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Frequency domain design of gain scheduling control for large wind systems in full-load region

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ABSTRACT

The paper presents the issue of power control law synthesis, in the case of a large wind system that operates under full-load regime, based on dynamic properties details in frequency domain. Solving this problem involves two phases: the establishment of a linearized model as faithfully as possible in various operating points of the full-load region, and synthesis of the power controller, considered with classic structure, taking into account frequency particularities of the obtained linearized model. Obtained linear model of the controlled process is of order 16 and encloses subsystems for tower fore-aft oscillations damping, and for drive-train torsion oscillations damping. The designed controller contains a PI component and a lag compensator for dynamic correction at high frequencies. It is known that the main features of wind system dynamics generated by the interaction of wind–tower–blade ensemble cause a gap in the gain characteristic of the model and complex conjugate zeros, which can move between right and left half-planes, depending on the average wind speed value. Consequently, for control law synthesis an interactive frequency solution is adopted. This is "transparent" in relation to particularities induced by wind–tower–blade interaction. This solution allows evaluation of the extent to which control law is affected by the subsystem for tower oscillations damping. Given the strong dependence between the model and the mean wind speed value, a gain scheduling control law is designed. At different values of average wind speed, controller synthesis is performed in two ways: one applying the desired values to the stability reserve, and the other requiring the minimization of a performance criterion, aimed at reducing mechanical stress, while the controller parameters are kept in an area that ensures admissible values to the stability reserve. This second way allows obtaining a solution for designing a simple classic controller, dedicated to large wind turbines, to which may be imposed requirements for mechanical fatigue mitigation. The proposed solutions are backed by numerical results obtained through numerical simulation.

1. Introduction

Among energy producing technologies based on renewable sources, wind energy conversion systems (WECS) had a remarkable evolution and have already gained a significant share [1], being used – most commonly – in wind farms [2,3]. The need for economic efficiency for investments in this area has generated an increase in wind turbines power capacity, most of them being multi-megawatt [4]. Currently, an essential issue is the need to equip these systems with high performance control structures.

Generally, the automatic control of a high-power WECS is achieved by means of two control channels: (a) one with electromechanical subsystem command, which mainly acts in partial-load region – i.e., region 2 of power–wind speed characteristic, and (b) one with blade pitch command, used for captured power limitation in region 3 of the previous mentioned characteristic.

Overall, the functions of WECS automatic control systems cover the following major requirements [5,6]: active power limitation at the rated value in full-load region and rotational speed limitation at the rated value; mechanical fatigues mitigation, especially of those experienced in region 3; wind energy conversion optimization in partial-load regime; reduction of power fluctuations fed into the grid and of the flicker phenomenon [7,8]. It is known that a "good control" entails meeting a large number of requirements, among those mentioned [9,10]. A particular attention is given to the optimal control in relation to a mixed criterion, that targets performance of power limitation in region 3 or energy efficiency performance in region 2, vs. mechanical fatigues mitigation

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[10,11]. This approach requires a detailed modeling of the WECS, especially of the aerodynamic subsystem and of the mechanical structure, namely of the tower-blades-drive train ensemble. The mathematical model of this ensemble, represented as a multi-resonant system, is essential for WECS control law synthesis in region 3. The proposed solutions are partly reflected in synthesis papers [5,12], but the variety of approaches is significantly higher than the one obtained from these works, being defined by how control objectives are formulated, and in particular by the type of control methodology used. Most papers deal with optimal command synthesis in relation to a mixed criterion, using LQG approach [11,13]. Due to the change of process properties in relation to the current operating point, dependent of wind speed, adaptive and, especially, gain scheduling approaches are often used [14–17]. Some meaningful uncertainties present within the system model have led to the use of robust control methods in different approaches: μ-synthesis approach [18], H_∞ based control [19], robust LMI-based control [20]. An important share have predictive [21,22] and intelligent control techniques [20,23]. Aside from these, exist solutions based on sliding-mode control [24,25], nonlinear control [26], fractional-order control [27], proportional-resonant control [28], graphical approach control [29], etc. Thus, it appears that focus is often oriented towards usage of different control methodologies than on a detailed analysis of the mathematical model properties of the controlled process, in various operating modes, which should guide the basic control methodologies.

In the case of multi-resonance model, such as that of a large WECS, the frequency model provides greater transparency to dynamic properties of the system in relation to its physical parameters. This eases the analysis of WECS dynamic behavior and allows controller synthesis in full-load regime by means of frequency procedures [26,30–32].

This paper approaches the issue of control law design in frequency domain, based on the detailed mathematical model of a 2 MW WECS, working at different operating points within region 3. A particular attention is given to the establishment as faithfully as possible of a linearized model of the controlled process, obtained from the complex nonlinear model of the WECS. This linear model of order 16 includes subsystems for tower oscillations damping and for drive train torsion oscillations damping. It is known that the interaction of wind–tower–blade causes a gap in the gain characteristic of the model and complex conjugate zeros, which can move between right and left half-planes, depending on the average wind speed value. The interactive frequency domain solution for control law synthesis, used in the paper, allows the assessment of the extent to which the controller parameters are affected by the properties of the subsystem that provides tower oscillations damping. The designed controller contains a PI component and a lag compensator for dynamic correction at high frequencies. Given the strong dependence between the model and the mean wind speed value, a gain scheduling control law is designed. Using the average wind speed as gain scheduling variable, a non-uniform discretization of this variable is adopted for local controllers' selection, according to the WECS model nonlinearities. At different values of average wind speed, synthesis of local controllers is performed in two ways: one applying the desired values to the stability reserve, and the other requiring the minimization of a performance criterion, aimed at reducing mechanical stress, while the controller parameters are kept in an area that ensures admissible values to the stability reserve. This second way allows obtaining a solution for designing a simple classic controller, dedicated to large wind turbines, to which may be imposed requirements for mechanical fatigue mitigation.

The paper is structured as follows. Section 2 presents the configuration of the considered 2 MW WECS and its control structure. Section 3 is dedicated to various WECS subsystems modeling and wind speed modeling in interaction with the dynamics induced within the system. Section 4 provides system frequency analysis at different operating points from region 3, the goal being to give a detailed overview over the dynamic particularities of the controlled plant in this region. Section 5 presents solutions for control law synthesis in two situations: first when having to meet a requirement regarding stability reserve, and second when, in addition to the previous, having to achieve the mitigation of mechanical structure fatigue. The last section is dedicated to conclusions.

2. System configuration

To illustrate the wind systems control approach, the following section shows a 2 MW WECS. This is equipped with an induction generator coupled to the wind turbine shaft through a flexible drive train. The electric generator is vector controlled and feeds energy into the grid via a back-to-back converter. The energy transfer to the grid is not an object of interest for the present paper, thus this will be neglected. The electromagnetic torque reference within the vector control is the command of the rotational speed loop, equipped with a PI controller. The considered WECS is controlled via two commands: blade pitch angle, β, and rotational speed loop reference, Ω_h^* (as depicted in Fig. 1).

The general scheme of WECS and its control structure is shown in Fig. 1. The following notations are used: v_m – mean wind speed; v – relative air speed in relation to the blade, assuming that tower and blades are rigid bodies (the speed v encloses the mean wind speed, v_m, the rotational turbulence and the periodic components caused by tower shadow and wind share effects); v_r – relative speed of the air in relation to the blade, assuming that tower and blades are flexible bodies; Ω_l and Ω_h – rotational speed to low-speed shaft and high-speed shaft, respectively; F_T – thrust force dependent of v_r, blade pitch angle, β, and tip speed ratio, $\lambda = R\Omega_l/v_r$, with R the rotor radius; d – tower displacement; ζ – angular displacement of the blades; T_w, T_{em} – aerodynamic and electromagnetic torques; P_{em} - electromagnetic power. Control loops references are noted with asterisk.

In partial-load region, the blade pitch angle is maintained constant at β_0 value. In this region, WECS power loop works with a power reference P_{em2}^*, and its controller imposes Ω_h^* to the rotational speed loop. The reference P_{em2}^* ensures system operation on the optimal regime characteristic (ORC) and is described by the expression:

$$P_{em2}^* = K \cdot (\Omega_h/i)^3 \tag{1}$$

where i is drive train multiplication ratio, and K is a constant given by [10]:

$$K = 0.5\rho\pi \cdot (C_p(\lambda_{opt}, \beta_0)/\lambda_{opt}^3) \cdot R^5 \tag{2}$$

with $C_p(\lambda_{opt}, \beta_0)$ the power coefficient corresponding to the optimal tip speed ratio, λ_{opt}, and blade pitch angle β_0. At high wind speeds, closely to rated, specific to region 2, the power controller command is limited to value $\Omega_{\lim}$ and thus, the rotational speed loop receives a constant reference $\Omega_h^* = \Omega_{\lim}$. The rotational speed loop's controller keeps rotational speed to the rated value by means of the electromagnetic torque reference T_{em}^* imposed to the vector control block. Region 2 is composed of two subregions that will be henceforth called: region 2a, where WECS operates on the ORC, and region 2b, where system operates at constant rotational speed $\Omega_{\lim}$. In region 3 of power – wind speed characteristic, limiting the captured power to the rated value, P_r, is achieved by means of the control loop that has as reference the signal $P_{em1}^* = P_r$. The controller of this loop imposes reference β^* to the blade pitch angle servo system. The servo system encloses a limitation bloc for blade pitch angle variation range, $\beta \in [1, 30]^\circ$ and also a limitation element for β speed