Power System Stability Model of DFIG Wind Turbine

Amit Kumar, **Arvind Sharma, Ajay Kumar Yadav**

***Abstract*— Theever growing quest in developing green energy worldwide to offset the demand of fast depleting convention energy to checkmate the climate change and to increase the life span of the valuable resources has led to the use of wind energy as a reliable source of energy. This paper gives an overview of study of power system stability model of Doubly Fed Induction Generator(DFIG) .Latest researches and development, which has been published in the imminent journals through rigorous review are overviewed in this paper. Because of the numerous advantages of the DFIG over other generators it is being used for most of the latest wind turbines. This paper summarizes the researches the stability model of DFIG coupled wind energy conversion system.**

***Index Terms*— Doubly Fed Induction Generator (DFIG),wind turbine ,wind energy conversion system, stability model, Fault Ride Through (FRT)**

I. INTRODUCTION

The wind energy conversion system industry is growing like anything owing to its capability of producing ecologically sustainable and economically viable source of energy. The most remarkable recent development is that in an increasing number of markets, wind power is the least cost option when adding new generation capacity the grid, and prices continue to fall. There are now commercial wind power installations in more than 90 countries with total installed capacity of 318 GW at the end of 2013, providing about 3% of global electricity supply last year. Major leading countries in producing wind energy are mainly China, U. S., Germany, Spain and India. The EIA projects that India and China will account for about half of global energy demand growth through 2040, with India's energy demand growing at approximately 2.8% per year.

India's wind energy installations by July 2014 were 21,693 MW out of total renewable capacity of 32,424 MW (excluding large hydro). Wind energy provided almost 67% of the total installed capacity of grid-connected renewable in the country. In 2011 the state run National Institute for Wind Energy reassessed India's wind power potential as 102,778 MW at 80 meters, up from the earlier estimate of approximate 49,130 MW at 50 meters at 2%land availability.[1]

Wind turbines can operate at fixed speed or variable speed. For a fixed speed wind turbine the generator is directly connected to the electrical grid. Whereas, in a variable speed wind turbine the generator is controlled by power electronic equipment. There are several reasons for using variable speed operation of wind turbines; among those are possibilities to reduce stresses for the mechanical structure. Acoustic noise reduction and the possibility to control active and reactive power, Most of the major wind turbine manufactures are developing new larger wind turbines in the 3 to 5 MW range[2]. These large wind turbines are all based on variable speed operation with pitch control using a direct driven synchronous generator (without gearbox) or a doubly fed induction generator (DFIG).Fixed speed induction generators with stall control are regarded as unfeasible for these large wind turbines. Doubly fed induction generators are commonly used by the wind turbine industry for larger wind turbines.

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II. DFIG WIND TURBINE

The major components of a DFIG wind turbine are shown in Fig.1. The stator of the DFIG is connected directly to the network meaning that it operates synchronously at grid frequency. The rotor current is controlled by a power converter to vary the electromagnetic torque and machine excitation. The power converter size is a fraction of the generator rating, normally in the range between 15 to 30 percent. Since the power converter operates in bi-directional power mode, the DFIG can be operated either in sub synchronous or in super synchronous operational modes.

The general control structure of the wind turbine model is shown in Fig. 2. A model of a DFIG wind turbine basically consists of (1) a generator and drive train,(2) a turbine rotor model, (3) a grid side converter and dc-link capacitor, (4) a pitch controller, and (5) a rotor side controller that controls the active and reactive power of the generator.[3]

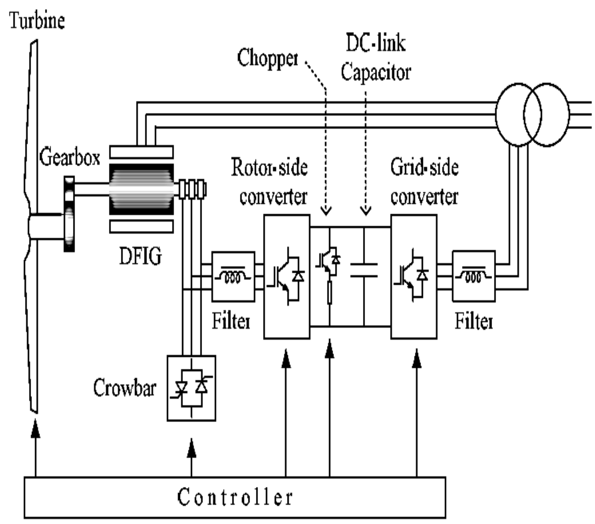


Figure1 Components of DFIG wind turbine.

III. DFIG MODEL

The main construction of a DFIG consists of two essential components, namely the stator winding and the rotor winding equipped with slip rings. The stator is provided with three-phase insulated windings making up a two-pole or four-pole design. This part is connected to the grid through a three-phase transformer. Similar to the stator, the rotor is also constructed of three phase insulated windings. The rotor windings are connected to an external stationary circuit via a set of slip rings and brushes. By means of these components, the controlled rotor current can be either injected to or absorbed from the rotor windings.

The stator and rotor are usually coated in a closed assembly to protect the machine from dust, damp and other unwanted intrusions. In wind turbine applications, this generator is mounted in the nacelle of the wind turbine system. The typical stator voltages for the megawatt class of wind turbines are 690 and 960 V [4].

The stator and rotor voltage equation can be written as

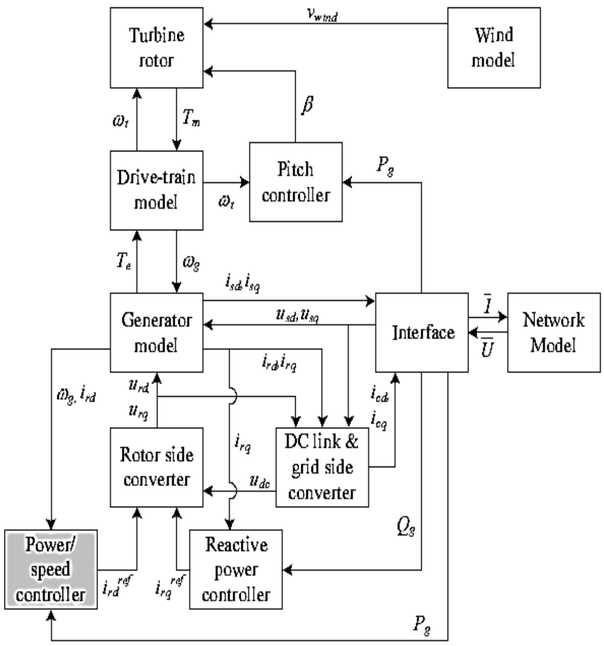
$$\vec{v_s} = \vec{i_s} R_s + j\omega_e \vec{\psi_s} + \frac{d\vec{\psi_s}}{dt}$$

$$\vec{v_r} = \vec{i_r} R_r + j(\omega_e - \omega_r)\vec{\psi_r} + \frac{d\vec{\psi_r}}{dt}$$

The complex power is given as

$$\vec{S} = \vec{v_s}^* \vec{i_s} + \vec{v_r}^* \vec{i_r}$$

Similar to a fixed-speed wind turbine, the generator model of a DFIG wind turbine can be represented in detail using a fifth-order model or represented in a simplified version using a first order model.



IV. POWER SYSTEM STABILITY MODEL OF DFIG WIND TURBINE

In a detailed model of a DFIG wind turbine, the generator is modeled as a fifth order induction generator and the rotor current is regulated using PI controllers. However ,despite its ability to demonstrate wind turbine responses at a high level of precision, the detailed model has practical problems when implemented in large-scale and long-term transient studies.

The first problem appears due to the inclusion of stator transient components, which prevents the model from being implemented in fundamental frequency simulation tools. Another problem is related to the small simulation time step required to run the model .Generally, the detailed model requires a time step size less than 1 ms. This figure is too small in relation to the typical time step for a transient study performed in a standardized simulation tool, such as PSS/E. Depending on the system frequency, the time step for such a simulation tool is normally in the range of 8-10 ms. This clearly makes the detailed model impractical for transient studies.

Models of DFIG wind turbines in fundamental frequency representation have been proposed in several papers and reports such as in [5].

In the DFIG is modeled as a set of algebraic equations. The generator speed is regulated using a PI controller, which provides a rotor current reference value. In this way, the generator loss quantities are preserved in the model. On the other hand, a complex iterative procedure is then necessary to solve a large number of equations involved in the generator and controller models.

Another model is proposed in [6], in which the DFIG is modeled as algebraic equations while the rotor controller is modeled as a combination of algebraic equations and time-lags. In order to avoid non-linearity of the generator model, the electromagnetic torque is assumed to be equal to the stator power, meaning that the generator losses are omitted. The reference value of the turbine output power is obtained directly from the turbine maximum power tracking curve as a function of incoming wind speed.

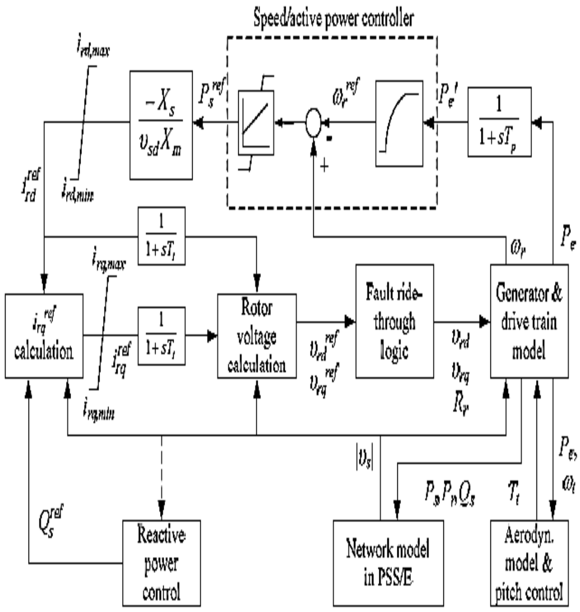


Figure 3 Block diagram of proposed model of DFIG wind turbine

In [7] and later was refined in [8], the DFIG is modeled as an ideal controlled current source driven by active and reactive current commands of the wind turbine system. This model allows the controller to cover a wide range of speed because it is not limited by the nonlinearity of the machine. However, the model is incapable of differentiating stator and rotor quantities.

Rotor current limiters were not involved in the models mentioned earlier. Therefore it is not possible to simulate the effects of current limitations during contingencies, such as during long-term voltage sag. Apart from this, a head to head comparison between a positive sequence phasor model and a detailed model is rarely found in literature.

In response to these problems, a model of a DFIG wind turbine for power system stability analyses is proposed in this paper. In the proposed model, the electrical part of the generator is constructed from a set of algebraic equations, while the controller is modeled as a combination of PI controllers and time lags. Simple expressions are derived to solve the generator equations. Rotor current limiters are involved in the proposed model. Rotor converter disconnection as a part of a fault ride through procedure is included in the proposed model.

The proposed model is implemented in the simulation tool PSS/E with a simulation time step of 10 ms. In order to achieve a high level of confidence, the transient responses of the proposed model are validated against the equivalent detailed model implemented in Matlab /Simulink. The overall structure of the proposed model is depicted in Fig. 3.The detailed explanation of each part of the model is given below.

V. Model Initialization

Various methods of initializing a DFIG model for power system stability studies have been suggested in several papers. In [9], the initialization is performed by assuming a lossless DFIG. Consequently, this assumption may result in less accurate initial values, which are undesired for simulating a large power system where the size of the model is substantial for the system. In [10], the initialization is performed using a steady state representation of a DFIG by employing an iteration procedure. However, the iteration procedure creates a difficulty in the model implementation. In [11], the initialization is carried out using a direct solution method based on torque balance equations. In this way, more accurate initialization results can be obtained without using an iteration procedure. However, this method is only applicable for the type 1speed/active power control where the relation between electrical torque and generator speed is known.

In this dissertation, the method of initialization of a DFIG is performed using a steady state model of a DFIG and a power speed curve. As a result, this method is able to provide accurate results for a DFIG model with the type 2 speed/active power control. Furthermore, the initialization can be done without employing an iteration procedure. In order to realize this method, the steady state model of a DFIG is represented in a *dq* reference frame aligned with stator voltage, i.e $v_{sd} = |\vec{v}_s|$ and $v_{sq} = 0$.

The initial total active power *Pe* and reactive power *Qgen* are given from the load flow. The grid side converter reactive power *Qc* is defined according to the control design, although normally this value is set to zero. The stator reactive power is calculated by *Qs* = *Qgen* -*Qc*. The initial *q*-component of the stator current *isq* can be calculated by (18). By substituting (1)-(8) into (14), *isd* can be calculated using the following quadratic expression

$$0 = a\,i_{sd}^2 + b\,i_{sd} + c$$

$$a = sR_s + \frac{R_r\left(R_s^2+X_s^2\right)}{X_m^2}$$

$$b = v_{sd}\left(1 - s - \frac{2R_rR_s}{X_m^2}\right)$$

$$c = \frac{R_rv_{sd}^2 - P_eX_m^2 + 2i_{sq}R_rv_{sd}X_s + i_{sq}^2\left(sR_sX_m^2 + R_r\left(R_s^2+X_s^2\right)\right)}{X_m^2}$$

Since (21) gives two solutions, the one with the smallest absolute value is chosen .Once *isd* and *isq* are found, the rotor current reference values $\left(i_{rd}^{ref} \text{ and } i_{rq}^{ref}\right)$ can be found using (1),(2),(5) and (6)

$$i_{rd}^{ref} = -\frac{1}{X_m}\left(R_s i_{sq} + X_s i_{sd}\right)$$

(22)

$$i_{rq}^{ref} = \frac{1}{X_m}\left(R_s i_{sd} - X_s i_{sq} - v_{sd}\right)$$

At steady state, the generator and the turbine speed are equal, *ωr*= *ωt*. Correspondingly, the shaft twist angle (Δθ= $_{\theta r-\theta t}$) can be calculated using

$$\Delta\theta = \frac{T_e}{K_s}$$

The corresponding wind speed is calculated by means of (10) by assuming the pitch angle is at its minimum value. Alternatively, if wind speed is known and is above the rated value, then the corresponding pitch angle can be found numerically from the *Cp*(λ,β¸) curve lookup table.

VI. Model Simulations

The proposed wind turbine model was simulated to investigate the responses of the model subjected to various disturbances. The simulations of the proposed model were performed in PSS/E using a standard time step which is 10 ms for a 50 Hz system frequency. A test network as shown in Fig. 5 was used throughout the simulations .Wind turbine parameters are given in Table A.1.The terminal voltage data from the simulations are then used as inputs for the detailed model, which was implemented in Matlab/Simulink. Subsequently, the simulation results of the proposed model are compared with those of the detailed model.

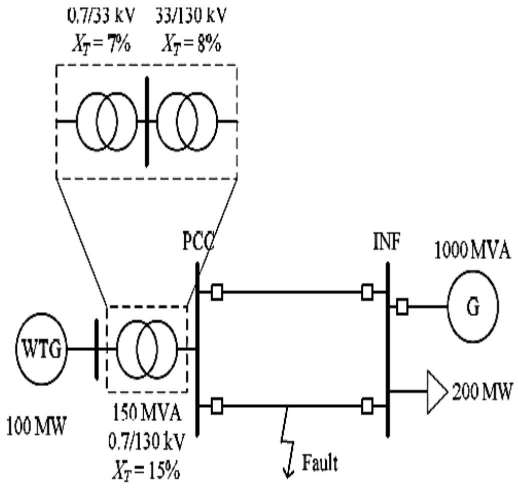


Figure 4. Test grid.

Table A.1: Wind turbine parameters.

Sl no.	Parameter	Value	Units
01	Hub height	30	m
02	Rotor diameter	23.2	m
03	Rotor rated speed	42	r.p.m.
04	Gearbox ratio	23.75	
05	Turbine inertia constant (*Ht*)	2.6	s
06	Generator inertia constant (*Hg*)	0.22	s
07	Stiffnessconstant (*K*)	141.0	p.u.
08	Mutual damping(when applied) (*D*)	3.0	p.u.

Table A.2: Generator parameters.

Sl no.	Parameter	Value	Units
01	Rated power	210	m kVA
02	Rated voltage	415	V
03	Stator resistance (*Rs*)	0.0121	p.u.
04	Stator leakage inductance (*Xs*)	0.0742	p.u.
05	Mutual inductance (*Xm*).	2.7626	p.u
06	Rotor resistance (*Rr*).	0.0080	p.u
07	Rotor leakage inductance (*Xr*)	0.1761	p.u.

Table A.3: Compensating capacitor parameters.

Sl no.	Parameter	Value	Units
01	Grid rated voltage	400	V
02	Capacitor bank susceptance (*B*)	0.11	p.u.

VII. WIND SPEED TRANSIENT

The aim of simulating wind speed transient is to assess the responses of the proposed model when subjected to an extreme increase in wind speed. In the simulation results, responses of the detailed model and the proposed model are compared.

As shown in Fig. 5, the wind speed is initially 7.5 m/s, which gives 0.3 pu of wind turbine power. The generator speed is 0.85 pu (15% slip), meaning that the generator operates at sub synchronous speed. Since wind speed and rotor speed are below the

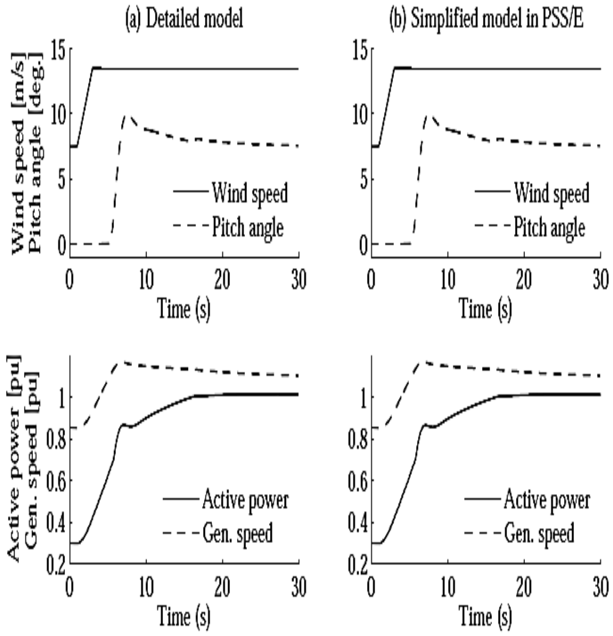


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Figure 5 Comparison between detailed and simplified models of DFIG wind turbine when subjected to wind gust.

rated value, the pitch angle is set at 0°. At this moment, the turbine runs within an optimum speed operating region

At *t*=1 s, the wind speed increases rapidly to 13.5 m/s within 2 seconds. Once the rotor speed exceeds the maximum speed (1.1 pu), the pitch controller reacts by increasing the pitch angle. At this stage, the turbine operation mode switches from the optimum speed operating region to the maximum speed operating region and subsequently to the power limitation operating region. The rapid change in wind speed, however, cannot be compensated by the relatively slow reaction of the pitch controller. As a consequence, there is a small overshoot in aerodynamic power. By letting the rotor speed increase to around the nominal value, part of the mechanical energy is diverted into rotating inertia, which results in a higher rotor rotation speed. This allows a smoother electric power output.[12]

The responses of the wind turbine models when subjected to wind transient are mainly governed by the pitch controller and aerodynamic models, which are identical for both the detailed and the proposed models. Therefore, the responses of these models are unsurprisingly very similar.

VIII. CONCLUSION

In this paper, a model of DFIG for power system stability studies was proposed. In the proposed model, the electrical part of the generator was constructed from a set of algebraic equations, while the controller was modeled as a combination of PI controllers and time lags. Simple expressions were derived to solve the generator equations. Rotor current limiters and rotor converter disconnection as a part of a fault ride through procedure were involved in the proposed model. A model initialization using a direct solution method was introduced in this paper.

The proposed model was implemented in the simulation tool PSS/E using the standard simulation step of 10 ms. In order to achieve a high level of confidence ,the transient responses of the proposed model were validated against the equivalent detailed model implemented in Matlab/Simulink.

The simulation results showed that the responses of the proposed model matched very well with the ones of the detailed model at various operating conditions, including wind speed transients and grid fault with and without rotor converter disconnection .The proposed model involved rotor current limiters, which were proven to be essential in producing accurate responses of a DFIG wind turbine during a transient event. Different active power control schemes can also be implemented in the proposed modelwith only minor modifications.

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