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A Robust SSSC Oriented Control Framework for Damping Sub Synchronous Oscillations in Wind Integrated Grids

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Abstract

Sub Synchronous Resonance (SSR) poses a serious threat to the stability of modern power systems, particularly those integrating Doubly Fed Induction Generator (DFIG) based wind farms with series-compensated transmission lines. The increasing penetration and stochastic nature of wind power further intensify SSR-related oscillatory instability, necessitating effective damping solutions. This paper proposes an optimized Static Synchronous Series Compensator (SSSC) based control strategy for mitigating SSR in wind integrated power systems. Detailed dynamic models of wind turbines and DFIGs are developed, while wind power uncertainties are incorporated using a probabilistic point estimation method. The SSSC is employed as the primary damping device, and its control parameters are optimally tuned using the Non-Dominated Sorting Genetic Algorithm (NSGA). Simulation results on a benchmark test system demonstrate that, in the absence of compensation, severe sub-synchronous oscillations drive the system toward instability. In contrast, the proposed SSSC scheme significantly suppresses oscillation amplitude, ensures rapid damping, and restores system stability. Comparative analysis confirms superior performance over conventional compensators, including TCSC, in terms of damping speed, robustness, and overall stability enhancement

Keywords: Sub-synchronous Resonance, Doubly fed induction generator, Static synchronous series compensator, Probabilistic point estimation Method, Power system stability.

1 | Introduction

The accelerated penetration of wind energy into contemporary power systems has led to profound changes in system dynamic behavior, particularly in transmission networks employing series compensation [1–4].

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Among the most severe stability concerns arising in such environments is Sub-Synchronous Resonance (SSR), a phenomenon resulting from energy exchange between the electrical network and generator shafts at frequencies below the synchronous frequency [5]. In wind power plants based on Doubly Fed Induction Generators (DFIGs), SSR is mainly associated with the induction generator effect, which makes these systems highly susceptible to weakly damped sub-synchronous oscillatory modes. Without proper mitigation, sub-synchronous oscillations tend to grow over time, subjecting turbine shafts to excessive mechanical stress, accelerating fatigue, and potentially causing critical failures in generator components [6–9]. Although traditional power systems benefit from inherent mechanical and electrical damping mechanisms that naturally suppress low-frequency oscillations, the widespread deployment of fast-response power electronic converters and series compensated transmission lines can introduce adverse damping characteristics. Such conditions may destabilize electromechanical modes and pose a serious threat to overall system security [10].

In response to these challenges, recent developments in advanced control methodologies have enabled the design of enhanced damping controllers, including adaptive, robust, neural network-based, and fuzzy logic schemes, aimed at overcoming the limitations of conventional approaches and ensuring satisfactory performance across diverse operating scenarios [11]. Concurrently, Flexible AC transmission system devices most notably the SSSC have gained considerable attention for their ability to regulate power flow, increase transmission capacity, and reinforce system stability. Through precise control of the magnitude and phase angle of the injected series voltage, the SSSC offers an effective means for actively suppressing power system oscillations and facilitating secure operation near thermal transmission limits [12–16].

The coexistence of DFIG based wind farms and series compensated transmission corridors equipped with SSSC devices represents a particularly critical operating condition in which the probability of SSR is markedly increased. Given the dominant role of DFIG technology in modern wind energy installations, the development of reliable and efficient SSR damping strategies for such hybrid systems is of substantial practical importance. Furthermore, the inherent variability of wind speed adds considerable uncertainty to the power system dynamics, requiring the use of robust and probabilistic modeling approaches to guarantee reliable controller performance [17–20].

This paper presents an integrated control framework for mitigating SSR in power systems comprising DFIG-based wind farms and static synchronous series compensation. The proposed methodology captures the coupled dynamic interactions among DFIGs, SSSC units, and synchronous generators, while explicitly incorporating wind power uncertainty into the analysis. A multi objective evolutionary optimization technique is employed to determine the optimal controller parameters, aiming to improve oscillation damping, stabilize rotor speed behavior, and maximize power transfer capability.

The proposed framework is evaluated through comprehensive simulation studies conducted on a standard benchmark test system. Comparative results demonstrate that the SSSC damping strategy significantly outperforms conventional compensation techniques by achieving faster attenuation of oscillations, reduced sub-synchronous vibration amplitudes, and superior overall power system stability

2 | Methodology

This section presents an integrated methodology for mitigating SSR oscillations in power systems incorporating DFIG–based wind farms and SSSCs. The proposed framework combines nonlinear dynamic modeling of system components, probabilistic characterization of wind power uncertainty, advanced SSSC compensation, and multi-objective evolutionary optimization into a unified control strategy.

The wind-integrated power system is represented using a set of nonlinear differentials algebraic equations, which describe the dynamic interactions among synchronous generators, DFIG wind turbines, transmission networks, and control devices [1–5]. The general system model is expressed as *Eq. 1*:

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

where x denotes the state variables associated with mechanical and electrical dynamics, y represents algebraic variables such as bus voltages and phase angles, λ includes uncontrollable disturbances and parameters, and p represents controllable parameters such as converter settings and FACTS controller references. This formulation enables simultaneous analysis of electromechanical and control interactions that are critical to SSR studies.

Wind turbine aerodynamics are modeled to capture variable speed operation under fluctuating wind conditions [9]. The mechanical power extracted from the wind is given by *Eq. 2*:

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

where ρ is air density, A is the swept rotor area, V is wind speed, and $C_p$is the power coefficient, which depends on the tip-speed ratio λ and blade pitch angle θ. The tip speed ratio is defined as *Eq. 3*:

$$\lambda = \frac{\omega_r R}{V}. \tag{3}$$

The mechanical torque applied to the generator shaft is computed as depicted by *Eq. 4*:

$$T_m = \frac{P_w}{\omega_r}. \tag{4}$$

The DFIG is modeled in the synchronous $d - q$ reference frame, allowing accurate representation of the electromagnetic and mechanical coupling. The electromagnetic torque is expressed as *Eq. 5*:

$$T_e = \frac{3}{2}\frac{P}{2}\left(\psi_{dr} i_{qr} - \psi_{qr} i_{dr}\right). \tag{5}$$

Rotor speed dynamics are governed by the swing as shown by *Eq. 6*:

$$\dot{\omega}_r = \frac{1}{2H}(T_m - T_e - D(\omega_r - \omega_s)), \tag{6}$$

where H and D denote the inertia and damping coefficients, respectively. The rotor-side converter is modeled as a current-controlled voltage source, enabling decoupled regulation of active and reactive power to ensure stable grid interaction [10], [11], [14]. Conventional synchronous generators are represented using a transient two-axis model to capture electromechanical oscillations and their coupling with wind generators and series compensation devices. The generator swing dynamics are given by *Eq. 7*:

$$\dot{\delta} = \omega - \omega_s, \dot{\omega} = \frac{1}{2H_g}\left(P_m - P_e - D_g \omega\right). \tag{7}$$

To account for the inherent uncertainty associated with wind speed variations, a probabilistic point estimation method is employed [13]. Using the $2m + 1$ point estimation technique, the statistical characteristics of system responses are obtained from a limited set of deterministic simulations. The mean and variance of an output variable Z are calculated by *Eq. 8*:

$$\mu_Z = \sum_{k=1}^{2m+1} w_k Z_k, \sigma_Z^2 = \sum_{k=1}^{2m+1} w_k (Z_k - \mu_Z)^2. \tag{8}$$

This approach efficiently propagates uncertainty through the nonlinear system model while maintaining low computational complexity. The SSSC is modeled as a controllable voltage source connected in series with the transmission line. By injecting a voltage in quadrature with the line current, the SSSC emulates a variable series reactance by *Eq. 9*:

$$V_{SSSC} = V_q \angle(\theta + 90°), X_{eq} = \frac{V_q}{I_{line}}. \tag{9}$$

The transmitted active power is regulated according to *Eq. 10*:

$$P_{\text{line}} = \frac{V_s V_r}{X_{\text{line}} + X_{\text{eq}}} \sin(\delta). \tag{10}$$

The NSGA employs evolutionary operators and Pareto selection to ensure convergence toward optimal solutions with enhanced robustness under varying operating conditions [16], [19]. Overall, the proposed methodology integrates dynamic system modeling, probabilistic uncertainty representation, advanced SSSC control, and evolutionary optimization into a cohesive framework. By coordinating the control of DFIGs, synchronous generators, and series compensation devices, the approach effectively mitigates SSR, improves rotor speed stability, and enhances the reliability of wind-integrated power systems.

3 | Results and Discussion

This section provides a detailed evaluation of the simulation results obtained from the proposed control strategy for mitigating SSR in power systems incorporating DFIGs and Static Synchronous Series Compensators (SSSCs). The effectiveness of the proposed approach is examined under a range of severe disturbance conditions, with particular emphasis on the dynamic interactions between conventional synchronous generators and wind-based generation units.

The study is conducted on a six-bus benchmark power system comprising two synchronous generators, denoted as G1 and G2, with rated capacities of 1100 MW and 5500 MW, respectively, along with a DFIG based wind generation unit connected to the grid through a step up transformer. The total system load is 1500 MW, representing a heavily stressed operating condition. To assess the robustness of the proposed damping strategy, a three phase short circuit fault is applied to transmission lines connecting buses 1 and 2. The fault is cleared after five cycles, creating a severe transient disturbance that is likely to excite sub-synchronous oscillatory modes.

The SSSC is installed in series near bus 2 to evaluate its effectiveness in suppressing SSR oscillations and enhancing transient stability. The simulation results, illustrated in Fig. 1, demonstrate the dynamic response of the system with and without SSSC compensation. These results clearly highlight the capability of the proposed SSSC control scheme to attenuate sub-synchronous oscillations, improve damping characteristics, and stabilize system dynamics following large disturbances.

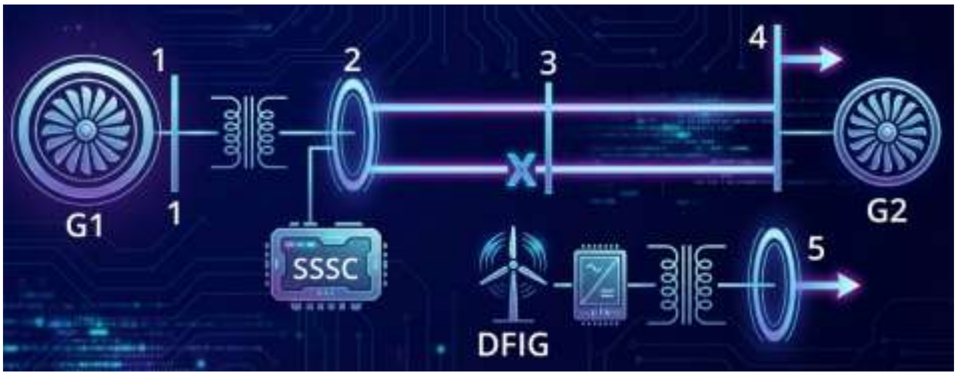

Fig. 1. Schematic diagram of the studied network equipped with DFIG and SSSC.

3.1 | Rotor Speed Dynamics of DFIG

The post fault dynamic response of the DFIG rotor speed is illustrated in *Fig. 2*. When no SSSC is employed, the rotor speed exhibits pronounced overshoot, reaching approximately 1.24 P.u., and is characterized by sustained sub-synchronous oscillations. This behavior indicates insufficient damping and highlights the system's vulnerability to SSR under severe disturbances. In contrast, the incorporation of the SSSC results in a significant improvement in dynamic performance. The oscillatory components are rapidly attenuated, and the rotor speed smoothly converges back to its pre-disturbance steady state value, thereby confirming the effectiveness of the proposed stabilization strategy.

A comparative assessment with a TCSC, as presented in *Fig. 3*, further demonstrates the superiority of the SSSC approach. The SSSC achieves lower oscillation amplitudes and a substantially reduced settling time, indicating enhanced damping capability and faster recovery following fault clearance. Moreover, the robustness of the proposed scheme is evaluated under more critical operating conditions, including the outage of a synchronous generator. As shown in *Fig. 4*, following the tripping of generator G1, the SSSC continues to effectively suppress SSR induced oscillations in the DFIG. Rotor speed deviations remain minimal, and stable operation is maintained, underscoring the resilience of the proposed control strategy against both network faults and generation contingencies

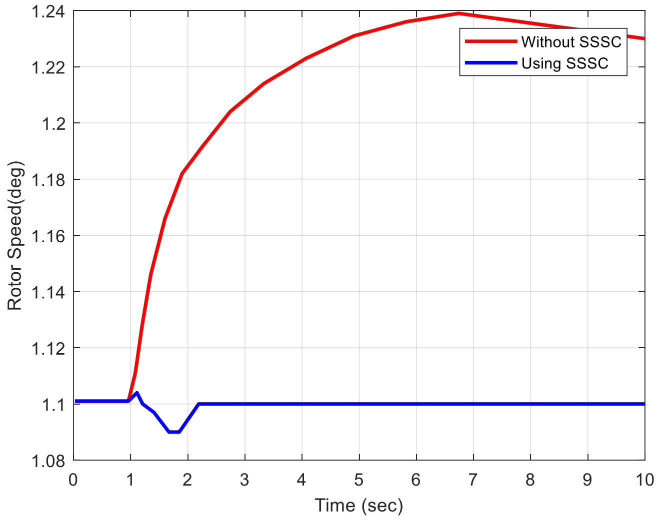

Fig. 2. Effect of SSSC on DFIG rotor speed response and sub synchronous oscillations.

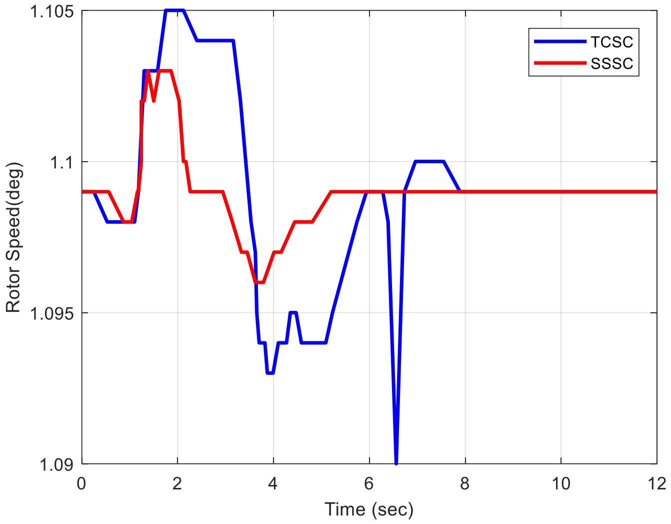

Fig. 3. Damping of DFIG rotor sub synchronous oscillations using SSSC and TCSC.

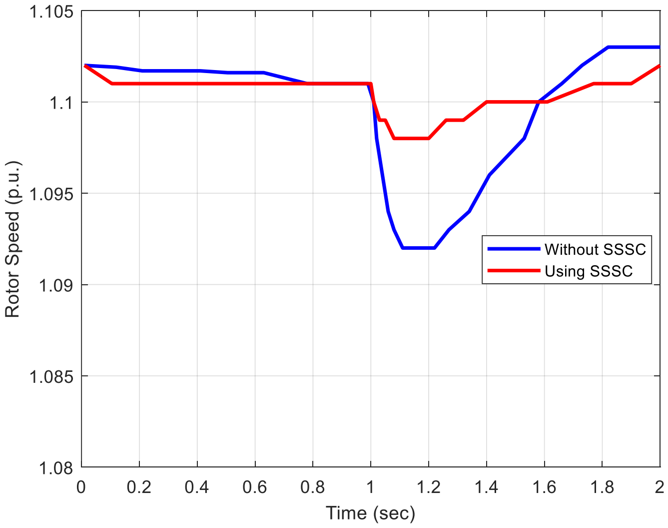

Fig. 4. Damping of sub synchronous oscillations and rotor speed stability of generator G1 following outageusing SSSC.

3.2 | DFIG Terminal Voltage Dynamics

The terminal voltage of the DFIG experiences significant degradation during fault conditions when the SSSC is not deployed, leading to a pronounced decline in active power output, as illustrated in *Figs. 5* and *6*. Such voltage instability adversely affects the dynamic performance of the wind generator and can potentially trigger further system disturbances. By contrast, the application of the SSSC effectively suppresses voltage deviations during and after the fault, thereby preserving voltage profiles and preventing instability. This enhanced voltage regulation capability enables the DFIG to sustain active power generation and ensures a smoother post-fault recovery.

Furthermore, the comparative results presented in *Fig. 7* demonstrate that the SSSC compensation strategy outperforms TCSC in terms of voltage support. The SSSC achieves faster voltage restoration and reduced oscillatory behavior, highlighting its superior dynamic response and effectiveness in maintaining voltage stability under severe disturbance conditions

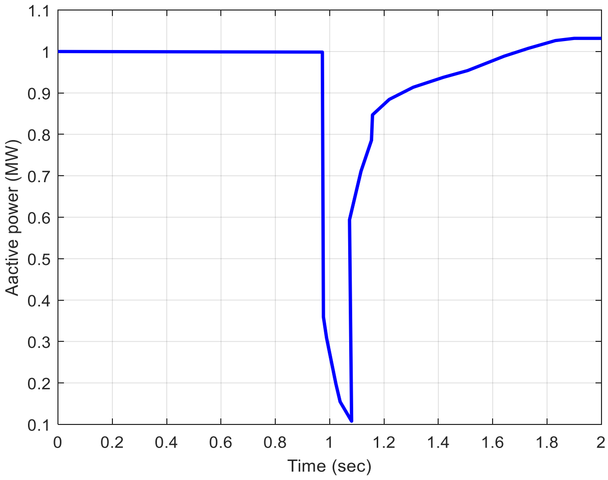

Fig. 5. Active power output of the DFIG generator without compensation.

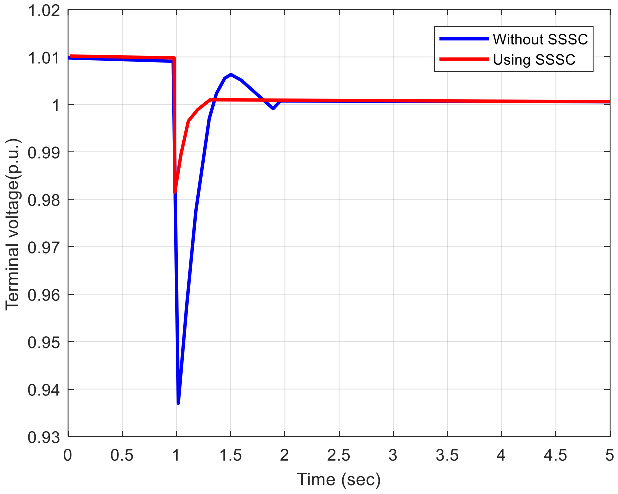

Fig. 6. Effect of DFIG terminal voltage with and without SSSC compensation.

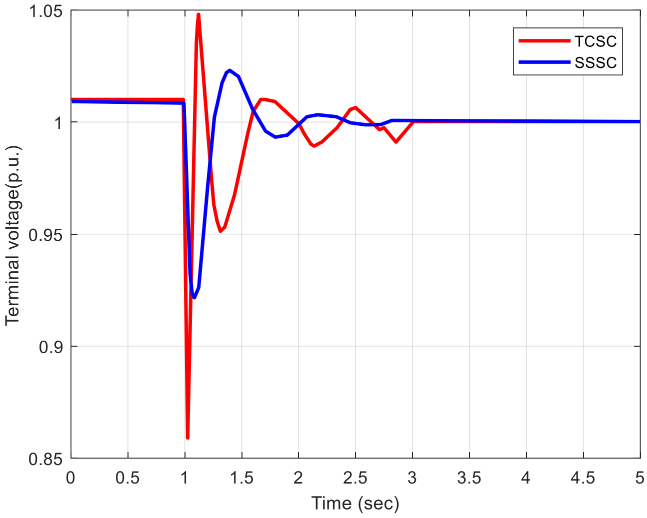

Fig. 7. Comparison of TCSC and SSSC performance in damping DFIG terminal voltage oscillations.

3.3 | Reactive Power Compensation

Figs. 8 through *11* illustrate the reactive power compensation characteristics of the TCSC and SSSC under disturbance conditions. In the case of the TCSC, the reactive power output exhibits wide fluctuations, ranging approximately from −60 MVAR to 50 MVAR in order to provide adequate damping of sub-synchronous oscillations. Such a broad operating range reflects a higher reactive power demand and increased stress on the compensation device.

In contrast, the SSSC achieves a comparable level of SSR mitigation while operating within a significantly narrower reactive power margin. The reactive power requirement of the SSSC is limited to approximately 0.8 MVAR, indicating a substantially more efficient utilization of compensation resources. This reduced reactive power demand underscores the superior operational efficiency of the SSSC and highlights its economic advantage over TCSC solutions, as effective oscillation damping is attained with lower reactive power injection and reduced device rating requirements.

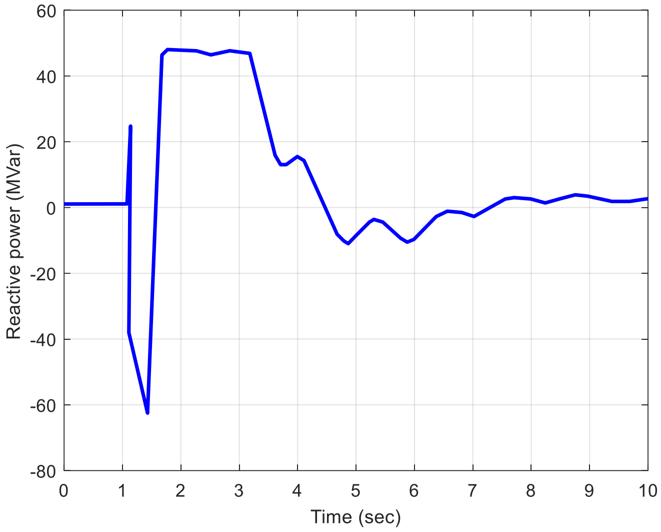

Fig. 8. Reactive power compensation using TCSC.

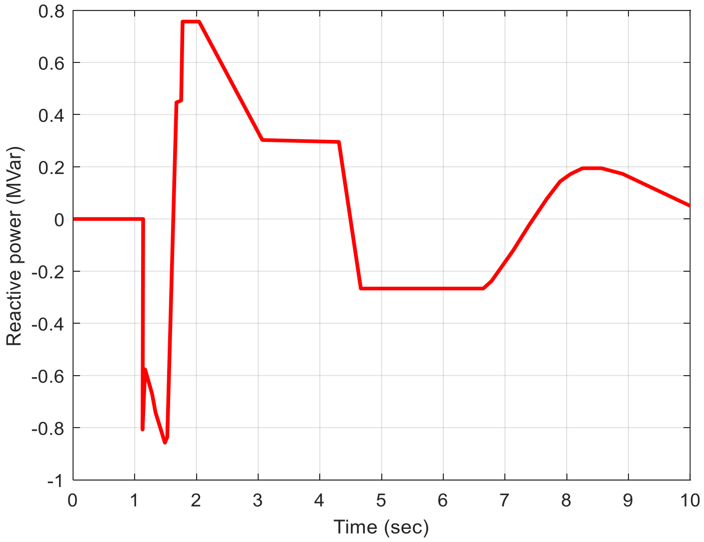

Fig. 9. Reactive power compensation using SSSC.

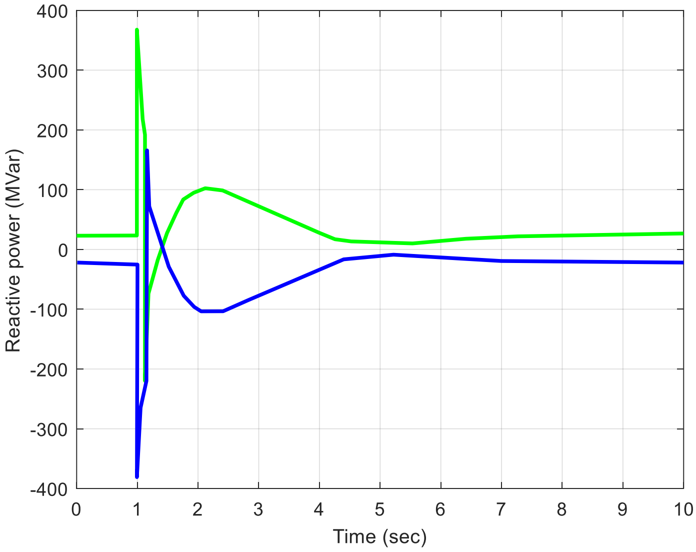

Fig. 10. Reactive power compensation by SSSC.

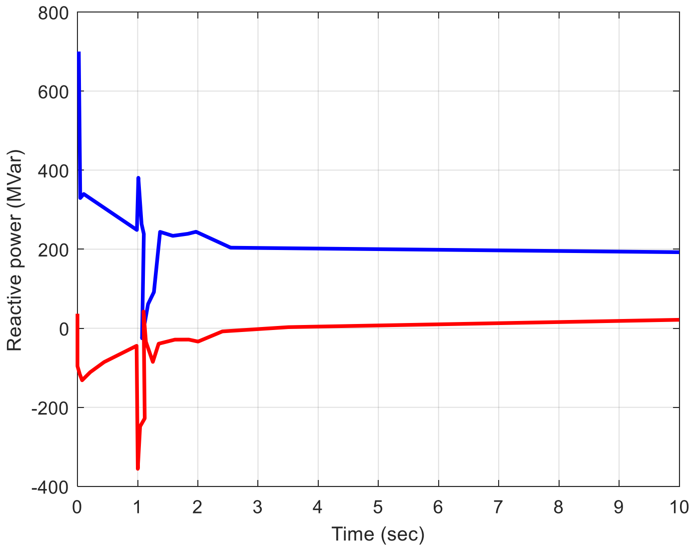

Fig. 11. Reactive power compensation by TCSC.

The simulation outcomes clearly confirm the effectiveness of the proposed SSSC control strategy in suppressing sub-synchronous oscillations in wind-integrated power systems. The results demonstrate consistent performance improvements across a range of operating conditions and disturbance scenarios.

First, the incorporation of the SSSC significantly enhances rotor angle stability in synchronous generators by reducing both oscillation magnitude and settling time, thereby improving overall transient stability. Second, the DFIG rotor speed response exhibits markedly reduced deviations and rapid damping, maintaining stable operation even under severe contingencies such as synchronous generator outages. Third, the proposed control scheme provides effective voltage support at the DFIG terminals by mitigating voltage fluctuations during and after faults, which contributes to improved power quality and sustained system stability. Finally, the SSSC achieves efficient reactive power compensation with substantially lower reactive power requirements compared to conventional TCSC solutions, while delivering equal or superior SSR damping performance. Overall, the proposed SSSC-based approach demonstrates superior capability in attenuating sub-synchronous oscillations, reducing oscillatory stress on system components, and enhancing transient stability in power systems with high levels of wind power penetration.

4 | Conclusion

This paper proposed an optimized SSSC control strategy for mitigating SSRA in wind-integrated power systems with DFIG wind farms. The approach integrates detailed dynamic modeling, probabilistic treatment of wind power uncertainty, and multi-objective evolutionary optimization to enhance damping performance under severe disturbances. Simulation results on a system test demonstrate that the proposed SSSC effectively suppresses sub-synchronous oscillations, significantly reduces rotor angle and rotor speed deviations, and improves voltage stability following fault conditions and generator outages. Comparative evaluations further confirm that, compared to conventional TCSC compensation, the SSSC achieves faster damping and improved transient stability while requiring substantially lower reactive power support. Overall, the results validate the proposed SSSC control scheme as an efficient and robust solution for SSR mitigation, enhancing system stability and reliability in modern power networks with high levels of wind power integration.

Author Contributions

Javad Pourqasem was responsible for the main conceptualization of the study, development of the proposed control framework, modeling of the power system components, and conducting the simulation analysis. Mingyue Wang contributed to the methodological design, implementation of the optimization algorithm, and

validation of the simulation results. Zhang Hao assisted in literature review, technical interpretation of the results, and critical revision of the manuscript. All authors contributed to the writing process and approved the final version of the paper.

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Data Availability

The results of this study are based on analytical modeling and simulation carried out in MATLAB/Simulink. The data supporting the findings of this research can be made available by the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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