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SSR damping in wind farms using observed-state feedback control of DFIG converters

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ABSTRACT

This paper studies sub-synchronous resonance (SSR) in doubly-fed induction generator (DFIG)-based wind farms. The paper first briefly reviews the main types of the SSR that may occur in DFIG wind farms, namely: (1) induction generator effect (SSIGE), (2) torsional interactions (SSTI), and (3) control interactions (SSCI). It is shown that the power system is highly unstable due to the SSR mode. Therefore, a supplementary SSR damping controller (SSRDC) is designed for the grid-side converter (GSC) controller of the DFIG. The SSRDC is designed using an observer-based controller tuned through an optimal quadratic technique. Model reduction is applied to the full model of the studied power system in order to obtain a lower order model to make the SSRDC design simpler and more practical. The IEEE first benchmark model, modified to include a 100 MW DFIG-based wind farm, is employed as a case study. In this work, MATLAB/SIMULINK is used for eigenvalue analysis and PSCAD/EMTDC for time-domain simulations, respectively.

1. Introduction

Nowadays, it is well-understood that the burning of fossil fuels in electric power station has a significant influence on the global climate due to greenhouse gases. In many countries, the use of cost-effective and reliable low-carbon electricity energy sources is becoming an important energy policy. Among different kinds of clean energy resources – such as solar power, hydro-power, ocean wave power and so on, wind power is the fastest-growing form of renewable energy at the present time [1–3]. Most wind farms in Europe and North America use adjustable speed generator wind turbines (ASGWT) [3]. One important class of ASGWT is the doubly-fed induction generator (DFIG), which has gained significant attention from the electric power industry in the past few years [4–7]. Large-scale integration of DFIG-based wind farms at the transmission and distribution level may require substantial upgrades of the transmission line infrastructure, such as building new transmission lines, in order to accommodate the increased wind-generated power flow [3].

Series compensation is considered to be a more economical solution to increase the power transfer capability of an existing transmission line compared to construction of new transmission lines [8]. However, a factor hindering the extensive use of series capacitive compensation is the potential risk of sub-synchronous resonance (SSR) [8–13], which may cause severe damage to the wind farm, if not prevented. The SSR in wind turbine generator systems is a condition where the wind farm exchanges energy with the electric network, to which it is connected, at one or more natural frequencies of the electric and mechanical part of the combined system, comprising the wind farm and the network. The frequency of the exchanged energy is below the fundamental frequency of the system. Three different types of SSR in DFIG wind farms have been identified in the literature [14–17]:

- Induction generator effect (SSIGE)
- Torsional interactions (SSTI)
- Control interactions (SSCI)

In case of the SSIGE, the magnitude of the equivalent rotor resistance at the sub-synchronous frequency can be negative, and if this negative resistance exceeds the sum of the resistances of the armature and of the network, there will be an overall negative damping at the sub-synchronous frequency, and consequently the sub-synchronous current would increase with time [14,15]. In SSTI, if the complement of the torsional natural frequency of the drive-train shaft system of the DFIG wind turbine happens to be close to the electric natural frequency of the electric network, the sub-synchronous torque components generated by the

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sub-synchronous induced armature voltage can be sustained [14,15]. The nature of the SSCI is different from SSIGE and SSTI, since in this type of SSR, the DFIG wind turbine controllers play the main role in creating the SSCI; indeed, the SSCI may occur as a results of interaction between the series compensated electrical network and the DFIG wind turbine controllers [16–19].

Damping of the SSR in wind farms has been studied in literature [20–28]. Karaagac et al. [20] present a method for SSR damping in series compensated wind farm by introducing an auxiliary SSR damping controller (SSRDC) in the reactive power control loop of the DFIG controller and in the reactive power control loop of the high voltage DC (HVDC) onshore modular multi-level converter of offshore wind farms. The SSRDC block is comprised of a multi-stage lead-lag compensator. Trial-and-error method using time-domain simulation is used to tune the multi-stage lead-lag compensator. Leon et al. [21] present a damping control method to mitigate sub-synchronous interactions (SSI) in DFIG wind farms. In that paper, the SSRDC is designed using a multi-input multi-output state-space method, and the input control signals (ICSs) to the SSRDC block are d-q axis currents of the DFIG stator and rotor windings.

Golshannavaz et al. [22] propose application of unified power flow controller (UPFC) for SSR damping in self-excited induction generator (SEIG) based wind farms. In that paper, two auxiliary SSRDCs are added to the UPFC controllers, one to the shunt inverter control system and the other to the series inverter control system. The SSRDCs are tuned using trial-and-error approach. El-Moursi et al. [23] and Golshannavaz et al. [24] present a damping control algorithm for static synchronous compensator (STATCOM) to mitigate SSR in SEIG.

Faried et al. [25] study SSR damping in nearby turbine generators by addition of a SSRDC to the controllers of the DFIG converters. For a steam turbine generator, located close to a DFIG wind farm, with N multi-mass shaft sections, the SSRDC composed of N channels, and the ICS for the *i*th channel is the rotor speed deviation of the *i*th shaft section. In [25], the trial-and-error method is used to tune the SSRDC parameters in each channel. Leon et al. in [26] study SSR mitigation in nearby turbine generators by addition of a SSRDC to the converter controllers of a fully-rated fully rated converter wind turbines. In [26], a multi-input multi-output (MIMO) approach is used to design the SSR damping controller.

Elhassan et al. [27] study the SSR damping in DFIG-based wind farms using the gate-controlled series capacitor (GCSC), a series FACTS device. Time-domain simulations are performed in [27] in order to show the capability of the GCSC in SSR damping in DFIG wind farms. The authors of the present work have also reported in [4] a SSRDC for the GCSC using eigenvalue analysis method. Residue-based analysis is used in order to identify the optimal ICS to the SSRDC and the root-locus method is used to determine the required gain in order to obtain a desired damping ratio for the SSR mode.

The capability of the DFIG converters to perform SSR damping has been studied in [28], where the SSRDC is designed using residue-based analysis and root-locus design method, and the SSRDC is inserted at the DFIG converters. In [28], the voltage across the series capacitor is selected as ICS in order to damp the SSR. However, the voltage across the series capacitor is not locally available to the DFIG converters, and it should be transmitted to the wind farm via communication, imposing communication delay to the controller, which may cause stability problems.

This paper studies the SSR in DFIG-based wind farms. In this regard, first we briefly describe the three common SSR types that may occur in wind farms. Then, using an observed-state feedback control method, a supplementary SSRDC is designed for the grid-side converter (GSC) of the DFIG in order to mitigate the SSR. The power system under study has 22 state variables. Since design of a SSRDC for a system with such a high order model is neither necessary nor practical, a balanced model truncation via square root method is used in order to obtain the reduced order model of the system. The advantage of the proposed SSRDC in this paper over that in [28] is that the ICS to the SSRDC is not limited to any specific signal, and a set of locally available measured signals can be used as ICS.

The content of the rest of the paper is as follows. Section 2 describes the studied power system, which is a modification of the IEEE first benchmark model for SSR studies [29] to include a 100 MW DFIG wind farm. In Section 3, different types of the SSR that may occur in wind farms are briefly reviewed. In Section 4, a SSR damping controller is designed for the DFIG in order to stabilize the unstable SSR mode. The design of the SSRDC is developed in three steps including a) obtaining the reduced order model of the power system, b) calculating the state-feedback control law using the optimal quadratic technique, and c) designing a state-observer in order to estimate the states of the reduced system needed for control. In Section 5, the effectiveness of the designed controller is examined using time-domain simulations. Finally, Section 6 reports the conclusion.

2. Wind turbine generator system (WTGS) under study

The power system under study, shown in Fig. 1, is a modification of the IEEE first benchmark model (FBM) for SSR studies [29]. In this system, a 100 MW DFIG-based wind farm is connected to the infinite bus via a 161 kV series compensated transmission line [4]. The 100 MW wind farm is an aggregated model of 50 wind turbine units, each unit having a power rating of 2 MW. In fact, a 2 MW wind turbine is scaled up to represent the 100 MW wind farm. This simplification is supported by several studies [30,31] showing that an aggregated wind farm model is adequate for power system dynamics studies. In this system, the overall power system model includes dynamic models of wind turbine aerodynamics, shaft system, induction generator (IG), rotor side converter (RSC) controller and grid-side converter (GSC) controller, DC link, and series compensated transmission line. These models are now briefly described.

The differential equations for eigenvalue analysis are obtained using the parameters of the system directly. Detailed modal analysis of the power system modes has been described in the authors' previous research in [4,5]. A sixth-order model is used to represent the IG stator and rotor current dynamics in the synchronous reference frame, while a third-order model is used to represent the shaft system. The high-frequency switching dynamics of the GSC and RSC are neglected, but both the inner and outer control loops of RSC and GSC are modeled in this paper. The dynamics of the DC link between RSC and GSC are also considered, represented by a first order differential equation. Additionally, a fourth-order model is used for the series compensated transmission line. Thus, the complete system model is of a 22nd order model.

In order to maximize power generation in the DFIG wind farm, maximum power point tracking (MPPT) control is used [4] so that for a given wind speed V_{ω}, the optimum reference power and optimum rotational speed are obtained from the MPPT curve.

3. A brief review of sub-synchronous resonance (SSR)

In this section, in order to better understand the SSR, different types of the SSR that may occur in wind farms are briefly reviewed.