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Input–output signal selection for damping of power system oscillations using wind power plants ☆

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ABSTRACT

During the last years wind power has emerged as one of the most important sources in the power generation share. Due to stringent Grid Code requirements, wind power plants (WPPs) should provide ancillary services such as fault ride-through and damping of power system oscillations to resemble conventional generation. Through an adequate selection of input–output signal pairs, WPPs can be effectively used to provide electromechanical oscillations damping. In this paper, different analysis techniques considering both controllability and observability measures and input–output interactions are compared and critically examined. Recommendations are drawn to select the best signal pairs available from WPPs to contribute to power oscillations damping. Control system design approaches including single-input single-output and multivariable control are considered. The recommendation of analysis techniques is justified through the tools usage in a test system including a WPP.

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1. Introduction

As a consequence of increased wind power penetration levels, transmission system operators (TSOs) are concerned with system stability. Wind power plants (WPPs) are required by TSOs to meet Grid Code requirements and sometimes to behave as conventional power plants — capable of providing support to the power system when requested to maintain stability [1–3]. Power system stability is divided in three main groups depending on the response of the system to a fault: frequency, rotor angle and voltage stability [4].

Rotor angle stability is defined as the capability of synchronous generators to keep or restore the equilibrium between their mechanical and electromagnetic torques. This stability issue is usually exhibited by synchronous generators as low frequency oscillations (LFOs). The main effects of such oscillations are to limit the power transfer capacity of the system and to cause large grid failures. This problem used to be solved by the installation of power system stabilizers (PSSs) at synchronous generators to increase the damping of the system. Nowadays, due to recent technological advances on power system devices, damping of electromechanical oscillations has been proposed in the literature to be provided by HVDC links, energy storage systems, flexible AC transmission systems and wind power generation [5–10]. It is worth mentioning that wind power is located where wind blows stronger and is more profitable; thus, it is difficult to geographically locate a WPP where its damping capabilities can be best achieved [11]. The physical location of the WPP plays an important role when defining the possible input and output signals for oscillation mitigation if they are measured locally [7,11]. When the WPP is far from the conventional generation, the low frequency oscillation on the electrical signals can be smoothed or hidden. This implies a lower observability, as stated in [7,11].

Different methods to select the best feedback signal to damp power oscillations have been discussed in [8,12–16], but the case for WPPs has not been yet well covered. Recent research focuses on the best input–output signal pairs employing controllability and observability analyses such as residues and geometric measures [13,17]. Other works study the interaction between different controllers for a multiple-input multiple-output (MIMO, multivariable) case and try to determine if a decentralized controller could be considered by using the relative gain array (RGA) [17,18]. In [19], fundamental limitations of control design by using local signals to damp remote oscillations are analyzed, where the interaction between local and remote signals has an important influence.

The aim of this paper is to compare different controllability and observability and signal interaction analyses for power system oscillation damping employing local signals from WPPs. The main

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advantages and drawbacks of each alternative are examined. Frequency domain tools such as the RGA and the multivariable structure function (MSF) [20–22] are employed to assess the interaction between signal pairs. Using the frequency domain approach, the arising control design and performance limitations under the presence of right hand plane zeros (RHPZs) are clearly defined [23]. The use of some of these methods is recommended to select the best input–output pairs which ensure a good controllability and observability of the desired oscillation mode, while providing a clear insight of the potential and limitations of the damping controller. These suggestions provide a guideline to select the best input–output signal pairs suitable to damp power system oscillations by means of WPPs signals –either through single-input single-output (SISO) or multivariable (MIMO) control schemes.

2. Contribution of WPPs to damp power system oscillations

WPPs comprising variable-speed wind turbines only (either based on doubly-fed induction generators or fully-rated converters) exhibit dynamics which are considerably faster than the synchronous frequency and the electromechanical dynamics found within power systems. Decoupling of WPPs from network dynamics can be achieved through the use of power converters [3]. For these reasons, WPP models can be simplified for small-signal stability analysis.

WPPs regulate the active power delivered to the grid through an adequate control of the generator-side converter. The aim is to transfer the maximum active power from the wind turbine following an optimum wind power extraction. On the other hand, reactive power regulation is achieved through the control of the grid-side converter [24]. Due to the availability of active and reactive power measurements for converter control, these could be used potentially as control signals for damping controllers. In general, either local or remote measurements could be selected as input signals for a damping controller sitting at a WPP, where electrical variables can be represented, for convenience, as phasors (*i.e.*, in terms of their magnitude and phase angle).

It should be emphasized that the input–output pair (or pairs) selection largely influences the performance of power oscillation dampers. This is particularly critical for the case of WPPs, since they can be located far away from the synchronous generators — where electromechanical oscillations originate.

In general, power systems can be described by a set of nonlinear differential and algebraic equations of the form

$$\begin{aligned} \dot{x} &= f(x,u) \\ y &= l(x,u) \end{aligned} \qquad (1)$$

where $x = [x_1, x_2, \ldots, x_n]^T$ is the state, $u = [u_1, u_2, \ldots, u_m]^T$ is the input, $y = [y_1, y_2, \ldots, y_r]^T$ is the output, and $f(\cdot) = [f_1(\cdot), f_2(\cdot), \ldots, f_n(\cdot)]^T$ and $l(\cdot) = [l_1(\cdot), l_2(\cdot), \ldots, l_n(\cdot)]^T$ are nonlinear functions [4].

For small signal analysis, system (1) is linearized around an operating point and can be written in state-space form as

$$\begin{aligned} \dot{\Delta x} &= A\Delta x + B\Delta u \\ \Delta y &= C\Delta x + D\Delta u \end{aligned} \qquad (2)$$

where Δx, Δu and Δy are small deviations with respect to the operating point (thereinafter, the Δ symbol is omitted for simplicity); A, B, C, and D are matrices of adequate dimensions; and the corresponding transfer function is given by

$$G(s) = C(sI - A)^{-1}C + D. \qquad (3)$$

Fig. 1 shows a feedback loop using a controller K relating the inputs with the outputs of system. It is worth to remark that K represents any linear time-invariant controller.

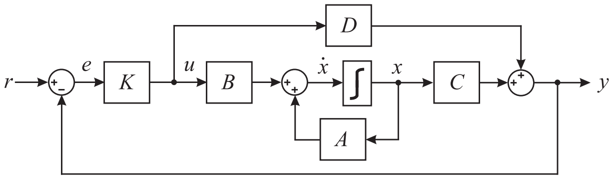

Fig. 1. Block diagram of a plant with feedback.

If power oscillation damping is provided by WPPs, the system inputs (or control signals) could be the active (P_{wt}) and the reactive power (Q_{wt}) delivered by the WPP. Conversely, the outputs (or measured signals) could be defined as the voltage magnitude (V_{wt}) and the voltage phase angle (θ_{wt}) at the point of connection of the WPP. The availability of these signal measurements provides different control alternatives, including both SISO and MIMO control schemes. For instance, if a SISO controller is considered, the input–output pair could be chosen, for example, as $u = P_{wt}$ with $y = V_{wt}$, or alternatively $u = Q_{wt}$ with $y = V_{wt}$, among others.

For the MIMO case, both inputs and outputs should be considered at the same time (*i.e.*, $u = [P_{wt} Q_{wt}]^T$, $y = [V_{wt} \theta_{wt}]^T$). The control scheme could be either centralized or decentralized. In the case of a decentralized controller, the input–output signal pair definition arising from a diagonal control structure has significant importance when designing effective controllers [23]. The pairing selection criteria for both SISO and MIMO control schemes are commonly based on controllability and observability properties, and performance limitations are established following a frequency response analysis of the open loop system [25,26].

3. Input–output selection methods

3.1. Controllability and observability measures

Controllability indicates how the state variables describing the behavior of a system can be affected by its inputs. Observability is associated with the possibility of determining the states from the outputs. More precisely, the system (2) is said to be controllable, if for any initial state $x(t_0)$, $t_1 > 0$ and final state x_1, there exists finite input u such that $x(t_1) = x_1$. The system (2) is observable if, for any $t_1 > 0$, the initial state $x(t_0)$ can be determined from $u(t_1)$ and $y(t_1)$ [23].

In damping of power oscillations, it is necessary to determine controllability and observability for specific eigenvalues. A brief description of tools commonly used for this purpose is presented next.

3.1.1. Popov–Belevitch–Hautus (PBH) test

This consists in evaluating the rank of matrices

$$\mathcal{C}(\lambda_k) = [\, \lambda_k I - A \quad b_i \,] \qquad (4)$$

$$\mathcal{O}(\lambda_k) = [\, \lambda_k I - A \quad c_j \,]^T \qquad (5)$$

where λ_k is the kth eigenvalue of the matrix A, I is the identity matrix, b_i is the column of B corresponding to ith input u_i and c_j is the row of C corresponding to the jth output y_j. The mode λ_k of linear system (2) is controllable if matrix $\mathcal{C}(\lambda_k)$ has full row rank. Similarly, the mode λ_k is observable if $\mathcal{O}(\lambda_k)$ is full column rank [23].

The rank of matrices $\mathcal{C}(\lambda_k)$ and $\mathcal{O}(\lambda_k)$ can be evaluated by their singular values. The singular values of a matrix M are defined as $\sigma_i = \sqrt{\lambda_k(M^T M)}$ $(k = 1, \ldots, n)$ with $\sigma_1 \geqslant \ldots \geqslant \sigma_n \geqslant 0$. The matrix rank is then given by the number of non-null singular values. In practice, due to numerical limitations, the rank is the number of singular values greater than a given tolerance. Therefore, the minimum singular values σ_n provide a measure of how close to

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