Electrical Power and Energy Systems 104 (2019) 827–839

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Impact of high-depth penetration of wind power on low-frequency oscillatory modes of interconnected power systems

Ahmed M. Khalil*, Reza Iravani

Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON M5S 3G4, Canada

A R T I C L E I N F O

Keywords:
Wind Power Plants (WPPs)
Type-3 WPPs
Type-4 WPPs
Small-signal dynamics
Inter-area oscillations
Enhanced generic models

A B S T R A C T

This paper investigates impact of high-depth penetration of wind power, i.e., up to 30%, on low-frequency (0–2 Hz) oscillatory modes of interconnected power systems. The wind power is integrated as large Wind Power Plants (WPPs) based on Type-3 and Type-4 wind units represented by enhanced generic nonlinear and linearized models. The studies are based on eigen analysis of the 16-machine/68-bus NPCC equivalent system with multiple WPPs added to it. The case studies consider different ratios of Type-3/Type-4 WPPs to investigate impact of interaction between WPPs adopting different technologies on power system low-frequency dynamics. The studies reveal that WPPs can (i) noticeably impact the damping ratios of existing inter-area oscillatory modes at low-depth penetrations more than at high-depth ones, (ii) introduce new low-frequency oscillatory modes and (iii) cause instability by interacting with existing controllers in the system.

1. Introduction

Technical and economical feasibility of large-scale wind power generation, based on Wind Power Plant (WPP) structures, has made wind power an integral part of the electric power generation portfolio [1]. The high-depth of penetration of wind power is substantially changing the operating characteristics of interconnected power systems [2–4]. This necessitates systematic quantification of the impact of WPPs on the control/operation/protection of the grid as the penetration depth of wind power and number of WPPs increase. Low-frequency oscillations are one of the main concerns for power system operators as they can affect the overall system integrity [5]. Thus, it is required to have sufficient damping for such oscillatory modes under all operating conditions to avoid sustained oscillations following major events, e.g., faults [6]. This paper investigates impact of WPPs on low-frequency oscillatory modes (up to 2 Hz), i.e., inter-area modes and local modes, of large power systems under high-depth of penetration of wind power.

Several studies in the technical literature have investigated the impacts of wind power on low-frequency oscillations [7,8]. Most of these studies report both beneficial and adverse impacts of WPPs on low-frequency dynamics [4,9–27] which shows the inconsistency of, and in several cases the contradiction between, these studies. Several studies, [4,9–14], report that (i) high-depth of penetration of wind power decreases the system damping and (ii) low penetration levels of wind power may result in system instability. Thus, different control techniques are being proposed to enhance the system stability, e.g. Wide-Area Control based on Energy functions [15], optimized controller parameters [12], and H-infinity control [16]. However, other group of studies, [17–20], indicates that high penetration level of Type-3 WPPs increases damping ratios of low-frequency oscillatory modes and enhances the overall system stability. Another set of studies [21–27] reports that wind power impact depends on fault location, WPP locations, and the operating conditions of the system. For example [26] indicates that Type-3 WPP can exhibit both stabilizing and destabilizing impact on power system small-signal dynamics. Therefore, no clear line can be drawn about the impacts of wind power on low-frequency oscillations of interconnected power systems. These inconsistent conclusions are due to the conditions/limitations of the study cases, i.e.,

(i) decreasing the capacity or eliminating the conventional power plants from the power system as wind power is integrated in the system [4,17,19,21,22],
(ii) neglecting the impact of load increase at high-depth of penetration of wind power [14],
(iii) arbitrary choice of WPP locations [28],
(iv) considering only one type of WPPs [14,21–23] and not considering impact of interactions of Type-3 and Type-4 WPPs.

Based on an eigen analysis, this paper investigates impact of wind

---

[*] Corresponding author.
E-mail address: ahmed.mohammedmohammed@mail.utoronto.ca (A.M. Khalil).

https://doi.org/10.1016/j.ijepes.2018.07.062
Received 23 August 2016; Received in revised form 29 March 2018; Accepted 26 July 2018

power on low-frequency oscillatory modes of the 16-machine/68-bus NPCC equivalent system. This paper largely overcomes the limitations/drawbacks of the reported studies in the technical literature which leads to generalized conclusions. The investigations consider:

(i) different WPPLs, i.e., 5%, 15% and 30%,
(ii) system load increase while keeping capacity of conventional power plants unchanged; thus, the change in damping ratios is only due to the added WPPs,
(iii) different allocation patterns of WPPs, i.e., cluster distribution and uniform distribution,
(iv) different capacities of Type-3 and Type-4 WPPs for a given WPPL to show the impact of interaction between different types of WPPs,
(v) enhanced generic nonlinear and linearized models of Type-3 and Type-4 WPPs [29,30].

This paper is organized as follows. Section 2 describes the enhanced generic models of Type-3 and Type-4 WPPs. Section 3 introduces the study system and its dynamical characteristics which constitute the Base Case for comparisons. Section 4 presents scenarios that are used for WPP impact studies. Section 5 discusses the impacts of wind power on the existing low-frequency oscillatory modes. Section 6 investigates low-frequency oscillatory modes due to the presence of WPPs. Section 7 concludes the paper.

2. Enhanced generic models of wind power plants

These models (i) provide representation of dynamic performance of WPP at the Point of Common Coupling (PCC) and not inside the WPP, (ii) are non-proprietary, and (iii) are only intended for transient stability analysis of power systems, i.e., up to 10 Hz [31]. The main advantage of the enhanced generic nonlinear models of WPPs is that they provide time-domain response that has been verified against field measurement results provided by wind turbine manufacturers [32]. Thus, providing results and conclusions with high degree of fidelity. Also, these models allow time-domain simulation of power systems under high-depth penetration of wind power, e.g. up to 30%, without increasing the computational burden to prohibitive levels. Simulation of such penetration depths cannot be achieved if detailed models of WPPs are adopted. The reason is that detailed models of WPPs (i) contain large number of equations and (ii) consider dynamics that are irrelevant to low-frequency oscillations. Therefore, enhanced generic models are recommended for transient and small-signal stability analyses of large interconnected power system with large-scale integration of wind power [33].

Salient characteristics of WPPs generic models are

i. Considering balanced electrical disturbances, e.g., faults, and not wind disturbances. Thus, uncertainties in wind power cannot be investigated using the generic models as the wind speed assumed to be constant over the simulation period of 20–30 s [31]. Therefore, impact of wind power intermittency on the system stability is out of scope of this paper.
ii. The hybrid nature of the models, i.e., including both continuous and discrete states. The discrete states arise from the switching and freezing algorithms implemented in the converter control [29,30].

2.1. Enhanced Type-3 WPP generic model

Fig. 1 shows the functional blocks of the enhanced Type-3 WPP generic model. It consists of (i) Generator/Converter, (ii) Converter Control, (iii) Wind Turbine and (iv) Pitch Angle Control.

2.1.1. Generator/converter block

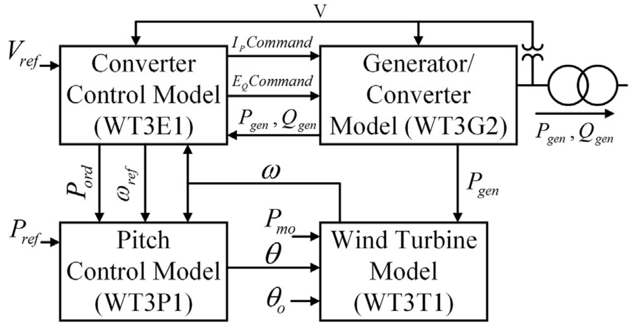

Fig. 1. Enhanced Type-3 WPP generic model blocks [29].

In this block, the generator dynamics are neglected, and an algebraic model is adopted based on the converters current commands. The reason is that the dynamics of WPPs at the PCC are mainly dominated by the converter's control, i.e.,

$$I_{SORC} = I_d + jI_q, \tag{1}$$

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} I_{Pord} \\ I_{Qord} \end{bmatrix}, \tag{2}$$

where current I_{SORC} is injected by WPP into the system, $I_{P_{ord}}$ and $I_{Q_{ord}}$ are current commands of the converter and ϕ is the phase angle of PCC voltage. The block also incorporates low voltage active power and reactive current management logics which are based on the value of the terminal voltage [30]. The injected active and reactive powers to the system are given by:

$$P_{gen} = I_P \times V, \tag{3}$$

$$Q_{gen} = -\left(I_Q + \frac{V}{X_{eq}}\right) \times V. \tag{4}$$

where V is the magnitude of PCC voltage and X_{eq} is the equivalent reactance of the generator.

2.1.2. Converter control block

The converter control consists of active and reactive power control paths of Type-3 WPP as shown in Figs. 2 and 3 respectively [29,30]. Fig. 2 shows the WPP active power control stream where ω_{ref} is derived from a piece-wise linear relation with the generated active power [30]. Active power control is based on the rated active power of the WPP while active current command to the generator is recalculated based on the WPP rated apparent power.

The reactive power control path shown in Fig. 3, includes a reactive power controller emulator [30] which is augmented with a freezing function [30] to prevent integrators wind-up, i.e.,

$$\frac{dx_{iv}}{dt} = \frac{K_{iv}}{f_n}(V_{ref} - V_{m_e}) \times y_{frz}, \tag{5}$$

$$\frac{dx_{pv}}{dt} = \frac{K_{pv}}{T_V f_n}\left(V_{ref} - V_{m_e} - \frac{f_n x_{pv}}{K_{pv}}\right) \times y_{frz}, \tag{6}$$

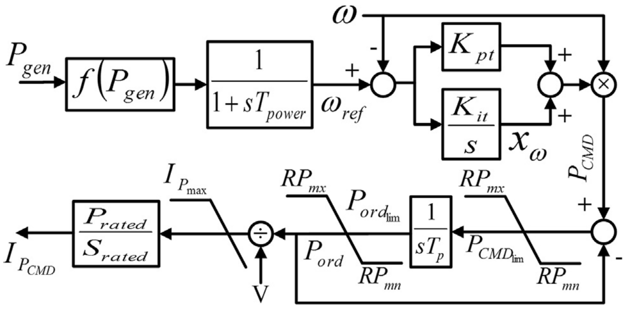

Fig. 2. Type-3 WPP converter control block – Active control path [29].