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Coordinated voltage control of wind-penetrated power systems via state feedback control

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This paper presents an optimal coordinated voltage control scheme for preserving long-term voltage stability of power systems. Linear quadratic integral (LQI) controller is employed to construct this scheme. Also, this paper considers the detailed dynamic model of doubly-fed induction generator (DFIG) wind turbine, synchronous generators, over excitation limiter (OEL) and under-load tap changer (ULTC) system, which are important elements influencing voltage stability of power systems. The proposed approach at each time instance involves following two major steps: First, the power system nonlinear equations are linearized and optimal controllers are obtained by LQI technique. Then, in the second step the system dynamic behavior is investigated via time-domain simulations by applying the attained optimal control signals at the first step. The impact of the proposed coordinated voltage control scheme is evaluated by time domain simulations on a well-known test system, under variable wind speed and fault conditions.

1. Introduction

The rapidly increasing share of the wind power in the existing power systems, poses new challenges for the system operation. Some of these challenges are: the system reliability, stability, security and power quality [1]. Voltage stability has been recently at the central point of attention due to various reasons such as growth of electrical energy demand, economic and environmental constraints in expanding the system, and market pressure to reduce the operation costs. Voltage stability is the ability of a power system to keep steady acceptable voltages at all buses under normal operating conditions and after being subjected to a disturbance. Voltage stability is classified into four categories: large-disturbance, small-disturbance, short-term and long-term voltage stability [2]. Several studies have been carried out on voltage instability detection and prevention methods [3–5]. The authors in [3] suggested a method based on trajectory sensitivities for emergency voltage control. In [4] a stabilizing scheme was proposed that brings the non-equilibrium post-contingency operating point back inside a stable region. Also, in [5] bifurcation theory has been used to predict how the system becomes unstable. Many researchers in the past have investigated the impact of wind turbines on transient voltage stability [2,6–10]. Also, Refs. [11–13] investigate the impact of the variable speed wind turbines on long-term voltage stability. Ref. [14,15] analyze the impact of wind turbines capability curves and its variable limits on the long-term voltage stability. The amount of reactive power reserve at generating units has a significant effect on power system voltage stability. It means, injecting reactive power to improve power system operation, reduces line currents and hence network losses, and contributes to stability enhancement [16]. Ref. [17] proposes a PI based approach to manage reactive power flow between a wind farm and grid. Paper [18] utilizes a PSO based scheme for reactive power management in reconstructed systems.

Secondary voltage control (SVC) has been developed and implemented in some power systems in order to improve system voltage stability [19,20]. It has been shown that SVC increases voltage stability via enhancing maximum deliverable power [16]. The aims of SVC are: (i) to keep the pilot bus voltage at a specified set point value, and (ii) to make the reactive power production of each generator proportional to its reactive power capability [16]. Lots of researches carried out on SVC strategies [19–24].

Ref. [24] introduces the Optimal Tracking Secondary Voltage Control (OTSVC) scheme for DFIG-based Wind Park. This controller aim is voltage regulation and optimal reactive power compensation. This paper compares the OTSVC with secondary voltage control, primary voltage control and optimal power flow analysis. However, this paper doesn't consider Under-Load Tap Changer (ULTC) transformers, Induction Machine (IM) and Over-Excitation Limiter (OEL) of synchronous generators that influence long-term

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Nomenclature

The bar in the notation indicates per unit (pu) quantities.

ω_b, ω_s, ω_m	basic, synchronous and rotor angular speed
$\bar{L}_s$, $\bar{L}_r$	stator and rotor leakage inductance
$\bar{L}_m$	magnetic inductance
$\bar{L}_{rr}$, $\bar{L}_{ss}$	STator and rotor inductance
$\bar{T}_0$	transient open-circuit time constant
$\bar{R}_r$, $\bar{R}_s$	rotor and stator resistance
$\bar{X}'$, $\bar{X}$	transient and open circuit reactance
$\bar{E}'$, $\bar{e}$	voltage behind transient reactance of the DFIG and synchronous generator
θ_s	angular position of the stator flux
$\bar{T}_{sp}$	reference torque
$\bar{P}_e$, $\bar{Q}_e$	active and reactive power generated by DFIG
$\bar{i}_r$, $\bar{i}_s$	rotor and stator currents
ϕ_s, ϕ_r	rotor and stator current angles
$\bar{v}_s$, $\bar{v}_r$	rotor and stator voltages
φ_s, φ_r	rotor and stator voltage angles
s	rotor slip
H	inertia
k_{is}, k_{ps}, k_{vc}, k_{iv}, k_{pv}	DFIG controller constants
$\bar{v}_{sref}$	stator voltage reference
R, I	real and image axes components
d, q	direct and quadrature axes components
$\bar{I}_{fd}$	synchronous generator field current
I_{fdmax1}, I_{fdmax2}	over excitation limiter constants
I_{LIM}	over excitation limiter output signal
$V_{oxl}\Psi$	stator flux

voltage stability. Also, wind speed regime, and wind turbine dynamic modeling are not addressed.

The aim of this paper is to keep power system voltage magnitudes within the desirable limits. Linear Quadratic with Integrator (LQI) controller for optimal tracking of the reference is proposed. The control law is derived by optimization of an objective function that considers the control input and state variables. Power systems dynamic models consist of differential and algebraic nonlinear equations [25]. However, the design of a LQI controller requires the representation of the system in state space. So Jacobian linearization of the system is done and the state space matrices of the linearized system were found in the equilibrium point at steady state.

A comprehensive time domain simulation is done to illustrate the proposed controller impact on long-term voltage stability. Also, this paper investigates the influence of DFIG on voltage stability of the system. The complete DFIG model and its control variable are considered. In addition, dynamics aspects of the generator OEL and ULTC transformers and dynamic load are properly considered. The simulations were conducted using the PST software [26] in MATLAB environment.

The paper is organized as follows: Section 2 describes the dynamic models of DFIG, OEL and ULTC. Section 3 introduces LQI controller, briefly. In Section 4, the proposed coordinated voltage control algorithm is explained. Simulation results are addressed and analyzed in Section 5 Finally, Section 6 concludes the paper.

2. Modeling

2.1. DFIG modeling

A typical block diagram of the DFIG wind turbine-generator is shown in [1]. The rotor winding is fed through a variable frequency AC/AC power converter that enables the wind turbine-generator to operate in the variable speed condition [27].

The set of differential–algebraic equations (DAEs) of the generator are obtained by assuming that the dynamics related to the stator are much faster than those of the rotor, mechanical motion and controllers [28]. Therefore, the DFIG model is simplified by neglecting the variations of these terms. This is a rational assumption as shown in [2]. The following equations describe the rotor circuit dynamics [27]:

$$\frac{d}{dt}\bar{E}'_d = -\frac{\omega_b}{\bar{T}_0}\left[\bar{E}'_d - (\bar{X}-\bar{X}')\bar{i}_{qs}\right] + s\omega_s\bar{E}'_q - \omega_s\frac{\bar{L}_m}{\bar{L}_{rr}}\bar{v}_{qr} \tag{1}$$

$$\frac{d}{dt}\bar{E}'_q = -\frac{\omega_b}{\bar{T}_0}\left[\bar{E}'_q + (\bar{X}-\bar{X}')\bar{i}_{ds}\right] - s\omega_s\bar{E}'_d + \omega_s\frac{\bar{L}_m}{\bar{L}_{rr}}\bar{v}_{dr} \tag{2}$$

where

$$\bar{X}' = \bar{\omega}_s\left[\bar{L}_{ss} - \frac{\bar{L}_m^2}{\bar{L}_{rr}}\right] \tag{3}$$

$$\bar{T}_0 = \frac{\bar{L}_{rr}}{\bar{R}_r} = \frac{\bar{L}_r + \bar{L}_m}{\bar{R}_r} \tag{4}$$

$$\bar{X} = \bar{\omega}_s(\bar{L}_{ss}) = \bar{\omega}_s(\bar{L}_s + \bar{L}_m) \tag{5}$$

2.1.1. Maximum power point tracking

Various control schemes have been proposed to implement the maximum power point tracking (MPPT) algorithm [29]. A method described in [30] is employed in this paper.

Fig. 1 depicts block-diagram of the employed MPPT. This model is a simplified version of the method presented in [25]. The wind turbine block input is wind speed. The wind turbine block, shown in this figure, uses (6) to calculate the mechanical torque, $\bar{T}_m$. This torque interacts with the electrical torque of the generator to set the rotor speed. The electrical torque, $\bar{T}_e$, as shown in Fig. 1, is achieved using MPPT curve. Using Fig. 2, the rotor motion equation is expressed as follows.

$$\frac{ds}{dt} = \frac{1}{2H}(\bar{T}_m - \bar{T}_e) \tag{6}$$

2.1.2. DFIG control

The PVdq control scheme is used for electrical control of the DFIG. In this method, the rotor current is divided into two components (i.e. d and q components): the q-axis component regulates the torque, while the d-axis component regulates the power factor or terminal voltage [29,31].

A block diagram of the torque control scheme is shown in Fig. 2. Given the wind speed, rotor speed and reference torque is provided by the MPPT curve that itself generates a reference value for the q-axis rotor current, $\bar{i}_{qref}$. The resulting error passes through a PI controller to construct rotor voltage, $\bar{v}_{qr}$. Also, a compensation term is added to minimize cross-coupling between speed and voltage control loops [27].

The aim of voltage controller block is to control terminal voltage or power factor of the DFIG. Both rotor side and grid side converters