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Dynamic state estimation of a doubly fed induction generator based on a comprehensive nonlinear model

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ABSTRACT

One important challenge in controller design for Doubly-Fed Induction Generator (DFIG) or dynamic analysis of networks with DFIGs, is its nonlinearity besides invisibility of some important state variables. In this paper, a state estimation algorithm based on Extended Kalman Filter (EKF) is proposed for grid connected DFIG. A complete 15th order nonlinear model of DFIG equipped with a nonlinear controller is utilized, and all state equations are derived in appropriate form to be used for EKF. The results of the proposed state estimation algorithm can be used for modeling and analysis of any disturbance such as wind speed variations or faults occurrence in the network. To obtain electrical measures required for state estimation, a Phasor Measurement Unit (PMU) is utilized and all measurement and process noise are modeled. Accuracy of the proposed algorithm is evaluated by five different case studies covering the effect of initial guess for state variables, the effect of process and measurement noises, variation in wind speed and occurrence of a solid short circuit close to the DFIG. The simulation results demonstrate robustness and accuracy of the proposed algorithm in estimating dynamic state variables.

1. Introduction

As the portion of renewable energies in energy production is increasing rapidly [1], wind energy is one of the most growing forms of renewable resources utilized for power generation [1].

Among different generators used for wind energy system, Doubly Fed Induction Generator (DFIG) has become very popular around the globe due to its efficiency, investment cost and reliability [2]. Although emerging gearless wind turbines are on the rise, a large number of multi megawatt DFIGs have been installing in the networks. Consequently, study of DFIGs in different aspects is a necessity, and the first step is to develop an appropriate model of the system.

In order to control active and reactive power and to improve transient performance of a grid-connected DFIG, a number of dynamic models and control strategies are presented in literature, while linearized state space equations and linear controllers for DFIGs are very common [3,4]. However, some papers propose nonlinear models and nonlinear controllers to improve system performance [5–8]. One of the main control strategies for grid connected DFIGs, which we have also used in this paper, is field oriented control strategy in both grid and generator sides, while two decoupled controllers are designed

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Nomenclature

v_{ds}, v_{qs}	Stator voltages in dq reference frame (pu);
i_{ds}, i_{qs}	Stator currents in dq reference frame (pu);
v_{dr}, v_{qr}	Rotor voltages in dq reference frame (pu);
i_{dr}, i_{qr}	Rotor currents in dq reference frame (pu);
v_{gdq}	dq components of grid-side filter voltage (pu);
$i_{rdq\text{-}ref}$	dq components of rotor reference current (pu);
i_{gdq}	dq components of grid-side filter current (pu);
$i_{gdq\text{-}ref}$	dq components of grid filter reference current (pu);
Ψ_{ds}, Ψ_{qs}	Stator flux linkages in dq reference frame (pu);
Ψ_{dr}, Ψ_{qr}	Rotor flux linkages in dq reference frame (pu);
L_s, L_r	Stator and rotor self-inductances (pu);
L_m	Mutual inductance (pu);
R_s, R_r	Stator and rotor resistances (pu);
L_g, R_g	Inductance and resistance of the grid-side filter (pu);
ω_s	Synchronous frequency (pu);
ω_b	Base angular frequency (rad/s);
ω, ω_2	Speed of dq reference frame and Rotor slip frequency (pu);
ω_r	Rotor speed which is equal to $\omega - \omega_2$ (pu);
θ_s, θ	Infinite bus voltage and stator flux angle (rad);
γ	Difference between θ_s and θ (rad);
V_∞	Infinite bus voltage (pu);
ω_t, ω_r	Turbine and generator speed (pu);
α, K_s	Shaft twist angle (rad) and shaft stiffness coefficient (pu/elec.rad);
H_t, H_r	Inertia constants of turbine and generator (s);
D	Damping coefficient (pu);
T_e	Generator electrical torque (pu);
P_m, T_m	Turbine mechanical power and torque (pu);
ρ, v_w	Air density (kg/m^3) and wind speed (m/s);
A	Area swept by the rotor blades (m^2);
$C_p(\lambda,\beta)$, λ	Performance coefficient and tip speed ratio (rad);
R, β	Radius of the rotor (m) and blade pitch angle (deg);
x_i, $\hat{x}_i$	Real and estimated values of *i*th state variable;
T	Sampling time (s).

for active and reactive power control. Reference [5] shows that linear model and controllers for DFIGs may face some troubles in some cases, especially in the case of large voltage dips, and then develops a full nonlinear two-mass model for the DFIG with fifteen state variables. Finally, a stator flux orientation Lyapunov-based nonlinear controller is proposed, and the benefits are presented [5]. In most nonlinear controllers, some state variables are used as the input signals of the controller and should be measured or estimated by a robust and precise technique [9]. Therefore, state estimation is necessary in such systems. Another application of estimation is parameters estimation. This method is used to estimate the model, parameters or controller coefficients [10,11].

State estimation algorithms use state space equation and some measured values to estimate some or all other state variables [12]. State estimation has been used in power system for decades, however, most of the studies have focused on static state estimation of power system electrical quantities rather than dynamic state variables [13–15]. Lately, due to advances in monitoring technique and installing Phasor Measurement Unit (PMU) in power system, estimating dynamic state variables has been more possible, and has attracted more consideration [16–22]. Dynamic state estimation of synchronous machine and induction motor are presented in [19–22] and [23–26] respectively. In [27] a dynamic state estimation of a permanent magnet synchronous generator based wind turbine is proposed. So, the dynamic state estimation is an important subject in controlling and monitoring of the power system and it is necessary to implement it on the DFIG.

DFIG has its own complex nonlinear model and its accurate modeling improves the analysis and control of the networks. However, dynamic state estimation of DFIGs has not been studied vastly in literature. References [28–30] are some of the very rare works on this issue. The model presented in [28] is mainly based on the model reference adaptive systems and its performance is highly sensitive to the inductance parameter [31]. In [28], the eighth order model is considered and the stator dynamics is neglected. The DFIG's model presented in [29] and [30] are also so simple. References [29,30] use the 6th order model of DFIG ignoring turbine dynamics and controllers. Consequently, these references do not consider the difference between speed of stator flux and synchronous frequency, which is the subject of all angular stability studies [2].