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Original Research Article

Coordinated controller design of grid connected DFIG based wind turbine using response surface methodology and NSGA II

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ABSTRACT

This paper presents a novel design procedure for the coordinated tuning of rotor side converter (RSC) and grid side converter (GSC) controllers of doubly fed induction generator (DFIG) wind turbine system. The RSC and GSC controller parameters are determined by simultaneously optimizing the controller performance indices. The performance indices considered are maximum peak overshoot (MPOS_{ω}), settling time (Tss_{ω}) of the generator speed and the maximum peak overshoot ($\mathrm{MPOS}_{\mathrm{Vdc}}$), maximum peak undershoot ($\mathrm{MPUS}_{\mathrm{Vdc}}$) and settling time ($\mathrm{Tss}_{\mathrm{Vdc}}$) of DC link voltage. The coordinated controller design is carried out in two steps. First step is to arrive at the analytical expression that relates the performance indices and the controller parameters. This is achieved using response surface methodology (RSM) thereby saving significant computational time. In the second step the determination of controller parameters is posed as a constrained multiobjective optimization problem. The constrained multiobjective optimization problem is solved using NSGAII (nondominated sorting genetic algorithm II). The proposed methodology is tested on a sample system with DFIG based WECS. Simulation results demonstrate the effectiveness of the proposed methodology.

1. Introduction

The rapid depletion of fossil fuels compounded by their detrimental environmental effects has accelerated the growth of wind energy. Currently, wind energy is one of the key players in the electric power sector [1]. The advent of variable speed WECS enabled overcoming one of the major impediments to the expansion of wind, its lack of controllability and flexibility. Variable speed WECS with their better energy capture, smoother operation, lower flicker and superior controllability [2–5] have superseded the fixed speed WECS and play a major role in expediting the growth of wind energy. The most commonly installed variable speed WECS is based on DFIG and it constitutes around 55% of the total market share.

Wind speed is variable in nature. Therefore, in order to maximize the power extracted from wind (speeds between the cut in and cut off speed) WTs operate continuously at the optimum tip speed ratio by changing the generator speed in proportion to the wind speed.This is achieved by RSC. GSC controls the power flow between the DC-link and the grid to maintain the DC-link capacitor voltage at a constant value. Hence performance of a DFIG is largely dependent on its converter and associated controls. The most popular and practical control scheme of DFIG is vector-oriented control based on proportional-integral (PI) controller [6–11].

Due to the stochastic nature of wind, generator speed varies continuously to track the maximum power point. These speed variations are translated into generator output power variations and in turn into DC link voltage fluctuations. Hence there arises a need for coordinated tuning of RSC and GSC controllers. Therefore optimization techniques are being utilized for the coordinated tuning of controllers. However, coordinated tuning of controllers using optimization techniques becomes cumbersome, challenging and computationally inefficient with increase in the number of the controller parameters [11–13].

This paper proposes a simplistic and computationally efficient design procedure for coordinated tuning of RSC and GSC controllers of DFIG based wind turbine system. In this paper Response surface methodology (RSM) is used to formulate the analytical expression that relates the responses and controller parameters thereby saving significant computational time. RSM is a collection of mathematical and statistical techniques that are useful for modeling and analysis of a system whose response is influenced by several variables and the objective is to optimize the response [14–18]. This paper applies RSM for the coordinated tuning of

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Nomenclature

WECS	wind energy conversion systems
WT	wind turbine
R–K	Runge–Kutta
t	time (s)
V_w	wind speed (m/s)
V_{wa}	average wind speed (m/s)
$V_{wr}(t)$	ramp component of wind speed (m/s)
$V_{wg}(t)$	gust component of wind speed (m/s)
$V_{wn}(t)$	noise component of wind speed (m/s)
$\hat{A}_r, \hat{A}_g$	amplitude of ramp and gust components respectively (m/s)
T_{sr}, T_{er}	start time and end time of the ramp component respectively (s)
T_{sg}, T_{eg}	start time and end time of the gust component respectively (s)
F	turbulence scale (m)
μ	mean speed of wind at reference height (m/s)
n_p	number of pole pairs
ω_s	synchronous speed = 1 p.u
ω_b	electrical base speed = $2\pi 50$ (rad/s)
ω_{wb}	mechanical base speed = $\frac{\omega_b}{n_p}$ (mechanical rad/s)
ρ	air density (kg/m^3)
A	area covered by the rotor (m^2)
R	turbine radius (m)
ω_r	generator speed (p.u)
P_b	base MVA
ω_t	wind turbine speed (mechanical rad/s)
α	pitch angle (degrees)
H_g	generator inertia (s)
$I_s = I_{ds} + jI_{qs}$	stator direct and quadrature current (p.u)
$V_s = V_{ds} + jV_{qs}$	stator direct and quadrature voltage (p.u)
$I_g = I_{dg} + jI_{qg}$	GSC direct and quadrature current (p.u)
$V_a = V_{da} + jV_{qa}$	GSC direct and quadrature voltage (p.u)
$V_g = V_{dg} + jV_{qg}$	grid direct and quadrature voltage (p.u)
$I_r = I_{dr} + jI_{qr}$	rotor direct and quadrature current respectively (p.u)
$V_r = V_{dr} + jV_{qr}$	rotor direct and quadrature voltage respectively (p.u)
ψ_{qr}, ψ_{dr}	rotor direct and quadrature flux linkage respectively (p.u)
V_{dc}, C	DC link voltage and DC link capacitance respectively (p.u)
R_s, R_r	stator, rotor resistance respectively (p.u)
L_s, L_r	stator, rotor inductance respectively (p.u)
L_m	mutual inductance (p.u)
σ	$= \frac{L_m^2}{L_s} - L_r$
L,R	grid side inductance and resistance respectively (p.u)
K_{pw}, T_w	proportional gain and time constant of RSC controller respectively
K_{pv}, T_v	proportional gain and time constant of GSC controller respectively
Gen	generation
Maxgen	maximum generation

RSC and GSC controllers of a DFIG based wind turbine. The RSC and GSC controller parameters are determined by simultaneously optimizing the performance indices. The performance indices considered are MPOS_{ω}, Tss_{ω}, $\mathrm{MPOS}_{\mathrm{Vdc}}$, $\mathrm{MPUS}_{\mathrm{Vdc}}$ and $\mathrm{Tss}_{\mathrm{Vdc}}$. The objectives are formulated using RSM. NSGAII is used to solve the constrained multiobjective optimization problem. It is a popular nondomination based genetic algorithm for multiobjective optimization. The salient features of this algorithm are (a) reduced complexity, (b) incorporation of elitism, and (c) parameterless diversity preservation mechanism [19–22]. Simulations are performed on a radial nine bus system with DFIG based WECS [23] to demonstrate the effectiveness of the proposed methodology.

The paper is organised as follows: Section 2 introduces the DFIG drive train model and associated controllers. Section 3 presents the design procedure for coordinated tuning of RSC and GSC controllers. The simulation results are presented in Section 4. A conclusion is given in Section 5.

2. Modelling of wind turbine with DFIG

The schematic diagram of a grid-connected DFIG based WECS is shown in Fig. 1. It consists of a wind turbine rotor coupled to DFIG through a gearbox. The rotor winding of the DFIG is connected to back-to-back voltage source converters (VSC) namely, rotor side converter (RSC) and grid side converter (GSC). The voltage source converter decouples the electrical grid frequency and the mechanical rotor frequency, thus enabling variable speed operation. The control system consists of pitch angle controller and the converter controller. The power flow to the grid is controlled by the converter controller according to the optimal power characteristic. The pitch controller is only used at high wind speeds to control the generator speed. As this paper concentrates on partial load operation (cut in speed to rated speed) of WTs the pitch controller is considered inactive and its design details are not presented.

2.1. Wind speed model

Wind speed usually varies from one location to another over time in a stochastic manner. As it maintains a direct relation to the mechanical torque its evolution must be taken into account to simulate WECS dynamics. The wind model chosen in this paper is a four-component model adopted from [24], and defined as

$$V_w(t) = V_{wa} + V_{wr}(t) + V_{wg}(t) + V_{wn}(t) \tag{1}$$

The ramp component representing a steady increase in wind speed is given as

$$V_{wr}(t) = \begin{cases} 0 & \text{for } t < T_{sr}, \\ \hat{A}_r \frac{(t-T_{sr})}{(T_{er}-T_{sr})} & \text{for } T_{sr} \leqslant t \leqslant T_{er}, \\ \hat{A}_r & \text{for } t > T_{er} \end{cases} \tag{2}$$

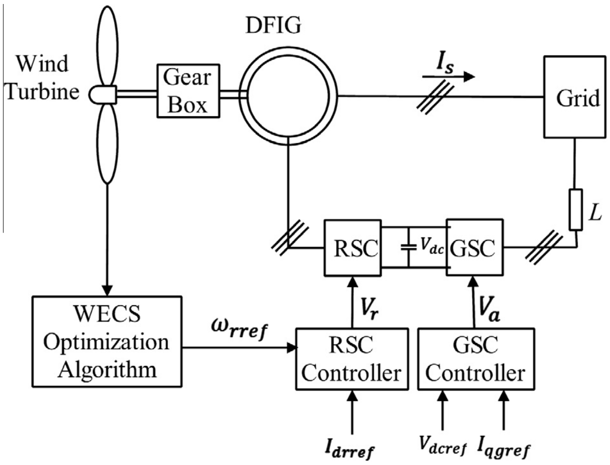

Fig. 1. DFIG based WECS and its control system.