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Optimal tracking secondary voltage control for the DFIG wind turbines and compensator devices

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ABSTRACT

The optimal tracking secondary voltage control (OTSVC) is a new developed voltage control scheme for wind park based Doubly Fed Induction Generator (DFIG). The proposed controller is developed to achieve efficient voltage regulation and provided optimal reactive power compensation to the interconnected power system. The performance of the controller for enhancing the network voltage profile is compared with secondary voltage control, primary voltage control and optimal voltage profile obtained from the optimal power flow analysis. Furthermore, the OTSVC is employed for controlling wind park based DFIG and other sources of reactive power such as static var compensator (*svc*). The dynamic performance of the controller for multiple sources of reactive power is tested for steady state operation and in response of system contingencies with considering the impact of communication time delays. Simulation results are presented and the capability of the controller in providing the desired reactive power compensation and voltage support for the power system are verified.

1. Introduction

HE concern about employing secondary voltage control is taken by researchers around the world to achieve better voltage regulation in power systems. The power system voltage control has a hierarchy structure with three levels: primary, secondary, and tertiary voltage control [1]. The secondary voltage control plays a vital role in preventing voltage deterioration and securing an optimal use of existing power resources [2–6]. The first type of secondary voltage control (SVC) was presented by EDF in 1980s [7]. The EFD's SVC technique relies on the decomposition of a large system into regions and an online decentralized closed loop controllers for regulating only a few load voltages in each region, referred to as the "pilot" voltages. For instant, in the French system a full automation of the system wide voltage regulation is achieved by employing such an intuitive reduced information structure at the regional level (the pilot busses) and regional controllers called secondary voltage control which control the pilot voltage by adjusting the terminal voltages of the regional generators. In this case the responsibility for coordinated voltage regulation of the entire France network is shared among regional closed loop controller and the operators at the national center [8]. Recently, the faster and the more efficient is the coordinated secondary voltage control (CSVC) which is used in France and expected to take over from existing SVC system in nearest future [4]. The use of the CSVC is still limited due to high precision of voltage characteristics of the loads, network data and high reliability of remote data acquisition and communication links which must be warranted for determining a target state. The interest of the secondary voltage control increased and is expected to play a vital role in providing a voltage support to the area of transmission network in an effective and coordinating manner during the normal operation and in emergencies [9–12]. Many papers have been published on secondary voltage control strategies. There are different techniques for implementing SVC; these techniques can be summarized as:

1. Multi agent system (MAS) is applied to SVC.
2. Fuzzy logic control is proposed in the design of SVC.
3. Model predictive control for SVC.

These techniques are well investigated and their control strategies are deeply described [13–16]. However, the previous techniques in designing and implementing secondary voltage control did not consider the impact of the communication time delays. Therefore, it is important to judge the actual performance of SVC under steady state and transient operation with the advance of communication links. The large penetration of wind energy and the capability of controlling the voltage and reactive power drive

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to use secondary voltage control for wind parks as a new approach for wind energy system.

This paper addresses a novel control scheme for wind energy system with employing DFIG-based wind turbine. The design and implementation of optimal tracking secondary voltage control (OTSVC) for DFIG-WT in a proposed power system is investigated with considering the impact of communication time delays, short circuit ratios for steady state and transient operation. In addition, the superior performance of the OTSVC for enhancing the network voltage profile is compared with other control schemes such as SVC, PVC and is validated with the optimal voltage profile that is obtained from the optimal power flow analysis. Furthermore, the use of the OTSVC for controlling multiple sources of reactive power compensation such as wind park based DFIG and static var compensator (*svc*) is presented.

2. DFIG wind park

The DFIG wind turbine comprises a back-to-back voltage source converter controlled by two separate control algorithms for rotor- and grid-side converters [15–22]. Both converters are modelled as ideal voltage sources and the *dc* link voltage dynamics are considered using the real power component of the grid- and rotor-side currents. The rotor-side converter is adjusted to control stator reactive current and generator electromagnetic torque, which is used to set the speed of the generator for maximum power point tracking (MPPT). The grid-side converter is interfaced with the *dc* link and is used to transmit the rotor power, additionally, it is used to exchange reactive power with the grid.

2.1. Rotor-side converter control

The rotor-side converter control consists of two outer control loops, which are the secondary voltage control loop (detailed in the Section 3, which sets I_{dr_ref}, and the active power control loop, which sets I_{qr_ref}, Fig. 1). The latter loop controls the electromagnetic torque in order to regulate the speed of the machine. The expression for T_e in terms of the *dq* variables expressed on the stator flux linkages $\bar{\psi}_S$ reference frame is:

$$T_e = -\frac{L_m}{L_{SS}}\psi_{sd}^{\theta_r} I_{qr}^{\theta_r} \tag{1}$$

The electromagnetic torque is proportional to $I_{qr}^{\theta_r}$, and this provides the basis for control of T_e and ultimately P_m. The rotor speed reference from the MPPT look-up table is used to determine the reference power for the power control loop. The electrical output power is added to the total power losses and is compared with the reference power obtained from power–speed characteristics curve, and a proportional and integral (PI) controller is used in order to minimize the power error to zero. The output of the regulator is the reference quadrature rotor current I_{qr_ref}, which is fed to the inner current control loop. The magnitude of the reference rotor current $I_{r\_ref} = \sqrt{I_{dr\_ref}^2 + I_{qr\_ref}^2}$, is limited to its current rating. This is done by limiting the magnitude of the reactive current to its maximum current ($I_{\max}$), which is dynamically adjusted to give priority to the real current control loop.[3]

2.2. Grid-side converter control

The grid-side converter controls the real power transfer between the grid and the *dc* bus capacitor to regulate the capacitor *dc* voltage. Furthermore, the grid converter can be used to absorb or generate the reactive power based on system conditions. This controller consists of two outer loops, which are responsible for controlling both active and reactive power, and inner current control loops which is analogous to the rotor-side converter (Fig. 2).

The first loop controls the reactive power provided by converter (whose details are again treated in the next section). In *dq* components, with a reference frame such that the direct axis coincides with v_s, the state-space representation of the converter currents is given by:

$$\frac{d}{dt}\begin{bmatrix} I_{dgc}^{\theta} \\ I_{qgc}^{\theta} \end{bmatrix} = \begin{bmatrix} 0 & \omega_s \\ \omega_s & 0 \end{bmatrix}\begin{bmatrix} I_{dgc}^{\theta} \\ I_{qgc}^{\theta} \end{bmatrix} + \frac{\omega_s}{X_a}\begin{bmatrix} v_{dgc\_ref} - v_{sd\_ref} \\ v_{qgc\_ref} \end{bmatrix} \tag{2}$$

where X_a is the leakage reactance of the coupling transformer and ω_s is the fundamental frequency. In this scheme, the reactive power is proportional to the *q* component of the converter current.

3. System voltage control

Here the system voltage control strategy is presented using a wind park consisting of 6 × 1.5 MW DFIG wind turbines (Fig. 3). Each of the WTGs is connected to the medium voltage network by 0.575 kV/25 transformer and then connected to the 120 kV network at bus B_{120} through a 10 MVA, 25 kV/120 kV step-up transformer. The control consists of a local wind park control, which communicates with the transmission system operator using a communication link, which are the supervisory control signals are exchanged. The OTSVC is used to determine the voltage set point for both rotor- and grid-side converter control loops.

Different voltage control strategies are presented in this section and applied to a wind park consisting of 6 × 1.5 MW DFIG wind turbines (Fig. 3). Two main approaches to voltage control are presented: primary and secondary voltage control. We describe one possible secondary voltage control and then extend the approach to a generalized voltage control that we referred to as optimal tracking secondary voltage control (OTSVC). Inherent in secondary voltage control is the need for a communication link; the delays associated with this wide-area measurement system are discussed and approaches to their modelling are presented.

This section presents three different controllers that are alternatively applied to the system described in Fig. 3 under the same circumstances. Therefore, the rotor- and grid-side converters are controlled in all cases with alternatively employing primary voltage control (PVC), secondary voltage control (SVC) based line drop compensation and optimal tracking secondary voltage control (OTSVC) to obtain the performance and the comparison among these controllers.

The justification of the controller's performances is based on the criteria of the comparison to the optimal voltage profile that is obtained from the OPF solution with considering the same objective functions of the voltage operating limits and the constraints limits for the active and reactive powers generation. The optimal voltage profile acts as benchmark of the superior performance of the controller. Therefore, all developed controllers in this paper are tested under the same circumstances with considering the voltage violation condition of 10%. The performance of each of the controllers is compared with the optimal voltage profile under steady state for different transmission system loadings.

3.1. Primary voltage control

Primary voltage control is the basic approach to voltage regulation of the high voltage bus to which the wind farm is

[3] The limit of the real component of the rotor current is set to 1 pu, which gives: $I_{\max,d}(t) = \sqrt{I_{r,rated}^2 - I_{qr}^2(t)}$.