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Investigation of subsynchronous control interaction in DFIG-based wind farms connected to a series compensated transmission line

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ABSTRACT

The aim of this paper is to investigate the risk for subsynchronous control interaction (SSCI) in doubly-fed induction generator (DFIG) based wind farms connected to series-compensated transmission lines. For this purpose, a detailed analytical model of the frequency-dependent input admittance of the DFIG is derived. The developed admittance model is then used to get insights on the frequency characteristic of the DFIG wind turbine generator unit. In particular, the power-dissipation properties of the DFIG are used to identify those control parameters and operating condition that mainly impact the behaviour of the wind turbine in the subsynchronous frequency range. The admittance model of the wind farm together with the impedance model of the series-compensated transmission line are used to identify the risk for SSCI. Through the use of the Generalized Nyquist Criterion, it is shown that the closed-loop bandwidth of the current controller that regulates the rotor current has a major detrimental impact on the stability of the system. Furthermore, results show that the active power set-point and the level of series compensation also play an important role on the overall system's stability. Time-domain simulations are conducted to validate the theoretical findings.

1. Introduction

Since several decades, fixed-series compensation has been successfully applied at transmission level to enhance the active-power transfer capabilities and at the same time increase the power system's stability margin [1]. Although various types of power-electronics based series-compensation schemes have been proposed and adopted in actual installations, the use of fixed-capacitor banks still remains the preferred choice, thanks to its simplicity and economic advantages. However, the presence of series capacitors in the vicinity of a generation plant might lead to poorly-damped oscillations below the system's rated frequency: a phenomenon know as subsynchronous resonance (SSR) [2]. Although it was a common belief that SSR would only involve classical generation units (for example, steam-turbine generators), recently this phenomenon has also been observed in other kind of generating plants, such as large wind farms employing variable-speed wind turbines [3–5].

Following the incident in South Texas in 2009 [6], which is recognized as the first recorded case of SSR involving a doubly-fed induction generator (DFIG) based wind farm, investigation with regards to SSR problems in wind farms connected to series-compensated transmission lines has gained significant momentum, aiming at identifying the root-causes of the problem [4,7,8]. In particular, it has been found that this kind of instability originates from an uncontrolled energy exchange between the series-compensated line and the power-electronic converter in the wind turbines, subsequently addressed to as subsynchronous control interaction (SSCI) [9].

Various methods such as eigenvalue analysis and frequency-domain analysis have been adopted in the literature to understand the origin of SSCI and thereby implement effective countermeasures. The use of numerical approaches through eigenvalue analysis, aims at determining the existence of undamped system poles in order to evaluate the risk for SSCI [7,8,10,11]. Although effective in identify unstable system conditions, eigenvalue analysis relies on the derivation of a single, large linearized model of the whole system; as a result, this analysis approach is bulky and presents limited flexibility, as changes in the modeled system would require the derivation of a new linearized system model. In addition, when using eigenvalue analysis it is difficult to clearly identify the impact of a specific component on the overall stability of the system.

In recent works, the frequency-domain analysis has gained popularity for the analysis of systems involving power-electronic controllers [12–17]. In [13], an impedance-based Nyquist stability approach has been employed to identify the risk for SSR in DFIG-based wind farms, where a space-vector approach is used to develop the frequency-dependent impedance both for the DFIG and the series-compensated transmission line. However, the DFIG model employed in this work

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presents limitations, due to the fact that the outer active- and reactive-power control loops as well as the dc dynamics and the phase-locked loop (PLL) are neglected in the analysis. The work presented in [14], which has been extended in [18], uses harmonic linearization method for the development of the DFIG model. The derived model includes the current controller, both for the rotor-side converter (RSC) and the grid-side converter (GSC), together with the synchronization loop. However, aiming at reducing the complexity of the analytical model, the outer-control loops are again ignored. The work presented in [19], takes into consideration the outer-control loops in the derivation of the DFIG impedance matrix. However, in order to obtain a scalar-impedance representation of the DFIG and due to the fact that the impedance matrix is unsymmetrical, an averaging technique is used to allow a single-input-single-output (SISO) representation of the system. It is of importance to stress that this analysis approach, which is widely used in the literature (and can also be found in the aforementioned references), is non-conservative and might thereby lead to erroneous conclusions. For this kind of investigation, a detailed modeling in combination with a multiple-input-multiple-output (MIMO) analysis is necessary to draw proper conclusions and thereby to help manufactures and system operators to understand the SSCI phenomenon.

The aim of this paper is to investigate the risk of SSCI in DFIG-based wind farms connected to series-compensated transmission lines. For this, a detailed model of the DFIG is important to understand its frequency characteristics and thereby to identify those control loops that have a significant impact on the system dynamics without the risk for erroneous assumptions or conclusions. Using the derived input admittance models, the frequency characteristic of the DFIG is evaluated based on its power dissipation properties which can be used to identify the impact of system and control parameters on stability. From the findings in this paper, the end-user might perform reasonable simplifications depending on the specific case study. In addition, the stability of the interconnected system will be evaluated using the generalized Nyquist criterion (GNC) where the wind farm components are modeled as MIMO for accurate system representation. Finally, analytical findings are verified through detailed time-domain simulations.

2. Investigated system

The system investigated in this paper is based on the well-known IEEE first benchmark model (IEEE FBM) for SSR studies [20], depicted in Fig. 1. The synchronous generator originally considered in the IEEE FBM is here replaced with a 100 MW DFIG-based wind farm, connected to a 161 kV series-compensated transmission line through a 33/161 kV step-up transformer. As a difference compared with the IEEE FBM, a parallel transmission line is included in the implemented model. This parallel line is only connected during system start-up, to guarantee the stability of the system. System parameters are reported in the Appendix.

The electrical parameters for the DFIG wind turbine are based on the 2 MW, 690 V model described in [21] (see also Appendix). The wind farm is here represented as a single-aggregated DFIG rated 33 kV, 100 MW whereas the collection grid of the wind farm is represented as one lumped Π-model, as shown in Fig. 2.

3. Frequency-domain stability analysis approach

As shown in Fig. 2, two subsystems are here defined: the first subsystem (Y'_{DFIG}) represents the aggregate DFIG-model, whereas the second subsystem (Z_{L}) represents the series-compensated transmission line together with the collection grid. The frequency-dependent input admittance, $\mathbf{Y}'_{\mathrm{DFIG}}$, and impedance, $\mathbf{Z}_{\mathrm{L}}$, models will be derived in the next section. Using these models, the equivalent circuit in Fig. 3 can be obtained for analysis purpose [22]. In the figure, the aggregated wind farm is represented by its Norton equivalent, where the current $I_{\mathrm{tot,eq}}$ sets the system's operating conditions; the other subsystem is represented with the Thevenin's equivalent with voltage $v_{\mathrm{B,eq}}$.

With reference to Fig. 3, the wind farm current, I_w is given by

$$I_w = [\mathbf{I} + \mathbf{Y}'_{\mathrm{DFIG}}\mathbf{Z}_{\mathrm{L}}]^{-1}[I_{\mathrm{tot,eq}} - \mathbf{Y}'_{\mathrm{DFIG}} v_{\mathrm{B,eq}}] \tag{1}$$

where $\mathbf{I}$ represents an identity matrix of appropriate dimension.

In order to perform the frequency domain stability analysis of the interconnected systems and considering that the DFIG is represented through a MIMO system, the Generalized Nyquist Criterion (GNC) applied to the open-loop transfer function $G_{ol} = \mathbf{Y}'_{\mathrm{DFIG}}\mathbf{Z}_{\mathrm{L}}$ is employed in this paper.

The GNC states that a system represented as in (1) with a stable open-loop transfer function G_{ol} is closed-loop stable if the Nyquist plot of the eigenvalues $\lambda_{ol1,2} = eig(G_{ol})$, makes no net anti-clockwise encirclement of the point −1 [23].

Expressing the open-loop transfer function G_{ol} as

$$G_{ol} = \begin{bmatrix} G_{ol,dd} & G_{ol,dq} \\ G_{ol,qd} & G_{ol,qq} \end{bmatrix} \tag{2}$$

The corresponding eigenvalues can be obtained by solving $det(\lambda_{ol} I - G_{ol}) = 0$, resulting in

$$(\lambda_{ol} - G_{ol,dd})(\lambda_{ol} - G_{ol,dd}) - G_{ol,qd}G_{ol,dq} = 0$$
$$\lambda_{ol1,2} = \frac{1}{2}[(G_{ol,dd} + G_{ol,qq}) \pm \sqrt{(G_{ol,dd} - G_{ol,qq}) + 4G_{ol,qd}G_{ol,dq}}] \tag{3}$$

Using the Nyquist plot of the expression in (3), referred to as the eigenloci of $\lambda_{ol1,2}$, the closed-loop stability of the investigated system can be assessed, as it will be discussed in Section 5.

While the GNC allows to confirm closed-loop stability from the total open-loop gain, it does not allow to indentify the contribution of each of the subsystems depicted in Fig. 3 on the stability of the interconnected system, and thereby to identify the main sources of SSCI. To achieve this, and under the consideration that the input admittance for the DFIG subsystem must be represented as a MIMO system (as it will be shown in the following sections), the power dissipation properties of the two subsystems should be investigated [12]. This kind of investigation can be considered an extension of the passivity approach applied to MIMO systems.

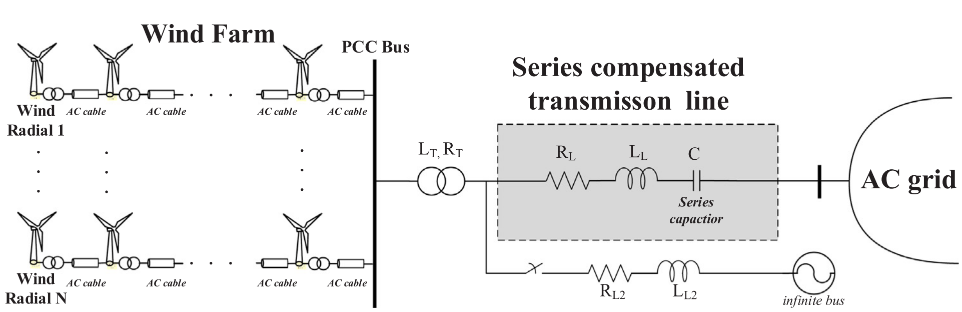

Fig. 1. Single-line diagram of wind farm connected to a series-compensated transmission line.