IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 20 February 2024, accepted 23 April 2024, date of publication 29 April 2024, date of current version 16 May 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3394507

RESEARCH ARTICLE

Sub-Synchronous Oscillation Mitigation for Series-Compensated DFIG-Based Wind Farm Using Resonant Controller

EZZEDDINE TOUTI [1], MOHAMED ABDEEN [2], MAHMOUD A. EL-DABAH [2], HABIB KRAIEM [1], AHMED M. AGWA [1], ABDULAZIZ ALANAZI [1], AND TAREK I. ALANAZI [3]

[1]Department of Electrical Engineering, College of Engineering, Northern Border University, Arar 91431, Saudi Arabia
[2]Department of Electrical Engineering, Faculty of Engineering, Al-Azhar University, Cairo 11651, Egypt
[3]Department of Physics, College of Science, Northern Border University, Arar 73222, Saudi Arabia

Corresponding author: Ezzeddine Touti (esseddine.touti@nbu.edu.sa)

This work was supported by the Deanship of Scientific Research at Northern Border University through Research Group under Grant RG-NBU-2022-1215.

ABSTRACT The sub-synchronous oscillation (SSO) phenomenon presents a significant risk to the overall safety and stability of power networks, as evidenced by numerous real-world incidents. This paper introduces a novel approach to mitigating SSO in series-compensated transmission lines by employing a resonant controller in conjunction with a control loop for the doubly fed induction generator (DFIG). To begin, the resonant controller is integrated into the converter controllers of the DFIG system to determine the optimal placement that yields enhanced damping characteristics. Subsequently, an analysis is conducted to explore the impact of different parameters associated with the resonant controller on system stability, with the goal of identifying the most suitable parameter configuration. The proposed control strategy is thoroughly evaluated through time-domain simulations and small signal stability analysis, considering various compensation levels, wind speeds, and sub-synchronous control interactions (SSCI). Furthermore, a comparative analysis is performed between the proposed method and a recent SSO damping technique to validate the efficacy and robustness of the proposed approach. The results of the comparison clearly demonstrate the superiority and effectiveness of the proposed control strategy in alleviating SSO. Specifically, the proposed method achieves the shortest SSO damping time across all feasible operational scenarios, thereby reinforcing its practical value and applicability.

INDEX TERMS Sub-synchronous oscillation (SSO) damping, series-compensated DFIG-based wind farm, resonant controller, small-signal stability.

I. INTRODUCTION

To address the substantial electricity demand, renewable energy sources (RES) are playing a crucial role in the current power system. Wind energy stands out as a prominent renewable source as it is freely provided by nature, being abundant and environmentally friendly. Among the various technologies available, the Doubly Fed Induction Generator (DFIG)-based wind energy conversion system distinguishes itself due to its variable speed operation, capability to function in both sub-synchronous and super-synchronous modes, cost-effectiveness, and high power density [1]. Offshore wind farms are integrated into the electric grid owing to their cleanliness and enhanced efficiency. However, the extended transmission lines required to convey the generated power to load centers result in a decrease in transmittable power due to the elevated transmission line reactance. To counteract this, a series capacitor is introduced into the transmission line to mitigate the reactance, subsequently boosting the transmittable power. Nevertheless, it has been observed that

The associate editor coordinating the review of this manuscript and approving it for publication was Mouloud Denai.

TABLE 1. SSO events in the real world [8].

Year of occurrence	Country /City	Natural frequency (Hz)	RES Type	Transmission voltage level (kV)
2017	China	37	Wind energy	220
2017	California	7	Solar farm	--
2018	Toronto	5	Wind energy	230
2019	Australia	7	Wind energy	--
2020	Australia	19	Wind energy	--
2021	USA	22	Solar farm	138

increasing the reactance of the series capacitor can render the system unstable. This occurrence is recognized as a sub-synchronous oscillation (SSO) [2], [3].

The complete assimilation of wind power facilities into the power systems has altered its conventional and rendered it more intricate [4]. Sub-synchronous resonance (SSR) in DFIG-based wind generators drew a lot of attention when it appeared in the southern power grid of Texas in 2009 [5]. SSR oscillations have also been reported in Minnesota, and the most recent incidence of SSR in a DFIG-based wind plant was observed in Hebei province, China, in 2012 [6]. Table 1 summarizes real-world SSO events over five years, spanning from 2017 to 2021 [7].

Upon analysis, it is revealed that such SSO bears a resemblance to the induction-generator effect (IGE). The IGE is triggered when the rotor's negative resistance surpasses the total network resistance at a frequency lower than the rated system frequency, i.e., sub-synchronous frequency [9]. This IGE can manifest in wind plant-based DFIG integrated with a fixed series capacitor transmission line, contingent upon the level of series compensation and wind speed [10]. The SSO is not limited to IGE type but it encompasses various aspects such as torsional interaction (TI), torque amplification (TA), sub-synchronous control interaction (SSCI), and sub-synchronous torsional interaction (SSTI) [11]. Among these, the DFIG is the most commonly utilized, owing to its capability to extract maximum power across variable wind speeds. Within the context of a DFIG-based wind turbine, the most prominent types of SSO are attributed to SSCI and IGE [12], [13], [14].

If suitable prevention strategies are not put in place promptly, SSO may have one or more repercussions like generation power loss, equipment damage, and power quality degradation [15], [16], [17]. Based on the literature, the suppression of SSR can be achieved through the utilization of a Flexible AC Transmission System (FACTS) [18], [19], [20] or the implementation of a Supplementary Damping Controller (SDC). The FACTS devices have the ability to effectively reduce SSR oscillations in wind plants that are based on DFIG technology. However, they do have a drawback in terms of the harmonic distortions that occur in the power signal as a result of their electronic switching mechanism. Additionally, these devices can be quite expensive [21]. Conversely, the SDC-based approaches offer a more economical solution, however, they tend to produce electrical variables with a less responsive and slower settling behavior when compared to FACTS devices [22]. As an alternative to FACTS techniques, control-based solutions are less expensive but provide an electrical variable response that is late-settling and poorly dampened. The literature has reviewed control-based solutions at the DFIG's grid-side converter (GSC) and rotor-side converter (RSC) in great detail. The IEEE first benchmarked model integrated with DFIG-based wind farms uses the widely used proportional-integral (PI) controller because of its ease of use and simplicity. The GSC uses a second linear controller to limit the SSR oscillation, but the GSC's power rating limits the controller's maximum reaction [23]. Numerous studies in the literature have extensively examined control-based strategies for both the rotor-side converter (RSC) and grid-side converter (GSC) of the DFIG [24], [25], [26]. The GSC utilizes an extra linear controller, but its effectiveness is constrained by the power rating of the GSC. To address the limitation of the GSC's capacity, a potential solution entails incorporating a controller at the RSC. In this design, the linear converter gain is distributed between the two sides of the back-to-back converter. However, implementing this approach requires measuring the voltage of the series compensator and leaves it vulnerable to SSCI. To harness the benefits of Multi-Input-Multi-Output (MIMO) capabilities, the control scheme proposed by the authors in [25] revolves around optimal state feedback. Additionally, in [26], A method for mitigating SSR (Sub-Synchronous Resonance) through phase compensation using lead-lag filters is introduced as a control scheme. This approach presents a more straightforward design and tuning procedure in contrast to the previously discussed model-based configurations.

According to the literature, the Proportional-Integral (PI) controller, which is widely utilized, has been selected by the IEEE benchmark model for integrating DFIG-based wind plants. This choice is primarily attributed to the controller's simplicity and straightforward implementation. The user-friendly nature of the PI controller is widely acknowledged and renowned; but, in anomalous grid situations, it might cause instability in the system when abnormal

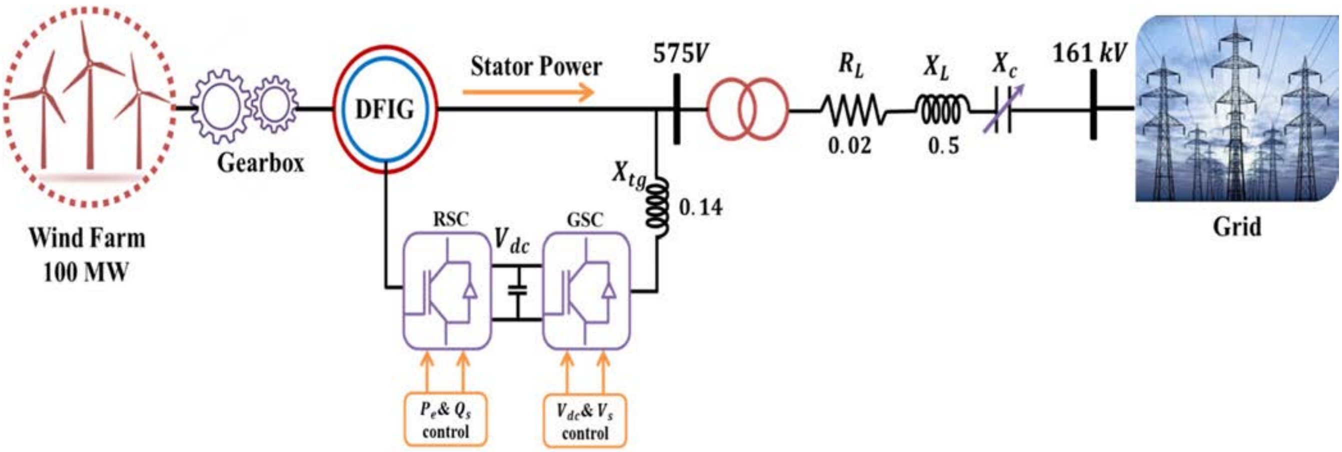

FIGURE 1. An amalgamated DFIG-based wind farm connected to a series-compensated transmission line.

grid situations are expected to arise. The proportional resonant (PR) controller has been gradually taking the position of the proportional-integral (PI) controller in several applications, such as grid-connected current control. In comparison to the PI controller, the PR controller offers improved performance under abnormal grid scenarios [27]. However, The resonant controller is utilized as an alternative control strategy to overcome many limitations like slow response time and the need for an extreme control chip memory. This approach has found extensive application in various fields such as active power filters [28], distributed generators, and parallel inverters. Its effectiveness lies in its ability to effectively mitigate multiple harmonics at resonant frequencies, owing to the flexibility, computational efficiency, and infinite gain of resonant controllers at these frequencies [29]. As per these advantages, the resonant controller will be employed in this research to alleviate the SSO effects in DFIG-based wind farms.

The primary contributions of this research can be summarized as follows:

i. The resonant controller is proposed to be embedded into the converter controllers of DFIG to identify the optimum location that achieves better damping.
ii. The influence of the resonant controller parameters on the system stability is investigated for selecting the optimal parameters.
iii. The proposed control strategy is examined at different compensation levels, variable wind speeds, and sub-synchronous control interaction (SSCI) using time-domain simulation and small signal stability analysis.
iv. The proposed method is compared with a recent SSO damping method to validate its effectiveness and robustness for SSO damping.
v. The comparison results demonstrate the effectiveness and superiority of the proposed control strategy for SSO alleviating, where the least SSO damping time is achieved by the proposed method at all possible operating conditions.

The rest of the paper is organized as follows: section II introduces the test system while Section III highlights the resonant controller structure and its best location when utilized in SSR damping. The eigenvalues and small signal stability of the resonant controller are analyzed in section IV. In Section V the time domain results will be discussed and finally, section VI presents the paper's conclusion.

II. TEST SYSTEM

The initial IEEE benchmark platform has undergone an update, substituting the synchronous machine with a DFIG-based wind plant to investigate SSR actions in DFIG. The research employs a 100 MW combined wind farm comprising 67 turbines, each with a capacity of 1.5 MW. The DFIG output voltage, set at 575 V, is connected to a 161 kV Series Capacitor transmission line through a step-up transformer, facilitating integration with a robust grid as shown in Fig.1. A mathematical model of a DFIG-based wind farm for SSR analysis was published in [9]. The parameters for this model are presented in many literatures [30], [31], [32], and [33].

III. RESONANT CONTROLLER STRUCTURE AND LOCATION

Due to the digital system's accuracy constraints and its limited bandwidth, the principle resonant controller is not practical in real-world situations [34]. As a result, the quasi-resonant controller will be employed in this research, so it can be formulated in Eq(1) as:

$$G_{RC}(s) = \frac{2k_r\omega_c s}{s^2 + 2\omega_c s + \omega_0^2} \quad (1)$$

where ω_c is the quasi-resonant controller's cut-off frequency, ω_0 is the resonant frequency, and k_r is the resonant factor. These parameters are crucial for the resonant controller's

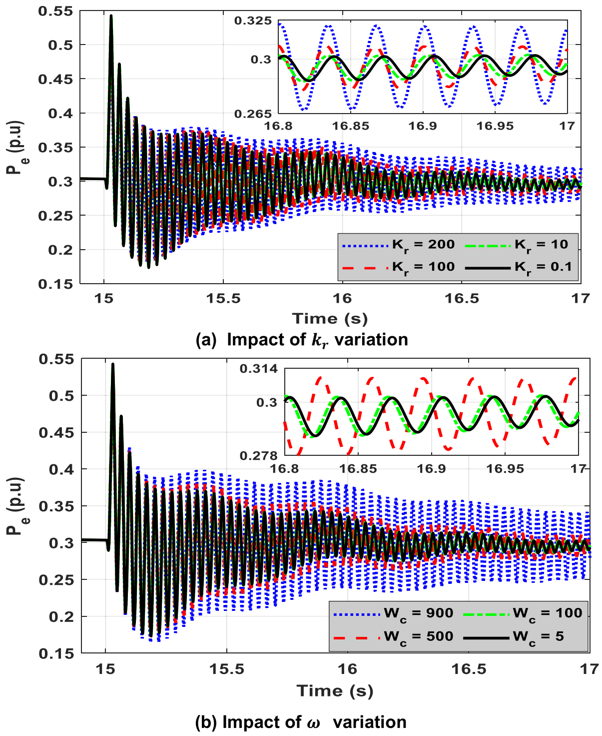

FIGURE 2. Plot of the electrical output power of the DFIG at various values of k_r and ω_c.

control performance. To design the resonant controller, k_r and ω_c were varied to select their appropriate parameters. This simulation is carried out when the wind speed is 8 m/s, level of compensation (K) is 50 %, and ω_0 equals 900 rad/sec. The output power signal (P_e) plot is shown in Fig.2. As illustrated in the figure, the system shifts towards the instability region with an increase in the resonant factor or the cutoff frequency, and vice versa. According to these results, the resonant frequency was chosen to be equal 1, and the cutoff frequency was set to 15 in this research.

The DFIG-based wind farms have two power electronic converters namely rotor side converter (RSC) and grid side converter (GSC). The main responsibility of RSC control is to govern the electrical torque and stator reactive power, while GSC control is tasked with ensuring a consistent level of stator terminal and DC link voltages. The PI controller is conventionally employed in these converters control. This research proposes the use of resonant controllers in cascade with PI controllers aiming at enhancing the damping capability of SSOs. Although there are four PI controllers in each converter control, there is a need for investigation for the most suitable location for applying resonant controllers as given in Fig.3. So, there are supposed eight locations (A-D) in RSC control and (E-H) in the GSC control. The system will be tested at a wind speed of 8 m/s & compensation level of 50 % with the resonant controller parameters set as mentioned previously. (i.e., $k_r = 1.0$ $\omega_c = 15$).

As seen in Fig.4, the system lost its stability when the PI controllers only were employed in converter control. This coincides with the case of a resonant controller embedded in the GSC converter control. However the damping capability was enhanced when the resonant controller was employed in the RSC in comparison with the GSC control as depicted in Fig.5. Moreover, the B-location of the RSC is more suitable than the other proposed locations., i.e. (A.C, and D). It is worth mentioning that the system stability deteriorates at low wind speed or high compensation levels. The damping enhancement feature can be promoted in these operating conditions when the resonant controller is employed in both locations of B and D and this will be employed in the next studied cases in this research.

As seen in Fig.4, the system lost its stability when the PI controllers only were employed in converter control. This coincides with the case of a resonant controller embedded in the GSC converter control. However, the damping capability was enhanced when the resonant controller was employed in the RSC in comparison with the GSC control as depicted in Fig.5. Moreover, the B-location of the RSC is more suitable than the other proposed locations., i.e. (A.C, and D). It is worth mentioning that the system stability deteriorates at low wind speed or high compensation levels. The damping enhancement feature can be promoted in these operating conditions when the resonant controller is employed in both locations of B and D and this will be employed in the next studied cases in this research.

IV. SMALL SIGNAL STABILITY ANALYSIS

As mentioned above, the presence of SSO in previous events has been thoroughly investigated and analyzed. These investigations have revealed the existence of an additional frequency, known as the natural frequency (f_n), which is lower than the synchronous frequency. This frequency can be calculated from Eq.(2) which requires values of both transmission line (X_L), coupling transformer (X_T), and compensation capacitors (X_C) reactance's. Consequently, in Eq.(3) a slip corresponding to this natural frequency, referred to as a Sub-synchronous oscillation slip(S_S), can be expressed as:

$$f_n = f_s\sqrt{K} = f_s\sqrt{\frac{X_C}{X_L + X_T}} \tag{2}$$

$$S_S = \frac{f_n - f_{em}}{f_n} \tag{3}$$

Equation (2) demonstrates that the S_S is influenced by two parameters, one of them is the electric frequency, f_{em}, which is impacted by the wind speed. The latter one is the natural frequency, f_n, which is determined by the compensation level (K). It is important to highlight that the S_S is characterized by a negative value due to the fact that f_{em} is always greater than f_n.

Conducting an eigenvalue analysis stands out as one of the optimal and most accurate methods for stability analysis. Ref. [9] provides a thorough explanation of how to calculate the eigenvalue of a series-compensated transmission line at each operating condition. Table 2 lists the

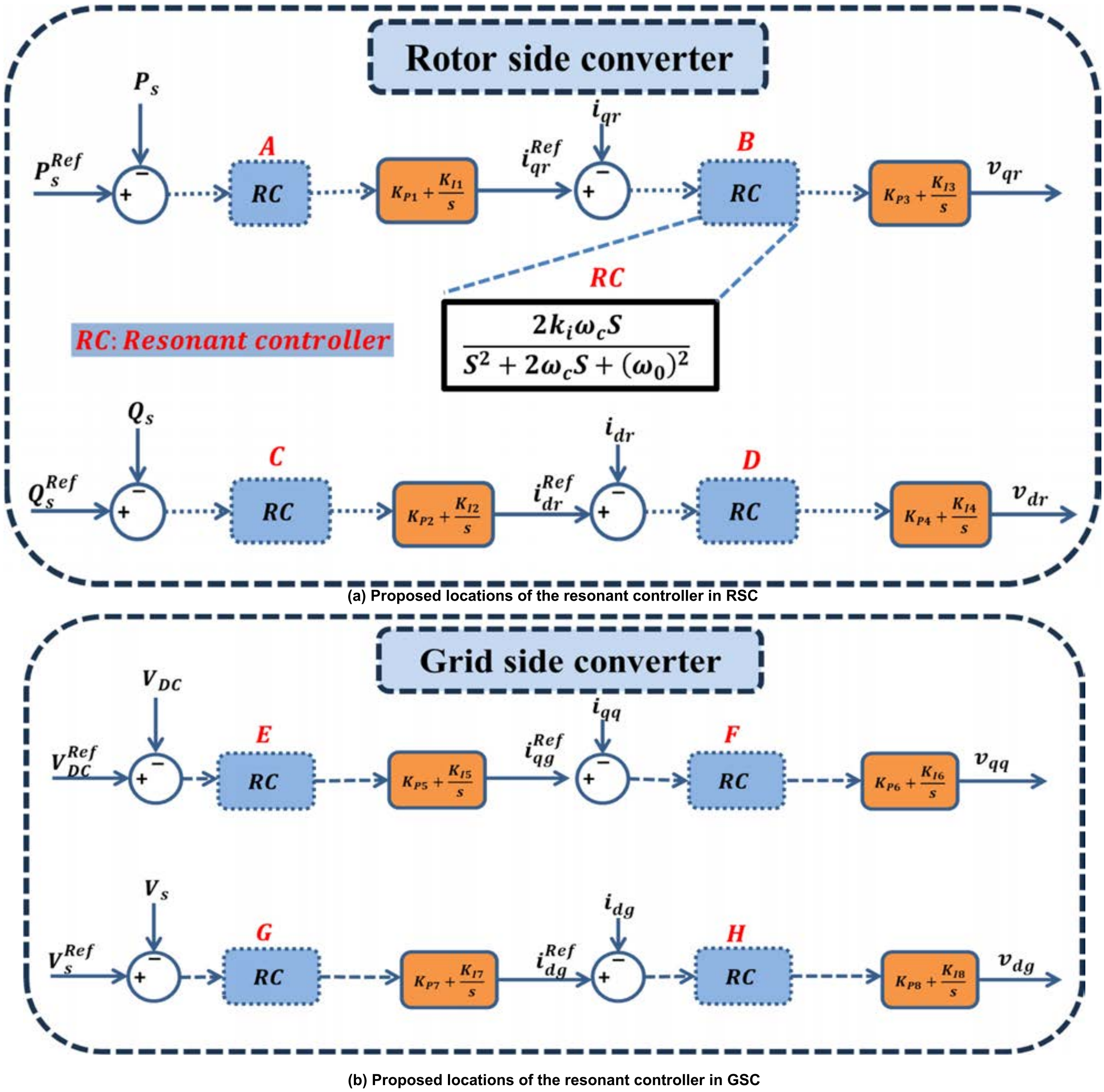

FIGURE 3. Proposed locations of the resonant controller in DFIG converters control.

system eigenvalues when the resonance controller is/isn't embedded in comparison with the case of employing the SDC action. This study investigated the interplay between compensation levels and control strategies in influencing the stability of a complex system. The analysis focused on scenarios with constant compensation levels (K = 50%), providing a controlled environment to assess the system's behavior. The key observation is the system unstable in the Sub-synchronous mode without any controller employed except at high wind speeds i.e. $V_w = 11$ m/s. Although it remains stable when the resonant controller was utilized in locations B and D as mentioned previously. Also, the stability margins were increased relatively in comparison with the SDC and PI controller as indicated in Fig.6.

Similarly, Table 3 lists the system eigenvalues when the resonance controller is/isn't embedded with wind speed constant at 8 m/s and variable compensation levels. The system experiences instability in sub-synchronous mode in the absence of a resonant controller or SDC. Although preserving stability in these high compensation levels when the resonant controller or SDC was employed, the stability margin increased in the case of the resonant controller in conjunction with the PI controller as supported by Fig.7. Hence, the resonant controller seems to be effective in addressing the instability issues and mitigation the SSO phenomena.

TABLE 2. Sub- and super-synchronous modes for 50% compensation level with different wind speeds.

Wind speed $V_\omega\left(\frac{m}{s}\right)$	Sub-synchronous mode			Super-synchronous mode		
	No resonant controller	SDC [11]	With a resonant controller at B_{RSC}& D_{RSC}	No resonant controller	SDC [11]	With a resonant controller at B_{RSC}& D_{RSC}
7	8.5 ± 193i	-3.5 ±189i	-8.5 ± 184i	-20.6 ± 568i	-18.5 ± 566i	-14.8 ± 567i
8	5.5 ± 190i	-5.2 ± 188i	-9.4 ±184i	-20.1 ± 568i	-18.2 ± 566i	-14.8 ± 567i
9	3.4 ± 188i	-6.1 ± 187i	-9.9 ± 184i	-19.8 ± 568i	-18 ±566i	-14.7 ± 567i
10	1.3 ± 187i	-7.1 ± 186i	-10.3 ±183i	-19.4 ± 568i	-17.7±566i	-14.6 ± 567i
11	-0.4 ± 185i	-7.7 ±186i	-10.5 ± 183i	-19.1 ± 568i	-17.5 ± 566i	-14.6 ± 567i

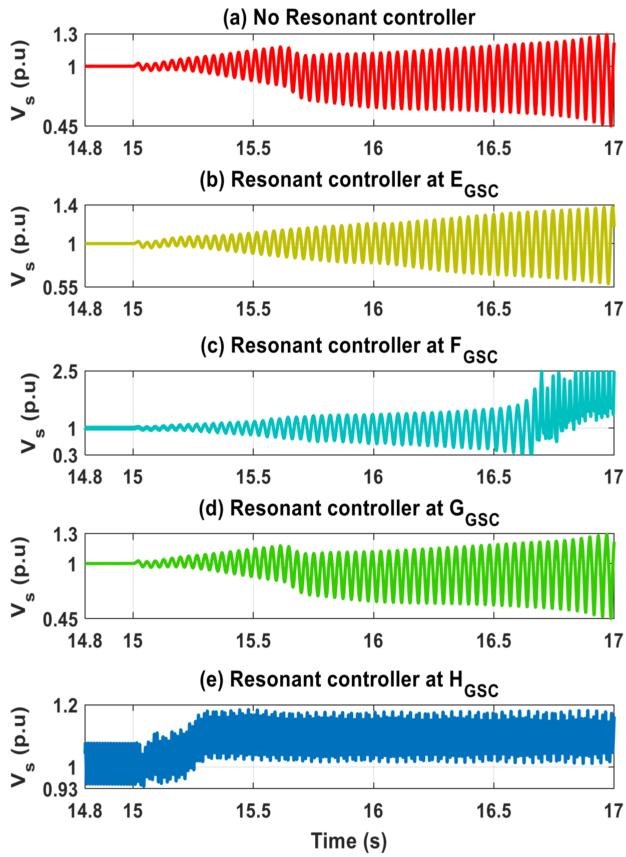

FIGURE 4. Terminal voltage signal with the resonant controller employed at different locations in the GSC converter control.

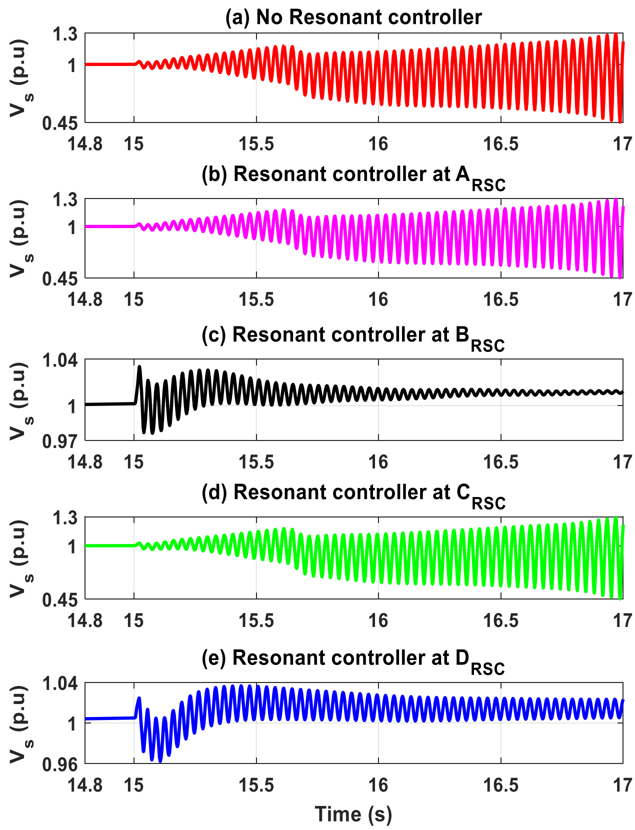

FIGURE 5. Terminal voltage signal with the resonant controller employed at different locations in the RSC converter control.

V. TIME DOMAIN RESULTS WITH DISCUSSION

This section uses MATLAB/Simulink software to do a time-domain simulation in order to confirm the superiority and efficacy of the suggested approach over the conventional approach for alleviating the SSO phenomena. The suggested approach is evaluated for every configuration seen in DFIG-based wind farms, including SSCI, varying degrees of compensation, and varied wind speeds.

A. OPERATION AT VARIOUS COMPENSATION LEVELS

Initially, the system operates at wind speeds of 8 m/s and a stable compensation level. However, at t = 15 sec, the compensation level is modified to three different values (40%, 50%, and 60%) as depicted in Figs 8, 9, and 10 respectively. The system's dynamic response is captured through double signals: the DFIG active power (Pe) and the terminal voltage (Vs). As shown in Figs 8-10, it is evident that the system requires resonant controller action to prevent instability. By utilizing it, the system's damping is improved, resulting in a fast response and lower settling time in comparison with the SDC approach. These findings are substantiated by the aforementioned analysis of the system eigenvalues.

B. OPERATION AT VARIOUS WIND SPEEDS

Certainly! It appears that in this case study, the focus is on adjusting the wind speed (V_w) to three different values:

TABLE 3. Sub- and super-synchronous modes for 8 m/s wind speed with variable compensation levels.

Compen. Level K %	Sub-synchronous mode			Super-synchronous mode		
	No resonant controller	SDC [11]	With a resonant controller at B_{RSC}& D_{RSC}	No resonant controller	SDC [11]	With a resonant controller at B_{RSC}& D_{RSC}
40 %	3.3 ± 208i	-5.5 ± 207i	-9.6 ± 204i	-18.6 ±548i	-16.7 ± 546i	-13.6 ± 547i
45 %	4.4 ± 199i	-5.4 ± 197i	-9.5 ± 194i	-19.4 ±558i	-17.4 ±556i	-14.2 ± 557i
50 %	5.5 ± 190i	-5.2 ±188i	-9.4 ±184i	-20.1 ± 568i	-18.2 ± 566i	-14.8 ± 567i
55 %	6.5 ± 182i	-5.0 ± 179i	-9.2± 174i	-20.9±577i	-19 ± 575i	-15.3 ±576i
60 %	7.6 ± 174i	-4.7 ± 170i	-8.9 ± 165i	-21.6 ± 586i	-19.7 ± 584i	-15.9 ± 585i

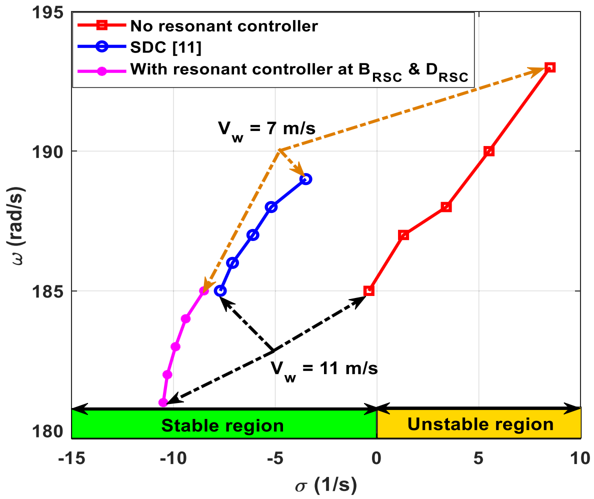

FIGURE 6. Eigenvalue trajectories of the SSR mode at variable wind speeds and K = 50%.

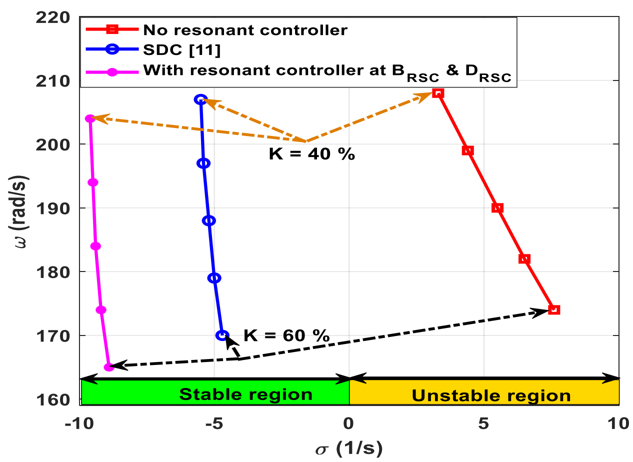

FIGURE 7. Eigenvalue trajectories of the SSR mode at variable compensation levels and V_W = 8 m/s.

7 m/sec, 8 m/sec, and 9 m/sec. However, the compensation level remains constant at 50%. The performance of the resonance controller is being analyzed and compared with the SDC approach and PI controllers. It's noted that the resonance controller, to maintain system stability, is capable of

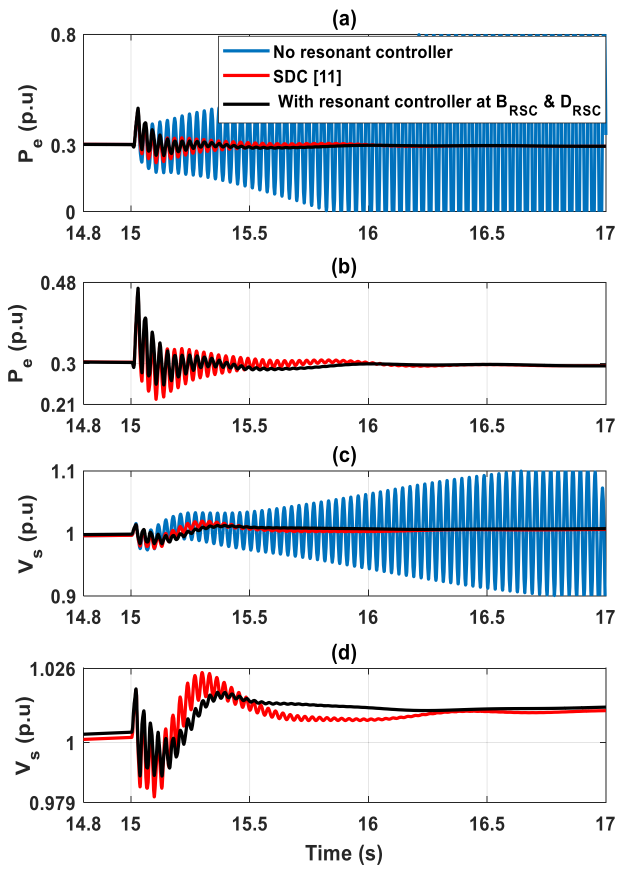

FIGURE 8. Behavior of SSO at wind speed of 8 m/s and K = 40%.

generating an appropriate damping signal. This is depicted in Figs 11, 12, and 13. Furthermore, the resonance controller exhibits a shorter settling time when compared to traditional competitive controllers. This indicates that the resonance controller is more efficient in achieving stability and faster response in the given conditions.

C. SUBSYNCHRONOUS CONTROL INTERACTION SIMULATION

The most dangerous kind of SSO event that arises in series compensated DFIG-based wind farms is the SSCI. Due to

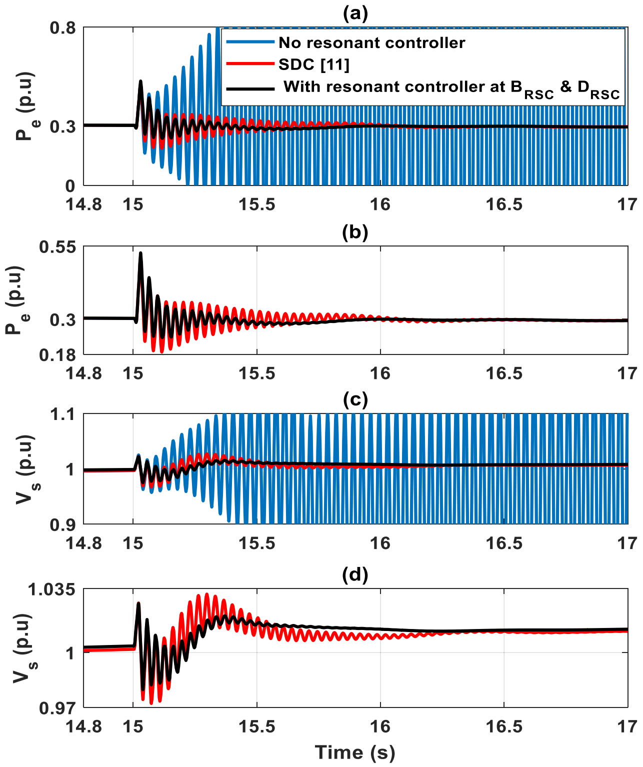

FIGURE 9. Behavior of SSO at wind speed of 8 m/s and K = 50%.

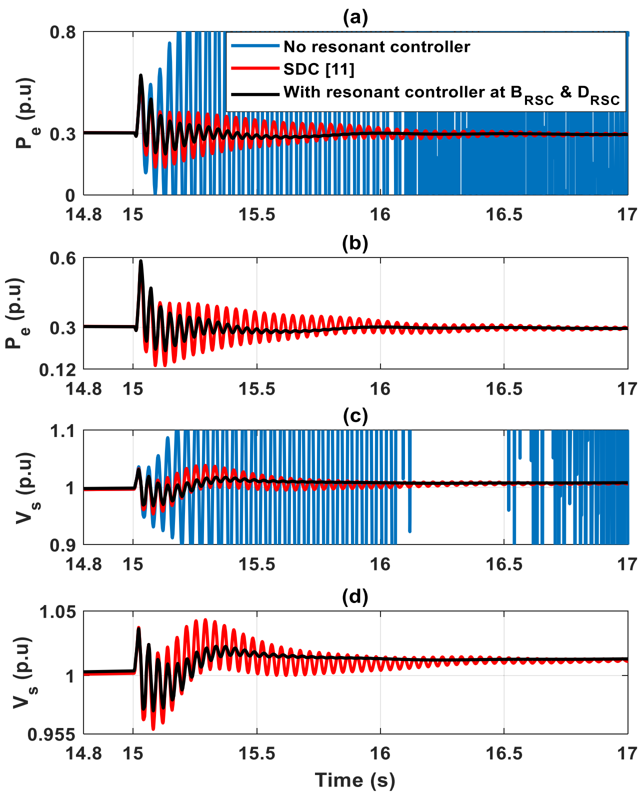

FIGURE 10. Behavior of SSO at wind speed of 8 m/s and K = 60%.

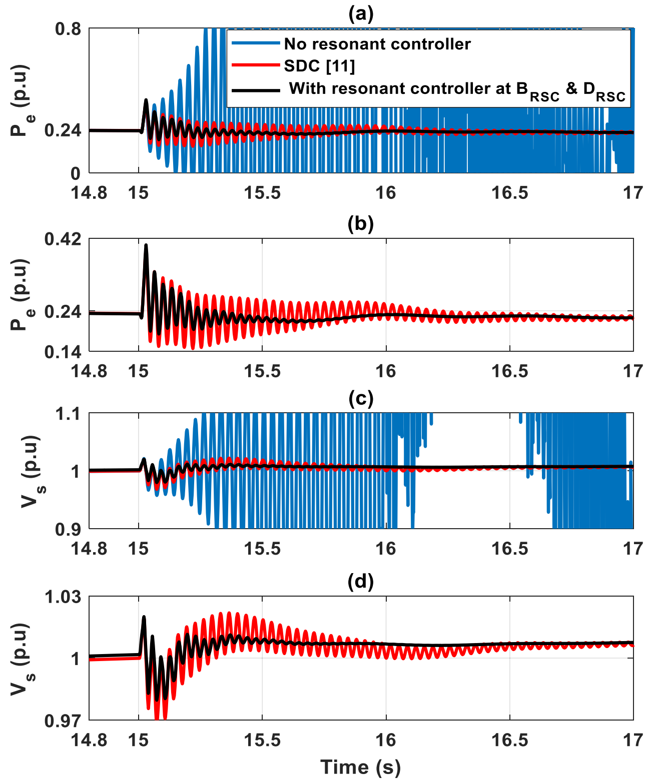

FIGURE 11. Behavior of SSO at wind speed of 7 m/s and K = 50%.

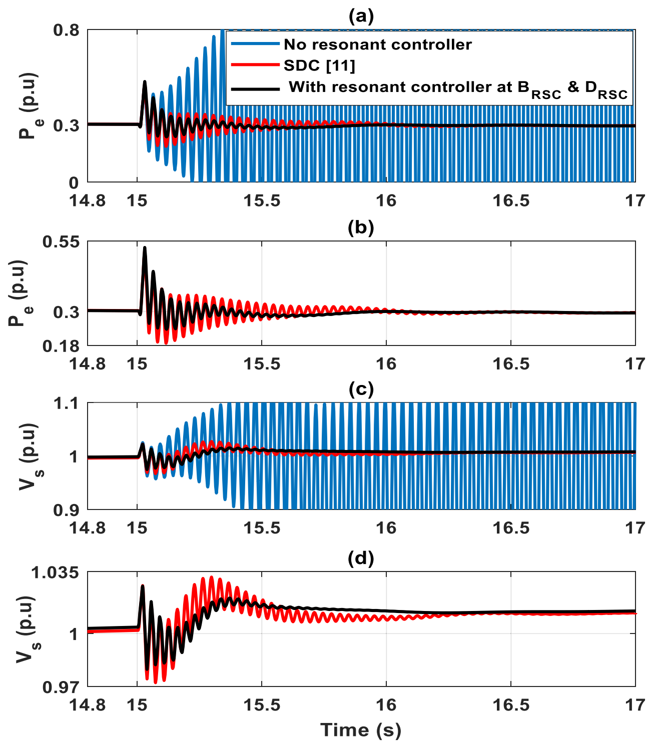

FIGURE 12. Behavior of SSO at wind speed of 8 m/s and K = 50%.

the unusual characteristics of the SSCI, oscillation might increase too rapidly and seriously damage the system if it is not sufficiently damped. At a relatively slow wind speed (7 m/s), compensation level of 60 %, and the presence of a symmetrical fault of type (LLLG), which is purposefully begun at t = 15 at the high voltage side of the coupling

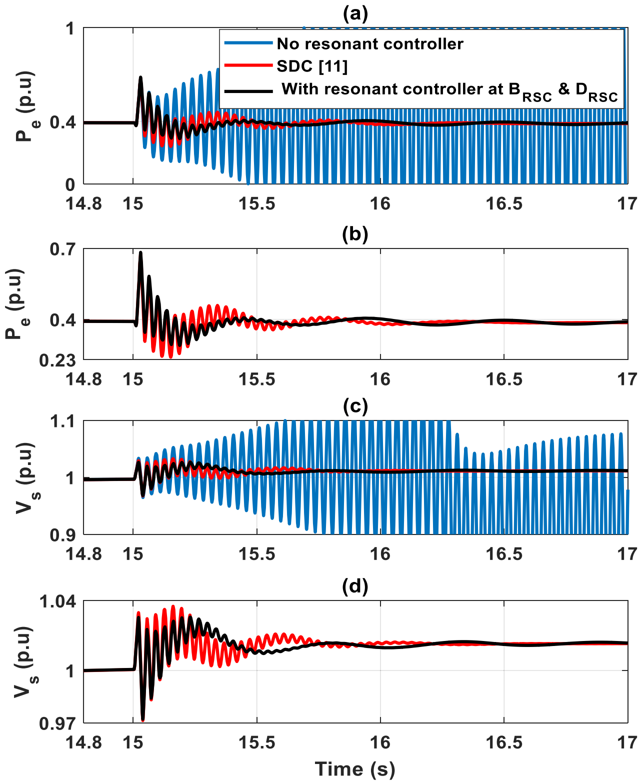

FIGURE 13. Behavior of SSO at wind speed of 9 m/s and K = 50%.

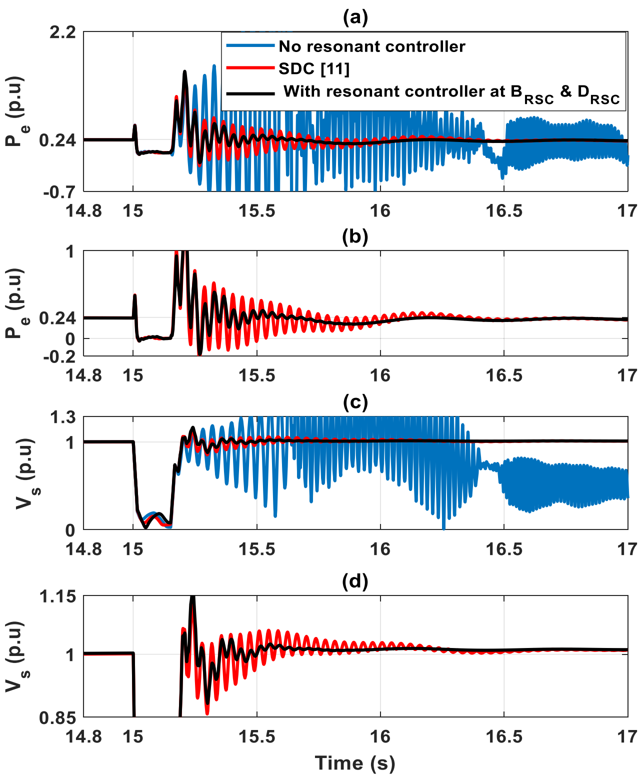

FIGURE 14. DFIG output power and terminal voltage response during SSCI.

transformer for a duration of 150 msec in this case study, are the two prerequisites for the occurrence of the SSCI. The suggested application of a resonant controller in the RSC is evaluated for robustness in the mitigation of the SSCI. As can be seen in Fig.14, the resonant controller performance is superior to the reported SDC and PI controllers only. Also, the settling time is approximately half its value in comparison with the SDC.

VI. CONCLUSION

The goal of this work is to reduce the SSR issue at the DFIG-based wind plant that is coupled to the series-compensated IEEE benchmark model. A control-based approach employs a resonant controller to mitigate the effects of SSO. To validate the performance of the resonant controller, the suggested scheme is successfully applied for dampening the SSR concern and evaluated with the traditionally utilized PI controller independently. The most appropriate location for the resonant controller is when embedded in the RSC control. Also, the damping capability will be enhanced when the resonant controllers are used to regulate the direct and quadrature current components. Moreover, the analysis of the eigenvalues proves that the stability margin increases if compared to both of the cases of utilizing PI controllers only and using supplementary damping controllers' action. The suggested scheme's muted and fast-settling response is verified by the time domain simulations at various operating conditions like wind speed and compensation level variations. Nevertheless, the time domain simulation for SSCI damping mitigation was carried out to show the damping ability of the proposed scheme. Soon, an investigation of the proposed control scheme with other utilized FACTs devices for transmission lines compensation of the DFIG-based wind farms will be accomplished. Also, an optimum selection of resonant controller parameters has to be investigated.

ACKNOWLEDGMENT

The authors extend their appreciation to the Deanship of Scientific Research at Northern Border University for funding this work through research group No. (RG-NBU-2022-1215).

REFERENCES

[1] M. Abdeen, M. H. Ali, A. M. A. Soliman, M. Eslami, and S. Kamel, "Improved methodology for damping sub-synchronous oscillation in a series-compensated DFIG-based wind farm," *IET Gener., Transmiss. Distrib.*, vol. 17, no. 14, pp. 3333–3341, Jul. 2023, doi: 10.1049/gtd2.12906.

[2] M. Abdeen, M. A. El-Dabah, J. L. Domínguez-García, and S. Kamel, "Gate-controlled series capacitor: A new methodology for mitigating sub-synchronous resonance in a series-compensated DFIG-based wind farm," *IET Renew. Power Gener.*, vol. 17, no. 10, pp. 2638–2647, Jul. 2023, doi: 10.1049/rpg2.12776.

[3] Y. Zhang, C. Klabunde, and M. Wolter, "Study of resonance issues between DFIG-based offshore wind farm and HVDC transmission," *Electr. Power Syst. Res.*, vol. 190, Jan. 2021, Art. no. 106767, doi: 10.1016/j.epsr.2020.106767.

[4] B. Liu, Z. Li, X. Chen, Y. Huang, and X. Liu, "Recognition and vulnerability analysis of key nodes in power grid based on complex network centrality," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 65, no. 3, pp. 346–350, Mar. 2018, doi: 10.1109/TCSII.2017.2705482.

[5] L. Wang, X. Xie, Q. Jiang, H. Liu, Y. Li, and H. Liu, ''Investigation of SSR in practical DFIG-based wind farms connected to a series-compensated power system,'' *IEEE Trans. Power Syst.*, vol. 30, no. 5, pp. 2772–2779, Sep. 2015, doi: 10.1109/TPWRS.2014.2365197.

[6] L. Wang, X. Xie, H. Liu, Y. Zhan, J. He, and C. Wang, ''Review of emerging SSR/SSO issues and their classifications,'' *J. Eng.*, vol. 2017, no. 13, pp. 1666–1670, Jan. 2017, doi: 10.1049/joe.2017.0615.

[7] Y. Cheng, L. Fan, J. Rose, S.-H. Huang, J. Schmall, X. Wang, X. Xie, J. Shair, J. R. Ramamurthy, N. Modi, C. Li, C. Wang, S. Shah, B. Pal, Z. Miao, A. Isaacs, J. Mahseredjian, and J. Zhou, ''Real-world subsynchronous oscillation events in power grids with high penetrations of inverter-based resources,'' *IEEE Trans. Power Syst.*, vol. 38, no. 1, pp. 316–330, Jan. 2023, doi: 10.1109/TPWRS.2022.3161418.

[8] V. Mohale and T. R. Chelliah, ''Impact of fixed/variable speed hydro, wind, and photovoltaic on sub-synchronous torsional oscillation—A review,'' *Sustainability*, vol. 15, no. 1, p. 113, Dec. 2022, doi: 10.3390/su15010113.

[9] M. Abdeen, H. Li, S. Kamel, A. Khaled, M. El-Dabah, M. Kharrich, and H. F. Sindi, ''A recent analytical approach for analysis of sub-synchronous resonance in doubly-fed induction generator-based wind farm,'' *IEEE Access*, vol. 9, pp. 68888–68897, 2021, doi: 10.1109/ACCESS.2021.3075965.

[10] W. Chen, X. Xie, D. Wang, H. Liu, and H. Liu, ''Probabilistic stability analysis of subsynchronous resonance for series-compensated DFIG-based wind farms,'' *IEEE Trans. Sustain. Energy*, vol. 9, no. 1, pp. 400–409, Jan. 2018, doi: 10.1109/TSTE.2017.2737599.

[11] M. Abdeen, H. Li, M. A. Mohamed, S. Kamel, B. Khan, and Z. Chai, ''Sub-synchronous interaction damping controller for a series-compensated DFIG-based wind farm,'' *IET Renew. Power Gener.*, vol. 16, no. 5, pp. 933–944, Apr. 2022, doi: 10.1049/rpg2.12400.

[12] H. Noh, H. Cho, S. Choi, and B. Lee, ''Mitigating subsynchronous torsional interaction using geometric feature extraction method,'' *Sustainability*, vol. 14, no. 23, p. 16110, Dec. 2022, doi: 10.3390/su142316110.

[13] N. Verma, N. Kumar, S. Gupta, H. Malik, and F. P. García Márquez, ''Review of sub-synchronous interaction in wind integrated power systems: Classification, challenges, and mitigation techniques,'' *Protection Control Mod. Power Syst.*, vol. 8, no. 1, p. 17, Dec. 2023, doi: 10.1186/s41601-023-00291-0.

[14] IEEE Power & Energy Society PES-TR80. (2020). *Wind Energy Systems Sub-Synchronous Oscillations: Events and Modeling*. [Online]. Available: https://resourcecenter.ieee-pes.org/publications/technical-reports/pes_tp_tr80_amps_wsso_070920#

[15] R. Devarapalli, N. K. Sinha, and F. P. García Márquez, ''A review on the computational methods of power system stabilizer for damping power network oscillations,'' *Arch. Comput. Methods Eng.*, vol. 29, no. 6, pp. 3713–3739, Oct. 2022, doi: 10.1007/s11831-022-09712-z.

[16] X. Xie, W. Liu, H. Liu, Y. Du, and Y. Li, ''A system-wide protection against unstable SSCI in series-compensated wind power systems,'' *IEEE Trans. Power Del.*, vol. 33, no. 6, pp. 3095–3104, Dec. 2018, doi: 10.1109/TPWRD.2018.2829846.

[17] S. Rezaei, ''An adaptive algorithm based on subharmonic and time domain analysis to prevent mal operation of overcurrent relay during subsynchronous resonance,'' *IEEE Trans. Ind. Appl.*, vol. 54, no. 3, pp. 2085–2096, Jun. 2018, doi: 10.1109/TIA.2018.2797878.

[18] X. Zheng, Z. Xu, and J. Zhang, ''A supplementary damping controller of TCSC for mitigating SSR,'' in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2009, pp. 1–5, doi: 10.1109/PES.2009.5275956.

[19] H. A. Mohammadpour and E. Santi, ''Modeling and control of gate-controlled series capacitor interfaced with a DFIG-based wind farm,'' *IEEE Trans. Ind. Electron.*, vol. 62, no. 2, pp. 1022–1033, Feb. 2015, doi: 10.1109/TIE.2014.2347007.

[20] M. Darabian and A. Jalilvand, ''Designing a wide area damping controller to coordinate FACTS devices in the presence of wind turbines with regard to time delay,'' *IET Renew. Power Gener.*, vol. 12, no. 13, pp. 1523–1534, Oct. 2018, doi: 10.1049/iet-rpg.2017.0602.

[21] H. A. Mohammadpour and E. Santi, ''Sub-synchronous resonance analysis in DFIG-based wind farms: Mitigation methods—TCSC, GCSC, and DFIG controllers—Part II,'' in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Sep. 2014, pp. 1550–1557, doi: 10.1109/ECCE.2014.6953603.

[22] M. Mokhtari, J. Khazaei, and D. Nazarpour, ''Sub-synchronous resonance damping via doubly fed induction generator,'' *Int. J. Electr. Power Energy Syst.*, vol. 53, pp. 876–883, Dec. 2013, doi: 10.1016/j.ijepes.2013.05.054.

[23] L. Fan and Z. Miao, ''Mitigating SSR using DFIG-based wind generation,'' *IEEE Trans. Sustain. Energy*, vol. 3, no. 3, pp. 349–358, Jul. 2012, doi: 10.1109/TSTE.2012.2185962.

[24] P.-H. Huang, M. S. El Moursi, W. Xiao, and J. L. Kirtley, ''Sub-synchronous resonance mitigation for series-compensated DFIG-based wind farm by using two-degree-of-freedom control strategy,'' *IEEE Trans. Power Syst.*, vol. 30, no. 3, pp. 1442–1454, May 2015, doi: 10.1109/TPWRS.2014.2348175.

[25] A. E. Leon and J. A. Solsona, ''Sub-synchronous interaction damping control for DFIG wind turbines,'' *IEEE Trans. Power Syst.*, vol. 30, no. 1, pp. 419–428, Jan. 2015, doi: 10.1109/TPWRS.2014.2327197.

[26] A. E. Leon, ''Integration of DFIG-based wind farms into series-compensated transmission systems,'' *IEEE Trans. Sustain. Energy*, vol. 7, no. 2, pp. 451–460, Apr. 2016, doi: 10.1109/TSTE.2015.2498312.

[27] A. O. Althobaiti, ''Proportional resonant control of three-phase grid-connected inverter during abnormal grid conditions,'' Ph.D. thesis, Newcastle Univ., Newcastle upon Tyne, U.K., 2018.

[28] J. He, Y. W. Li, F. Blaabjerg, and X. Wang, ''Active harmonic filtering using current-controlled, grid-connected DG units with closed-loop power control,'' *IEEE Trans. Power Electron.*, vol. 29, no. 2, pp. 642–653, Feb. 2014, doi: 10.1109/TPEL.2013.2255895.

[29] Z. Pan, F. Dong, J. Zhao, L. Wang, H. Wang, and Y. Feng, ''Combined resonant controller and two-degree-of-freedom PID controller for PMSLM current harmonics suppression,'' *IEEE Trans. Ind. Electron.*, vol. 65, no. 9, pp. 7558–7568, Sep. 2018, doi: 10.1109/TIE.2018.2793232.

[30] H. Li, M. Abdeen, Z. Chai, S. Kamel, X. Xie, Y. Hu, and K. Wang, ''An improved fast detection method on subsynchronous resonance in a wind power system with a series compensated transmission line,'' *IEEE Access*, vol. 7, pp. 61512–61522, 2019, doi: 10.1109/ACCESS.2019.2915545.

[31] M. Abdeen, A. Emran, A. Moustafa, D. Kamal, R. Hassan, E. Hassan, F. Ahmed, M. Mahmoud, S. Kamel, and F. Jurado, ''Investigation on TCSC parameters and control structure for SSR damping in DFIG-based wind farm,'' in *Proc. 12th Int. Renew. Energy Congr. (IREC)*, Oct. 2021, pp. 1–5, doi: 10.1109/IREC52758.2021.9624934.

[32] S. Ul Islam and S. Kim, ''Design and implementation of optimal control scheme for DFIG based wind plant to mitigate sub-synchronous resonance issues,'' *IEEE Access*, vol. 11, pp. 141162–141171, 2023, doi: 10.1109/ACCESS.2023.3341884.

[33] J. Shair, X. Xie, and G. Yan, ''Mitigating subsynchronous control interaction in wind power systems: Existing techniques and open challenges,'' *Renew. Sustain. Energy Rev.*, vol. 108, pp. 330–346, Jul. 2019, doi: 10.1016/j.rser.2019.04.003.

[34] H. A. Mohammadpour and E. Santi, ''SSR damping controller design and optimal placement in rotor-side and grid-side converters of series-compensated DFIG-based wind farm,'' *IEEE Trans. Sustain. Energy*, vol. 6, no. 2, pp. 388–399, Apr. 2015, doi: 10.1109/TSTE.2014.2380782.

EZZEDDINE TOUTI received the B.S. degree in electrical engineering from the Higher National College of Engineers of Tunis, Tunisia, in 1997, the master's degree in electrical engineering from the National College of Engineers of Tunis, Tunisia, in 2005, and the joint Ph.D. degree in induction generators wind turbine, power quality, and electric drives from the National College of Engineers of Monastir, Tunisia, and Artois University, France, in 2013. In 2005, he joined the Laboratory of Industrial Systems Engineering and Renewable Energies (LISIER), University of Tunis, Tunisia, as a Researcher Faculty Member. Currently, he is an Associate Professor with the College of Engineering, Northern Border University. His research interests include renewable energy, the control of electrical systems smart grids, electric vehicles, and power electronics.

MOHAMED ABDEEN received the B.Sc. and M.Sc. degrees in electrical engineering from Al-Azhar University, Cairo, Egypt, in 2011 and 2016, respectively, and the Ph.D. degree from Chongqing University, Chongqing, China, in 2020. He is currently an Assistant Professor with the Department of Electrical Engineering, Al-Azhar University. His research interests include power system stability, optimization, and control.

MAHMOUD A. EL-DABAH was born in Kafr El-Shaikh, in 1985. He received the B.Sc., M.Sc., and Ph.D. degrees from the Faculty of Engineering, Al-Azhar University, Cairo, Egypt, in 2007, 2012, and 2016, respectively. He is currently an Associate Professor with the Electrical Engineering Department, Faculty of Engineering, Al-Azhar University. His research interests include power system operation, control, planning and optimization, and renewable energy resources integration in electrical power systems. He is a Reviewer of several journals, such as IEEE ACCESS, *Energies*, IET, and different springer nature journals.

HABIB KRAIEM received the Ph.D. degree in electrical engineering from the National Engineering School of Gabes, Tunisia, in October 2010. He joined the Department of Electrical, Higher Institute of Industrial Systems, Gabes, Tunisia. He is currently with the Department of Electrical Engineering, Faculty of Engineering, Northern Border University, Saudi Arabia. His current research interests include power electronics, machine drives, automatic control, and renewable energy.

AHMED M. AGWA was born in Egypt, in 1979. He received the B.Sc. (Hons.), M.Sc., and Ph.D. degrees in electrical engineering from the Faculty of Engineering, Al-Azhar University, Cairo, Egypt, in 2003, 2009, and 2012, respectively. He is currently an Associate Professor with Northern Border University, Saudi Arabia (on leave from Al-Azhar University, since 2018). He has published many articles in specialized and reputable journals. He was ranked of the highest-published researchers at Northern Border University, in 2022. He has performed some electrical designs of strategic plans for the Egyptian Electricity Ministry in New Cities, from 2006 to 2007. His research interests include power system analysis, renewable energy systems, and artificial intelligence applications in electrical power engineering.

ABDULAZIZ ALANAZI received the B.Sc. degree (Hons.) in electrical engineering from the King Fahd University of Petroleum and Minerals, Saudi Arabia, in 2006, and the M.Sc. and Ph.D. degrees in electrical engineering from the University of Denver, Denver, CO, USA, in 2015 and 2019, respectively. He is currently an Assistant Professor with the Department of Electrical Engineering, Northern Border University, Saudi Arabia. His research interests include microgrids, smart grids, renewable energy, energy storage systems, and power system planning and operation.

TAREK I. ALANAZI is currently an Assistant Professor with the Department of Physics, Northern Border University, Saudi Arabia. During his academic journey, he became a part of the Materials and Biological Physics Group a renowned figure in the field of perovskite and organic solar cells. This group is recognized for its outstanding research quality and was awarded the Research Excellence Framework accolade, in 2021, ranking first in the U.K. Through his experimental work, he identified the superior structural and optoelectronic properties of triple-cation perovskites, resulting in improved film, and device stability. His research also delved into the role of hole transport materials, highlighting the importance of further investigation in this area and the use of charge-selective interlayers to achieve both high efficiency and long-term stability in perovskite solar cells. He expanded his research to include the simulation of various types of solar cells.