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Small signal stability enhancement of DFIG based wind power system using optimized controllers parameters

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ABSTRACT

This paper presents the state space modelling of doubly fed induction generator (DFIG) for small signal stability assessment. The gains of PI controller in torque and voltage control loop of rotor-side converter (RSC) are optimized by particle swarm optimization (PSO) to improve the dynamic performance of DFIG. These optimized parameters results in improved damping of DFIG and minimizes the oscillations in rotor currents and electromagnetic torque. The nature of modes of oscillations for DFIG integrated to infinite bus are analysed under different operating conditions such as varying wind speed and grid strength. The transient analysis with optimized parameters shows the enhancement in LVRT capability during voltage sag and three phase fault as desired by grid codes.

Introduction

The use of wind power has increased significantly over recent decades and its integration with the power system is now an important topic of study. India ranks fifth amongst the wind energy producing countries of the world after USA, China, Germany and Spain. The installed capacity of wind power in India has reached about 20 GW by 2013. Estimated potential is around 49,130 MW at 50 m above ground level and 102,788 MW at 80 m above ground level [1].

The wind energy conversion system (WECS) could be operationally classified into fixed speed and variable speed wind turbine generating system (WTGS). In the early stage of wind power generations, most wind farms were equipped with fixed speed induction generators (FSIG). The operation of FSIG is fairly simple but it is unable to extract maximum power at varying wind speed as its slip can be varied in a very small range. The development in technology has encouraged to switch from the fixed speed WTGS to variable speed WTGS mainly due to its advantages such as improved efficiency for wider range of wind speeds, independent control of active and reactive power, better fault ride through capability, etc. Currently the most common variable-speed wind turbine configurations are DFIG wind turbine and fully rated converter (FRC) wind turbine based on a synchronous or induction generator. Amongst many variable speed concepts, the DFIG equipped wind turbine is very popular as it has many advantages over others like improved power quality, higher efficiency, the power converter rating can be kept fairly low, approximately 25% of the total machine power, more economical than a series configuration with a fully rated converter, the controllability of reactive power and thus it help DFIG equipped wind turbines play a similar role to that of synchronous generators [2–5].

PI controllers are the most common controllers as they have simple structure. Their performance greatly depends on an optimal tuning of the gains. The tuning of the PI gains is very important task and even more vital to have optimized performance for varying operating conditions. The sound knowledge of the dynamic modelling of DFIG integrated to power system is required to adjust the PI gains in order to have optimized performance of DFIG in normal operating conditions as well as under severe disturbance on the system [6].

One of the major advantages of DFIG is to have decoupled control of active and reactive powers with the use of different control strategies for grid side and rotor side convertors. The decoupled control of DFIG has the following controllers, namely $P_{ref,} V_{sref}, V_{dcref}$, and q_{cref}. These controllers are required to maintain maximum power tracking, stator terminal voltage, dc voltage level, and GSC reactive power level respectively. The coordinated tuning of these controllers may or may not result into optimized performance of DFIG while adopting hit and trail method for tuning of gains [7]. The coordinated tuning of the controllers to improve

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the damping of the electromechanical mode in the DFIG was presented in [8] by replacing the DC link capacitor with battery energy storage (BES) system which eliminated the oscillatory mode corresponding to DC link.

With increasing penetration level of DFIG type wind turbines into the grid, it is very important to investigate the impacts of wind turbine generating units on the power system stability [4,9]. The wind farms are generally located far from demand centres where the network is relatively weak and congested. Therefore, if the integration and penetration of wind energy are not properly assessed for the given network, it is difficult to maintain the reliability and stability [10]. In order to protect the security and operation of the transmission system, it is imperative to investigate the impact of wind at various penetration levels.

A detailed investigation to analyse the small signal behaviour of squirrel cage induction generator (SCIG), DFIG and permanent magnet synchronous generator (PMSG) based wind turbines are carried out in [11] to see how each turbine technology affects the local, inter area, torsional and control modes of the system. The comprehensive studies regarding the modelling of DFIG and to identify their interaction with the power system have been reported in [12]. [13] shows the presence of DFIG can alter the local and inter-area mode shapes and shows the improvement in dynamic behaviour of multi machine power system.

Large voltage dip occurs as a result of a large network disturbance, such as a short circuit, and it may trigger a sequence of other events in the network. Most of the countries have introduced and implemented the gird code regulations to fulfil the fault ride through requirements as the penetration level of wind power generation in the power system has increased drastically. In [14], the importance of the correct design of the control system is discussed where, an adequate adjustment of the PI gains helps to limit the generator currents during a fault. Hence the operations of the crowbar can be avoided and the convertors continuously remain in operation.

PSO is an evolutionary computation technique, motivated by the simulation of social behaviour. In searching the optimal solution of a problem, information of the best position of each individual particle and the best position among the whole swarm are used to direct the searching. Hence, in comparison with GA, PSO is quite immune to local optima and is reasonably efficient in solving problems with complex hyperspace [15].

This paper presents the state space model of DFIG to study its small signal and transient performance. The dynamic performance of DFIG under different wind speeds and system disturbances for strong and weak grid are presented in the paper. Therefore, the objectives of the paper are as follows:

1. To formulate the state space model of DFIG connected to infinite bus for small signal and transient stability assessment.
2. To optimize the controllers gains by PSO for dynamic performance improvement of DFIG.
3. To investigate the impact of optimized controllers' gains on the nature of modes of oscillations with varying wind conditions and with different strength of transmission network.
4. To investigate the fault ride through capability of DFIG with optimized controllers gains under fault and voltage sag conditions.

The paper is organized in six sections. Section 'Mathematical modelling of DFIG' presents the modelling concepts of wind turbine generating system associated with DFIG along with its control strategies. Interfacing of DFIG with infinite bus is discussed in Section 'Interfacing of DFIG with infinite bus'. Section 'Particle swarm optimization' defines the objective function and describes the PSO algorithm for the optimization of the controller gains. Section 'Results and discussions' details the approach to analyse the impact of DFIG on small signal and transient stability along with results and discussions of different scenarios. The conclusion is drawn in Section 'Conclusion'.

Mathematical modelling of DFIG

Fig. 1 shows the schematic of a DFIG connected to an infinite bus through transmission line and transformer. The DFIG is wound rotor induction generator whose stator is directly connected to a power grid. The rotor of DFIG is connected to the power grid through IGBT based controlled back-to-back voltage source converters. The rotor-side converter (RSC) controls the injected rotor voltage that allows the control of the electromagnetic torque, which must follow the reference speed provided by the control system. It can also provide reactive power control and voltage control or power factor control of the machine. This ensures the variable speed operation of DFIG with maximum power point tracking characteristics. The grid side converter (GSC) is connected to the grid through a grid-side filter and is used to control dc-link voltage and reactive power exchange with the grid. Thus GSC represents a shunt power converter. As RSC can provide reactive power control, GSC may offer additional voltage support capabilities in conditions of excessive speed ranges or in transient operations. In this work for the proposed model only the control of RSC is discussed and it was assumed that the dc link voltage between the converters is kept constant by converter. Thus in order to evaluate the performance of the DFIG based scheme proposed to control the RSC, operational aspects concerning to the GSC control will not be depicted in detail because it is not the main objective of this work.

Induction generator model

Assumptions:

The following assumptions are made while modelling the induction generator.

(1) Stator current is negative when flowing toward the machine, i.e. generator convection is used.
(2) Equations are derived in the synchronous reference frame.
(3) q-axis is 90° ahead of the d-axis.

The stator of the induction machine carries three-phase windings. The windings produce a rotating magnetic field which rotates at synchronous speed. The dynamic equations for stator and rotor in d–q reference frame rotating at synchronous speed [3,16,17] are described in (1)–(3).

Stator voltage equations:

$$\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} = R_s \begin{bmatrix} -i_{ds} \\ -i_{qs} \end{bmatrix} + \omega_s \begin{bmatrix} -\varphi_{qs} \\ \varphi_{ds} \end{bmatrix} + \frac{1}{\omega_b}\frac{d}{dt}\begin{bmatrix} \varphi_{ds} \\ \varphi_{qs} \end{bmatrix} \quad (1)$$

Rotor voltage equations:

$$\begin{bmatrix} v_{dr} \\ v_{qr} \end{bmatrix} = R_r \begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} + s\omega_s \begin{bmatrix} -\varphi_{qr} \\ \varphi_{dr} \end{bmatrix} + \frac{1}{\omega_b}\frac{d}{dt}\begin{bmatrix} \varphi_{dr} \\ \varphi_{qr} \end{bmatrix} \quad (2)$$

Flux equations:

$$\begin{aligned} \varphi_{ds} &= -X_{ss} i_{ds} + X_m i_{dr} \\ \varphi_{qs} &= -X_{ss} i_{qs} + X_m i_{qr} \\ \varphi_{dr} &= X_{rr} i_{dr} - X_m i_{ds} \\ \varphi_{qr} &= X_{rr} i_{qr} - X_m i_{qs} \end{aligned} \quad (3)$$

The expression for the stator and rotor currents as the state variables are obtained by substituting the flux Eqs. (3), into the stator and rotor voltage Eqs. (1) and (2), respectively.