REVIEWS ON STABILITY ANALYSIS OF GRID CONNECTED WIND POWER GENERATING SYSTEM

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ABSTRACT

Wind power technology has been developing widely in recent years. Several research fields in power systems such as prediction of wind speed, wind generator system modeling, system stability and control of wind energy conversion system are emphasized further with the consideration of wind power. With increasing penetration level in power system, the issue concerning the influence of wind power on power system stability has arisen the interests of researchers. This paper reviews various models of generators for studies of stability of power systems and then analysis, effects and enhancement of power system stability of grid connected wind power system.

Keywords: Wind power, doubly fed induction generator, small signal stability, transient stability and dynamic stability.

1. INTRODUCTION

Growing environmental concerns and attempts to reduce dependency on fossil fuel resources are bringing renewable energy resources to the mainstream of the electric power sector. Among the various renewable resources, wind power is assumed to have the most favorable technical and economical prospects. In the last five years, the world wind turbine market has been growing at over 30% a year and wind power is playing an increasingly important role in electricity generation. By 2020, wind power would account for more than 12% of the world's total installed capacity.

When deployed in small scale, the impact of wind turbine generators on power system stability is minimal. When the penetration level increases, the dynamic performance of the power system can be affected. Among the several wind generation technologies, variable speed wind turbines utilizing doubly fed induction generators (DFIGs) are gaining prominence in the power industry. DFIG has been popular among various other techniques of wind power generation, because of its higher energy transfer capability, low investment, and
flexible control. The DFIG is different from the conventional induction generator in a way that it employs a series voltage-source converter to feed the wound rotor. The feedback converters consist of a rotor-side converter (RSC) and a grid side Converter (GSC). The control capability of these converters gives DFIG an additional advantage of flexible control and stability over other induction generators. A detailed design and a full stability analysis are necessary for the DFIG before connected to the grid. Also simulation is one of the most important points for system modeling.

With increasing penetration level in power system, the issue concerning the influence of wind power on power system stability has arisen the interests of researchers. Such influence can occur in two ways: it can be caused by the uncertainty of wind energy, or a disturbance or faults on grids influence the wind plant first, then the instability of wind turbines affect the grid significantly. With the increased number of wind farms in operation, the system experiences a change in dynamic characteristics. In case of DFIGs, generator load disturbances also give rise to variations in the speed and the position of the rotor. However, due to the asynchronous operation involved, the position of the rotor flux vector is not dependent on the physical position of the rotor and the synchronizing torque angle characteristic does not exist. In the event of grid disturbances due to grid faults, an energy storage system or a control device for a large-scale high-capacity power generation system is generally required to compensate fluctuating components when connecting to a power grid.

Small signal stability analysis is carried out based on the system nonlinear equations, describing the dynamic behavior of the system, linearized around a chosen operating point. Transient stability is the ability of a power system to maintain synchronism when subjected to a large disturbance. The severe disturbances include equipment outages, load changes or faults that result in large excursion of generator rotor angles. The resulting system response is influenced by the nonlinear power-angle relationship. The time frame of interest in transient stability studies is usually 3–5 s following the disturbance. The duration may extend up to 10–20 s for a very large system with dominant inter-area swings.

This paper provides review on various models of induction generators for wind energy conversion system and then analysis, effects and enhancement of stability of grid connected wind power system. The rest of the paper is organized in the following sections. Section II gives the details of models of the DFIG and literature survey of the DFIG models for power system stability studies. In section III, analysis, effect and enhancement of stability of wind energy conversion system. Conclusions are given in section IV.

II. DOUBLY FED INDUCTION MOTOR MODELLING FOR STABILITY ANALYSIS

A wind turbine (WT) consists of turbine blades, rotor, generator, nacelle (gearbox and generator drive), shaft, drive or coupling device, converter and control system.
Wind turbines can be classified as fixed speed wind turbine and variable speed wind turbine. Fixed speed turbine can only operate at a fixed speed and induction machine as generator. Variable speed wind turbine use double fed induction machine (DFIG) or permanent magnet synchronous machine (PMSM) as a generator. In brief, Wind turbine model can be mainly divided into three parts namely mechanical drive and control, generator, converter and control system. The model of the generator is most important.

In this study, DFIG model is considered. It consists of a wound rotor asynchronous generator, whose stator windings are directly connected to the grid, while the rotor windings are interfaced with a back-to-back variable frequency voltage source converter. This unit allows a variable speed operation with a wide range from sub-synchronous to super-synchronous speed. Fig. 1 reports the basic configuration of a DFIG wind turbine. The use of a back-to-back power converter on the rotor side allows to decouple the control action on the DFIG. In such a way, the rotor side converter is used to optimize the power generation of the DFIG and improve the stability, while the grid side converter ensures a quite constant voltage on the DC link with a desired power factor. Grid side and rotor side converters are modelled as four quadrant Pulse Width Modulation (PWM) AC/DC and DC/AC inverters. By adjustment of the switching of the Insulated Gate Bipolar Transistors (IGBT) in both converters, the power flow between the rotor circuit and the supply can be controlled both in magnitude and in direction. This is effectively the same as connecting a controllable voltage source to the rotor circuit. The DFIG can be regarded as a traditional induction generator with a nonzero rotor voltage.

![FIG: 1 CONFIGURATION OF A DFIG WIND TURBINE [10]](image1)

![FIG: 2 EQUIVALENT CIRCUIT OF DFIG](image2)
Associated mathematical equations of the dfig are given below.

Stator voltage
\[ v_{ds} = r_s i_{ds} + \omega_s \psi_{qs} \]  
\[ v_{qs} = r_s i_{qs} - \omega_s \psi_{ds} \]

Rotor voltage
\[ v_{dr} = r_r i_{dr} - s \omega_s \psi_{qr} + \frac{dv_{dr}}{dt} \]  
\[ v_{qr} = r_r i_{qr} + s \omega_s \psi_{dr} + \frac{dv_{qr}}{dt} \]

Flux linkage
\[ \psi_{ds} = -L_{ss} i_{ds} + L_{m} i_{dr} \]  
\[ \psi_{qs} = -L_{ss} i_{qs} + L_{m} i_{qr} \]  
\[ \psi_{dr} = -L_{ms} i_{ds} + L_{rr} i_{dr} \]  
\[ \psi_{qr} = -L_{ms} i_{qs} + L_{rr} i_{qr} \]

Electromagnetic torque
\[ T_{em} = \psi_{qr} i_{dr} - \psi_{dr} i_{qr} \]

Kazachkov et al [2] reviewed and discussed the most significant characteristics and models of fixed and variable speed wind turbine which are developed in the PSSE (Power System Simulator for Engineering) program. Also detailed models such as air dynamical mechanical and electrical factors have been reviewed and have been constructed in PSCAD/EMTDC. Symmetrical fault is considered. These detailed simulations helpful to understand the functionality of the controls and their interaction and were critical in terms of working out the approach to reducing the order of models for stability studies. It is observed that for the bandwidth of transient stability, the PWM control can be considered as instantaneously generating rotor current components or even electrical power and reactive power as inputs for a machine model. Suggested that these models will allow the wind farms to be represented in the load flow and stability analysis involved in the planning and operation of power systems.

Pablo Ledesma et al [3] proposed a model of the doubly fed induction generator (DFIG) suitable for transient stability studies. The proposed model is based on two main simplifications. The first one assumes that the EM transients in the stator and in the branch between the inverters and the grid can be neglected. The second simplification assumes that the current control may be considered instantaneous neglecting the dynamics in the current control loops. MATLAB software is used for the study. The Power System Toolbox uses a predictor-corrector numerical integration algorithm. The iterative process used to solve the DFIG model has converged satisfactorily in all of the simulated cases. The small number of iteration steps in the simulated cases indicates that the DFIG model does not consume an excessive processing time. Further, the integration step used in the simulations is a typical one in transient stability simulations (10 ms), because the DFIG model does not impose a small integration step as there are not small time constants. This is a great advantage compared to a detailed model, including the current control systems and the inverter’s operation, which need smaller integration steps (on the order of 1 ms).

Istvan Erlich et al [4] analyzed modelling of the doubly-fed induction generator (DFIG) and the corresponding converter for stability studies. To enable efficient computation, a reduced-order DFIG model is developed that restricts the calculation to the
fundamental frequency component. However, the model enhancement introduced in this paper allows the consideration of the alternating components of the rotor current as well, which is necessary for triggering the crowbar operation. Suitable models are presented for the rotor and grid side converters as well as the dc-link, taking into account all four possible operating modes. The proposed model for speed and pitch angle control can be used when wind and rotor speed variations are significant. Since the reduced-order model does not consider the dc-components of the stator current and thus the corresponding alternating rotor currents, it is not suitable for triggering crowbar switching. For this purpose, a model enhancement is proposed in this paper that allows using the ROM further on, but an additional model part is activated when necessary to superimpose the dc-components on the simulation results. The presented model is suitable for power system simulation studies.

Yazhou et al [5] developed DFIG wind turbine model in which the power converter is simulated as a controlled voltage source, regulating the rotor current to meet the command of real and reactive power production. This model has the form of traditional generator model and hence is easy to integrate into the power system simulation tool such as PSS/E. The model performance and accuracy was also compared with the detailed model developed by DIgSILENT. In this paper, a controllable voltage source in the rotor circuit was used to simulate the power converter. Such simplifications allows for reduction of the model order whilst retaining the capability of observing principle features of the converter such as the maximum current levels. Such capability is important for assessing criteria such as fault-ride-through performance. The response of the wind turbine to a step increase in the wind speed and to an electrical bus three phase fault was studied. However, due to the assumption adopted, the model cannot be used to study the internal dynamics of the power converter.

Andreas et al [6] presents an alternative way of obtaining the third order model for the doubly-fed induction machine model and introduced the possibility of modeling voltage sources in the rotor circuit, which can be very useful when simulating some generating schemes, such as variable speed asynchronous wind turbines. The purpose of this paper is to obtain a set of more simplified equations than those generally used. A model is presented in order to make it easier to dynamically simulate doubly-fed induction machines. Simulations are presented to prove that the model is adequate from the point of view of steady-state. The advantage of the model is that it allows one to deal with the machine with only one differential equation in the electrical part.

Kretschmann et al [7] presents an extension of [m3] which accounts for the neglected stator DC-components without increasing the modeling and simulation effort considerably. Thus the converter DC-circuit can be considered to represent the triggering of the crowbar firing more realistically to the stability model of the doubly fed induction generator (DFIG) used for wind turbines. With the proposed extension it is possible to consider the alternating components of the rotor current and thus the variation of the converter DC-link voltage. With realistic DC-voltage responses, a more accurate modeling of crowbar switching will be possible. The paper also presents suitable models for rotor and line side converters, as well as for the DC link. Moreover, the paper provides simulation results not only for model verification but also for demonstrating the behavior of the DFIG and the corresponding control system during fault. Also shows the dynamic performance of a typical wind energy DFIG system's response to a 3-phase grid fault. The proposed model extension allows the simulation of the true sequence of the DFIG-response to grid faults by using basically the reduced order models (stability model) and the corresponding simulation algorithm. The grid is modeled in this approach by algebraic equations, so that the simulation performance is much better than the alternative instantaneous value calculation based on full order models.
for both DFIG and grid as well. Therefore, it is essential to consider the true control sequence and crowbar switching of DFIG-based wind turbines when simulating power system dynamic behavior. Moreover, this paper provides simulation results suited not only for model verification but also for demonstrating the behavior of the DFIG and the corresponding control system during fault.

Samuel Neto et al [8] developed a reduced order model for grid connected wind turbines with doubly fed induction generators. The model is based on the field oriented control of the generator, considering that the rotor is fed by an ideal current regulated voltage source. This assumption makes the order if the induction machine model to be reduced to three but still allows representing with good accuracy. A simplified model is presented in order to reduce the computational effort of simulating grid connected wind farms driven by doubly fed induction generators (DFIG) in ATP, which is a software free and one of the most used programs around the world for power system transient studies. Some considerations are presented to show how the time step for the simulation can be increased with the reduced models. Simulation results are used to compare the dynamic responses of complete and reduced models. In the reduced model presented here, the generator rotor current components and also the GSC output filter current components are considered to be ideally imposed. This assumption greatly simplifies the system model, since the induction machine model has its order reduced to three due to the previous assumption of the rotor currents imposition. The simulation results showed that that proposed reduced model is adequate for evaluating the effects of connecting wind farms with doubly fed induction generators to large power systems using ATP.

Janaka et al [9] derived a dynamic model which can be used to simulate the DFIG wind turbine using a single-cage and double-cage representation of the generator rotor, as well as a representation of its control and protection circuits. The model is suitable for use in transient stability programs that can be used to investigate large power systems. The behavior of a wind farm and the network under various system disturbances was studied using this dynamic model. The influence of the DFIG control on the stability of the wind farm was also investigated by considering different control gains and by applying network voltage control through both stator side and rotor side converters. The generalized reduced order machine model was developed based on the following conditions and assumptions. a) The stator current was assumed positive when flowing toward the machine. b) The equations were derived in the synchronous reference frame using direct and quadrature axis representation. c) The -axis was assumed to be 90 ahead of the -axis in the direction of rotation. d) The component of the stator voltage used within the model is chosen to be equal to the real part of the generator busbar voltage obtained from the load flow solution that is used to initialize the model. e) The dc component of the stator transient current was ignored, permitting representation of only fundamental frequency components.f) The higher order harmonic components in the rotor injected voltages are neglected. In order to investigate the effect of various control approaches to the behavior of the machine and the network after the fault was cleared, the following three cases were simulated using the DFIG double-cage model. In all three cases the proportional gain of the controller was set low . a) Compensation for the generator magnetising reactive power (No load PFC) was applied. b) Compensation for the generator magnetising reactive power (No load PFC) and terminal VC were applied through .c) Compensation for the generator magnetizing reactive power (no load PFC) was applied on and terminal VC on. The models that have been developed are suitable for including in large power system transient stability programs.
Mohamed et al [10] analyzed the doubly fed induction generator (DFIG) for wind energy conversion system. In order to control the power flowing between the stator of (DFIG) and the grid, a control law is synthesized using PI controllers. In this study, the control strategy of power flow exchanged between the stator of (DFIG) and the grid are considered. After modeling the (DFIG), active and reactive powers are controlled with Integral-Proportional (PI) controller. The performances of the controller are then studied in terms of reference tracking and sensitivity to perturbations. Two types of regulators are studied and compared: hysteresis and Integral-Proportional (PI) controllers. The proposed system has been simulated using Matlab simulink to validate all the control strategy and then evaluate performance of the PI controller. Stator flux orientation control (SFOC ) technique have been applied in order to control stator active and reactive power exchanged between the grid and the doubly fed induction generator (DFIG) for wind energy conversion systems. A mathematical model of the (DFIG) is established and a synthesis of the PI controller. The performances of this controller are compared to a hysteresis controller in terms of power reference tracking and sensitivity to perturbation. The better results are obtained with PI controller.

Andreas et al [11] analyzed the fault response of a DFIG wind turbine system and to verify simulations with experimental results. Also studied how a reduced-order (second-order) model manages to predict the response of the DFIG system. In this paper, simulations and experimental verification of the dynamic response to voltage sags of a DFIG wind turbine were presented. Simulations were carried out using a full-order model and with a reduced-order model. Both models produced acceptable results. Perfect results were not expected, since simulations were carried out on a fictitious DFIG wind turbine. The response to symmetrical as well as unsymmetrical voltage sags was verified. The reduced-order model used in this paper includes the flux dynamics, which is not the case for the reduced-order models found in the literature. In this paper, the rotor current was put to its reference value, and thereby, it was possible to preserve the main dynamical behavior of the DFIG that corresponds to the flux dynamics.

EI-Sattar et al [12] developed a variable speed wind turbine model with its proposed control system for studying the operation of controllers at different wind speeds and flow of rotor power. The overall model has been developed using Matlab/Simulink. Four controllers are used namely, pitch angle, active power, reactive power and speed controllers. A dynamic model of the DFIG has been derived to develop a vector controller to decouple dynamically active and reactive power control.

Xingjia et al [13] sets up a complete DFIG dynamic model, including the generator model, converter model and converter protection, grid model etc. to study the transient characters. The method of sensorless direct torque control (DTC) and model referencing adaptive system (MRAS) method were used in the converter control. In this paper, the dynamic model of the DFIG, the control model of rotor side converter and stator side converter for DFIG will be set up respectively, as well as the protection of the converter. Then a complete model of DFIG will be founded in PSCAD platform. So here the doubly fed induction generator based on variable-speed wind turbines use dynamic fifth-order model of induction machine in a two-axis d-q reference frame rotating at synchronous speed. The simulation of the transient analysis is done when the power system take the phase ground fault. The result of the simulation indicate that the DTC control and MRAC principle used in the DFIG can improve the power system fault ride-through capacity ,that is to say when the system fault is phase ground in a little time ,the DFIG can implement the running of
disconnected network. And this give the theory base for future study the ride through the network fault to wind farm.

Luis et al [14] proposed a new equivalent model of wind farms with doubly fed induction generator wind turbines to represent the collective response of the wind farm by one single equivalent wind turbine, even although the aggregated wind turbines operate receiving different incoming winds. The effectiveness of the equivalent model to represent the collective response of the wind farm is demonstrated by comparing the simulation results of equivalent and complete models both during normal operation and grid disturbances. In this paper, a reduced model of a DFIG wind turbine has been implemented by means of the third-order model of induction generator and modelling the power converter, as two controlled sources, as usual for power system simulations. The modelling and simulation of the complete model of a wind farm with high number of wind turbines suppose the use of a high-order model and a long computation time if all the wind turbines are modelled. In order to reduce the model order and computation time, equivalent models have been developed to represent the collective response of the wind farm at point common coupling (PCC) to grid. These wind farm models have been implemented and simulated by using MATLAB/Simulink.

Milton et al [15] presented an integrated dynamic model of a DFIG-based WECS. The mathematical models of wind, rotor and gear and induction generator are simulated and validated using realistic data. The proposed model is also applied for choosing an appropriate WECS for any given wind regime. This paper presents simulation of mathematical models for wind, rotor, gear and doubly-fed induction generator using MATLAB Simulink. The model will be useful for wind energy developers in proper designing of wind energy conversion systems at the time of planning wind power stations.

Miguel et al [16] analysed the simplest representation of generators on wind turbine modelling, giving the accuracy required in power system disturbance studies. The order of the generator model and the numerical integration methods employed are compared. Since time simulation is a significant parameter, large power systems require simulating with the simplest possible wind generator models. This paper presents a comparative study considering the order of the model and the numerical integration methods used. Furthermore, a new equivalent model is proposed in order to ameliorate the accuracy for representing the dynamic response of wind farm on power system simulations with an important reduction on simulation time. In order to compare the numerical integration methods used in the simulation, the software packages PSS/E and PSCAD/EMTDC are considered. PSS/E uses a fundamental frequency simulation which is based on the modified explicit Euler method, whereas PSCAD/EMTDC is instantaneous value simulation software. The fifth-, third- and first order models have been considered in the PSS/E study. The aggregated wind farm models allow reducing the computation time more than the order of the generator model used.

Balasubramaniam et al [17] analyzed the steady state characteristics of a WECS using doubly fed induction generator (DFIG) using MATLAB. Simulation analysis is performed to investigate a variety of DFIG characteristics, including torque-speed, real and reactive-power over speed characteristics. Based on the analysis, the DFIG operating characteristics are studied. From the simulation analysis it is clear that the DFIG characteristics are affected by its injected rotor voltage. The simulated stator real power characteristics of the DFIG show that with increase in the rotor injected voltage, the DFIG real power characteristics shifts more in to the sub-synchronous speed range and the pushover power of the DFIG rises. It can
also be seen that the DFIG rotor power is capacitive when the DFIG operates in the generating mode under a subsynchronous speed and is inductive otherwise.

Chowdhury et al [18] presented a complete and aggregated wind farm models with Doubly Fed Induction Generator (DFIG) are presented. Simulations have been carried out for both models and compared to demonstrate effectiveness of the aggregated model in terms of accuracy in approximation of the dynamic collective responses at the Point of Common Connection (PCC) and reduction in simulation computation time. The wind farm models have been implemented and simulated by using Matlab. The parameters used for comparison are active and reactive power at the PCC. The simulations have been carried out under two operating conditions: (1) normal operation and (2) grid disturbance. It is observed that the proposed simplified aggregated model gives an accurate approximation of the collective responses at the PCC having minor discrepancies in magnitude with a faster simulation computation time.

Chitti Babu et al [19] presented the complete modeling and simulation of wind turbine driven doubly-fed induction generator which feeds ac power to the utility grid. The complete system is modeled and simulated in the MATLAB Simulink environment in such a way that it can be suited for modeling of all types of induction generator configurations. The model makes use of rotor reference frame using dynamic vector approach for machine model can be simulated as both motoring and generating mode when testing control strategies. Through the model developed in this paper can be used for simulating all types of induction generator configurations. The choice of synchronous rotating reference frame makes it particularly favorable for the simulation of doubly-fed configuration in transient conditions.

Mattia Marinelli et al [20] presented the dynamic behavior of a wind turbine equipped with a doubly fed induction generator (DFIG) in case of disturbances in the interconnected grid. A model of a DFIG is presented and adapted for analyzing the response of the wind generator to voltage control, frequency control, voltage sags and wind variations.

Ekanayake et al [21] investigated the impacts of the DFIG installations on the operation and control of the power system, accurate models are required. A fifth order and reduced order (3rd) machine models are described and the control of the wind turbine discussed. The capability of the DFIG for voltage control (VC) and its performance during a network fault is also addressed. For detailed representation of fault current contribution, the 5th order model provides better resolution although it must be recognized that the behavior of the converter control systems is likely to have a dominant effect on fault currents. A three-phase short circuit on the network close to the generator was investigated. As, expected, the 5th order generator model represented the behavior of the generator in more detail and included the transient behavior of the stator current. The 3rd order representation gave a similar mean value of the stator current correctly but did not show any details of the transient. For classical, phasor domain electro-mechanical dynamic studies of large power systems the simplicity and reduced computation time of the 3rd order model appears attractive. For more detailed representations of fault current contribution and investigation of the required ratings of the converters then the 5th order representation may be preferred. However, other effects, such as the control system and various limits of the converters as well as the transient behavior of the generator rotor circuits are also likely to be important in more detailed studies.

Katherine et al [22] compared the behavior of different order models, for large scale wind farms comprising doubly fed induction generators (DFIGs). It is also important to have simple models, not only to reduce computation time, but also to simplify the design of
controllers. This article compares the characteristics of different order models for DFIGs and their responses to control. Eigen value analysis and numerical simulations are used to compare the characteristics of the different order models. Simulations are performed using Simpow. Higher order models are often used, but these introduce high frequency dynamics which are not usually of interest in classical electro-mechanical dynamic studies of large power systems. The first order model gives almost the same information about the inter-area oscillations as the third order model does, but does not show the same effect that the controllers have on the real valued eigenvalues. The first order model is clearly capable of representing lightly damped oscillatory modes of the system, and may be of interest for designing non-linear damping controllers because of its simplicity. However, the third order model may be a more suitable model for analyzing transient stability.

Maider Santos et al[23] presented the simulation results of various dynamic models of a variable speed doubly fed induction generator (DFIG) wind turbine, the control system is made up of two control levels developed in MATLAB and PSCAD. The main goal is to develop and to validate reduced models of wind turbines which are suitable for wind turbine grid integration studies. To achieve this aim a complete MATLAB Power System Blockset (PSB) model will be compared with several reduced models. Generator models with and without flux transient terms have been compared. In the case of the converter, models with and without PWM have been used. The control system has been modeled with and without current regulators. The grid has been modeled in the static reference frame. Even thought the obtained results using PSCAD and MATLAB are very similar it is necessary to emphasize that PSCAD compiles much better electrical circuits than MATLAB does, what means that the simulation takes less time. Even so, MATLAB has tools make easier the introduction of the control systems.

III. STABILITY ANALYSIS, EFFECTS AND ENHANCEMENT

According to the classification of power system stability in reference [1], power system stability could be categorized into voltage stability, frequency stability and rotor angle stability. Stability of the system is analyzed for two types of disturbances mainly, small and great disturbances. Small disturbances occur continually due to small variations on load and generation. The system must be able to adjust to the changing conditions and operate satisfactorily, and must also be able to survive numerous disturbances of a severe nature, such as a short circuit or loss of a large generator. It is classified as small signal stability.

A. SMALL SIGNAL STABILITY

Small signal stability is defined as the capability of a power system to return to a stable operating point or to the original steady, after the occurrence of a disturbance that leads to an incremental change in one or more of the state variables of the power system. The definition of small signal stability refers to the system's response to a small change in one or more of its state variables. The small signal stability problem normally occurs due to insufficient damping torque which results in rotor oscillations of increasing amplitude. The Eigen values of the system matrix characterize the stability of the system. The change in design and operating condition of the power system is reflected in the Eigen values of the system state matrix. The effect of the system parameters on the overall system dynamics can be examined by evaluating the sensitivity of the Eigen values with respect to variations in system parameters. The variable speed wind turbine generator (WTG) design consisting of power electronics converter imparts significant effect on the dynamic performance of the DFIG. The introduction of large amounts of wind generation does have the potential to change the electromechanical damping performance of the system.
An approach for computerized formulation of power system linearised state equations including those of transmission network and the associated apparatus is introduced in [24]. A small-signal Eigen analysis software tool is developed based on the proposed state space formulation. The application of the packages is primarily for the analysis of power system small-signal dynamics in the high-frequency range (above 5 Hz), e.g. interactions among power electronic devices such as multiple SVCs. An application example of the software tool has also been reported. A novel method using particle swarm optimization (PSO) is proposed for optimizing parameters of controllers of a wind turbine (WT) with doubly fed induction generator (DFIG) in [24]. The implementation of the algorithm for optimizing the controllers’ parameters is described in detail. In the analysis, the generic dynamic model of WT with DFIG and its associated controllers is presented, and the small signal stability model is derived. The small signal stability analysis of the WT system with and without controllers has also been carried out. In addition, using the optimised parameters, the dynamic performance of WT system can be improved, and therefore the capability of the fault ride through can be enhanced. Small signal stability analysis considering grid-connected wind farms of doubly-fed induction generator (DFIG) is addressed in [25]. The power system small signal stability analysis is then carried out to explore and exploit the essential impacts on the existing power grid by Eigen value analysis for a specific test system. A simplified and practical DFIG model is presented with the stator flux-oriented vector control based method utilized to implement stator active and reactive powers control. The power system small signal stability analysis is then carried out on IEEE 3-generator-9 bus test system as benchmark to explore and exploit the impacts on the power grid due to the high penetration of grid-connected wind farms of DFIG type. The full order model of the DFIG with series grid-side converter is given in [26]. The stability of this system considering the linearized model is analyzed. This model is feasible for applications where the grid voltage is unbalanced. The configuration presented in this paper can be a good alternative to mitigate the effects of voltage unbalance and stator flux oscillations. The super/subsynchronous operation of the doubly fed induction generator (DFIG) system is addressed in [27]. The impact of a damping controller on the different modes of operation for the DFIG-based wind generation system is investigated. The effectiveness of damping controller under super/subsynchronous modes of operation is also investigated. This study would help in understanding the interaction of the oscillatory modes of DFIG-based WT with other components of power systems. This paper [28] investigates modes of response introduced by wind parks with doubly fed asynchronous generators (DFAGs) as well as their impact on electromechanical oscillations in interconnected power systems. The purpose is to further the stability studies referred to above by showing the effect of system stiffness, as well as some possible interactions (and their causes and remedies) between DFAG voltage/reactive power control and electromechanical oscillations. A model of the wind turbine (WT) with direct drive permanent magnet generator (DDPMG) and its associated controllers is presented in [29]. Small signal stability analysis model is derived from the model. Dynamic simulations are performed on a single machine infinite bus (SMIB) system and a four machine system to simulate the dynamics of the WT with DDPMG and to evaluate the control capability of the proposed controller under the system disturbances. The simulations were performed to evaluate the control capability of the proposed controller under the system fault in MATLAB/SIMULINK, and the dynamic responses of the WT with DDPMG were compared with those of the WT with DFIG to illustrate the impact of the wind generation with different configurations on the stability of the power systems. The simulation results have illustrated that in comparison to the WT with DFIG, the WT with DDPMG has better dynamic responses. The small signal stability of renewable energy based distribution system is investigated in [30]. The distribution system is fed by synchronous, induction and
static generators. Eigen-sensitivity with respect to active power fluctuations is proposed as a sensitivity parameter to study the impact of penetration. The results show that rotor flux variables of wind generators participate significantly in the system oscillations. Hybrid methodology for small signal stability assessment is addressed in [31]. The proposed methodology is validated against an electromagnetic transient simulation program (PSCAD/EMTDC) using time responses. The impact of the increased penetration of general induction generator based WTGs on small signal stability is examined for a single machine infinite system in [32]. To examine the performance difference of WTGs and the synchronous generators, wind farm within and without dynamic reactive compensation are developed. Small signal stability of large scale variable speed wind turbines with doubly fed induction generator integration is addressed in [33]. In this method, stability analysis is done by computing Eigen values and right and left eigenvectors of a Jacobian matrix which obtained from the power flow equations.

B. CONTROL OF DFIG

Dawei Xiang et al [34] analyze the ability of a doubly fed induction generator (DFIG) in a wind turbine to ride through a grid fault and the limitations to its performance. The fundamental difficulty for the DFIG in ride-through is the electromotive force (EMF) induced in the machine rotor during the fault, which depends on the dc and negative sequence components in the stator-flux linkage and the rotor speed. The investigation develops a control method to increase the probability of successful grid fault ride-through the current and voltage capabilities of the rotor-side converter. A time-domain computer simulation model is developed and laboratory experiments are conducted to verify the model and a control method is proposed. The performance of fault ride-through control is verified with the DFIG initially operating with no load. Simulations based on a validated model provide the feasibility regions, in terms of fault severity and prefault speed, of successful ride through control for DFIG connected to the grid through a double-circuit network.

Feng Wu et al [35] presented a detailed model of the WT with DFIG and its associated controllers based on which the small signal stability model is derived. Small signal stability analysis shows that the DFIG control can significantly improve the stability of WT system. Applying a set of optimized controller parameters, the stability can be further enhanced. Dynamic simulations are performed to illustrate the control performance. It has been recognized that the DFIG controllers have significant effects on the system stability. In order to address this issue, a dynamic model including the dynamics of converters and controllers is presented. The rotor side converter controllers aim to control the DFIG active power output for tracking the input power of the wind turbine, and maintain the terminal voltage to the reference value. The grid side converter controller aims to maintain the DC link voltage, and control the terminal reactive power. In this paper, Particle Swarm Optimization (PSO) algorithm is utilized to optimize the parameters of the DFIG controllers. Simulations, which were performed in MATLAB/SIMULINK, aimed to verify the improvement in stability by the DFIG controllers with the optimized parameters. It can be seen that using the optimized controller parameters, the dynamics of the WT have been significantly improved. The oscillation after the disturbance was damped out very quickly. In particular the peak DC link voltage was reduced noticeably, which is very beneficial to the operation of the fed back converters.

Ming et al [36] analyzed model of DFIG and developing control strategy for grid-connected DFIG. In order to study the influence of the grid disturbances on the DFIG, grid voltage dip and quick frequency change are simulated in MATLAB/Simulink. Control
designing methods such as the pole-placement method and internal model control method are implemented for designing the PI controllers.

Lie Xu et al [37] presented an analysis and control design of a doubly-fed induction generator (DFIG)-based wind generation system operating under unbalanced network conditions. A rotor current control strategy based on positive and negative (dq) reference frames is used to provide precise control of the rotor positive and negative sequence currents. Simulation results using EMTDC/PSCAD are presented. Methods for providing enhanced system control and operation for DFIG-based wind turbines during network unbalance i.e., power, torque, or current oscillation minimizations, are identified.

Seung-Ho et al [38] investigated the dynamic response of WECS to the events in power system, an accurate simulation model for DFIG (doubly-fed induction generator) system is developed using PSCAD/EMTDC and a hardware-in-loop simulator is implemented. The model consists of wind model, rotor dynamics, wound rotor induction generator, power electronics converter and control strategies. Control strategies can be programmed at torque-speed plane as needed and implemented in DSP controlled power converters. Simulation and experimental results shows smooth change of control modes and efficient power variables such as the control performances.

Abolfazl et al [39] focused on modeling and controlling of a doubly-fed induction generator (DFIG). The presented model is developed based on the basic flux linkage, voltage and torque equations. In order to control the DFIG's active power, a suitable method based on PSO algorithm has been proposed. The simulation results show that the presented method using PI controller is a useful way to improve the output power of DFIG.

Yi Wang et al [40] investigate the control of doubly-fed induction generator (DFIG) based wind farms for compensating voltage unbalance in weak networks. A control strategy for compensating grid voltage unbalance using DFIG systems is proposed. Various methods such as the required negative sequence current is solely provided by the DFIG stator through the RSC. The required negative sequence current is solely provided by the GSC. The required negative sequence current is provided from both the RSC and GSC. The required negative sequence currents for the RSC and GSC are for coordinating these two converters and their impact on system operation are analyzed. The capabilities of the converters with a DFIG system for negative sequence current compensation are also discussed. The validity of the proposed control strategy is demonstrated by Matlab/Simulink simulations. With the proposed strategy, DFIG based wind farms can provide voltage unbalance compensation for the connected weak grid to improve the performance and stability of the whole wind energy system.

Lingling et al [41] converted a wound rotor induction motor to a DFIG by injecting a three-phase voltage to the rotor at various frequencies. The stator is connected to a three-phase resistance load. Both computer simulation and experiments are performed to demonstrate the frequency, voltage and power relationships between the rotor and the stator. Using the relationship between the stator and rotor voltages, a PWM based slip control scheme together with volts/Hz control for the rotor side converter is developed and the performance verified in PSIM. The DFIG with the proposed control scheme generates a constant voltage with constant frequency at the stator. The experiments, simulation and analysis help to understand DFIG operation and PWM control.

Ghennam et al [42] dealt with the modeling and control of the doubly fed induction generator based wind conversion system. A model of the DFIG is then detailed in dq
reference frame. A decoupled dq control is adopted for both GSC and RSC. For GSC control algorithm, the q-component of the filter current is used for the DC voltage regulation and the d-component is devoted for the reactive power regulation. Beside this, for the RSC control algorithm, the q-component of the rotor current is used for controlling the active power injected by the DFIG to the grid while the d-component deals with the control of the reactive power. Both GSC and RSC control algorithms are implemented on a DSPACE board. The presented experimental results show good performances of the decoupled d-q control.

Milton et al [43] developed a mathematical model of the DFIG in an appropriate d-q reference frame for simulation purpose. Secondly, the controller is designed to control the power exchange between the stator of the DFIG and the utility grid network. Two types of control strategies are considered - PI control and pitch angle (Pitch-to-feather) control. The respective performances of the two types of controllers are compared in terms of power reference tracking, response to sudden speed variations, sensitivity to perturbations and robustness against machine parameters variations. controller are designed based on pole placement theory.

Wei et al [44] presented and developed two different models in PSCAD/EMTDC to represent a variable-speed wind turbine equipped with a doubly fed induction generator (DFIG). One is the most detailed switching-level (SL) model. The other is a simplified fundamental-frequency (FF) model. The effect of different shaft system representations on the dynamic behavior of the wind turbine generator (WTG) system and the issue of damping low-frequency tensional oscillations are investigated. Dynamic and transient simulation studies are carried out to compare two models with different shaft system representations. This detailed switching-level (SL) model uses excessive computation time and is unsuitable for dynamic and transient study of large power systems with a high-level penetration of DFIG wind turbines. Therefore, the two-mass shaft model should be used for the study of power system transient dynamics.

Luna et al [45] presents a new VOC [voltage oriented control] strategy able to control the operation of DFIG with no need of flux position estimation, something that conducts to a more simple and robust algorithm. In order to evaluate the advantages of this new control proposal, namely VOC-RRF, their performance will be compared with the response obtained with a classical VOC algorithm by means of PSCAD/EMTDC simulation models. The simulation and experimental results have demonstrated that the VOC-RRF can be considered as a good alternative for the classical VOC-SRF control algorithm as its performance has been proven to be robust and fast.

Yongfeng et al [46] derived the wind turbine model and the dynamic mathematical model of DFIG. The control of the rotor current inner loop and the rotating speed outer loop are designed based on internal model control (IMC) strategies, respectively. A complete variable speed constant frequency (VSCF) DFIG wind power generation system model is developed based on PSCAD/EMTDC. The simulation results show that the system has fast dynamic response under various run conditions and can operate at sub-synchronous speed and super-synchronous speed.

Hamon et al [47] several computer programs exist to carry out dynamic simulations and this study will focus on one of them, namely DigDilent Power Factory. It offers two built-in models of doubly-fed induction generator. A new model has also been developed, based upon a controllable voltage source. These three models are compared, in terms of dynamic behavior and simulation time. A third new DFIG model has been created using a voltage source. The behaviors of the two built-in models and the new model are compared.
Two PI controllers are used to control either active and reactive powers or active power and stator voltage. It is more complicated to use than built-in components but it is more flexible because it relies on code and can be made to do exactly what the user wishes.

Jiabing Hu et al [48] presented a mathematical model of a doubly fed induction generator (DFIG) in the positive synchronous reference frame under distorted grid voltage conditions. The oscillations of the DFIG’s electromagnetic torque and the instantaneous stator active and reactive powers are fully described when the grid voltage is harmonically distorted. Four alternative control targets are proposed to improve the system responses during grid harmonic distortions. A new rotor current control scheme implemented in the positive synchronous reference frame is developed. The control scheme consists of a proportional–integral (PI) regulator and a harmonic resonant (R) compensator tuned at six times the grid frequency. Consequently, the fundamental and the fifth- and seventh-order components of rotor currents are directly regulated by the PI–R controller without sequential-component decompositions. The feasibility of the proposed control strategy is validated by simulation studies on a wind-turbine-driven DFIG system. Compared with the conventional vector control scheme based on standard PI current controllers, the proposed control scheme leads to significant elimination of either DFIG power or torque oscillations under distorted grid voltage conditions. Simulations of the proposed control strategy for a DFIG based wind power generation system were carried out using MATLAB/Simulink.

TRANSIENT STABILITY

Transient stability is the ability of a power system to maintain synchronism when subjected to a large disturbance. The severe disturbances include equipment outages, load changes or faults that result in large excursion of generator rotor angles. The resulting system response is influenced by the nonlinear power-angle relationship. The time frame of interest in transient stability studies is usually 3–5 s following the disturbance. The duration may extend up to 10–20 s for a very large system with dominant inter-area swings.

Three main aspects of wind farm that affect the transient stability. These are listed below.

Location of wind generator: Especially when high wind resources are located in one particular area leading to highly modified power flows including increased tie-line flows, critical fault clearing times can be considerably reduced and additional lines might be required.

Generator technology: Variable speed wind generators are able to improve transient stability margins, when being equipped with low voltage ride-through capability, reactive current boosting and ideally with fast voltage control.

Connection of large wind farms to lower voltage levels: The integration of wind generation into sub transmission and distribution systems has a negative impact on transient stability, because the reactive contribution is highly limited due to reactive losses in sub-transmission and distribution systems.

Claudio et al [49] analyzed the transient stability of electrical power systems including the influence of induction generators. Also overviewed induction generators. Using an existing transient stability program, simulations are carried out to compare the performance of a typical electrical system with and without the presence of induction generators. With the event of a system disturbance, such as a loss of a generator, this tends to
cause transient stability problems, the presence of these induction generators acts as a stabilizing factor. Thus, these machines cause the electrical system to become stiffer from the point of view of the stability.

Nunes et al [50] analyzed the transient stability margin of variable speed wind turbines with the doubly fed induction generator connected to the electric grid. The controller model of the DFIG including rotor current limits and its effect on the transient stability of the wind system will be considered. The models presented are implemented using MATLAB. The simulation results clearly show that the DFIG improves the short-term post-fault stability of wind turbine generators when integrated to power systems with conventional generation. The doubly fed machine is more robust than cage generators in the events of critical faults, as a short-circuit. The DFIG is able to keep the torque equilibrium, still maintaining the necessary transient stability margin. It was also observed that it is possible to reduce the dynamic reactive compensation demands when using the DFIG. This is an important feature considered in the choice of the wind system integrated on strong or weak electrical grids.

Julio et al [51] addressed two main issues. First, models for dynamic studies are described; Secondly, transient stability studies involving wind energy conversion systems are presented. These studies will include fixed speed and variable speed devices, and several situations on the grid are considered. Studied the analysis of the dynamic response of the system to network faults such as short circuits, line trips, and generator trips. From the analysis performed, it has been concluded that the effect of fluctuations of wind power generation is negligible compared with the effect of short circuits in the power grid. Also concluded that simplified models of wind energy systems may be used for dynamic studies, without significant loss of accuracy. Variable speed devices seem to be better for system stability than fixed speed ones.

Markus et al [52] presented a fundamental frequency doubly-fed induction machine model including a typical control system and discussed the accuracy of reduced order models under various operating conditions. It includes models of all components, the induction generator, the rotor-side- and the grid-side converters and typical approaches for the control circuits and aerodynamics of the wind turbine. All models have been implemented and tested in the power system analysis program Dig SILENT. In the simulation of the fifth order model, not only stator transients of the induction machine but also the transient behaviour of transformers and lines was considered (EMT-compatible network model). Together with the third order machine model, a quasi-steady-state network model was used, corresponding to the classical stability approach are described. When comparing the results from both models, it can be noted that the reduced order model represents the average of power and voltage very well. The reduced order model can therefore be used for analyzing the influence of doubly-fed induction machines to the power system, but it is not possible to predict peaks in electrical power or torque correctly. Therefore, the fifth order model together with a "transient" network model is required. Every reduced order model was validated against higher order models. The results of the test cases show that a third order induction machine model including crow bar protection together with a simplified model of the grid-side converter provides sufficient accuracy and the necessary computational efficiency for carrying out stability studies in large power systems with several hundreds of machines.

Tao et al [53] concentrated on transient analysis of variable speed wind turbines with doubly fed induction generator (DFIG) after an external short-circuit fault. A simulation model of a variable speed wind turbine with DFIG developed in PSCAD/EMTDC is presented, and the control and protection schemes are described in detail. When the post-fault
situation is not serious enough to trigger the protection devices in the rotor circuit, the control schemes of the DFIG operates as normal and are capable of forcing the rotor speed down and re-establishing the voltage at the wind turbine terminal after the short-circuit fault is cleared. The simulation results demonstrate how the control schemes effectively manage to restore the wind turbines normal operation after the clearance of an external short-circuit fault.

Muyeen et al [54] analyzed the transient stability of WTGS using the six-mass, three-mass and two-mass drive train models for severe network disturbance in two different types of power system models. A detailed transformation methodology from the six-mass to two-mass drive train models is presented, which can be used in the simulation analysis with reasonable accuracy. For transient stability analysis the symmetrical three line-to-ground faults (3LG) is considered. Some unsymmetrical faults such as double line-to-ground fault (2LG), double line-to-line fault (2LS) and single line-to-ground fault (1LG) (phase a) are also considered. The simulations have been done by using PSCAD/EMTDC. By using the transformation procedure, the inertia constants, spring constants, self-damping’s of individual masses and mutual-damping of adjacent masses of the six-mass drive train model can be converted to reduced order models. The effects of drive train parameters such as inertia constants, spring constants and damping constants are examined for the above mentioned three-types of drive train models. Considering all the simulation results, it can be concluded that the WTGS can be expressed by the simple two-mass shaft model with reasonable accuracy and that this model is suitable for the transient stability analysis of grid connected WTGS.

Katherine et al [55] derived a third order model for a DFIG which is suitable for use with the standard one-axis model for synchronous generators, also developed a mathematical model of a complete system, and described the linearization of the system. Results presented and compared from eigenvalue analysis and dynamic simulations. Eigenvalue analysis is used as a method for tuning control parameters. We have noted that a determination of the eigenvalues is not sufficient for describing post-disturbance behavior, and that dynamic results are also required. Converters might be utilized to improve this behavior.

Libao et al [56] focused on studying the dynamic performance of the DFIG based wind farm and investigating the impacts of the DFIG based wind farm on power system transient stability. Two kinds of indices are employed to evaluate the system transient stability. Power angle-based stability margin or index and Critical clearance time (CCT) of faults .CCT is the longest allowed fault clearance time without losing stability. This is obtained, using a binary search method, within a specified fault clearance range with a set threshold. If the change of the system operation can increase CCT, it is considered that such change is favorable to improve power system transient stability. All simulations are conducted on the DSATSAT/UDM™. The analysis and simulation results show that under the specified fault condition, the increased penetration level, i.e. replacing synchronous generators with the DFIG based wind farm in the case studies, tends to improve the transient stability for a specific test power system.

Chenxi et al [57] presented a study on the transient characteristics of a power generation when the power is generated from wind turbine using DFIGs. The transient behaviours of active power, reactive power and voltages in a wind power generation system are analyzed. In this study, a third-order system of nonlinear differential equations is used to describe the behavior of a DFIG, in terms of the voltage magnitude dynamics, voltage angle dynamics and the dynamics of its electromechanical system. A novel analysis is proposed based on the linear state space representation of the system. The study finds that the stable
operation region of the PV curve remains almost the same when the system faces perturbations such as changes in wind speed and load, which means that the system presents a stable behavior under these disturbances.

Li et al [58] analyzed the transient stability of a grid connected wind turbine with SCIG, a three-mass wind turbine equivalent model has been proposed by considering both the bending flexibility of the blades and the torsional flexibility of the drive drain shaft. Combined with the electromagnetic transient models of SCIG, the transient behaviors of wind turbine system are simulated and compared when the stator terminal of SCIG is subjected to a three-phase fault. The results of transient stability analysis are also compared with the traditional two-mass shaft model and one-mass lumped model, respectively. The comparative results have shown that the influence of blades flexibility on transient responses of the wind turbine system is more and more obvious as the wind turbine capacity increasing, a three-mass wind turbine model that takes into account both shaft flexibility and blades flexibility may be more suitable than the traditional models of the wind turbine drive train. In addition, in order to quickly estimate the transient stability limit of wind turbine system considering both generator electrical transients and the drive train flexibility, a direct method based on the normal form theory has been investigated.

HAN Pingping et al [59] constructed a model for a simple electric power system with a large wind power plant consists of Doubly Fed Induction Generator (DFIG). The studies include examining the transient stability of the power plant in serious system fault under two operation strategies, i.e. fixed power factor operation and fixed voltage operation. Following conclusions could be obtained, under fixed voltage operation strategy; the wind power generation system could help to increase the voltage level of stator terminals by regulating its reactive power output. Therefore, the ability of fault ride-through and transient stability of the wind farm are improved. During serious disturbances of the grid, such as a three-phase ground fault, the power balance between two sides of the DC-Link are destroyed, causing the voltage to increase rapidly and reach the over-voltage limit in short time, protection schemes are triggered to protect damage on the wind turbine system. Therefore, taking measures to limit rotor power output and reduce the power imbalance of the converters under large disturbances so that the grid-connection is preserved are of importance to increase the ability of fault ride-through and the global transient stability and dynamic voltage stability of wind power generation system.

Hongjing et al [60] focused on the comparison of transient stability characteristic between wind farm based on double fed induction generator (DFIG) and tradition power plant with the same capacity. During steady state, the reactive power between wind farm and the grid is zero. The study indicates that, in this system, when the scale of wind farm connected is below 12.3%, the transient stability is better than synchronous generator integrated with the identical capacity. And with the increasing capacity of wind farm, the fault critical clearing time (CCT) is shorter, and it lasts longer time during the recovery. When the scale of wind farm exceeds 12.3%, the terminal voltage of point of common coupling (PCC) is below 0.95 p.u. The stability is inferior to the synchronous generator connected. Under the circumstance, the stability will be enhanced through adding the reactive power compensative device.

Melicio et al [61] focused on the transient stability of variable speed wind turbines with PMSG at a pitch control malfunction. Hence, we study the influence of a pitch control malfunction on the quality of the energy injected into the electrical grid, analyzing the transient stability with different topologies for the power-electronic converters. Also
proposed a new control strategy based on fractional-order controllers for the variable-speed operation of wind turbines with PMSG/full-power converter topology. The performance of disturbance attenuation and system robustness is ascertained. Computer simulations obtained by using Matlab/Simulink.

Lasantha et al [62] presented transient stability analysis for a power system with high wind penetration. The transient stability has been evaluated based on two stability criteria: rotor angle stability and voltage stability. DiGsILENT power factory has been used as the main simulation tool for this analysis. The installation of DFIG based wind farms has also yielded a significant improvement in system stability due to their reduced reactive power consumption. Although these factors have improved the stability at low wind penetration levels, system stability is significantly degraded at high penetration levels (50%) due to the high reactive power absorption of wind generators under transient disturbances.

Khosravi et al [63] evaluated transient stability of a power system when large amounts of wind farm with the DFIG technology is connected to the system. Digsilent software is used for simulating program. Simulation studies are carried out to demonstrate and compare the transient performance of test system with and without wind power integration during a severe grid fault. The results are extracted and diagrams are drawn by MATLAB. During the simulation, a 150 ms three-phase short circuit is applied. Simulation results show that ever the more penetration level of wind farm we have in the system, the worse transient stability and more rotor angle and rotor speed oscillations. Also we could not have an unlimited DG generation in the power system and at a certain penetration level, the power network would become unstable and the synchronous generators will lose their synchronism because of the weak capability of the wind turbines in fault detection and their cooperation in supplying additional current due to fault occurrence.

Piergiovanni et al [64] presented the model and control scheme of a Doubly-Fed Induction Generator (DFIG). The controllers are designed in order to take into account the different operating conditions of the generator. In normal operations the DFIG can work with variable rotor angular speed between a minimum and a maximum value, covering a wide range from subsynchronous to supersynchronous angular speeds. Up to the rated value, the rotor angular speed is regulated to those values which allow transferring the maximum wind power into electrical power. For angular speeds higher than the rated one, a blade pitch angle regulation limits the transferred power to prevent damages to the machine and instability. A single DFIG connected to a high voltage network has been implemented with ATP-EMTP. Simulations are obtained considering normal operating and fault conditions. Related to this last case, a new stabilizing technique is proposed to improve transient stability. The system has been simulated under normal operating and fault conditions.

B. EFFECTS AND ENHANCEMENT OF STABILITY IN WIND ENERGY CONVERSION SYSTEM

Perdana et al [65] developed a model to investigate the dynamic response of a wind turbine with DFIG connected to the power system during grid disturbance. This model includes aerodynamics, the mechanical drive train, the induction generator as well as the control parts. The response of the system during grid disturbances is studied. An inclusion of saturation effect in the generator during faults is included as well. A wind turbine model with DFIG is developed in Matlab/Simulink and simulations of the model during grid disturbance. Two different operation modes, i.e. sub-synchronous and super-synchronous operation, are treated separately. In the simulation, a three-phase fault is applied at the middle bus. The magnitude of fault is controlled by the selection of an appropriate fault resistance. Various
simulations are conducted. In the first simulation, the ability of the DFIG controller to recover terminal voltage after fault clearance is investigated. The second simulation describes the sequence action of the over-current protection during a fault, which leads to converter blocking. The terminal voltage recovery of the DFIG is somewhat better than the identical squirrel cage induction generator. DFIG is sensitive to severe voltage dips that result in an excessive stator and rotor current, which leads to the rotor converter being blocked.

Vinodh et al [66] has presented a study on grid-connected wind electric generators, WT-SCIG and WT-DFIG, subjected to transient faults on transmission lines connected to the windfarm. All simulations are performed in MATLAB/Simulink. The dynamic responses to wind speed variations and transient faults on transmission line are studied. The author includes monitoring of critical values of voltage and power as well as stability assessment at several points in the simulated model of a wind farm-grid interface. Different types of faults (L-G, L-L-G and L-L-L-G) are simulated. Results obtained from the study provide useful information regarding the behavior of these generators when connected to grid and helps a comparison between the two types.

Fei et al [67] studied the impact of large scale wind farm integration on power systems transient stability. Then the 8th and 5th order dynamic models of DFIG of wind turbines based on DFIG is used to study the impact of wind power integration on the transient stability of the grid. The simulations are carried out by MATLAB and PSS/E to verify the theoretical analysis. It is concluded in the paper that the performance of DFIG for integration is better than that of synchronous generation units at a same point in the power systems as far as transient stability is concerned. Also with the voltage control, the transient stability of power system is enhanced as the fault happens, and concluded in the paper that the transient stability of DFIG connected to power system is better than that of synchronous generation units.

Li et al [68] modelled grid-connected wind farm which contains SCIGs and DFIGs is built, and the transient operation characteristics of DFIGs and SCIGs which have different rates of capacity are studied. A new control measure is put forward to improve the transient performance of the DFIG, which is proved effective through the simulation. Also the impact of the control measure on the SCIG running in parallel with the DFIG is also investigated. The detailed model of grid-connected wind farm which contains the DFIGs and SCIGs is carried out in PSCAD/EMTDC. The fault event is a three-phase to ground short-circuit fault. The transient operation characteristics of DFIG and SCIG with or without RSC voltage control are studied. With the DFIG RSC voltage control, the transient performance of DFIG is greatly improved. Also there is an apparent impact on the transient performance of SCIG, which can recover to pre-fault stable operation state, furthermore the recovery time is much less along with the capacity of DFIG increasing.

A.A. El-Sattar et al [69] studied the transient response of variable speed wind turbines with DFIG after the clearance of short-circuit fault at the generator bus. A simulation model of wind turbine with DFIG is presented, and the control schemes of the wind turbine are described in detail. Based on the wind turbine model, the stability of wind turbine after a short-circuit fault has been investigated. The simulation results show how the control schemes effectively manage to restore the wind turbine’s normal operation after the clearance of an external short-circuit fault. During faults a high rotor currents will flow in the rotor converter which could damage it. A crowbar is used to disconnect the rotor converter during fault to protect it against short-circuit currents. Different cases are simulated to study the response of variable speed wind turbine and its control when subjected to three phase short
circuit at the generator bus (worst case). The analysis was carried out in MATLAB/SIMULINK environment.

Wei Qiao et al [70] investigates the effect of wind power integration on power system transient stability, based on a SG is replaced by a large wind farm equipped with the DFIG wind turbines. Simulation studies are carried out in PSCAD/EMTDC. DFIG wind turbines can successfully ride through grid faults and have no problem of angular stability associated with the conventional SGs. Because of these features, the DFIG wind turbines might be superior over the SGs to help maintain power system transient stability during some severe grid disturbances. System components, such as the SGs, the DFIG and the two-mass shaft system model in the WTG are built with the standard component models from the PSCAD/EMTDC. Three-phase short circuit is applied to the system. Therefore after the fault, the system changes to a new operating condition. Results show that better transient performance and stability are achieved by the 39-bus system with wind power integration.

Guo Jia-hu et al [71] analyzed the behaviour of DFIG and converter under symmetrical and unsymmetrical grid fault with mathematic method in details, and gave the equation of flux and dc-voltage under grid fault. The fault response of the DFIG system includes DFIG and converters are analyzed. From the investigating of the response of the DFIG system due to different grid disturbances, it has been shown that the amplitude of the flux oscillation when the voltage returns after a voltage sag can vary between zero and twice the initial amplitude of the flux oscillations due the sag. The maximum grid fault current have been derived and also it occurs moment. It shows that the maximum value of DFIG current is independent of flux and only depends mainly on the stator and rotor leakage inductance. At last, the methods of grid fault ride-through are proposed including crowbar solution and compensating for the changes in stator flux.

Folly et al [72] investigated the impact of fixed speed and variable speed grid-connected wind generators on the transient stability of a power system. The wind generators considered are the squirrel cage induction generator (SCIG), the doubly-fed induction generator (DFIG) and the converter driven synchronous generator (CDSG). We investigated the level of penetration of the wind generators that can cause system instability or significantly reduce the stability margins under three-phase fault conditions. Two scenarios are investigated. Under the first scenario, the conventional synchronous generator is not equipped with an Automatic Voltage Regulator (AVR) when the system is subjected to a three-phase fault. Under the second scenario, the AVR of the conventional synchronous generator is included. It was found the squirrel cage induction generator performs poorly and contributes negatively to the transient stability of the network as compared to both the doubly-fed induction generator and the converter driven synchronous generator. The converter driven synchronous generator has the best performance. When the AVR is included, the penetration level of the squirrel cage induction generator could be further increased without loosing the stability of the system. Simulations were carried to investigate the impact of the above discussed three types of wind generators on the transient stability of power systems using DigSilent Software package. A three phase fault was applied at the middle of the transmission line. The external voltage controllers improve the transient stability margin of the power systems due to the ability to control the voltage at the terminal of the generators. When the AVR was included, it improves the transient stability.

Durga Gautam et al [73] this paper presents a systematic approach based on eigenvalue sensitivity to examine the effect of penetration of DFIGs on a large system. The approach involves detailed analysis of a fairly large system using commercial grade software.
The analysis of the critical modes of oscillation is further extended to observe whether or not the system is transiently stable when the particular mode is excited due to a large disturbance. The simulation results carried out for the two different study objectives, namely, small signal stability and transient stability are detailed. With the objective of observing the system response for small and large disturbances, the same base case operating scenario is considered for small signal stability and transient stability study cases. The study is conducted using the package DSATools developed by Powertech Labs, Inc. This includes power flow and short circuit analysis tool (PSAT), transient security assessment tool (TSAT) and small signal analysis tool (SSAT).

He Ren-Mu et al [74] investigated the impact of DFIG-based wind farm on power system load modeling. Then, the ZIP (the constant impedance, constant current, and constant power load model, namely ZIP load model) in parallel with induction-motor was adopted to fit the load characteristics. It was concluded that wind farm based on small scalar capacity does not have much impact on the load modeling, thus using the ZIP in parallel with induction-motor load model is appropriate. Wind farm based on large-scale capacity have changed the load flow largely. If the ZIP in parallel with induction-motor load model is still used it will bring a large error in system analysis. Using the ZIP in parallel with asynchronous generator model can bring more accurate results.

Milton et al[75] development of a model of a grid-connected DFIG-based WECS for studying its dynamic behaviour during grid disturbance. This model includes aerodynamics, the mechanical drive train, the DFIG and the controller. It is observed that the generator-side controller provides good decoupling between active and reactive power. development of a wind turbine model with DFIG in Matlab/Simulink, followed by simulations of the model during grid disturbance. In the simulation, the ability of the DFIG to recover terminal voltage after grid disturbance is presented. The response of the DFIG to faults and subsequent action of the over-current protection is described. The results from the super-synchronous operation mode are evaluated here. The inclusion of the saturation effect in the generator to provide better prediction of current magnitude is included as well.

Sundeep et al [76] presented modelling and effect of Doubly Fed Induction Generator (DFIG) for wind turbines on transient stability analysis when connected to grid system. A reduced order model for the DFIG has been used. A controller for speed, voltage and power factor has also been implemented. The DFIG model and the controller are presented as Differential Algebraic Equations. The behaviour of DFIG with and without synchronous machine under the fault condition has been observed. Method used to solve DAE equation is “Simultaneous Implicit” method. first the Differential equations are converted to algebraic equations using the trapezoidal integration method and the resulting algebraic equations along with the other algebraic equations are solved simultaneously using the Newton’s method at each time step. DFIG was simulated with a three phase fault. PSO technique has been implemented for optimizing the controller gains. From the results it has been observed that, the behaviour of both DFIG and synchronous machine under fault conditions has been affected by each other’s presence in the power system network. When connected to infinite bus system (which is a strong network) and to a synchronous machine system (which is a weaker network), the DFIG remains stable for both the cases. This shows that DFIG is capable of withstanding grid faults when interconnected with the grid. This is one of the major advantages of DFIG when compared to its other equivalent machine types. Also, DFIG-based wind generation with the basic control scheme used provides better performance in terms of voltage control and damping.
Djilali et al [77] developed a full model and the control strategy of the DFIG. The mechanical model of the wind turbine is also introduced in order to investigate the maximum power point tracking (MPPT) and the pitch angle control. The paper mainly focuses on the DFIG transient state variables prediction for various operating conditions with regard on the crowbar design. To demonstrate the behaviour of the system, simulations have been performed using MATLAB/SIMULINK software. The crowbar circuit used in simulation consist of simple resistance added to the rotor resistance during fault, in the same time the rotor circuit is disconnected from the rotor side converter. The effect of crowbar system, in different cases, is examined. Thus, it present a good approach to provide the optimal crowbar resistance.

Libao et al [78] examined transient stability simulation of power system with consideration of large-scale grid-connected wind farms of DFIG. The multiple wind farm integration with replacing synchronous generators is studied first. Furthermore, the impact on the power system transient stability with direct connection of wind farm of DFIG. It should be pointed out that these conclusions and comments can provide useful information for power system planning and design when considering integrations of large wind farms with the existing power system.

Muyeen et al [79] analyzed the stabilization of wind farms connected with multi-machine power system in a severe network disturbance. For this purpose, the STATCOM incorporated with battery energy storage system (BESS), i.e., STATCOM/BESS topology is proposed to enhance the transient stability of entire power system. At each wind farm terminal one PWM based STATCOM/BESS is connected. Two-mass drive train model of wind turbine generator system (WTGS) is used in the analyses as the drive train modeling has great impact on the dynamic characteristics of fixed speed wind generator. Both of symmetrical and unsymmetrical faults are considered as network disturbances. It can also enhance the low voltage ride through (LVRT) capability of WTGS. Simulations have been done by using PSCAD/EMTDC. A symmetrical 3LG fault is considered. It is concluded that the proposed STATCOM/BESS can be applied effectively to enhance the transient stability of multi-machine power system including wind farms.

Hansen et al [80] concentrates on the fault ride-through capability of doubly fed induction generator (DFIG) wind turbines. The main attention in the paper is, therefore, drawn to the control of the DFIG wind turbine and of its power converter and to the ability to protect itself without disconnection during grid faults. The dynamic behaviour of DFIG wind turbines during grid faults is simulated in PowerFactory DIgSILENT. The presence of the damping controller is very important for minimizing the grid fault effect both on the mechanical and on the electrical side of the turbine.

Nayeem et al [81] investigates possible improvements in grid voltage stability and transient stability with wind energy converter units using modified P/Q control. The simulations are done using the power system simulation software PSS/E. A three-phase to ground fault is applied at the middle of the line, and the generator rotor-angle and the grid power are studied in the presence of different types of WECS. For the investigated power system considered in this paper, the critical fault clearing time of the generator was increased by two cycles, when the suggested method was used.

Tarafdar et al [82] studied a wind farm modeling and UPFC using are to solve the wind farms power transmission problems. In this paper structure and UPFC functional basics under stable conditions and induction generator model and wind turbine model is mentioned.
initially and then the effect of UPFC connected to a sample wind farm, in respect wind velocity changes and wind farm distance to grid and power flow are studied. Wind turbines are studied in wind velocity changes conditions and also reactive and active power flow control in the presence of UPFC and without that is examined in modeling. UPFC is simulated in MATLAB/Simulink. A FACTS device in order to transmit maximum wind farm generated power by keeping their stability under various system conditions is considered. In this paper UPFC function in wind farms generated maximum transmission power is studied.

Mamta et al [83] presented a pitch controlled Wind Turbine Generation System (WTGS) used to have optimum power flow and to reduce overloading of wind turbine when higher wind speeds are available. Also, a pitch control system is used for stabilization of the wind turbine at grid faults. A simple control strategy for STATCOM is adopted, where only measurement of rms voltage at induction generator (IG) terminal is needed. For the stability behavior of a Fixed Speed Wind Turbine (FSWT) connected to the grid, after a short-circuit fault in the utility, the model is developed in the simulation tool MATLAB/SIMULINK and created as a modular structure. From the results it is observed that with STATCOM the oscillations are reduced as compared to the capacitive bank compensation and no compensation. Finally we can conclude that STATCOM gives better performance than the static capacitive bank.

Muyeen et al [84] presents a new method to enhance the transient stability of multimachine power system including wind farms, when a severe network disturbance occurs in the power system. For this purpose, the energy capacitor system (ECS) composed of power electronic devices and electric double layer capacitor (EDLC) is proposed. The control scheme of ECS is based on a sinusoidal PWM voltage source converter (VSC) and fuzzy logic controlled dc–dc buck/boost converter using insulated gate bipolar transistors (IGBT). Two wind farms are considered to be connected to the power system. To obtain the realistic responses, the two-mass shaft model of WTGS is considered in this paper. Fuzzy logic controller (FLC) is proposed as the control methodology of dc–dc buck/boost converter since it can be applied to a system with uncertainties. The symmetrical three-line-to-ground fault, and the unsymmetrical double-line-to-ground fault, double-line fault, 2LL, and single-line to ground fault are considered as a network disturbance, Simulations have been done by using PSCAD/EMTDC. Simulation results clearly show that the proposed ECS can enhance the transient stability of wind generators in multimachine power system as well as their low voltage ride through (LVRT) capability.

Tarafdar et al [85] studied a wind farm modeling and STATCOM used to increase the upper limits of induction generators dynamic stability in various distortion conditions in grid. Also studied the effects of using a local resistance (stabilizer) and STATCOM in keeping and increasing stability of wind farms by MATLAB SIMULNK software. In this issue, FACTS devices usage in distribution voltage level in order to wind farms stability conditions optimization in system different conditions is considered visually. In this paper STATCOM application role in induction generators stability increase to grid is studied.

Mishra et al [86] studied the effect of the damping controller on the DFIG system; 2) to tune damping controller to improve the damping of the oscillatory modes; 3) to study the effect of the damping controller on the variation of the dc voltage across capacitor; and 4) to study the efficacy of the damping controller in improving the fault ride-through capability of the system. Tuning of the damping controller to enhance the damping of the oscillatory modes is presented using bacterial foraging (BF) technique. Among various methods for the optimization, BF is selected because of its better capability of locating optimal solution and
higher convergence speed has been applied for the optimization of the controller for the RSC in time domain. The nonlinear simulation of the DFIG system is observed to validate the efficacy of the damping controller. The optimized controller parameters are used and the system is simulated in MATLAB using ODE15s. The efficacy of the optimization procedure is observed and the fault ride-through capability is also studied. A damping controller using the auxiliary signal of speed deviation is used in the angle control of the RSC controller in the DFIG system. It gives promising results in damping out the low frequency oscillations, and hence, improves the system stability of the grid-connected DFIG system. The coordinated tuning of the damping controller with the other DFIG controllers is also reported in this paper. It is observed that this tuning is helpful in not only improving the damping of the oscillatory modes but also in enhancing the fault ride-through capability of the DFIG system. Hence, tuned damping controller is necessary for enhancing the stability of the DFIG system connected to the grids.

Zengqiang et al [87] studied the use of static synchronous compensator (STATCOM) for wind farms integration composed with DFIGs, and proposes a reactive power cooperative control strategy for the wind farm combined with STATCOM. On PSCAD/EMTDC, a detailed whole dynamic model for VSCF wind power system and STATCOM are established. Then optimization cooperative control strategy of the DFIG is proposed. To control a nonlinear system is to design a linear controller using the linearized model of the nonlinear system dynamics at a desired operating point. Among a variety of linear control techniques, the PI controllers are the most commonly used ones. In this paper, the control method used the PI controller. Finally, simulation studies are carried out to examine the dynamic performance of the PCC with and without STATCOM. the wind farm equipment tendency can be predicted that: as wind farms become larger and further away from the point of connection, reactive power compensation provided by STATCOM might become essential in order to meet Grid Code requirement for the wind farm connection.

Bijaya et al [88] this paper evaluates the use of STATCOM to provide dynamic reactive power compensation for mitigating transient disturbances in DFIG-based wind farm hence enhancing the overall performance of DFIG-based wind farm interconnected to weak distribution grid. The study here in this paper is based on the three phase non-linear dynamic simulation, utilizing the SimPowerSystem block-set in MATLAB/Simulink. The different cases studied on this test system are: (1) 2-cycle, 3-phase, high impedance fault to ground, (2) sudden change in load in the system and (3) voltage swelling and sagging in DFIG wind farm. Hence with the presence of STATCOM in the system, the power factor of the wind farm generated power can be controlled. DFIG-based wind farm connected to weak distribution network requires disturbances mitigating system to enhance the voltage stability of the wind farm. Dynamic reactive power compensation using STATCOM at the point of common coupling (PCC) is a feasible option for minimizing effects of grid-side disturbances on wind farm. Mechanically switchable capacitor bank can also be combined with STATCOM for making compensation system economical. STATCOM also helps wind farm to generate power with controllable power factor as per the demand of the locally connected customer load. Hence STATCOM also improves the performance of overall distribution system.

Olimpo et al [89] DFIG-based wind farm connected to weak distribution network requires disturbances mitigating system to enhance the voltage stability of the wind farm. And the ability to provide Power System Stabiliser (PSS) capabilities that improves overall network damping. A three-generator network model that combines synchronous and wind farm generation has been developed to assess dynamic performance. Simulation results are
presented and discussed that demonstrate the capabilities and contributions of this DFIG controller to network dynamic and transient stability. Dynamic reactive power compensation using STATCOM at the point of common coupling (PCC) is a feasible option for minimizing effects of grid-side disturbances on wind farm. Mechanically switchable capacitor bank can also be combined with STATCOM for making compensation system economical. STATCOM also helps wind farm to generate power with controllable power factor as per the demand of the locally connected customer load. Hence STATCOM also improves the performance of overall distribution system.

Zengqiang et al [90] studied the use of static synchronous compensator (STATCOM) for wind farms integration composed with DFIGs, and proposes a reactive power cooperative control strategy for the wind farm combined with STATCOM. On PSCAD/EMTDC, a detailed whole dynamic model for VSCF wind power system and STATCOM are established. Considering the reality, the target of the control strategy is to maintain the voltage prescribed at the point of common coupling (PCC) and supply the optimization reactive power for the grid. To make the wind farm meet the regulation drawn up by grid and further more realize optimization economic, the reactive power provided by DFIG is hope to remain zero. The reactive power absorbed by wind farm is provided by Dynamic reactive power compensation firstly. The Cooperative control strategy of wind farm is also needed. To control a nonlinear system is to design a linear controller using the linearized model of the nonlinear system dynamics at a desired operating point. Among a variety of linear control techniques, the PI controllers are the most commonly used ones. In this paper, the control method used the PI controller. To analyze the transient performance of wind farm with STATCOM, the three-phase short fault is considered to occur again. From the results we obtained, the wind farm equipment tendency can be predicted that: as wind farms become larger and further away from the point of connection, reactive power compensation provided by STATCOM might become essential in order to meet Grid Code requirement for the wind farm connection.

IV. CONCLUSIONS

In this paper, review on various models of wind energy conversion system, analysis of small signal stability and transient stability and enhancement of stability is given. Various models for wind energy conversion system for stability studies are proposed by various researchers and reported in [4-14]. These models are varied from simple models to reduced order models. Model simplification is important to keep a balance between computation time and result accuracy. In this context, third order, fifth order and sixth order models have been proposed for the study of stability analysis of wind energy conversion systems.

Unlike the synchronous machine whose operating characteristics have been documented and understood for decades, the generation of bulk ac electricity using non-synchronous machine-based generators is a relatively new phenomenon. With increased penetration level of wind power, the influence of wind power on power system stability has drawn great attention to the power system engineers and scientists. One of the most important issues is the impact of wind power penetration on power system small signal stability [5]-[19] of an existing interconnected large-scale power system. Small signal stability is is analysed in [21-31]. Various methods are proposed for analysis of small signal stability and presented. Small signal stability is closely related to the eigenvalues of the system (state) matrix. Several computational techniques for calculating the eigenvalues of realistic power systems have been developed.
The behavior of the DFIG is well known and has been modeled in detail by several authors in order to design the control system. Some works studied the model of the wind turbine with a DFIG for transient stability analysis to demonstrate the capability of the DFIG to maintain system stability for various faults such LG, LLG and symmetrical faults. Dynamic mathematical models of DFIG and its converters are also discussed. Transient stability analysis is done for other than electrical parameters variations like pitch control and wind speed disturbance. In [32-46], various models and methods are proposed for the analysis of transient stability of wind energy conversion systems.

Enhancement of stability or stabilization of wind energy conversion system is important in real time operation. Power system controllers are receiving a wide interest since many technical studies have proven their effects on damping system oscillations and stability enhancement. In order to improve the damping of electromechanical oscillations when necessary, such systems should be designed to allow proper processing of stabilization signals, usually derived from the machine rotor-speed or electrical power.

Voltage or current source inverter based flexible AC transmission systems (FACTS) devices such as static var compensator (SVC), static synchronous compensator (STATCOM), dynamic voltage restorer (DVR), solid state transfer switch (SSTS) and unified power flow controller (UPFC) have been used for flexible power flow control, secure loading and damping of power system oscillation. Various methods have been proposed in [47-74] for enhancement of the stability of wind energy conversion systems. Tuning parameters of some controllers can be optimized using some optimization methods such as genetic algorithms, particle swarm optimization and etc.

Many authors have developed various models in commercial software’s like PSSE, Matlab(Simulink), PSCAD and EMTC. These models can be used for offline studies of wind energy conversion systems.

From the Literature survey, it is observed that for the analysis of transient stability of DFIG Connected to Grid the most suitable order is third order, also it is found that MATLAB software has tools make easier to analyze the transient stability. In Future, authors will be focusing on Transient stability studies using MATLAB. For analyzing the stability studies three phase fault can be considered. And for improving the transient stability STATCOM can be adopted.

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