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Sub-Synchronous Resonance damping via Doubly Fed Induction Generator

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ABSTRACT

Interests of low frequency oscillation damping with the Doubly Fed Induction Generator (DFIG) has been increased recently. In addition, it is widely accepted that, the Sub-Synchronous Resonance (SSR) is another unfavorable dynamical phenomenon in power systems. In this study, the implementation of the DFIG in SSR mitigation will be investigated. The IEEE second benchmark model aggregated with a DFIG based wind farm is employed as the case study. Two different control methodologies are proposed: a Fuzzy Logic Damping Controller (FLDC) and a conventional damping controller (CDC) that are added to the main control loop of the DFIG in order to damp the SSR. To validate the results of SSR suppression via DFIG, several case studies are introduced based on changing the operation point of the system and duration of the fault. It has been shown that the DFIG can damp the SSR through both proposed methodologies, but when the system operating point or fault duration is changed, the FLDC can present a cost-effective solution for SSR damping. The Fast Fourier Transform (FFT), simulation results, and a method based on performance index (PI) are conducted to compare two controllers through various cases in Matlab.

1. Introduction

As the wind power penetration continually increases in the power systems, it is of paramount importance to study the effect of wind integrated power systems on overall system stability. In the literature, power system researchers have investigated the dynamic behavior of the wind turbine generators [1,2] and have proposed several methods to enhance the dynamic performance of these systems [3–6]. The Doubly Fed Induction Generator (DFIG) is one type of wind turbine generators that is very popular among various other techniques of wind power generation due to its higher capability, lower investment, and flexible control [3]. This can be noticed as utilizing the DFIG to improve the power system dynamics [4–6]. In [4], a classic phase compensator has been investigated with the DFIG for inter-area oscillation damping, or references [5,6] have presented the ability of the DFIG in inter-area oscillation damping with adding an auxiliary damping controller to the main control loop of the DFIG. Another dynamical phenomenon that may occur in a power system is the Sub-Synchronous Resonance (SSR) [7]. The main idea that should be considered is that, can the DFIG be implemented in SSR attenuation? The SSR is a frequent adverse phenomenon in the series compensated lines threatening either or both mechanical facilities and power system stability. After the first genuine SSR occurrence at the Mohave station in early 1970 [7], mitigating the SSR has been and continuous to be an interesting topic of investigation and development in the power system dynamic field. Furthermore, with increasing penetration of wind power systems, interests in damping the SSR phenomenon in wind energy systems have been arisen and several articles have been published about the SSR issues in a wind farm interconnected with the series compensated transmission lines [8–14].

Reference [8] has investigated the SSR in a series compensated wind park while effects of series compensation level and power generation level on SSR are examined. A novel controller for the static synchronous compensator and static synchronous series compensator for mitigating the SSR in a series compensated wind park have been proposed in [9,10]. In [11,12], the small signal analysis or modal analysis has been performed to identify the system modes and their characteristics for modeling of the DFIG-based series compensated wind energy systems. In addition, in [13,14] the ability of the power converters of the DFIG in mitigating the SSR has been comprehensively discussed. In this work, with adding an auxiliary damping controller to the main control loop of the DFIG, the control potential of the DFIG based wind turbine generator in SSR mitigation in series compensated asynchrony generator is investigated.

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In the mentioned references, the auxiliary damping controller which has been designed for the DFIG is based on the linearized system model and the controller parameters have been tuned to some nominal operation states. However, the characteristics of the power plants are inherently nonlinear and their operation is of a stochastic nature. Moreover, the controller parameters that are optimal for one set of operating conditions might be ineffective for other sets. Besides, the system configuration also keeps changing either due to switching actions in the short term or system enhancements in the long term [15]. To overcome such challenges, the nonlinear dynamics of the power system should have been taken into account in the controller design technique [16]. Another solution for the nonlinear control problems is application of fuzzy logic controllers [17]. Fuzzy control provides a systematic way to control a nonlinear process based on human experience. This may be considered as a heuristic approach that can improve the performance of closed loop systems. A properly designed fuzzy controller can give higher performance in presence of variations in parameters, or in load and external disturbances. It has been shown that the fuzzy logic controller can play an effective role in stabilizing the power systems in a wide range of operating conditions and various devices such as PSS and FACTS [17,18]. In addition, fuzzy logic controller can be successful in SSR and LFO damping [19]. So, the major contribution of this paper is to design a fuzzy logic based auxiliary damping controller supplemented to the DFIG for SSR mitigation. The Fuzzy Logic Damping Controller (FLDC) is varied widely by a suitable choice of membership functions and parameters in the rule bases. In order to assess the capability of the FLDC in SSR suppression, a conventional damping controller (CDC) based on the Particle Swarm Optimization (PSO) method is also designed and enhanced to the main control loop of the DFIG to suppress the SSR. The PSO method is appeared as a promising algorithm for managing the optimization problems. The PSO not only eliminates the deficiencies of other conventional optimization methods, but also, it utilizes a few parameters and is easy to implement [20,21]. The Fast Fourier Transform (FFT), simulation results, and analysis based on performance index (PI) have been implemented to compare two controllers in various cases.

2. Study system

The power system for the SSR study as shown in Fig. 1 is the IEEE second benchmark model [22] aggregated with a DFIG-based wind farm. A single generator of 600 MVA, 22 kV is connected to the infinite bus through two parallel transmission lines. One of the lines is series compensated by the capacitor. The mechanical system is composed of two stage steam turbine, the generator and a rotating exciter. A DFIG-based wind farm (entire capacity of 90 MW from aggregation of 60 turbines with capacity of 1.5 MW) is connected to the system at point B (see Fig. 1). It means that the wind farm penetration is adopted to provide 15% of the generator nominal power. The collective behavior of the group of wind turbines is represented by an equivalent lumped machine. This supposition is investigated by several recent studies [6,11,12]. In these papers, it has been mentioned that the wind farm aggregation provides a rational estimation for the system interconnection studies. When some single wind turbines are aggregated for this studies, the aggregated inertia is scaled up, and the base power is also scaled up, therefore the per unit values of parameters are constant, so the parameters of a 1.5 MW DFIG in per unit values can be used for the equivalent DFIG-based wind farm. The parameters of the 1.5 MW DFIG and the aggregated wind farm are shown in Appendix A. The performance of the system is first studied without any damping controller supplemented to the DFIG. The main objective is to validate the dominant mode of oscillations in the generator rotor shaft. In this case, the operating condition of the synchronous generator system in per unit is set to $P = 0.6$ p.u and $Q = 0.1$ p.u.

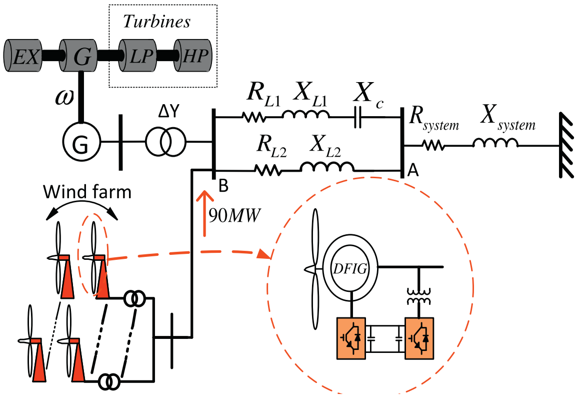

Fig. 1. IEEE second benchmark model aggregated with the DFIG based wind farm.

The contingency simulated is a three phase to ground fault located at point A (see Fig. 1) which will be applied in $t = 2$ s and will be removed after 0.07 s (case 1). When the fault is removed, large fluctuations will be experienced between the different parts of the turbine generator shaft. Fig. 2 shows the generator rotor speed (in p.u) for the first case. It can be noted that after clearing the fault, oscillations will be increased and the system will be completely unstable.

Fig. 3 depicts the FFT plot of the generator rotor speed in time interval of 1–3 s in case 1. Percentage of compensation which means the proportion of the series capacitive reactance to the line reactance ($10^2 \cdot X_C/X_L$) is set to 55% to entice the oscillatory modes of the generator rotor shaft. It is founded by FFT analysis that, three modes exist in the rotor speed in this study and the maximum destabilization is for 24.67 Hz, or in a technical expression, the dominant mode which has the sub-synchronous frequency is 24.67 Hz. Furthermore, this figure shows that, an electromechanical power oscillation appears in the system at a frequency of 1.33 Hz which corresponds to the zero mode. There is also another mode with frequency of 32.33 Hz which is visible in the figure.

In addition, the FFT analysis of the generator rotor speed is performed in 2–8 s with the time division of 1.5 s in order to expand the subject of resonance and amplification of the dominant mode. The results which are obtained from the FFT analysis are shown in Fig. 4.

Referring to this figure, it can be observed that, as the time progresses, the dominant mode component (24.67 Hz) increases significantly while all the other torsional mode components decay. Consequently, for 55% series compensation, the complement of electrical resonance frequency matches with the critical torsional mode (24.67) and the system becomes unstable. Therefore, there should be a controller in order to mitigate this adverse oscillatory component from the rotor shaft in or der to retrieve the power system from suffering.

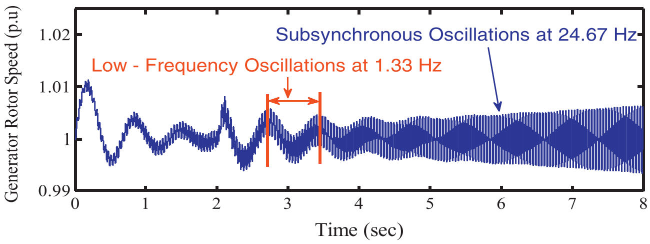

Fig. 2. Generator rotor speed (p.u) after the fault in case 1.