proposed to improve the power quality and reduce flicker from direct connected fixed speed wind turbines.

Renewable energy sources are mostly located in isolated parts of the network. Such sources are integrated through long transmission line, which increases the grid impedance. With high penetration of Distributed Generators (DGs), power injection level increase and equivalent impedance of single inverter also increase, which improves the weak grid. Generally, inverters with vector controlled strategy, PLL has been employed to synchronise converter with Grid. Converter adjust the power angle to change the power injection level. Since, power level has been basically employed in power current loop structure, it has been referred as power - current control. In such a case, converters are controlled as current sources. The deterioration of power quality with increase in grid impedance has been mainly attributed to the control structure [122]. As a result of this, there will be a relatively strong coupling between inverter and weak grid dynamics, which has been ultimately results into stability issues like distorted grid voltage, harmonic oscillations and instability [123, 124, 125, 126, 127, 128, 129, 130, 131, 132, 133]. These issues may destabilise the grid connected inverters.

Usually grid impedance has been considered as zero while designing the power current controller. But in actual condition, the impedance of grid is a non-zero positive value, which will decrease the gain of controller and thus reduce the system phase margin. This may further lead to instability due to harmonics [134, 128]. It unveils that PLL essentially affects the stability limit and dynamic performance of converters under weak grid condition [130]. PLL can go into unstable region due to positive feedback mechanism with high grid impedance [130]. It has been also established that, the inverter impedance increases with the increasing bandwidth and push inverter into the unstable region [135]. The reshaping of inverter by decreasing the bandwidth is one of the way to expand the stable region, but as a consequence of this, the tracking performance and noise reduction ability of controller is getting affected. Thus, it can only be applied in limiting span to reshape the converter impedance and eliminate unwanted dynamic interactions with the grid by tuning the main inverter control parameters. Different impedance reshaping methods have been proposed in [136, 137, 138] to improve the performance of operation of converter in a weak grid. The grid voltage feed forward method has been effective to ensure reliable operation in a weak condition, but it introduces time delay. Multiple Passive Filters, tuned at different harmonic frequencies, can also be used to increase the output impedance [137]. Similar to this approach, phase compensation method is another method to increase the output impedance [138]. Impedance reshaping by tuning control parameters has been done at a selected operating points and thus, it doesn′t ensure stable operation under grid impedance variation [137, 138]. To avoid the PLL induced instability, synchronization method similar to synchronous generator has been proposed in [124, 139, 140] to improve the control performance up to certain extent. A control structure, differing far from conventional vector control strategy, has been used in [141, 142, 143] for improvement in performance of converter with weak grid.

To overcome the problems with conventional vector control strategy, a power control strategy based on the capacitor feedback has been used with LCL filter. In this method, feedback has been taken from the capacitor of LCL filter. The synchronization and power control method taking real and reactive power feedback and regulating output through voltage magnitude and phase angle control has been used in [139, 141]. However, the real and reactive power only can be decoupled with small power angle, which has not been possible with weak grid condition. As an alternative method, *d*-*q* voltage of capacitor has been controlled to achieve decoupling of real and reactive power. This method is quite easy to implement in commercial converters, as it modifies only the voltage control loop. In reference [141, 142], the virtual synchronous generator control has been implemented to improve the dynamic performance of converter. The interactive stability of converter using impedance based analysis in D-Q domain has been proposed in [130, 144]. The negative resistance characteristics of conventional vector controlled converter has been revealed in [138], which is responsible for harmonic resonance in converter. In [145], the analytical expression for output impedance with power - voltage controlled converter has been developed. This work takes into consideration, the third order characteristics of the LCL filter. According to this work, the power - voltage control strategy successfully reshape the converter output impedance and greatly improves the stability margin. It changes the negative resistance characteristics in to the capacitive behaviour. Add on to this, power - angle control characteristics also makes controller adaptive to large variation in system parameters and operating conditions [137].

As the penetration of renewable increases, the new grid code and standards put stricter requirement that wind turbine should remain connected to grid during the faults and should have such fault ride through capability [146]. There are two major problems, when remain connected with faulty system, one is the high rotor inrush current, which may damage the converter and another is the DC overvoltage. Also, the transient response of wind converter should be appropriate during the voltage dip to reduce the stress on gearbox and other mechanical components. Several measures have been adopted to attend the enhancement of LVRT capability such as Crow-Bar approach, Hardware modification and converter control. The Crow-Bar approach has been the simplest one, in which bypass resistors are connected at the rotor terminal to reduce the inrush current [147, 148]. Several crow-bar strategies have been explained in references [147, 148, 149, 150, 151, 152, 153]. However, the crow-bar degrades the performance of the DFIG machine as it turns the DFIG machine in to squirrel cage induction motor (SQIM). For long duration fault, SQIM absorbs the large reactive power, which may adversely affects the voltage stability. Among the several alternatives, one of the most popular method is machine demagnetization through Rotor Side Converter (RSC) control. The other approaches are, compensating Stator Transient Voltage and Rotor Back Electromotive Force (EMF). For short duration fault, the LVRT requirement can be met by controlling RSC control, but it may not be suffice, if the duration is large and the depth of the voltage dip is significant. In this case, rotor current may increase to significant level and can damage the converter [154]. As an additional measure, series connected Grid Side Converter (GSC) has been suggested in [155, 156, 157]. Such measure has been technically feasible, but, incurs additional cost. Reference [155, 156, 157] discusses about the hybrid approach, where Crow-Bar and demagnetising methods has been used in combination to improve the LVRT capability.

Another problem during fault or voltage dip is the oscillation of rotor torque and the rotor instantaneous power. The effect of balance and unbalance dip is different on the machine dynamics. Some of this effects are described in [156, 158, 159, 160]. The torque oscillation puts additional stress on the mechanical system of wind turbine and may have a severe impact, if such faults are occurring frequently. Also, oscillating power cause oscillation in dc link voltage, which may exceed the defined limit during the fault. Therefore, current limit and torque oscillation both are important for effective LVRT.

Reference [161] proposes an efficient control strategy using passive and active LVRT compensators. The passive compensator is new crow-bar arrangement in series with the stator windings. The active compensation is achieved through the rotor voltage control. Through theoretical analysis and simulation results, the effectiveness of the proposed strategy has been proved. It has been shown that, the inrush current is reduced considerably at the instant of fault occurrence and fault clearance. It also reduces the torque oscillations and rotor instantaneous power during the voltage dip. Thus, the proposed solution achieves both objectives of ride through capability.

Under the fault or grid disturbance condition, the grid voltage reduces significantly. Reduction in terminal voltage causes decrease in output power and torque. For small duration of fault, the mechanical power to wind turbine remains constant and this cause machine to accelerate. With the speed increase of induction machine, the slip increases and result in increased reactive power consumption. Even after the fault is cleared, the machine continues to draw large reactive power from the grid. If this continues for longer time, machine will speed out of control and gets disconnected from power system. To prevent this, the reactive power support at the terminal is required.

STATCOM has been one of the alternative, which compliments the wind farm in functionality and helps to become grid compliant [162]. STATCOM has been able to provide fast reactive power support and overcome the limitations of the wind farm. STATCOM and Battery Energy Storage System (BESS) have become a promising devices for power system applications [163]. The converter used in STATCOM is a non-linear device and difficult to control due to non-linear characteristics. A simple solution to this is to provide two separate Proportional Integral PI controllers to control the reactive power and DC link voltage [164]. However, this method adds delay in the control and response becomes slow. Also, it is difficult to find appropriate parameters of PI controller. This can be partly addressed by linearize the system around operating point [165]. But, this method also lacks in two aspects. First, the effectiveness of controller is poor for large disturbances. Second, the performance is dependent on operating point.

Several methods, to control Pitch Angle and STATCOM, have been reported in literatures. However, most of the control strategy like PID control, Gain Scheduling control, Robust and Non-Linear control, are operating point dependent. LQG controller reshape the frequency behaviour of the system and provides good gain margin and phase margin. But, it is unable to give robustness against the uncertainties due to change in operating conditions. Robust control has been mainly applied to enhance voltage and transient stability in power system. In [166] H_∞ control using Linear Matrix Inequality (LMI) for pitch angle has been proposed to reduce the power fluctuations of wind generators. LMI can also be applied for simultaneous control of pitch angle and BESS [167]. However, in most of the controllers, the non-linearities of wind turbine has been neglected. The deficiencies of linear controllers can be overcome by using non-linear control technique. But, the major hurdle with non-linear control is, difficulty in implementation [168]. Non-linear controllers are complex in structure and difficult to realise in practice. So, from an application point of view, simple controller has been preferred without compromising robust performance.

In [165] effective nonlinear control technique using Cauchy reminder has been proposed. Cauchy reminder method use linearization technique, but, also considers the non-linearities of the system [169]. The mean value theorem keeps system non-linearities in the system model and improves modelling accuracy. The non-linear dynamics of wind generator has been modelled as linear system and uncertainties in the form of norm-bound is derived from Cauchy reminder of Taylor series. This will enlarge the effective area of control and thus improves the capability to handle the large disturbances. In this work, potentially severe disturbances are addressed in controller design and this makes controller robust against the non-linear disturbances. The designed robust controller gives acceptable performance post fault, for both, large and small disturbances. Using simulation results, it has been proved that the robust controller designed enhances voltage stability and transient stability of the system.

Reference [170] discusses the loss of synchronism in post-fault condition. It has been observed that, the Loss of Synchronism (LOS) occurs when the terminal voltage falls near to zero level and wind turbine current characteristics is not similar to the impedance characteristics. During the fault condition, Wind Turbine injects active and reactive power in the line having resistive - inductive impedance. The current references generated during fault is not proper and if the ratio of active to reactive power is not close to the R/X ratio of the line, the LOS can occur. Five different cases are presented with different active and reactive power injection. It is concluded that LOS do not occur, if the current injection is kept zero during the fault or if the current injected is having the same angle as the angle of impedance. During LOS, the angle estimation by PLL becomes erroneous, which cannot control active and reactive power appropriately. LOS occurs due to the frequency protection tripping or loss of current control. The LOS trips the Wind Power Plant (WPP). The frequency saturation limit of PLL has been kept at 40 Hz and 60 Hz. Frequency control beyond this range is not possible for PLL and thus triggers the frequency tripping. Fast detection of fault and immediate reduction of power injection can reduce the chances of LOS, however, this method is against the grid codes. The solution of this problem is to decrease the active current injection as per the voltage drop [171]. Such a solution can help with high active power current, however, can fail with only reactive current reference. Another solution is to inject active and reactive power in the ratio of R/X i.e.. impedance angle. However, this method requires accurate estimation of X/R value, which is a practical difficulty.

LVRT requirement is amended considering the increasing level of converter integrated generation and the number of voltage sags and swells occurring every year [172]. Unlike anti-islanding protection, LVRT requires generation to be connected during the grid disturbance and contribute actively in keeping system voltage and frequency stable. As per typical LVRT criterion, generator is allowed to disconnect itself from the grid when the depth and width of the fault area is beyond the allowable limits. Apart from this, generators are required to inject reactive current during the fault. To accommodate the grid code requirements, the control techniques have to be modified, because the converter operation under the normal condition and fault condition is widely different. Several issues needs to be considered during the fault condition like overcurrent, sudden terminal voltage drop, surge of DC link voltage, fault detection and response of Phase Lock Loop (PLL). Several methods has been proposed to achieve successful LVRT by addressing these issues. In reference [173, 129, 174, 175], different aspects of the LVRT control strategy are studied like sequence abstraction, PLL structure and its response, current controller and different control strategies. About 95% of the faults are asymmetrical or unbalanced in nature. To enhance the converter performance under asymmetrical fault, a vector control method has been proposed in [176, 177]. In this method negative sequence voltage is feed forwarded in the control loop (VCCF-Vector Current Control Feed-forward). During fault, DC link voltage fluctuates with double the line frequency. To limit the ripple of double frequency, Dual Vector Current Control (DVCC) has been proposed in [178, 179]. However, this method injects constant real power into the grid to achieve the ripple free DC voltage. But, this cause the line current distortion due to injection of negative sequence current into the grid. In comparison to DVCC method, VCCF method maintains the output current quality and keep DC voltage ripple at double the line frequency. Reference [180] proposes adaptive DC link control method for two stage converter during LVRT period. The DC link voltage has been controlled to follow the grid voltage to maintain the high modulation index, so that the high frequency harmonics is attenuated significantly. This method also attenuates double frequency DC link ripple voltage to a certain extent to keep DC link voltage in safe operating range. In this work, the theoretical results are verified using MATLAB simulations.

With increasing share of grid integrated wind generation, the safety and stability of system has been facing new challenges due to volatility of generating sources. Particularly, during the grid disturbance, fast response and connection continuity are necessary requirements to assure the grid stability. Different countries have defined their own strict grid codes to direct the behaviour of the renewable energy generating systems [181, 182, 183]. Among other clauses, LVRT is the important clause. The Low Voltage Ride Through (LVRT) defines the mandatory response during grid disturbance condition [184, 185]. As per the most of the LVRT clauses, the generating system should keep connected to the grid and inject the appropriate reactive power for speedy grid voltage recovery post fault condition [186, 187]. According to new Chinese grid code, the grid connected converter should deliver reactive power till 30 ms after the occurrence of grid voltage sag [185]. This requires accurate detection of the voltage sag depth as fast as possible to inject the reactive power timely.

Since, every grid code asks the grid connected converter to respond according to the line and phase voltage variations under different fault conditions, the voltage detection method should have capability to detect every phase voltage. This requirement may not be satisfied by the traditional Phase Lock Loop (PLL) like PLL using D-Q transformation. Several other methods like RMS Voltage detection [188], Peak Voltage detection [189], and Discrete Fourier Transform (DFT) are proposed. But this method also lacks in speed and accuracy due to voltage unbalance, frequency variation and low order harmonics in the system. This drawback can be overcome by using digital filters in PLL [190, 191, 192, 193] or use positive and negative sequence separation method [194, 195, 196]. Single Phase PLL can also be one of the solution for asymmetrical grid voltage, but it′s time delay is unacceptable [197, 198, 191].

A new method has been proposed in [199] for fast and accurate detection of voltage for ride through period. The proposed method consists of one Synchronous Reference Frame (SRF) and two voltage detection module. The voltage detection module derive the amplitude, phase and frequency accurately before the occurrence of grid fault. On detection of predefined out of boundary condition, the voltage detection module start to compute the real time voltage variation in parallel. The voltage detection module tracks the maximum and zero point under different condition like three phase unbalance, voltage sag and surge, frequency variation and phase shift. The low order harmonics is filtered using cascaded delayed signal cancellation without much time delay (few milliseconds). This delay is less than the transient response of the converter reactive power output. This method meets all the requirement of the strict grid code and it has been verified using MATLAB simulations.

Doubly Fed Induction Generator (DFIG Type 3) is most widely used wind power generation technology. In DFIG based wind turbine, a simple Crow-Bar resistor has been directly connected with the rotor circuit for Fault Ride Through (FRT) [200, 201]. But in this method, the controllability of DFIG is lost and DFIG behaves as a Squirrel Cage Induction Machine (SQIM). It consumes reactive power under fault condition, which further deteriorates the grid voltage [202]. To solve this problem, various methods have been proposed to enhance the LVRT capability [202, 120, 203]. In [120], demagnetising current control has been proposed, in which the rotor current is controlled to counter the negative sequence, zero sequence and dc components of stator flux during a grid fault. However, under sever voltage dip condition, the current control cannot be achieved due to insufficient rating of Rotor Side Converter (RSC). A unique transient restructuring of DFIG has been proposed in [204] to improve FRT performance. In this method, Grid Side Converter (GSC) of DFIG is reconfigured as Dynamic Voltage Restorer (DVR) to compensate stator voltage dip during transient. However, to achieve the full range of voltage compensation the GSC rating should be at-least equal to the rating of the generator. There are several other methods based on hardware like Rotor Side Dynamic Series Resistance [205], Series Grid Side Converter (SGSC) [156], Dynamic Voltage Restorer (DVR) [206], Supplementary Energy Storage Device (ESD) [207] and Multi-Switch GSC [208] have been proposed.

In addition to LVRT, a little concern has also been shown towards the transient reactive power control of DFIG. Recently updated grid code requires WTG to provide transient reactive power support during fault transient [209, 203, 147, 210]. In [147], a method has been proposed in which RSC is reconfigured to connect with stator in parallel with GSC to provide additional reactive power support, while, the crow bar protection is applied to rotor to damp the excessive rotor current. The main disadvantage of this method is that, the DFIG works as an Induction Motor (IM) and absorbs reactive power from the grid. In [211], a method has been suggested to reduce the dc and negative sequence of rotor current by accelerating the DFIG (by active power injection) to increase the effective capacity of RSC for transient reactive power compensation. Also, in [210], increase in the loading of RSC and GSC has been suggested for transient reactive power control. However, this method will induce additional stress on power electronics converters and reduce the life time of the equipment.

In reference [212], a novel method has been proposed in which RSC is reconfigured and work with Electric Storage Devise (ESD) to enhance the LVRT capability and transient reactive power support strategy. The GSC has been reconfigured in such a way that, it is connected in parallel with RSC across the rotor circuit. Due to this, the GSC provides additional path for the rotor current. RSC and GSC are controlled in a coordinated manner to compensate transient rotor current. There are basically two rotor current component, one is demagnetizing current, produced to reduce the dc and negative sequence component of stator flux, which diminish the transient Electro-Motive Force (EMF). Another rotor current is proportional to the reactive power requirement for supporting the terminal voltage. The DC link voltage is maintained by ESD. Therefore, with transient reconfiguration of DFIG and coordinated control of GSC, RSC and ESD, much better performance of DFIG can be achieved under severe asymmetrical fault condition in comparison to other conventional methods.

In [213], a novel method for detection of islanding of two stage converter has been proposed. The novelty of this method is that, it doesnt depends on the instantaneous value of the voltage for detection of islanding condition. The islanding condition has been detected by the saturation of PI controller of the voltage control loop. This makes method more reliable as compared to other voltage detection based method. It is immune to malfunction caused by the sudden load changes or other transients. In this work, a simple but effective, LVRT strategy has been proposed which is integrated with the anti-islanding operation. This method has been implemented in the same control structure and works seamlessly with grid connected and islanding mode of operation. The work is concluded with the results of hardware prototype.

DFIG alone can achieve LVRT objectives to a major extent, but as a further improvement and to get better performance, Dynamic Voltage Restorer/Compensator (DVR or

DVC) has been installed at a Wind Farm or Wind Power Plant level. Dynamic Resistor (DR) has also been installed between stator and grid to support the stator voltage under disturbance. It can increase the decay rate of rotor EMF and thus eliminate the overcurrent and overvoltage. However, it requires additional hardware, which cause additional cost and also affects the reliability of the overall system. As an alternative solution to this, different control strategies has been proposed to use existing hardware of DFIG to improve the LVRT and transient performance [202, 214, 215, 161, 120, 216, 217]. Some of them act on the conventional control algorithm. For example, additional feed-forward of stator flux is added in to the current loop to improve the immunity to EMF disturbance [202].

In [214], feed-forward of actual rotor control is introduced to change the controlled object. Robust controller or non-linear controller, in place of simple PI controller, has also been an effective way to improve the controllability under disturbance [215, 161]. These controllers effectively calculate the required rotor voltage to suppress the disturbance and thus increase the utilization of RSC. However, the conventional control objective requires sufficient capacity of RSC to counter transient EMF and limit fault current, even with different controller. When transient EMF exceeds the DC link voltage under severe fault condition, rotor voltage requirement cannot be satisfied with the limited RSC capacity and there will be steady state control error. In this case, the control hits the saturation limits and loose its controllability. Some control strategies select overcurrent reduction as their primary objective and modified their current reference to release certain transient and negative sequence rotor current, so that the required rotor voltage can be reduced to RSCs range and then RSC operate in the permissible range without losing its controllability [120, 216, 217].

Reference [218], addresses the effect of wind power injection on voltage stability and losses of the power system. Also, investigated the role of reactive power compensation. For analysis purpose, bifurcation analysis has been used. To characterize the impact of wind power on voltage stability, various indexes has been proposed. These are active power loss per unit (η_P), reactive power loss per unit (η_Q), and voltage offsets per unit ($\frac{\Delta V}{P}$). It has been importantly highlighted in this work that, reactive power compensation can delay or suppress the occurrence of saddle node bifurcation, but it can′t completely overcome the ill-effects of continually increasing wind power injection. Also, the effectiveness of proposed indexes has been proved through quantitative analysis of effect of reactive power compensation on losses reduction and stability improvement.

Reference [219] considers the role of reactive power supply limit on voltage instability. It emphasise the role of FACTS devices like STATCOM and SVC for improvement of voltage stability by enhancing the reactive power handling capacity. In this work influence of STATCOM and SVC has been studied in a comparative manner to see the effect on Low Voltage Ride Through (LVRT) capability of wind farms. The wind farms considered with Fixed Speed Induction Generator (FSIG) with pitch control. The voltage instability has been attributed to the asynchronous operation of the Induction Generator, which takes excessive reactive power during and after the fault due to large rotor slip. For study, models of wind turbines, STACOM and SVC is developed in EUROSTAG. Also, the Automatic Voltage Regulator (AVR) of conventional generator has been modelled in detail. In addition to this, different load models has been used and Under Load Tap Changer (ULTC) has also been taken in to consideration. Finally, it is concluded that as the wind power injection increases, the capacity of STATCOM and SVC also increases.

Reference [220] validates the different wind turbine generator models for stability study. This work has been carried out by the Ad-Hoc Task Force on wind generation validation model. The model validation has been achieved in three steps. The first part of validation process is to define the wind turbine structure under study. The second part is the collection of the data from actual site or test systems. These data are monitoring of large disturbance, change in reference set points of different controller (i.e.. voltage reference point) and any other abnormal events. The third and important part of the process is the simulation model built in step 1 and apply the same set of events, which are monitored and see the response of model. The response of model is then compared with the actual response received from the site or test data. The simulated events mainly are the effect of change in various parameters on the voltage. It has been studied that, how different models responds to the change in voltage (i.e. voltage dip, voltage sag /swell, voltage ramp up/ramp down, and voltage oscillations). The work is concluded with remark that, the model has to be evolved with the time, as there may be various unforeseen conditions.

Reference [221] is again on the validation of the model. In this work the model of Type-3 Wind Turbine with voltage controller and power factor controller has been modelled and validated as per IEC standard 61400-27-1. Also, the model response with full grid and simplified grid model has been compared. In addition to this, the survey has been carried out on other validations studies for recommendation on the future modelling and validation tasks. The IEC model is then tuned to match the measurements accurately and also various control parameter has been validated with respect to reference model. It has been shown that the IEC models are accurate enough to reproduce the Wind Power Plant behaviour. It has been pointed out that the Wind Power Plant can be modelled using IEC models to analyse the short-term and long-term voltage stability. Also, in this work the power factor controller at Wind Power Plant level has been examined first time. It has also been recommended that, for the future validation of model, various other measurements from field are required like data from single Wind Turbine, response under different control configurations (voltage control at Wind Power Plant (WPP) level), frequency drop or voltage drop close to WT terminal.

Reference [222] put forward the active voltage control to curb the voltage variation due to active and reactive power variation, occurs due to wind speed variation. A large scale Wind Farm (WF), when integrated by long distance transmission line, power grid will not be unable to support the access point voltage of wind farms and due to this Wind Farm voltage suffers from voltage stability problem. As per this work, only reactive power compensation is not enough. Even with the decoupling control, the reactive power delivering capacity of DFIG is restricted by the active power output. This work proposes the coordinated control of active and reactive power to curb the voltage stability under variable speed condition. The reactive power capability and reactive power demand has been studied and access point control of voltage has been analysed. In the proposed active voltage control strategy, the voltage control has been achieved by reactive power adjustment, active speed control and pitch angle control. Using simulation it has been proved that the proposed method adequately uses the reactive power capability to meet the reactive power demand. Also, the proposed method effectively reduce the Wind Farm voltage variations under variable wind speed condition.

Reference [223] is based on the case study of Danish Power System with increased amount of wind power under islanding condition. In Denmark, the contribution of wind power has been increasing and due to this, the conventional generation has been reducing. The maintenance of reliable and stable system becomes a great challenge for Danish Power System Operator. Currently, they totally depend on the neighbouring power system and strong AC connections. They are using the reactive power capability of neighbouring power systems and central power plants of Denmark to control the voltage. This work presents the results of the study carried out by Danish Transmission System Operator (DTSO) on the western Danish Wind Power System under islanding condition. In this condition, the main ac lines connecting Western Denmark to the Union for the Co-ordination of Transmission of Electricity (UCTE), which is a synchronous area (area with conventional power plants), were out of service and wind power generation was high. It is shown that the voltage control and reactive power of conventional power plants is necessary for maintaining the short term voltage stability of Western Danish Wind Power System and it becomes almost necessary when strong AC connection to the strong transmission system of UCTE is out of service. This study can be applied to other system as well to assess the system capability of accommodating variable wind power.

Reference [224] studied the Transient Voltage Stability (TVS) using Superconducting Fault Current Limiter (SFCL) based passive voltage compensator and Transient Voltage Control (TVC) based active voltage compensator. Both works in coordinated manner. The first step of study is to model the SFCL and TVC. Also, the adjustment of gains of PI controller has discussed. It has been acknowledge that, the SFCL along with TVC acts in a self-compensation mode and restore the voltage to nominal value. Using simulation results, it has also been tried to show that the coordinate control of SFCL and TVC can provide high stator voltage output and reactive power output for effective grid connection and voltage support.

Reference [225] prefers active compensator like STATCOM as compared to conventional VAR compensation devices like capacitor banks and synchronous condensers. According to this work, conventional devices loses it′s effectiveness with time. Also, this devices are less effective to meet the stringent requirement of Grid Code and short-term voltage stability in a system with high wind power contribution. This work proposes retirement based approach, wherein, the old devices are slowly and slowly are replace with new FACTS devices. In a way, this has been a systematic approach for optimal VAR resource planning and up-gradation of power system with high wind power penetration. STATCOM with dynamic and rapid reactive power capability has been an ideal solution to the challenges created by variable wind power. An objective function with multiple objectives is proposed to achieve objectives. There are three main objectives. First, reduction in the cost of up-gradation. The second is, the proximity to steady state voltage collapse. And, third is, accepted performance of transient voltage. Further, a real time approach has been followed by considering multiple contingencies and uncertain load models are used in simulation. Add on to this, Low Voltage Ride Through (LVRT) and High Voltage Ride Through (HVRT) abilities of Wind Farms (WF) are also modelled. The study was carried out on 39-Bus IEEE standard test system.

Reference [226] investigates the impact of Wind Farm (WF) response on the nearby grid during network conditions. In this study only modern variable speed WT has been considered and new E.ON Netz fault response code for WF has been taken into consideration. The study has been carried out on 32-Bus CIGRE system. It shows that Wind Farms complying with new Grid Code are effective and performance is better in meeting the fault challenges as compared to traditional power factor based control approach. Not only this, but the response time has also been improved. Also, the effect of larger capacity of variable speed wind turbine converter has been exploited in order to improve the stability of nearby grid portion by extending reactive power support. It has been shown that, by using large converter capacity, voltage profile at Point of Common Coupling (PCC) and transient stability of the grid has been improved with new Grid Code as compared to old Grid Code. On the other side, the disadvantage of large converter has also been pointed out with large offshore Wind Farm connected through long cables. This makes difficult to support the grid with extra reactive power during disturbance.

Reference [227] presents a comprehensive study on the use of Energy Storage System (ESS) for regulating wind power variation and effective integration of Wind Power Plant (WPP) for grid voltage stability. The design and application of ESS includes the setting of reference output of ESS, charging - discharging of ESS and optimal sizing of ESS. The efficiency of this method has been evaluated using system includes 14-Wind Farms, Compressed Air Energy Storage (CAES) and 27-Bus transmission grid. The proposed methodology has been supported by results showing that the use of ESS is effective in reshaping farms output and increase in both revenue and voltage stability. It has also been shown quantitatively the improvement in integration of Wind Farm and voltage stability with use of optimal ESS.

Reference [228] is based on the study of application of STATCOM to facilitate the seamless integration of Wind Farm (WF) into a week power system. A week power system with two WF is first introduced. Then, power quality issues with WF has been highlighted based on the actual field data. To overcome power quality issues, centralized STATCOM has been proposed. This approach has been effective in solving the problems, particularly short-term (seconds-minutes) voltage variations. In addition to this, steady state model for power system, WF and STATCOM has been proposed. Also, this has been validated by using actual field data. Finally, a control strategy for STATCOM has been presented for suppressing voltage fluctuations. Dynamic simulations has been carried out to verify the performance of proposed control strategy of STATCOM.

Reference [229] proposes novel adaptive strategy to obtain the technically justified Fault Ride-Through (FRT) requirement. The stringent FRT requirement with still low level of wind penetration is not justifiable. The core objective of this work is to achieve effective grid integration of Wind Power Plant based on technical feasibility and economical viability. According to this work, the FRT requirement has to be evolved with time, based on the wind power penetration level and system characteristics. The main idea is to introduce stringent requirement, only when required, to secure power system. In the proposed strategy, voltage stability support and FRT requirements has been considered. Simulation has been carried on mid-sized Chilean power system with low penetration of Wind Power. Simulation includes the Fixed Speed Induction Generators (FSIG) and Doubly Fed Induction Generators (DFIG). Results of both strategy, one with stringent FRT requirement and other with adaptive FRT requirement, has been compared and technically feasible requirements are proposed for Chilean case.

Reference [230] highlights the importance of dynamic reactive power system with comparatively least presence of conventional power plants. This method proposes a optimal dynamic allocation of reactive power, in a large scale wind power integrated power system, based on mixed integer dynamic optimization. This method is superior to static optimal power flow based optimization, as it considers the detail system dynamics and WT Grid Code compliance, while optimally allocating the dynamic reactive power. This work emphasises two major aspects of the operation of wind integrated power system. First, better utilization of existing WTs, especially Wind Farms with additional grid support functionalities like dynamic support (e.g. dynamic reactive power support). Second, equip the existing power plants with synchronous condensers to provide the dynamic reactive power and also to strengthen the system inertia. The proposed methodology is applied to Western Danish Power System, which is a perfect example of large-scale wind power integration and least presence of the conventional power plants.

Reference [231] investigates the control and stability of offshore Wind Farms with Medium Voltage (MV) AC power collection and High Voltage Direct Current (HVDC) transmission to onshore power grid. In this work, Type-IV (Full Converter) WT and Voltage Source Converter (VSC) based rectifier has been considered. Then, output impedance of Wind Turbines (WTs) and input impedance of rectifier has been modelled in positive sequence and negative sequence. An Impedance based stability criterion has been applied to determine the stability of the offshore AC power collection bus. Also, possible AC bus voltage instability and resonance in Wind Farm (WF) and HVDC rectifier are examined through impedance model. The analytical impedance models has been used to identify the root-cause of instability, resonance problem and then to develop possible solutions. A detailed circuit simulation has been carried out to validate the analysis. Also, the converter impedance models has been validated by measurements of experiment set up by building low-scale prototype.

Reference [232] explored the possible improvements in voltage stability and transient stability with wind energy converters using modified P/Q control. To achieve this, Voltage Source Converter (VSC) in variable speed wind turbines has been used. In this work, it is mentioned that, the improvement is merely achieved by available hardware without any alteration or modification. Moreover, it has been found that the improvement is larger with variable speed wind turbine as compared to fixed speed wind turbine. The proposed method has also been implemented in existing VSC to improved short-term voltage stability. It has been found that, with altered control of Wind Farm (WF), the steady-state power transfer capacity of a transmission line can be increased by 17% during a low wind speed situation. It has also been shown that, Wind Turbine with such control can support the grid to delay or prevent voltage collapse event. Again, the improvement in variable speed Wind Turbine is larger than the fixed speed Wind Turbine. Moreover, it has been demonstrated that, the transient stability of nearby synchronous generator can be increased using variable speed control along with variable power factor. It has been noted that, with this arrangement, the critical clearing time has been increased by two cycles.

Reference [233] addresses the issue of low frequency (4 Hz to 30 Hz) oscillation observed in Wind Farms with week grid interconnection. Such oscillations limit the wind power delivery to grid. This work proposes feedback control strategy for VSC used in Type-3 and Type-4 Wind Turbines to enhance the overall system stability. First, it has been demonstrated that, the root cause of week grid stability issue is because of the coupling of power delivery and voltage at Point of Common Coupling (PCC). Increase in power transfer leads to reduction in the PCC voltage. When this is further explored, it establishes mechanism that lead to instability in week grid scenarios. The solution to this problem lies in the reduction of coupling between power delivery and voltage stability. Two different control strategy has been proposed to modulate the power or DC-link voltage with either d-axis current or PCC voltage as the input signal. The proposed strategy has been tested using analytical models in MATLAB/Simulink on Type-3 and Type-4 Wind Turbine. Finally, it has been concluded that voltage feedback strategy enhances the stability greatly and power delivery of wind can be significantly improved.

Reference [234] proposes the voltage and VAR control using Direct Drive Synchronous Machines (DDSM) during normal and transient conditions. In actual, the WTs are equipped with voltage and reactive power control for normal operations and under-voltage ride through. The simulations has been carried out for two different test cases as well as on the Belgian grid. Simulation reveals that, the preferred mode for the voltage support during voltage dips depends on the grid short circuit level and X/R ratio. Further, it has been pointed out that angle stability of both Induction Machines and nearby Synchronous Generators can be improved by providing reactive power support by WTs. From Belgian case study, it has been concluded that, voltage control is very much necessary especially in remote area to maintain operations between extreme limits of voltage. Also, it has been noted that the co-ordinate control of different WTs can lower the magnitude of voltage reduction.

Reference [235] adopts the approach of reactive power or VAR tracking for assessment of stability of power system with high wind power penetration. However, accurate tracking has not been possible, as it has been impacted by factors like wind conditions, external power grid approximations and internal operation constraints of Wind Farms. An algorithm based on the optimal sensitivity has been proposed for tracking Reactive Power Reserve (RPR) of Wind Farms. It also adapts to the internal and external constraints. The proposed method has been tested on actual WF in China and the result confirms the effectiveness of this method.

Reference [236] worked on the feasibility study of the utilization of reactive power of grid connected variable speed wind generators to improve the steady state voltage stability margin of the system. It has not been possible to allow wind generators to work at maximum reactive power limit, as this may push the system near to the steady state stability limit, which is very not desirable. This calls for proper coordination of different Wind Turbines (WTs) for reactive power output. This work presents the framework for coordination of various reactive power sources for voltage stability improvement. Case study has been carried out on 418-Bus system, equivalent to the southern grid of India, indicates the effectiveness of proposed methodology in enhancement of steady state voltage stability limits.

Reference [237] proposes consideration of voltage stability margin in sizing of Wind Farm. Currently it is being avoided. In this work a new method has been developed to increase the wind power penetration level by placing wind generator at strong buses (voltage stable buses). Placing wind generator at strong bus has least impact on Voltage Stability Margin (VSM). This work also provides comprehensive methodology to identify the system weakness for each penetration level. The new method also includes the modal analysis and traditional Q-V method in sizing and placing of wind farms. The study further shows that, the sizing and location of SVC is also important in wind penetration limit.

It has also been recognised that, the wind power penetration level can be increased when SVC is placed at the weakest buses instead of locating them at the wind generation buses.

Reference [238] introduces the concept of Constant Power Load (CPL) for improving the Fault Ride Through (FRT) capability. Every Grid Code demands that the Distributed Generator (DG) remains connected during fault. Under the asymmetrical fault, negative sequence flux circulate in air gap of Induction Generator and gives rise to oscillatory torque. This may reduce the lifetime of turbine. This work proposes CPL for asymmetrical FRT. Generally, STATCOM has been used to mitigate the voltage unbalance and VAR compensation. But, according to this work, the CPL works better than centralized STATCOM. The compensation of positive sequence voltage reduces the possibility of voltage collapse at the low voltage level and hence improve the stability and reliability of Wind Farm. Also, the compensation of negative sequence voltage reduces the torque ripples. The results of STATCOM have been compared with the result of CPL and concluded that the CPL is better in mitigating asymmetrical fault.

Reference [239] pointed out that the voltage stability issues is caused by the active power fluctuations and irrational regulations of reactive power. The problem becomes severe with high penetration of wind power. In this work, the Optimal Reactive Power Dispatch (ORPD) has been proposed as a solution to static voltage stability problem. The ORPD strategy has been achieved by Automatic Voltage Control Capability of Wind Turbines (WTs) and reactive power compensation device at central substation level. The ORPD strategy works based on the present and historical wind speed data. The proposed strategy has been tested using simulation of Wind Power Plant Cluster (WPPC) in North China. The result shows that, the ORPD strategy improves the voltage control performance and maintains the static voltage stability by coordinate control of various discrete dynamic devices

Reference [240] proposed a fast voltage fluctuation control of isolated power system with high wind power penetration by Phasor Measurement Units (PMUs). It is claimed in this work that this method reduce the fast voltage variations and improve post fault voltage dynamics. First, an isolated power system with high penetration of wind power has been taken and model reduction has been derived using PMS measurements. Then, the delay compensation has been achieved by Pade′s approximation. Then a model is established using reduced model and time delay compensation. The problem is then formed as a Linear Quadratic Regulator (LQR) problem. The problem has been solved by well-known Riccati equation. Finally, using simulation results the effectiveness of the method has been proved.

Reference [241] addresses the impact of integration of variable speed wind turbine on long term voltage stability. The two control strategies have been proposed and implemented in Type-3 (DFIG) and Type-4 Fully Rated Converter (FRC). The proposed strategies are unity power factor control and variable power factor control. It has been achieved by Grid Side Converter (GSC). This work also considers the capability curves and various limits of Wind Turbines. It has been pointed out that the operating point and wind speed keeps on changing because of several limitations of Wind Turbines. The study considers the dynamic model of system, Overt Excitation Limit (OEL), On-Load Tap Changers (OLTC) and static as well as dynamic load. Then, the time domain simulation has been carried out. Based on the result of simulation, it has been concluded that the long term voltage stability can be improved by controlling reactive power by GSC. Further, the role of reactive power in maintaining the long term voltage stability and importance of capability curve of WTs are appreciated.

Reference [242] illustrate the effect of addition of 100 MW of wind generation (DFIG) to a weak power transmission network. The effect of wind power capacity addition in discrete step (25%, 60% and 100%) has been considered. The simulation has been carried out and results are compared with 100 MW conventional power system. The results demonstrated that, DFIG provides better damping performance under different wind power penetration. This is because of in-built capacity of VAR /voltage regulation in modern Wind Turbines (WTs). For study purpose, Western Electricity Coordinating Council (WECC) power system has been taken. This system is located far from major generation and contains large motor loads. Also, the connecting transmission line is week. The simulation has been carried out in time domain using positive sequence phasors. The response of large induction motor has been observed. It has been concluded that the FRT capability is improved with DFIG.

Harmonic Stability is also an important aspect of operation of renewable energy souces. Many problems have been observed in the field in recent years, which are related to the harmonics. This aspect has been also studies in this work. So, the related literatures on the topic has been studied and findings are summarised here. Various literatures has been investigated to find out the work done in the field wind power effect on power quality. There are quite a few numbers of literatures are available, which has focused primarily on the power quality aspect of the wind power.

In reference [243], harmonic emission from four different wind park has been measured and their harmonic spectrum is compared. Further, it is found that, the harmonic emission from the wind power converter is small as compared to any harmonic emission load. And mostly inter-harmonics are generated by wind converters. The most important thing found in this work is the frequency - duration plot, depicts how the spectrum has been changing over a period of time. The significant change in the spectrum has been observed during the measurement period, not only in magnitude, but also the ratio of different components. It is interesting to know from this work that, some components of harmonics are co-related with the active power variation, but others are not. This is very confusing. Finally, the work is concluded with the comment that, a measurement of one location during a short period of time cannot be represented as the harmonic emission due to wind power installation.

In reference [244], measurement of voltage and current distortion, at two locations inside the wind farm, has been compared. The variation of the spectrum with respect to time has been presented to show the emission in a Wind Park.

Harmonic variation with the wind farm operating point and the random characteristics of their magnitude and phase angle has been measured extensively and the deterministic and stochastic characterization has been analysed in reference [245]. Similar work is found in reference [246]. In this work, the author has done extensive field measurements on commercially available wind turbines and revealed several important observations. As per the opinion of author of this work, the spectrum of harmonic from a wind turbine is extended to few kHz, but with the increase in size of WT, the spectrum remain limited to low frequency, around less than 1 kHz. Among several other observations, the important observation is about the presence of lower frequency harmonics (5th, 7th etc...). The lower order harmonics are generally not expected from PWM converter. The lower order harmonics follows the Normal distribution, whereas Rayleigh distribution is found in higher order harmonics. Further, the low order harmonics synchronized with fundamental frequency, but high order harmonics varies randomly between 0 to 2π.

A structured framework has been presented in reference [247] to analyse the harmonics emission and the resonance condition in the wind power interconnection with the grid. According to this work, the wideband harmonics from wind turbines are stochastic in nature and they are associated with the active power production. They may adversely interact with the grid impedance and cause unexpected harmonic resonance. This issue needs to be addressed comprehensively at the planning stage, otherwise it may become more critical as wind power contribution increases in the grid.

Unlike conventional power generation, wind power is distributed in nature. So, it is very complex when it comes to analysing the harmonic generation from wind converters. To address this issue, an approach of aggregation of harmonics from individual turbine using a method, similar methodology of IEC 61400 - 21, has been presented in reference [248]. In this work, the wind farm with different layout has been simulated. Then, these results are compared with the aggregated harmonics calculated using proposed methodology. The result presented in this work suggests the use of the proposed methodology for summation of harmonics from the wind farm. According to this work, for better result, both, the accurate modelling of wind farm topology and supply system is very much essential. Similar to this work has been found in reference [249], where power quality assessment has been done as per IEC 61400-21 procedure.

Another approach of aggregation of wind farm for harmonic propagation has been reported in [250]. In this work, detailed model of DFIG has been used and using this an aggregated DFIG model has been developed to study the harmonic propagation. Frequency domain approach has been taken to study the problem. The author emphasizes that, all the elements of a system are important, because they are frequency dependent and the whole system can affect the resonance frequencies. The analysis part of this work showed that increase in number of aggregated DFIG cause a shift in the harmonic resonance order.

Reference [251] presented the network reduction method for reducing detailed low - voltage wind farm network to assess the effects of its connection onto a main interconnected transmission system. Application of this method reduces the number of network to be modelled and number of injection nodes which reduces the study time. To demonstrate and prove it′s validity and effectiveness, the results are compared with the IEC current aggregation method.

Harmonic problems become a concern with the growing number of Wind Power Plant [252], because along with a non-linear load, generation side also contributes to the harmonic emission. In Wind Farm, several conditions may give rise to the resonance phenomenon, which will amplify the effect of the harmonic frequency. Add on to this, overview of international standards, grid codes, and basic modelling of Wind Power Plant has also been given in this literature.

Reference [253] discusses how a wind power installation can affect the harmonic level in a number of ways. According to the author, Wind Turbines has been an additional source of harmonics, particularly non-characteristics harmonics. The resonance point is also depends on strength of the grid. Stronger grid will have a higher order of harmonics, whereas weaker grid gives rise to a lower order of harmonics. Further, the author has extensively explained the sources of primary distortion and secondary distortion. Also, how increase in no of wind power installation weakens the grid has been elaborated.

There are lots of literature available on assessment and enhancement of small-signal stability. Here, the relative and recent literatures are discussed.

In reference [254], probabilistic small signal analysis based on Monte Carlo Simulation has been proposed. The eigenvalues are calculated for iteratively, where in each iteration load and generation has been varied using Gaussian distribution. The CDF of probabilistic instability risk index based on damping ratios of oscillatory modes are calculated. Further, based on the results, location of Power System Stabilizer (PSS) is decided. Also, the impact of long distance power flow on oscillatory mode has been evaluated. Effect of small signal stability on transfer capacity has also been studied in the work.

In reference [255], Small-Signal Stability of distribution system based on renewable energy has been studied. The considered system consists of static and dynamic load, supplied by synchronous, induction and static generator. The existing oscillatory modes are systematically investigated. Also, the effect of controllable capacitor bank at various locations has been studied. The capacitor bank is connected to support the Small-Signal Stability. An index based on controllability matrix has been used to quantify the effect of controllable capacitor. And, an observability matrix has been used to design the controller of capacitor bank for damping control. The main drawback of this study is the lack of proper explanation about the mathematical modelling of the system. Only symbolical state matrix is given as an explanation, which is insufficient to understand the work.

In work [256], the modes introduced by connecting DFIG in existing interconnected system have been investigated. Also, their impact on electromechanical oscillation has been studied in depth. Various control loops are explained. In this work, it has been shown that absence of controller or inappropriate controller tuning of Voltage / VAR controller. Further, the effect of increased penetration level on inter-area oscillation mode has been studied. Finally, it has been concluded, that the effect of penetration of DFIG is generally favourable, but there are cases where inter-area oscillation mode can become unstable. This work also lack the explanation of detail model of DFIG. Also, the work has used the commercial available software PSS/E and results are compared with MATLAB, but explanation has not been given, how this software is calculating eigenvalues?

Reference [257] investigates the impact of different type of generator, Squirrel Cage Induction Generator (SCIG) and Doubly Fed Induction Generator (DFIG) using Small-Signal Analysis method. SCIG is a fixed wind speed generator and DFIG is variable wind speed generator. So, the effect of wind turbine speed on eigenvalues has been inherently embedded in this work. The analysis has been carried out on IEEE 14 Bus system. According to this work, SCIG is simpler in operation, but DFIG is more reliable and stable. Detail of Model considered has not been discussed in this work. Moreover, the simulation is carried out using PSAT tool. How different states are participating in different eigenvalues has also not been included in this work. These are the main drawbacks of this work.

In reference [258], eigenvalue analysis and frequency response method has been applied to power system for Small-Signal Analysis (PSA) of power system. This work presented AESOPS method for eigenvalue estimation. The downside of this work is the consideration of only conventional generation and exclusion on renewable generation. Also, the work is relatively non-relevant, as now-a-days many software are available, which calculates the eigenvalues efficiently. The best example of such software is MATLAB. In short, this work focuses on the efficient calculation of eigenvalues and not the system stability.

In reference [259], probabilistic Small-Signal Analysis has been carried out using eigenvalues. Uncertainties like variation in generation and demand is considered. The Monte Carlo Simulation (MCS) method has been applied, which consider one set of uncertainty at a time and iteratively calculates the eigenvalues from all possible sets of uncertainties. This work does not consider the renewable generation directly. But, the methodology can be applied to mixed generation (conventional + renewable). The proposed analysis method has been tested on two different benchmarking systems. Also, in this work, different modes of oscillation like local mode, inter-area oscillation mode and electromechanical modes has been classified. The mean value of eigenvalues, damping factor and oscillation frequency has been carried out using set of eigenvalues obtained through iteration. One more point worth noting that, in this work, only generation and load variation has been considered, but other parameters of power system, such as parameter of network can be considered.

In work [260], the focus is given on the operational changes conventional generator has been experiencing due to increased penetration of variable speed renewable generation. As the wind turbine penetration is increased, the conventional generator will experience change in dynamic and operational characteristics. In this work, an approach has been suggested to analyse the impact of increased penetration of DFIG (variable speed generation) based wind turbine on Transient Stability and Small-Signal Stability of a large power system. The essence of this method is conversion of DFIG in to conventional round rotor synchronous generator and then evaluate the sensitivity of eigenvalues with respect to inertia. The modes that are beneficial and detrimental and are affected by inertia is identified. These modes are then deliberately excited by appropriate disturbances and the impact of inertia reduction is analysed. In this work, the much weightage has been assigned to the methodology and modelling part is completely ignored. Finally, the work is concluded with remark, the real part of eigenvalue is much sensitive to the inertia change. This simply implies that, the inertia is affecting the damping factors of relative oscillatory mode.

The work [261] is dedicated to study the effect of correlation of wind power output from different wind turbine on the system stability. According to this work, correlation of output power wind turbine generator has considerable influence on stability of power system. To prove the hypothesis, the copula theory is used to show the complicated dependence of multidimensional wind power injection. Monte Carlo Simulation (MCS) is used to analyse the small signal stability of test system. The probabilistic stability is evaluated under different correlation. The work is concluded with remark that the copula model is efficient as compared to linear correlation coefficient model and gives better reflection of actual dependence of various wind power output. It is also suggested that the use of copula method in the modelling of wind power correlation can significantly improve the accuracy of the probabilistic Small-Signal Analysis.

The reference [262] is relatively older, but, its contribution is significant and still applied in analysis of large system. This work suggests the framework for studying selected modes of the large system. This method is popularly known as Selective Modal Analysis (SMA). In this work the emphasis has been given to poorly controlled low frequency (0.1 - 2 Hz) oscillatory modes. These modes are frequently associated with the electromechanical oscillation in the system and are known as the swing mode of the system. The oscillatory modes of the system covers the extensive part of the system, but critical modes are usually a small fraction of the total modes. The important part of the work is the modal reduction methodology.

According to reference [129], the conventional Small-Signal Stability (SSS) model is insufficient in actual system, where time delays occur in measurement and transmission of various states and algebraic variables. Conventional Small-Signal Stability model is based on the linear control system derived by Taylor's series expansion about the equilibrium point without using time delay. But according to this work, the time delay can actually degrade the stability of system and may eventually cause the instability. This work investigates the stability performance by constructing new Small-Signal Stability Assessment Problem based on Lyapunov-Krasovskii functional method. The upper bound of time delay, beyond which system become unstable, has been defined as a delay margin. The case study has been carried out on the synchronous machine based model. The similar approach has been applied to renewable energy system. This statement has been made on the experience gained by exploring numerous research paper published recently.

Reference [263] is somewhat related to reference [129]. In this work impact of the delay on power system stability has been studied. First, the inclusion of time delay in differential algebraic equation has been discussed. Then, an optimization based method has been given to find the boundaries of the small signal stability region with significant time delay. In order to exemplify the proposed theory, two simple systems are used for verification of underline theory. In this study it has been found that the time delay significantly affect the boundaries of the small signal stability region, particularly when the time lag is large. According to this work, the consideration of time delay is helpful in design of the controller.

Reference [264] is also based on the Small-Signal Stability of Wind Turbine. But here, Wind Turbine with Direct Drive Permanent Magnet Generator (DDPMG) has been considered. First, the DDPMG and its controller is modelled, Then, the Small-Signal Stability analysis has been carried out first without controller and then same study is carried out with controller. It has been tried to show with the result that, the DDPMG is stable, but stability can further be improved with the controller. To evaluate the controller effectiveness, a Single Machine Infinite Bus (SMIB) system and Four- Machine System are taken and simulation has been performed. The dynamic performance of DDPMG has been compared with the dynamic performance of DFIG and it has been tried to establish that, the dynamic performance under fault condition is better for DDPMG as compared to DFIG. The Critical Clearing Time (CCT) has also been examined for transient stability evaluation. Finally, it is concluded that DDPMG based WT gives enhanced performance as compared to DFIG.

Reference [265] is relatively quite old as, this work was published in the year 1996.

However, the importance of this work is worth considering here. In this work Isolated system consisting of Permanent Magnet Synchronous Machine with Fixed Capacitor and Thyristor Controlled Reactor (FC+TCR) has been studied for performance analysis. The terminal voltage is varied by controlling firing angle of thyristor. The complete system is linearized and modelled in terms of the state variable. Then based on the Optimal Quadratic Regulator (OQR), the controller has bee designed. The controller's effectiveness has been examined by evaluating closed loop response under sudden load change condition. Finally, it has been concluded that the terminal voltage can be maintained at the rated value for a typical range of load variation using FC+TCR static VAR compensation system and improved system response can be obtained with proposed controller under sudden load variation.

In reference [266], the performance of DFIG has been evaluated under different operating conditions. The different operating conditions are three phase fault, voltage sags, change in wind speed, and grid conditions. In this work Teaching - Learning Based Optimization (TLBO) has been used to design and optimize the DFIG controller. For this purpose, a state space modelling approach has been adopted for carrying out Small-Signal Stability analysis. For comparative analysis purpose, the TLBO based PI controller has been compared with Partical Swarm Optimization (PSO) based PI controller. The results given in this work show that, the TLBO based PI controller is effective in minimizing rotor current oscillations and fluctuation in electromagnetic torque. At the end, it has been concluded that the TLBO based PI controller is better than the PSO based PI controller.

In [267], the issue of Sub Synchronous Resonance (SSR) with DFIG has been addressed. In this work the Gate Controller Series Capacitor (GCSC) for series compensation has been considered for addressing SSR issue. The mathematical model of DFIG, Transmission line and GCSC is linearised and then eigenvalues based Small-Signal Stability analysis is carried out. It is demonstrated with the help of eigenvalues that the GCSC is effective to solve the SSR issue with DFIG. The damping controller has been designed using residue-based analysis and root locus diagram. It has been tried to show that, the controller designed is effective in damping SSR mode without affecting other modes.

Referene [268] proposed the Optimal Power Flow based on Small-Signal Stability constrained. The system is stressed using selected parameters. The loading margin and eigenvalue analysis has been carried out. Then, OPF has been performed based on Small Signal Stability Constrained. Then, again eigenvalues are checked. The result is preserved if the eigenvalues shows the stable operating point, otherwise the loop is directed back to OPF and new operating condition is derived. This work suggests the redispatching procedure to resolve the stability issue. It helps system operator to maintain the appropriate level of security for system operation. The proposed method ensures required security margin. At the end, simulation results has been presented to show the effectiveness of the proposed methodology.

Reference [269] focus on the Small-Signal Stability of DFIG based wind power system under different wind speed condition. Due to change in wind speed, the speed of Wind Turbine Generator (WTG) changes from sub synchronous to super synchronous. The stability margin will be different under different operating condition. In this work, first the impact of damping controller on different modes has been investigated. Then, tuning based on Bacteria Foraging (BF) has been proposed to enhance the damping of oscillatory modes. The result of eigenvalue analysis has been presented to establish the effectiveness of the tuned damping controller. Additionally, the robustness of controller is investigated.

Reference [270] is highly appreciated work and it has been the base of many work published later. It is on the modelling of DFIG for Small Signal Stability analysis. In this work, the model of DFIG is derived from basic flux linkage, voltage and torque equations. Then, the eigenvalue analysis has been carried out considering constant slip. The analysis has been repeated for strong grid as well as weak grid. Further, the work has been carried out for 2-Mass system and 1-Mass system for 8^{th}, 6^{th} and 4^{th} order system. The work is concluded with three important findings. First, there are three different oscillatory modes (slow, medium and fast oscillations, 3- 15 Hz). Second, the DC link voltage and rotor flux is responsible for decaying modes. And third, there is a minimum grid strength under which the operation of DFIG is not possible. The modelling part of this work is widely accepted and found in many literatures.

In reference [271], the modelling of DFIG has been carried out for grid integration study. According to this work, the model based on the fundamental frequency is complicated and computationally intensive. This work proposes a simple Wind Turbine Model, in which the DC link voltage is simulated as controlled voltage source and rotor current is regulated to meet the demand of real and reactive power. This model has been developed using traditional generator model approach, hence it is easy to integrate into the power system simulation tool like PSS/E. Also, the results has been compared with the DigSILENT results for verification purpose.

Reference [272] is based on the vector/matrix computing technique for the modelling of DFIG. Using developed model of DFIG, several simulations has been carried out to demonstrate the free acceleration of DFIG, active and reactive power control, and inter area oscillation damping. This work claims that, this methodology saves the modelling time and debugging time. Also, it is easy to understand. How DFIG is integrated with the network has also been demonstrated in this work. The voltage and current phasors are transformed though two reference frames for interconnecting purpose. The effectiveness of inner control loop and outer control loop has been demonstrated using MATLAB/Simulink model.

Reference [273] examines the impact of wind power penetration by DFIG on power system oscillations for two-area interconnected power system. In this work, the study has been carried out on two-area interconnected system with and without wind power to analyse the effect on oscillation. For study purpose, eigenvalue analysis has been carried out to investigate the Small-Signal Stability behaviour of the test system and participation factor is calculated to identify the participation of states in different modes. In this work, Wind Turbine is connected to different bus and eigenvalue is generated. Finally, it is concluded that the penetration of DFIG results in an oscillatory instability, which can be stabilized with the action of Automatic Voltage Regulator (AVR) and Power System Stabilizer (PSS) of Synchronous Generator (SG). This work is basically carried out using software PSAT. So, it does not include the model of DFIG and also does not explained how it is integrated with the power system. Basically the state matrix formation step is simply avoided by taking readymade inbuilt model of software. Also, it is not clear that how the participation factor is calculated.

In reference [274], the dynamics of DFIG with closed loop control is anlyzed. The work basically checks the adequacy of simplified model of DFIG with rotor and stator dynamic neglected. In this work PI controllers are used for control of rotor speed, reactive power and pitch angle of blade. The eignevalues, participation factor and time domain simulation has been used to proove the adequacy. The work is ended with conclusion that, simplified model is enough to study the low frequency oscillations occurs due to the interaction of controller and mechanical parts of DFIG.

The comparative study of performance of control of DFIG is carried out in reference [275]. In this work, three different control structures have been used for comparative study. The study is basically based on the control of active and reactive power through set points allocate to Wind Turbine by Wind Farm. Out of three control strategy, two control strategies are existing control strategies and the third strategy is claimed as novel and proposed in this work. According to this work, the third control strategy with down power regulation performs better than other two strategies.

DFIG has no inertia virtually. So, the penetration of DFIG will reduce the system inertia considerably and affects frequency response, when it replaces conventional generation. If, it is simply added without replacing Synchronous Generator (SG), the effect on speed regulation is negligible. If DFIG can contribut to inertial response, it will be a great relief on the power system. But, it should be ensured that, too much kinetic energy is not taped, otherwise it may stall the DFIG. Reference [276] is based on the frequency regulation support by DFIG. It is inverstigated that, how different governer settings and system inertia is affecting the frequency. Different cases are evaluated in order to study the effect of DFIG penetration on frequency response. A new concept of artificial speed coupling has been discussed. Particularly, the emphasis has been given on the significance of inertial response in frequency regulation. Also, the influence of limit settings of different control blocks and auxilliary loop parameters on inertial response has been discussed. The optimum frequency response can be provided with the help of combined action of aerodynamics of turbine and converter with consideration of limits. The work presented an algorithm to extract high energy from turbine without compromising the stability of DFIG.

With increase in share of renewable energy sources in the system, the harmonic distortion of power supply is inevitable. The functioning of DFIG under distorted voltage condition is worth to know. Reference [277] has been dedicated to dynamic modeling of DFIG to investigate the effect of distorted grid voltage conditions. In this work, the oscillations of torque, instantaneous active and reactive power are described under distorted voltage condition. To achieve smooth operation, four alternative control objectives are proposed. The response of proposed control is compared with standard / conventional PI controller. The feasibility of porposed control is validated through simulation of 2 MW DFIG Wind Turbine.

It is clear from the available literature on stability of DFIG that, increased penetration of DFIG in existing power system may degrade inter-area oscillations. This is generalized for small power system, but the statement cannot be applied to large power system in absence of study. The effect may be or may not be favourable. It may cause instability in case of less damped inter-area mode. Improved controller tuning has been proposed in reference [256] to avoid instability. It is also shown that, under certain conditions and absence of appropriate controller tuning the voltage / VAR control loop may become unstable. In this work, it is warned that the possibility of rise of such unstable modes may be quite negligible, but increased wind power penetration without proper study may increase the risk of adverse interaction.

As the idea of renewable energy sources gaining momentum, the rise in autonomous power systems, concept of mini-grid and micro-grid is also increases. It is exciting to see the working of integrated wind power under isolation from grid during fault or other contingencies. Reference [278] investigates the contribution of Wind Turbine in frequency control under non-interconnected island systems. The contribution of WT in primary frequency control is discussed. Also, transient frequency control (inertial response) and permanent frequency control (droop characteristics) and combined application of this has been investigated. In this work, the power system of Rhodes Island with different types of generators, includes Synchronous Generator (SG) and three different types of Wind Turbine is considered. Different cases has been studied and quantitative analysis has been presented for expected benefits and drawbacks of each method. The weightage has also been given on the parameter selection of the controller.

Reference [279] is also dedicated to the frequency response of WT. In this work, the frequency response of Full Converter Variable Speed Synchronous Generator (FCWTG) and Permanent Magnet Synchronous Generator (PMSG) has been considered. A control scheme for these WTs has been proposed that improves frequency response. Also, the response of WTs are compared with conventional Synchronous Generator (SG).

Reference [126] is on the comprehensive review of Small Signal Stability analysis of power system with high penetration of wind power. First, different type of wind turbine and principles of grid connected structures of wind power generation systems has been discussed. Then, the effect of WT on Small Signal Stability and potential problems has been very well studied. Finally, the different control strategies has been discussed to enhance the stability.

Reference [280] presents the extensive modelling and control of DFIG based WT. A detail dynamic model includes DFIG, transmission line, and controllers has been presented. In this work, a new voltage control based control strategy has been proposed, which is compared with the performance of conventional control scheme. The proposed scheme manipulates reactive power, dynamically controlled from Voltage Source Converter (VSC), considering the limits of different controllers. In nut and shell, the work concludes that variable speed DFIG with appropriate power converters can be made to take active part in improvement of voltage at remote location. Also, it is claimed that the operating power based reactive power control scheme is effective.

1.3 Limitations of Existing Works

In course of this work, various literature related to the stability of power system is reviewed and are discussed in the section 1.2 of this chapter. The gap identified in the available research work are considered here point by point.

In voltage stability, most of the work focused on the transient voltage stability, affected by the fault. However, there were few literatures considered the long and short term voltage stability. But the effect of increase of wind power penetration is not explicitly discussed. Also, the load variation along with the wind power variation has not been discussed explicitly. The load variation generally follows the Gaussian PDF, whereas, the Wind Energy Sources are following the Weibull distribution. Interaction of two different kind of variables with different PDF give rise to complex variation in power imbalance and this will cause complex variation in bus voltages. This has to be addressed with due consideration. In this work, the load and Wind power variation with different PDF is taken to study the effect of their distribution parameters. Also, the effect of correlation of different Wind Energy sources on voltage variation has been worked out.

The harmonic stability word is coined in this work to establish the formal link between stability of power system with problem of harmonics. Evaluation of Harmonics indexes has been found in plenty of literatures, but how it is related with stability of power system is missing. Various problems has been reported from the field, which mentions the de-synchronization of wind converters and when the problem is analysed it is found that the root cause was the poor power quality. Such one case also has been covered in this work. The standard planning study to ensure the hassle free operation of WTG is not found in any of the literature. Also, the most of the studies are useful for post installation of WTG. Also, these studies are acting on the symptoms of the problem. For e.g. the harmonic resonance point has been shifted to new resonance point. It is well known that the suppression of one harmonic resonance point may give rise to one or more resonance point. So, these methods are not very effective. How WTG shall be evaluated to ensure stable operation of WTG has not been explicitly answered in the reviewed literatures.

The filter design is an important aspect of renewable energy sources. The filters are mainly used for two purposes. First, to connect converter with grid and second, to filter the harmonics to achieve grid code compliance. The most of the literature available attempted the filter design to avoid the resonance. The available works completely neglected the structural changes required to avoid the resonance. There are literatures on the eigenvalue analysis of system for harmonic study. However, this literatures are limited in approach as the evaluation of eigenvalues and participation factors has been done, but it is not logically related with the structural passive components. It is very much required to understand the participation of various components in resonance. If it is known, then the resonance can be avoided by making structural changes in the system without adding filters, which acts on the specific resonance points. Also, the formulation of objective function using eigenvalues has not been attempted in any of the work. The traditional approach to filter design has been followed in most of the literature. In this approach of filter design, the resonance point, which are very panic and creating trouble, is identified and tuned filter is designed to suppress harmonics of resonance frequency. This is, however, the post installation approach. The filter design mostly has not been done at the planning stage as it will increase the design cost and also the effectiveness of filter will always remain questionable. Not only this, but future changes in the power system may make filter un-suitable and will affect the system negatively. The probability of such changes are very small, but it should be considered at the planning stage. The filter design at the planning stage is very effective and it will reduce the probability of any future problem. This is the prime reason behind the carrying out of this work.

The current harmonic spectrum of different WTG's are different. Any WTG is not suitable for connecting at a given point in the grid. Specific studies has to be made to check the compatibility of any given WTG for a concerned point of connection. The harmonic performance of any WTG is depend on the three main factors; Harmonic spectrum of WTG, Grid strength at the point of connection, and the modal impedance at the point of connection. Lower harmonic spectrum ensures the low current distortion. The lower modal impedance at any given frequency ensures the lower harmonic voltage distortion. This together ensures the good power quality.

The operation of WTG under harmonic condition depends on the converter parameters and the output filter topology. The stability margin with different control structure and filter topologies is an important aspect. The evaluation of margin has not been found in the contemporary literatures. The gain margin and phase margin is an important aspect of filter design. The converter′s stability margin shall be evaluated with various output filter topologies. It has been discussed in this work.

The dynamic stability has been evaluated using small signal analysis method. In most of the literatures reviewed, the method of small signal analysis has been applied to find out the standalone stability of WTG. Different optimization algorithm has been followed to achieve the best parameters for overall operation of WTG over entire operating range. However, single set of parameters for WTG is not enough to perform best under varying wind condition. To ensure this WTG has to be studied statistically. The available literatures are based on the deterministic approach and are not suitable for power system with volatile energy sources. To get the realistic view of dynamic stability of WTG, the problem of small signal stability has to be encapsulated in the stochastic form. This kind of treatment to the problem of stability has not been found in most of the literatures. It is addressed in this work.

As discussed, there are numerous literature available on the optimization of WTG parameters. But, very few literatures are available, which checks the effectiveness of optimized parameters in meeting the grid code requirement. As the grid code requirement are not globally same, the set of parameters has to be evaluated with the concern grid code. Also, it has to be evaluated to check its compliance in the future also with more stringent requirement. This kind of work has not been found in the studied works. The checking of compliance to the grid code with optimized parameters has been attempted in this work.

In short, most of the work found are related with only one aspect of the stability.

1.4 Motivation

The following points are the core drivers of this research work.

1. Assessment of system stability is an important aspect to effectively address the stability issues. It requires proper method of assessment, which can give accurate results in short time frame.

2. There are various literatures available on the compliance to grid code and improving the LVRT response of WTG. However, the work related to steady state voltage stability is far less. Various stochastic techniques has been applied to address the impact of wind variability on voltage. The stress is given to probabilistic load flow to analyse the problem. In probabilistic load flow, the Point Estimation Method (PEM) is also applied. However, problem assosiated with its application is not discussed. Also, the application of point estimation is remain limited to two points

and applied only to normally distributed data. Also, any improvement / degradation with multi point estimation has not been duly addressed.

3. The main drawback if PEM is, large number of data required for point estimation, to calculate the location and weight of the data point, to achieve desired level of accuracy. It ultimately increase the computational burden. So, an alternate solution is required to achieve the balance between accuracy and computation.

4. The result obtained from Point Estimation Method (PEM) gives mean value and standard deviation. So, the exact probability distribution function is not possible with PEM. To get the probability distribution of output variables, generally series expansion methods are used. But the limitation of currently used method is large error, as the focus is given on the convergence of series and not on the accuracy. So, the current used method is very conservative in nature. Here, in this work, various methods of series expansion are discussed results are compared to visualize its effectiveness.

5. The effect of wind speed correlation on voltage variability is not much discussed. Also, it is found that the method used to generate the correlated data is not efficient.

6. There are various literatures available on power quality issues with Wind Turbine Generators. However, the harmonic resonance problem and its root cause has not been addressed effectively. Most of the harmonic problems are solved with use of filters by changing the resonant point. This method doesn't address the root cause. Also, two different methods are required to analyse the harmonic problem and working out the solution. So, a simple and yet effective method is required, which addresses both the problem.

7. The majority of harmonic analysis methods require tremendous efforts in modelling part, which inhibits its usability.

8. Much work has been done in the domain of small signal stability. Various authors have addressed the problem of small signal stability by using different modelling techniques and using different controllers. However, due attention is not given in the probabilistic evaluation of small signal stability.

9. Along with the points discussed above, there are many problems observed from the field also, which were desynchronising the WTG. These problems are the foundation of this work.

1.5 Thesis Structure

The thesis is divided in to chapters and the detail of each chapter is given here.

1. **Chapter 1** discusses the stability with penetration of wind power. The consise literature survey and motivation for research on a given topic is discussed in this chapter.

2. **Chapter 2** is on the voltage stability with wind power. Different methods of voltage assessment are discussed and comparative evaluation of methods are done to find out pro and cons. Using different methods and different test systems, different cases are studied and results are discussed.

3. **Chapter 3** is dedicated to the harmonic stability with wind power. The harmonic resonance phenomena is discussed in detail. The modal analysis method for harmonic resonance analysis is used for analysis and design of optimized filter. Finally, the optimized filters performance is evaluated for compliance to harmonic standard.

4. **Chapter 4** is on the power electronics converter stability analysis. The converter performance with different topology of output filter is given in this chapter. Finally, the shaping of converter output impedance is discussed.

5. **Chapter 5** is on the real time case study, which discusses the problem and solution of harmonic resonance from the field. This chapter is based on the real time problem observed in the field. It is explained that, how this problem was tackled with simple solution.

6. **Chapter 6** is on the small signal stability analysis. In this chapter probabilistic small signal analysis of DFIG is carried out. The small signal stability of DFIG is analysed using Latin Hypercube Sampling (LHS) method.

7. **Chapter 7** is dedicated to the simulation of DFIG to check the effectiveness of controller to meet LVRT requirement. In this chapter the simulation is carried out with different fault duration. The results shows that, the DFIG works well within the boundary defined in grid code and fails outside.

8. **Chapter 8** is conclusion of the work. The conclusion on effect of wind power on voltage stability, harmonic stability and small signal stability is given. Also, the possible future work is discussed.