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Optimized SSSC-Based Mitigation of Sub-synchronous Oscillations in Wind-Integrated Power Networks

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Abstract

Sub Synchronous Resonance (SSR) presents a significant threat to the stability of modern power systems, particularly those integrating Doubly Fed Induction Generators (DFIGs) and series compensation devices. The growing penetration of wind energy and the inherent variability of wind power exacerbate SSR phenomena, highlighting the need for robust and effective damping strategies. This study develops a comprehensive approach for mitigating SSR oscillations in power systems incorporating DFIG-based wind farms and Static Synchronous Series Compensators (SSSCs). Detailed dynamic models of wind turbines and DFIGs are formulated, while uncertainties in wind power generation are addressed using a probabilistic point estimation method. The SSSC is employed as the primary damping device, with its control parameters optimally tuned via a Non-Dominated Sorting Genetic Algorithm (NSGA). Simulation results on a benchmark test system reveal that, in the absence of SSSC compensation, sub synchronous oscillations exhibit large amplitudes, driving the system toward instability. Implementation of the proposed SSSC scheme significantly reduces both the amplitude and severity of SSR oscillations, achieving rapid damping and enabling the rotor angle to converge to its pre-fault steady state value. Comparative analyses demonstrate that the proposed SSSC outperforms conventional compensators, including TCSC, by providing faster damping, fewer oscillations, and enhanced overall system stability. The findings confirm that the probabilistic SSSC control strategy delivers superior performance in damping SSR and improving power system stability. Furthermore, the SSSC demonstrates enhanced robustness against disturbances associated with DFIG rotor side converters, achieves more economical stabilization of rotor speed oscillations compared to TCSC, and provides superior reactive power control capabilities.

Keywords: Sub synchronous resonance, Doubly fed induction generator, Static synchronous series compensator, Probabilistic point estimation method, Power system stability.

1 | Introduction

The rapid integration of wind energy into modern power systems has fundamentally altered system dynamics, particularly in networks incorporating series compensated transmission lines [1-3]. One of the most critical

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stability challenges in such systems is Sub Synchronous Resonance (SSR), which occurs when electrical networks exchange energy with turbine generator shafts at frequencies below the synchronous frequency [2-5]. In wind farms employing Doubly Fed Induction Generators (DFIGs), SSR is predominantly induced by the induction generator effect, rendering these systems particularly vulnerable to poorly damped sub-synchronous oscillations [6-9]. Uncontrolled sub synchronous oscillations can amplify over time, leading to severe mechanical stress, shaft fatigue, and, in extreme cases, catastrophic failure of turbine generator components [7-6]. While conventional power systems may naturally attenuate low frequency oscillations through inherent mechanical and electrical damping, the integration of fast acting power electronic converters and series compensation devices can introduce negative damping, destabilize electromechanical modes and jeopardize overall system stability [9], [10]. Recent advances in control theory have fostered the development of sophisticated damping strategies, including adaptive, robust, neural network, and fuzzy logic-based controllers, designed to overcome the limitations of classical approaches and enhance oscillation damping under a wide range of operating conditions [15]. Parallel to these advancements, Flexible AC Transmission System (FACTS) devices, particularly the Static Synchronous Series Compensator (SSSC), have emerged as effective tools for controlling power flow, enhancing transmission capacity, and improving system stability [20-24]. By regulating both the magnitude and phase angle of the injected series voltage, SSSC provides additional flexibility to actively damp power system oscillations, thereby enabling secure operation of transmission networks near their thermal limits [23-28]. The combination of DFIG-based wind farms and series-compensated transmission lines controlled by SSSC devices represents a scenario in which the risk of SSR is significantly elevated [13]. Given the widespread deployment of DFIGs in modern wind energy systems, developing effective damping strategies for SSR in networks incorporating both DFIGs and SSSC is of paramount importance. Furthermore, the inherent variability and uncertainty in wind speed introduce additional complexity to system dynamics, robust and probabilistic modeling approaches [3], [27-30]. This paper proposes an integrated control framework for damping SSR oscillations in power systems with DFIG-based wind farms and static synchronous series compensation. The proposed approach simultaneously models the dynamic interactions between DFIGs, SSSC devices, and synchronous generators, while explicitly accounting for wind power uncertainty. An evolutionary optimization-based control strategy is employed to tune controller parameters optimally, with the objective of enhancing damping performance, improving rotor speed stability, and increasing maximum power transfer capability. The effectiveness of the proposed framework is validated through extensive simulation studies on a benchmark test system. Comparative analyses demonstrate that the SSSC based damping strategy achieves superior performance in mitigating SSR, providing faster damping, reduced oscillation amplitudes, and improved overall system stability compared to conventional compensation schemes.

2 | Methodology

This section presents a comprehensive methodology for mitigating and damping SSR oscillations in power systems integrating doubly fed induction generator DFIG wind farms and SSSCs. The proposed framework encompasses detailed dynamic modeling of power system components, probabilistic representation of wind power uncertainty, SSSC modeling and control, and optimal parameter tuning using NSGA.

2.1 | Dynamic Modeling of the Wind-Integrated Power System

For dynamic analysis, the power system is represented using a set of nonlinear Differential-Algebraic Equations (DAEs), capturing the interactions among generators, loads, and control devices [1-5] The system dynamics can be expressed as *Eq. 1*:

$$\dot{x} = f(x, y, \lambda, p), 0 = g(x, y, \lambda, p), \quad (1)$$

where x represents the vector of state variables associated with generators, wind turbines, and controllers, y denotes algebraic variables such as bus voltage magnitudes and phase angles λ includes uncontrollable

parameters and $\mathbf{p}$ denotes controllable parameters, including converter settings, excitation system parameters, and FACTS controller references. This formulation provides a unified framework for analyzing both electrical and mechanical interactions within the system.

2.2 | Wind Turbine and Aerodynamic Modeling

Wind turbines convert kinetic energy from the wind into mechanical torque applied to the generator shaft [8-10]. The aerodynamic power extracted is modeled as Eq. 2.

$$P_w = \frac{1}{2} \rho C_p(\lambda, \theta) A V^3, \quad (2)$$

where ρ is air density, A is the rotor swept area, V denotes wind speed, and C_p is the power coefficient dependent on the tip-speed ratio λ and blade pitch angle θ . The mechanical torque applied to the generator shaft is calculated in Eq. 3:

$$T_m = \frac{P_w}{\omega}, \quad (3)$$

where ω is the turbine rotor speed. A detailed dynamic model of the wind turbine, including pitch and power controllers, is implemented to accurately represent variable-speed operation and grid interactions.

2.3 | DFIG Modeling and Control Structure

The DFIG is modeled in the synchronous rotating d-q reference frame, allowing the dynamic interaction between electrical and mechanical subsystems to be captured [11-14]. The electromagnetic torque is given by Eq. 4:

$$T_e = \psi_{dr} i_{qr} - \psi_{qr} i_{dr}. \quad (4)$$

Rotor speed dynamics follow the swing in Eq. 5:

$$\dot{\omega} = \frac{1}{2H} (T_m - T_e), \quad (5)$$

where H denotes the inertia constant. The rotor-side converter is modeled as a current controlled voltage source, enabling independent regulation of active and reactive power. Active power is controlled via the rotor speed controller, while reactive power is regulated based on terminal voltage or power factor control, ensuring efficient interaction with the grid.

2.4 | Synchronous Generator Modeling

Synchronous generators are represented using a two-axis transient model with four state variables, including transient electromotive forces, rotor speed, and rotor angle [20-23]. This modeling approach captures electromechanical oscillations and their interactions with DFIGs and series compensation devices, making it suitable for SSR analysis.

2.5 | Probabilistic Modeling of Wind Power Uncertainty

To incorporate wind speed variability and generation uncertainty, a probabilistic Point Estimation Method (PEM) is employed. Using the $2m+1$ point estimation technique, where m is the number of uncertain input variables, PEM evaluates the effect of random inputs on system outputs using a limited set of deterministic

samples. The method leverages the first three statistical moments (mean, standard deviation, skewness) and efficiently propagates uncertainty through the nonlinear system model, providing accurate estimates of system response statistics with low computational complexity.

2.6 | SSSC Modeling and Control

The SSSC is modeled as a controllable voltage source connected in series with the transmission line via a coupling transformer [18]. By injecting a series voltage with adjustable magnitude and phase angle, the SSSC can emulate either capacitive or inductive reactance, facilitating both power flow control and oscillation damping [19]. Its control strategy is based on transmitted active power regulation. When line power exceeds a reference value, the SSSC absorbs reactive power to relieve line loading. Conversely, it injects reactive power when transmitted power falls below the reference. This dynamic control directly contributes to SSR damping and enhances overall system stability [13].

2.7 | Optimization Using Non-Dominated Sorting Genetic Algorithm

The optimal tuning of SSSC controller parameters is achieved using NSGA, an evolutionary algorithm suitable for multi-objective optimization problems involving conflicting performance indices such as damping ratio, settling time, and stability margins [19-23]. Candidate solutions evolve through crossover and mutation, followed by non-dominated sorting based on Pareto dominance and crowding distance. This approach ensures convergence toward optimal controller parameters while maintaining diversity among solutions, thereby enhancing SSR damping and system robustness under varying operating conditions.

3 | Discussion

The proposed methodology integrates detailed dynamic modeling, probabilistic representation of wind power uncertainty, advanced series compensation, and evolutionary optimization into a unified framework. By coordinating the control of DFIGs, synchronous generators, and SSSC devices, the approach effectively mitigates SSR oscillations, improves rotor speed stability, and enhances the overall robustness of wind integrated power systems. This section presents a comprehensive analysis of the simulation results obtained from the proposed approach for damping SSR in power systems integrating DFIGs and SSSC. The performance of the proposed control strategy is evaluated under multiple fault scenarios, considering interactions between synchronous generators and wind power units.

3.1 | Test System Description

The test network comprises six buses, two synchronous generators (G1 and G2) rated at 1100 MW and 5500 MW, respectively, and one DFIG connected via a step-up transformer. The total system load is 1500 MW. To simulate severe disturbances, a three-phase fault is applied on line 1 and 2 and cleared after five cycles. The SSSC is installed near bus 2. *Fig. 1* to assess its damping capability and its influence on system transient stability.

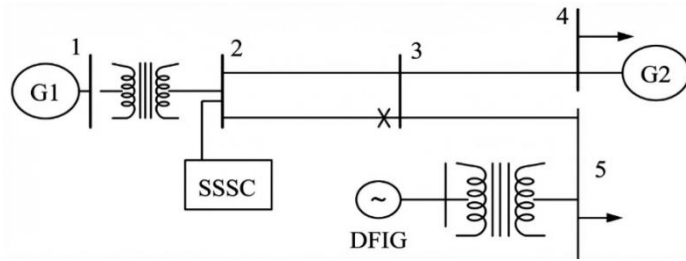


Fig. 1. Schematic diagram of the studied network equipped with DFIG and SSSC.

3.2 | Impact of SSSC on Rotor Angle Dynamics of Synchronous Generators

Fig. 2 illustrates the rotor angle response of synchronous generators in the absence of wind generation. Following the fault, G1 exhibits a significant deviation from its pre fault trajectory but converges to a new steady-state following fault clearance. G2 remains largely unaffected due to its spatial separation from the fault location.

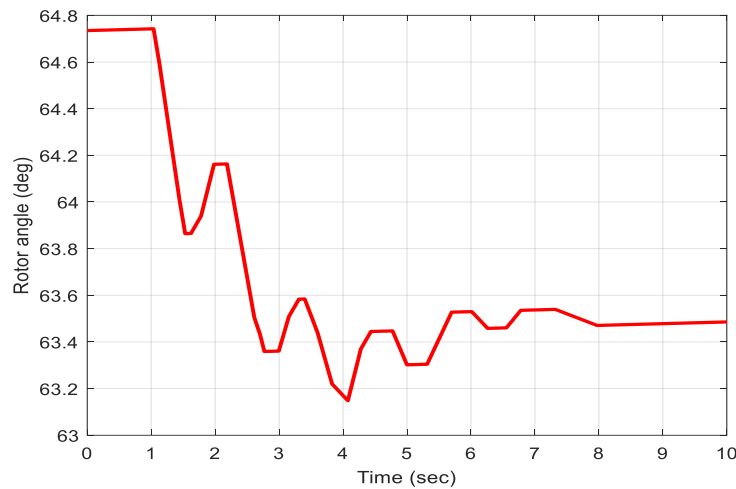


Fig. 2. Rotor angle response without the presence of wind power sources.

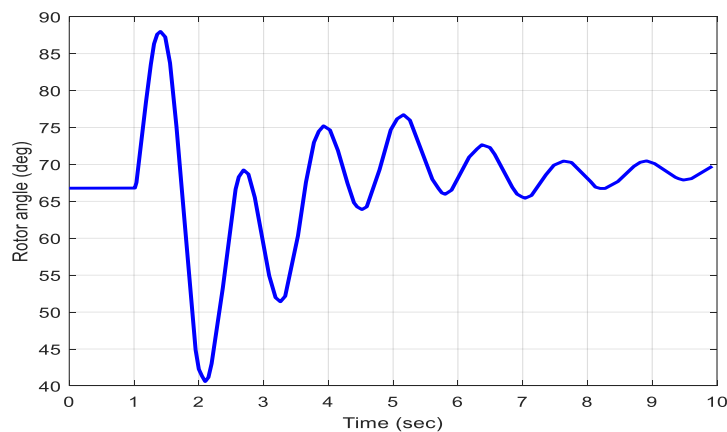


Fig. 3. Rotor angle response of generator G1 in the presence of wind power sources in the network.

When wind power is integrated as Fig. 3, G1 experiences pronounced sub-synchronous oscillations, which, if left uncontrolled, could compromise system stability. G2 remains marginally influenced, indicating that proximity to the disturbance critically determines SSR amplitude and severity.

The damping effect of SSSC on rotor angle oscillations is depicted in *Fig. 4*. Without SSSC, oscillations exhibit large amplitude and extended duration. Incorporating SSSC significantly reduces both the magnitude and duration of oscillations, thereby enhancing transient stability. When the fault is relocated near G2 as depicted in *Fig. 5*, SSSC similarly mitigates oscillations, demonstrating robust performance across various network locations. The *Fig. 6* illustrates the time domain response of the rotor angle, in degrees, under three different compensation scenarios following a disturbance at approximately $t=1$ s. Following the fault, the uncompensated system (red line) exhibits the largest transient deviation, reaching a peak of approximately 70 degrees, and subsequently suffers from poorly damped, sustained oscillations that persist throughout the 12-second simulation period. The inclusion of series compensation, via both the TCSC and the SSSC, significantly improves the transient stability of the system. The TCSC compensated system experiences a lower initial peak than the uncompensated case and damps the oscillations effectively, settling back to the pre fault angle by around $t=6$ s. The SSSC compensated system demonstrates the superior performance, yielding the lowest first-swing peak and the fastest damping of electromechanical oscillations, returning to a stable steady-state condition even more quickly than with the TCSC. This analysis clearly indicates that both FACTS devices enhance system stability, with the SSSC providing the most effective oscillation damping and transient stability improvement in this scenario. Consequently, comparison between SSSC and TCSC under peak load conditions as shown in *Fig. 6* reveals that while both devices improve system stability, SSSC provides superior damping by reducing oscillation amplitude, the number of cycles, and settling time more effectively.

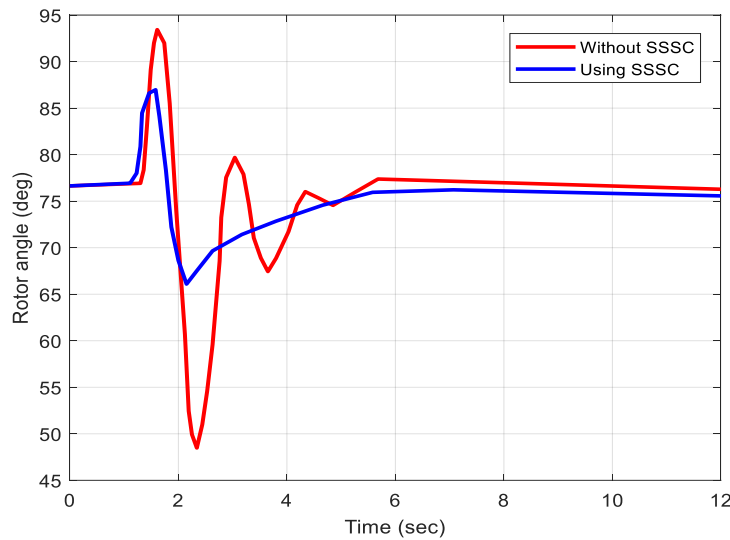


Fig. 4. Rotor angle response of synchronous machine G1 in the presence of wind power under two conditions: with and without the SSSC compensator.

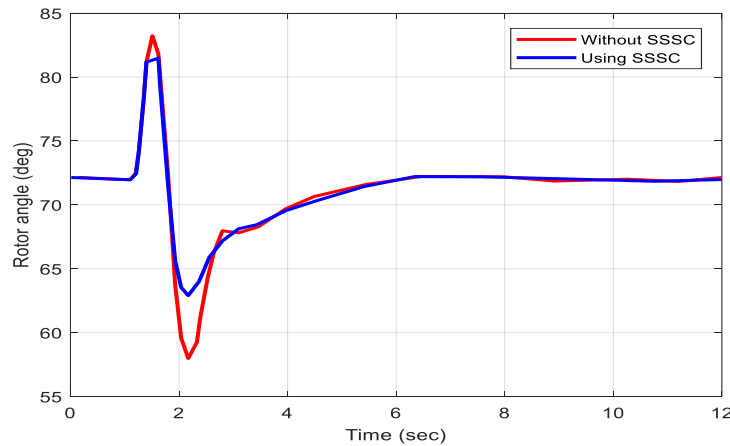


Fig. 5. Rotor angle response of synchronous machine G2 in the presence of wind power under two conditions: with and without the SSSC compensator.

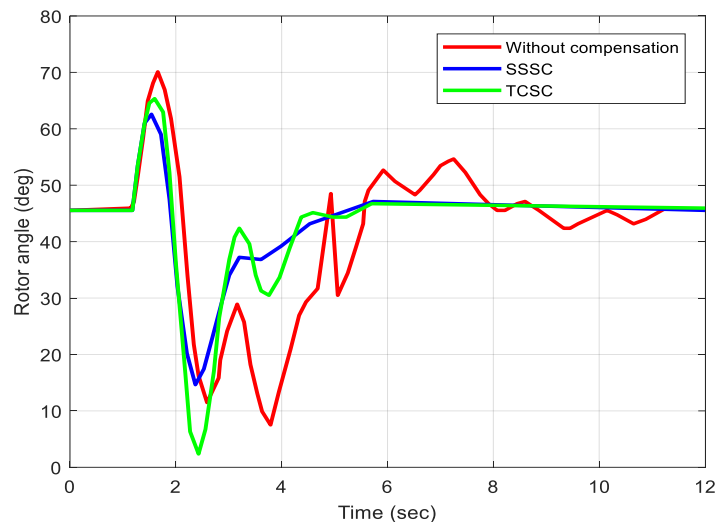


Fig. 6. Comparison of sub synchronous oscillation damping using TCSC and SSSC compensators.

4 | Conclusion

This paper presented an optimized SSSC-based control strategy for mitigating Sub-Synchronous Resonance (SSR) in power systems with DFIG-based wind generation and series-compensated transmission lines. A detailed nonlinear dynamic model was developed, incorporating wind power uncertainty through a probabilistic point estimation method to reflect realistic operating conditions. Simulation results demonstrated that DFIG integration significantly intensifies sub-synchronous oscillations in the absence of compensation, whereas the proposed SSSC controller effectively reduced oscillation amplitudes, improved damping, and ensured stable rotor angle convergence following severe disturbances. Optimal tuning of the SSSC parameters using the Non-Dominated Sorting Genetic Algorithm (NSGA) provided robust performance across varying fault locations and loading conditions. Comparative analysis confirmed that the SSSC outperforms conventional devices such as TCSC by achieving faster damping, fewer oscillatory cycles, and enhanced overall system stability. These results validate the proposed SSSC-based framework as an effective and reliable solution for SSR mitigation in wind-integrated power networks.

Authors' Contributions

All research activities and manuscript development were conducted by the author, who also approved the final manuscript.

Data Availability

All data supporting the reported findings in this research paper are provided within the manuscript.

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No funding was received to conduct this study.

Conflict of Interest

The author declares that in this paper, there is no conflict of interests.

Consent for Publication

The author has provided their consent for the publication of this manuscript.

Ethics Approval and Consent to Participate

No studies involving human participants or animals were performed in this research.

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