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Research article

Analysis and simulation of sub-synchronous resonance in steam turbine on a series-compensated network

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Abstract

In series compensation networks (where capacitors are added to transmission lines to improve power transfer), transient events (such as faults or disturbances) can amplify the torque on the turbine generator shafts. Series capacitors are used to increase the power transfer capability by compensating for some of the reactance in the transmission lines. The use of series capacitors may cause the phenomenon of sub-synchronous resonance (SRR). This phenomenon may cause torsional oscillations in the turbine-generator shaft system and electrical oscillations with sub-synchronous frequency. In this paper, the objective is to study and analyze the phenomenon of sub-synchronous resonance in a steam turbine in a series compensated power system. The system has a synchronous generator connected to an infinite bus via two transmission lines, one with series compensation. A three-phase fault followed by fault recovery excites the torsional modes of the system, leading to a potential torque amplification on the generator shaft. The mechanical system is modeled as a three-mass system consisting of a generator, a low-pressure turbine, and a high-pressure turbine. The system starts in steady state. A three-phase fault is considered for 0.017 seconds (starting at 0.1 seconds). This excites torsional modes and leads to oscillations in the shaft torques. Increasing the compensation percentage reduces the series capacitor voltage and phase current, but increases the magnitude of the oscillations in the masses and mass velocities. The simulation results are shown using the MATLAB Simulink implementation of the studied system model.

Keywords: Compensation network, Multi-mass shaft, Steam turbine, Sub-synchronous resonance.

1- Introduction

In recent years, the development and application of renewable energy generation technologies have been expanding [1-3]. The rapid increase in the penetration of renewable energy due to its high availability and security indicates that renewable energy is becoming a major energy source. The expansion of renewable energy can effectively reduce the concern of energy demand. The expansion of power electronics-based energy generation will cause changes in the dynamic characteristics of the power system, which will lead to increased susceptibility to sub-synchronous oscillations (SSO) [4-11].

Power system outages can actually be caused by insufficient oscillation damping, which can lead to instability and subsequent failures. Sub-synchronous oscillation in power systems can be amplified and sustained due to physical interactions, which involve the exchange of energy between two power facilities [12,13]. Such phenomena are called sub-synchronous interactions (SSI) [14,15], which can be classified into sub-synchronous torsional interactions (SSTI) [16,17], sub-synchronous control interactions (SSCI) [18,19], and sub-synchronous resonance (SSR) [20,21]. Sub-synchronous oscillation is a harmful phenomenon, and it exhibits oscillations with a frequency of 5 to 55 Hz with a fundamental frequency of 60 Hz, and is different from low frequency oscillation (LFO) that occurs at around 0.5 Hz to 3 Hz. Sub-synchronous oscillation involves simultaneous oscillations between two or more power system elements. Sub-synchronous oscillations can cause instability in the operation of entire power systems, and therefore, there is a possibility of damaging the electrical equipment of the systems [22,23]. Methods for analyzing sub-synchronous oscillations can be divided into two groups: frequency domain analysis and time domain simulation methods [24,25]. Sub-synchronous oscillations include torsional interference with power system controls, torsional fatigue tolerance due to network switching, and sub-synchronous resonance. Sub-synchronous resonance is a condition of an electric power system, in which the electrical network exchanges significant energy with a generator-turbine at one or more natural frequencies of the system below the synchronous frequency of the power system [26,27]. There are three types of sub-synchronous resonances: induction generator effect (SSR-IGE), torsional interaction (SSR-TI), and torque amplification (SSR-TA) [28,29]. The classification of sub-synchronous resonance is shown in Fig. 1 [30]. SSR-IGE involves purely electrical self-excitation without significant mechanical interference. This occurs when sub-synchronous currents in the generator armature create a rotating magnetic field that induces voltages in the rotor at sub-synchronous frequency. In steam turbines, IGE is more likely in systems with high series compensation, where the generator behaves like an induction generator at sub-synchronous frequencies, potentially sustaining unstable currents.

SSR-TI is the most common and severe form of SSR in steam turbines, involving the coupled interaction between the mechanical torsional modes of the turbine shaft and the electrical network. Steam turbines are particularly vulnerable due to their large shaft masses and low damping in certain modes, often caused by network disturbances such as faults. SSR-TA is caused by large transient disturbances in the network, such as short circuits or switching events. This type causes sudden, high-magnitude torque pulses on the shaft that can be amplified if the complement of the electrical resonance frequency is aligned with the torsional mode. In steam turbines, SSR-TA is a concern in highly compensated lines, where peak torques can be double or more compared to uncompensated systems [31-35].

Sub-synchronous resonance can be caused by series compensated lines, which will lead to damage to the turbo-generator shaft [36,37].

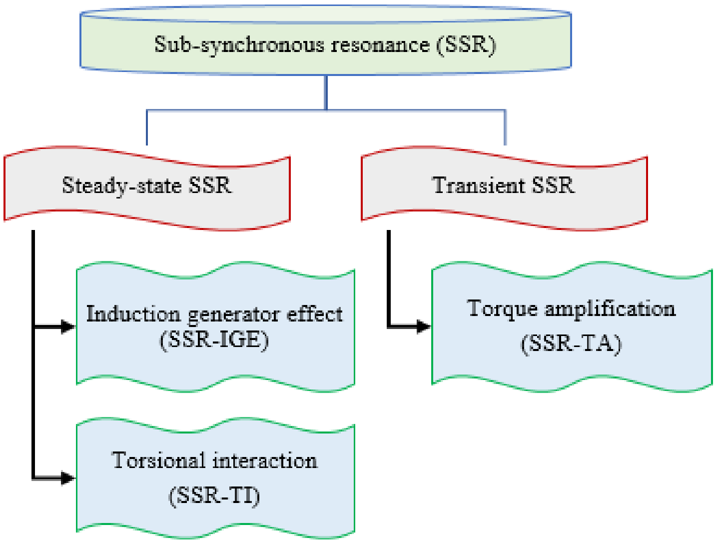


Fig. 1 Sub-synchronous resonance classification

Literature review

Any power system condition where energy exchange at a given sub-synchronous frequency is possible may cause SSR oscillations. There are many ways in which the system and the generator can interact at sub-synchronous frequencies. The increasing penetration of renewable energy sources has led to the widespread use of series compensators. Series compensated capacitors in AC transmission lines not only increase the overall load carrying capacity of the system, but also improve transient stability and power control, and reduce losses. However, capacitors can cause sub-synchronous resonance due to their interaction with turbine generators, which can lead to shaft failure. The phenomenon of sub-synchronous reson-ance (SSR) in series compensated trans-mission networks has been investigated in various studies [38-41]. A number of studies are mentioned in this section.

Sub-synchronous resonance in power systems where a steam turbine-generator is connected to a long transmission line with series compensation is investigated in [42], which evaluates the distributed static series compensator (DSSC) [a device from the distributed flexible ac transmission system (D-FACTS) family] as a mitigation tool, enhanced with advanced controllers. Two controllers (PSO-based CDC and FLBDC) are designed for DSSC to effectively suppress SSR. The performance of each controller is evaluated under normal and severe fault conditions. A custom performance index (PI) is considered to quantify the damping effectiveness based on the power system dynamics. Simulation results show that FLBDC outperforms PSO-based CDC by providing superior damping and stability, especially in severe transient scenarios.

A solution for suppressing sub-synchronous resonance in wind farms under weak grid conditions, which is caused by impedance interactions between the wind farm and the grid, is discussed in [43], where a synchronous compensator with a battery energy storage system (STATCOM/BESS) connected to the grid in parallel is used to mitigate SSR. A virtual synchronous generator strategy is used to increase grid rigidity. This strategy allows the STATCOM/BESS to operate with low rated active power and high rated reactive power, reducing the battery capacity requirement by more than 50%. This reduction reduces costs and improves system security. The control strategy ensures that the grid and STATCOM/BESS impedances are primarily inductive, resulting in a lower parallel impedance compared to the grid alone, effectively increasing the grid rigidity from an impedance perspective.

Torque amplification can lead to excessive loss of fatigue life or sudden shaft failure. A scheme for instantaneous transient torque protection is presented in [44], which is designed to increase the safety of turbine generator shafts in power networks with series compensation. In this method, real-time shaft speed measurements are used to estimate the transient torque. The estimated torque is compared with predefined trip thresholds to decide whether to trip the generator and prevent damage.

The ability of power converters in doubly fed induction generator wind farms to reduce the effects of sub-synchronous resonance has been investigated in [45], where the design of the auxiliary SSR damping controller and the selection of control signals have been considered. Simulation results using MATLAB Simulink show simultaneous improvement of both sub-synchronous and super-synchronous resonance modes.

The graphical state space-based impedance modeling method in [46] is used to determine the accurate impedance model of the thermal power unit, which includes the shaft torsion characteristics. The responses of each torsion mode of the thermal power unit to the wind force fluctuation are analyzed in time domain simulation. The simulation results show that the possibility of torsional oscillation is possible when the wind power oscillation frequency approaches the torsional mode frequency, but the risks will be different in different torsional modes, which can be investigated through the shaft torsion characteristics in the thermal power unit's impedance.

The phenomenon of sub-synchronous oscillations in a wind farm based on doubly fed induction generators is investigated in [47]. The voltage waveform recorded during the sub-synchronous resonance event is analyzed, and then an equivalent model of the system including the wind farm, static synchronous compensator, and power grid is determined. The simulation results provide a criterion for the occurrence of sub-synchronous resonance in the time domain and spectrum analysis.

A method for enhancing SSR detection by combining the frequency analysis of the generator magnetic flux linkage (an electrical signal) with the shaft speed (a mechanical signal) is presented in [48]. In this method, the magnetic flux linkage provides a local and easily accessible indicator without the need for a communication channel, but its use requires invasive sensors.

Sub-synchronous resonance in series compensated power systems has been investigated in [49], where the influence of various parameters on the torsional mode damping is shown. In this study, eigenvalue analysis, validated with PSCAD simulations, is used to evaluate the effects of series compensation levels, generator parameters, speed control systems, and excitation systems on the characteristics of SSRs. The simulation results show the dominant influence of series compensation levels on torsional mode damping, such that the generator, speed control, and excitation system parameters play a role, especially in low-frequency oscillations.

Structure of the paper

Sub-synchronous resonance occurs when, between the electrical resonance frequency f_{er} and the synchronous frequency f_s, the complementary frequency (the difference between the two frequencies f_s and f_{er}) matches the rotor frequency. As the level of transmission line compensation increases, the resonance point will move towards the system frequency, exposing the power plant to potential problems of sub-synchronous resonance. Sub-synchronous resonance can cause sustained or increasing oscillations that potentially lead to turbine-generator shaft failure due to fatigue. In this paper, the aim of the study of sub-synchronous resonance in a steam turbine in a compensated network is to study.

The power system under study consists of a synchronous generator connected to an infinite bus through two parallel transmission lines. To investigate the effect of series compensation, one of the two parallel lines is compensated with a capacitor. By implementing the power system under study in the MATLAB Simulink environment, the simulation results in the time domain for different synchronisms are shown. The simulation results show the speed deviations and torques transmitted between the shaft masses.

The highlights of this study include the following:

- The phenomenon of sub-synchronous resonance in a series compensated power system connected to an infinite bus via two lines, one with series compensation, has been analyzed.
- The effect of compensating series capacitor on sub-synchronous oscillations is shown.
- The effects of transmission line impedance changes on simulation results are investigated.

The structure of the paper is as follows. In the section 2, the model of the power system under study is shown. In the section 3, the analysis and discussion of the simulation results using MATLAB software are presented. Finally, in the section 4, conclusions and suggestions for further research are expressed.

2- Model of the studied power system

Sub-synchronous resonance is a phenomenon in which the electrical network of the power system interacts with the mechanical system (turbine-generator shaft) at frequencies lower than the synchronous frequency of the system. Adding series capacitors to the transmission lines increases their power transfer capability. However, it can also cause sub-synchronous resonance. The interaction between the electrical and mechanical systems during sub-synchronous resonance can cause the generator shaft to experience amplified torsional oscillations, potentially leading to damage [50,51].

The studied power system consists of a single synchronous generator connected to an infinite bus via two parallel transmission lines (Fig. 2). One of the transmission lines is compensated using a series capacitor. After applying and removing the three-phase fault, series compensation can induce sub-synchronous oscillations, which can lead to torque amplification in the multi-mass shaft. The turbine-generator shaft is considered as a system of three interconnected masses, namely: a generator, a low-pressure turbine, and a high-pressure turbine.

In turbines with long lengths, there is a possibility that different parts will have different angles relative to each other. A steam turbine is made up of various parts, and the discussion of torsional oscillations is very important in it. Torsional oscillations are modeled by choosing the angles of different parts of the system as follows:

$$\frac{d^2}{dt^2}\theta = -[K]\theta \tag{1}$$

where K is stiffness coefficient matrix of the system and θ are the angle vectors of the masses forming the system. The eigenvectors of the K matrix show how the natural frequencies are distributed on the rotor. Also, the eigenvectors of the K matrix show how the natural frequencies are distributed on the rotor.

The natural frequency (torsional oscillation frequency) of the i^{th} mode is determined by the eigenvalues of the mass stiffness coefficient matrix, and is given in Hz by the following equation:

$$f_i = \frac{\sqrt{2\pi f_b |\lambda_i|}}{2\pi} \tag{2}$$

where f_b is the nominal frequency and λ_i is the i^{th} eigenvalue of the stiffness coefficient matrix of the system. In the system under study, considering three masses, the stiffness coefficient matrix will have three eigenvalues.

The zero mode represents a free rotating body, and when the generator is connected to the system, the frequency of this mode increases, which is the rotor oscillation frequency. Ignoring the rotational friction coefficient and considering the angles of the three different masses of the high-pressure turbine (θ_{HP}), low-pressure turbine (θ_{LP}), and generator (θ_G), the equations of torsional oscillations are expressed as follows:

$$\ddot{\theta} = -\underbrace{\begin{bmatrix} \frac{K_{H-L}}{J_{HP}} & -\frac{K_{H-L}}{J_{HP}} & 0 \\ -\frac{K_{H-L}}{J_{LP}} & \frac{K_{H-L}+K_{L-G}}{J_{LP}} & -\frac{K_{L-G}}{J_{LP}} \\ 0 & -\frac{K_{L-G}}{J_G} & \frac{K_{L-G}}{J_G} \end{bmatrix}}_{K}\theta$$

$$\theta = \begin{bmatrix}\theta_{HP} & \theta_{LP} & \theta_{GE}\end{bmatrix}^T \tag{3}$$

3- Analysis and discussion of simulation results

When the electrical resonance frequency of the system, under the influence of the series capacitor, matches or is close to the mechanical resonance frequency of the turbine-generator shaft, the system becomes susceptible to SSR. This frequency matching allows energy exchange between the electrical and mechanical systems at sub-synchronous frequencies. The system under study consists of a 600 MVA, 22 kV, 60 Hz, 3600 rpm generator connected to an infinite bus through two transmission lines, one of which is a 55% series compensated transmission line. The reactance of the series capacitor is 0.08 per unit.

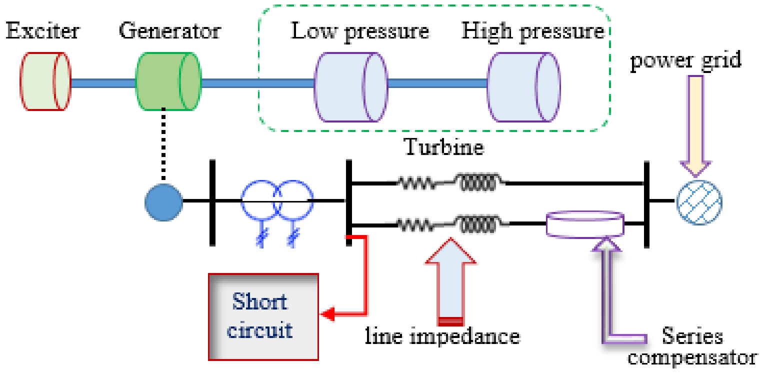


Fig. 2 Diagram of the studied power system

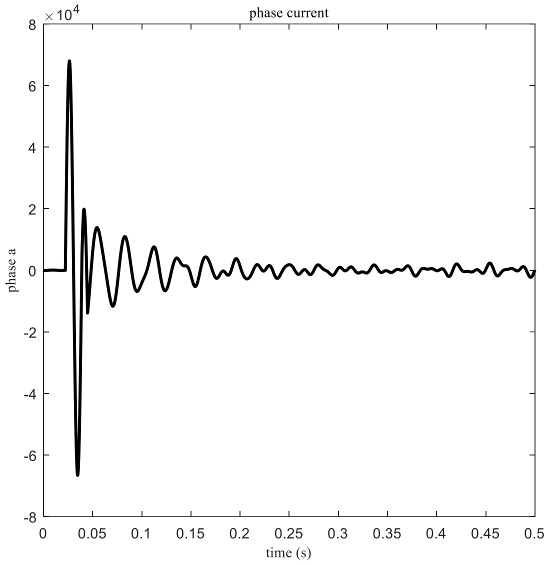
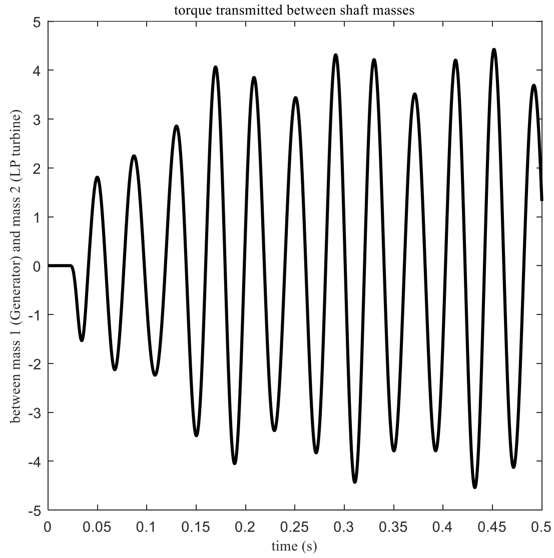
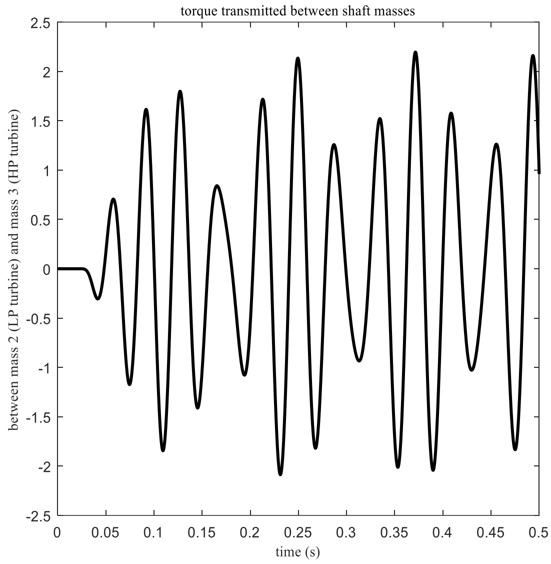


Fig. 3 The changes in current in phase a



(a) Generator and low pressure turbine masses



(b) Low pressure turbine and High pressure turbine masses

Fig. 4 Torque between different masses

Table 1: Base parameters

Parameters	Value	Unit
Base voltage (Vrms ph-ph)	500	KV
Frequency	60	Hz
Base power	100	MVA
Base impedance	2500	Ω
Base current	200	A
Base inductance	6.6315	H
Base capacitor	9.42×10^{5}	F

The sub-synchronous state created by the compensation capacitor after applying and removing the three-phase fault excites the oscillating torsional modes of the multi-mass shaft, and the torque amplification phenomenon is observed. The mechanical system is modeled with three masses, which include the generator (mass 1), the low-pressure turbine (mass 2), and the high-pressure turbine (mass 3).

The nominal speed of the synchronous machine is 3600 rpm. The base values are given in Table 1. The changes in phase a current are shown in Fig. 3. The torque between the masses of the generator-medium pressure turbine and the medium pressure turbine-low pressure turbine is shown in Fig. 4. As can be seen, the peak torque between masses 1 and 2 is more than 4 per unit and the peak torque between masses 2 and 3 is more than 2 per unit. The changes in the fault current in phase a are shown in Fig. 5.

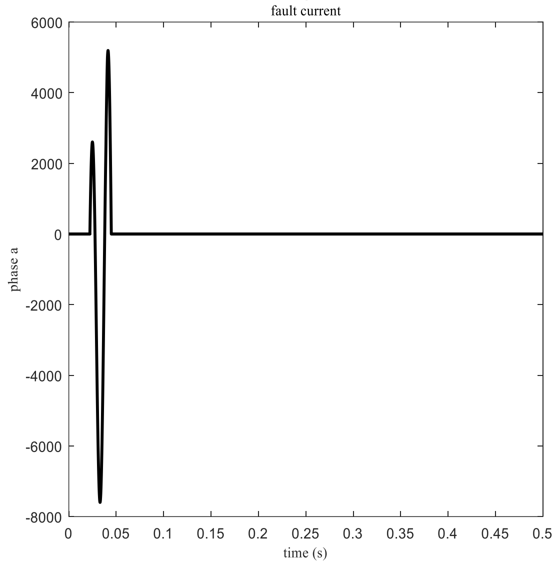
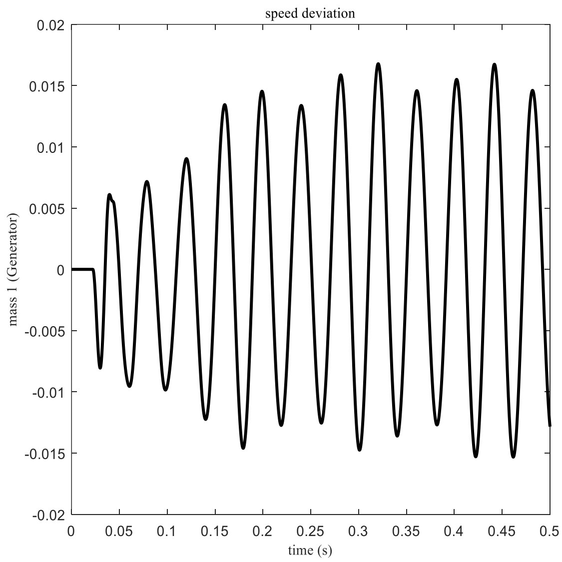
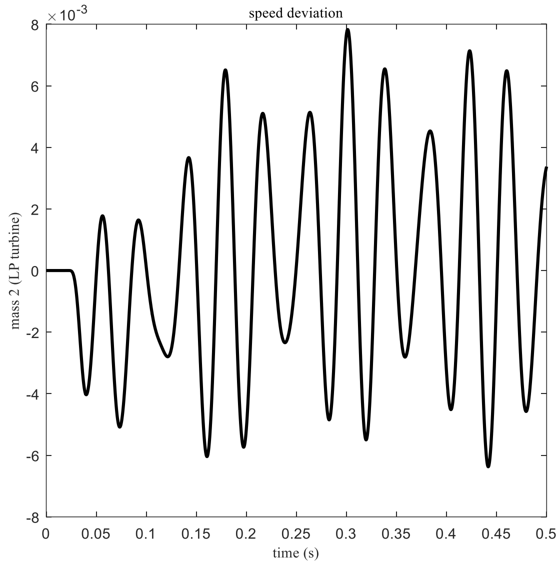


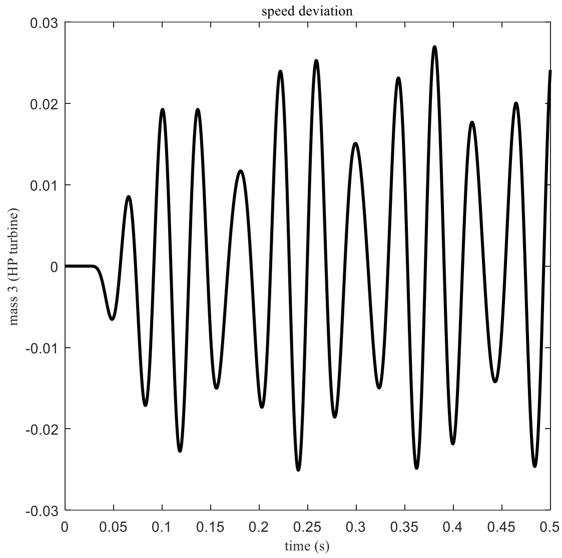
Fig. 5 Fault current changes in phase a



(a) Generator

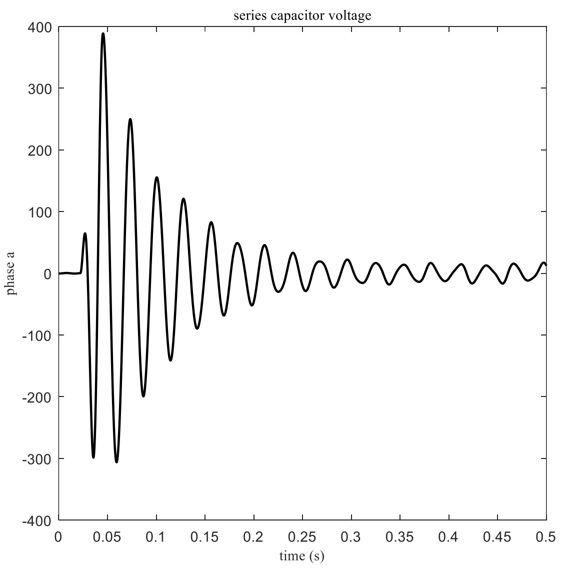


(b) Low pressure turbine

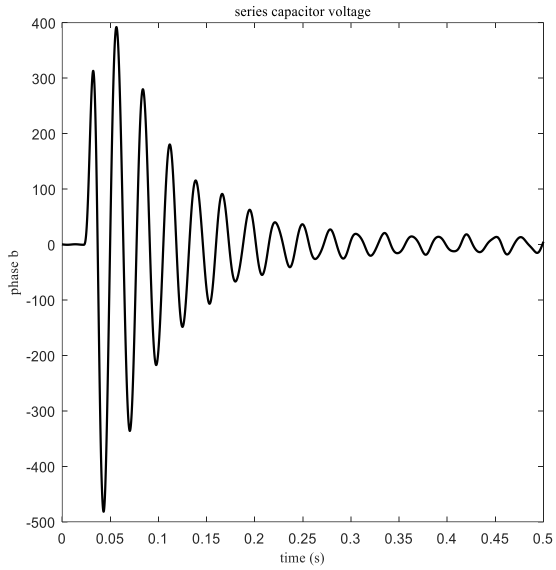


(c) High pressure turbine

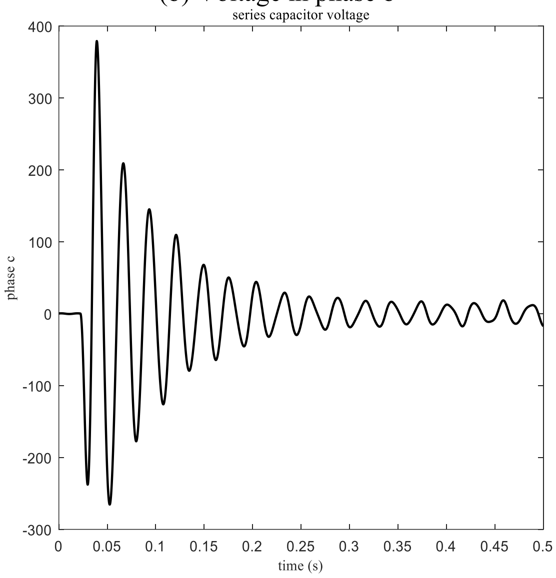
Fig. 6 Speed changes in different masses



(a) Voltage in phase a

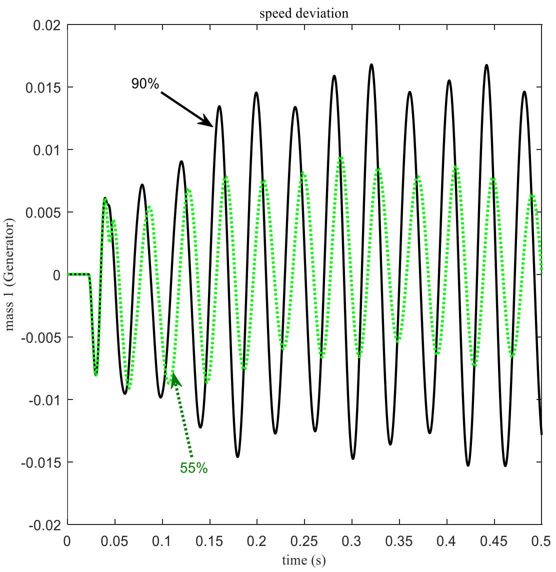


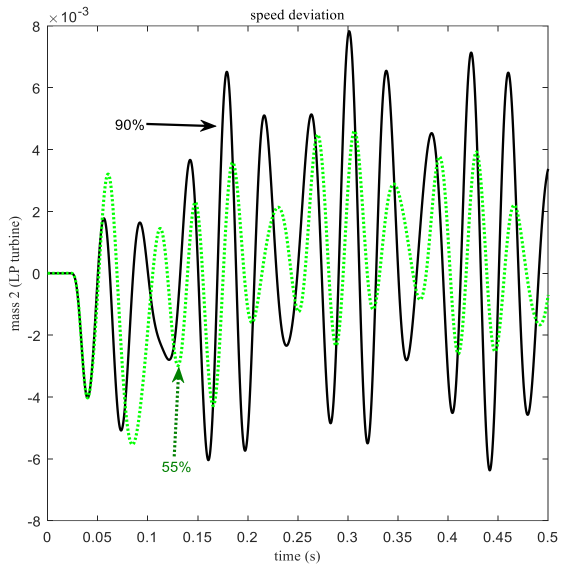
(b) Voltage in phase b



(c) Voltage in phase c

Fig. 7 Series capacitor compensation voltage





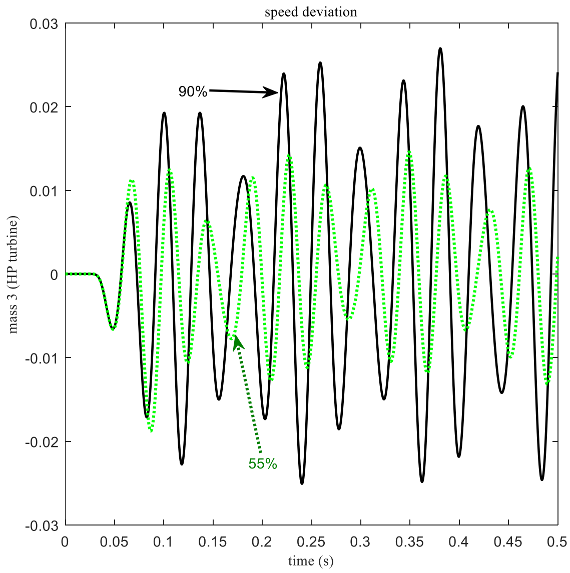


Fig. 8 The effect of compensation changes on the speed of different masses

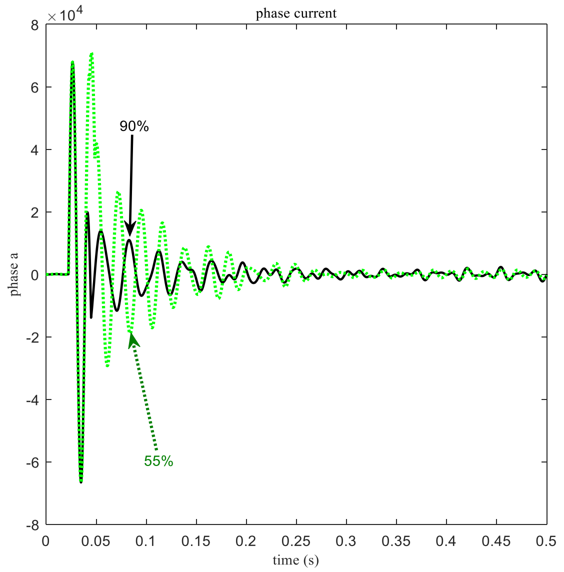


Fig. 9 Effect of changing the compensation percentage on phase current

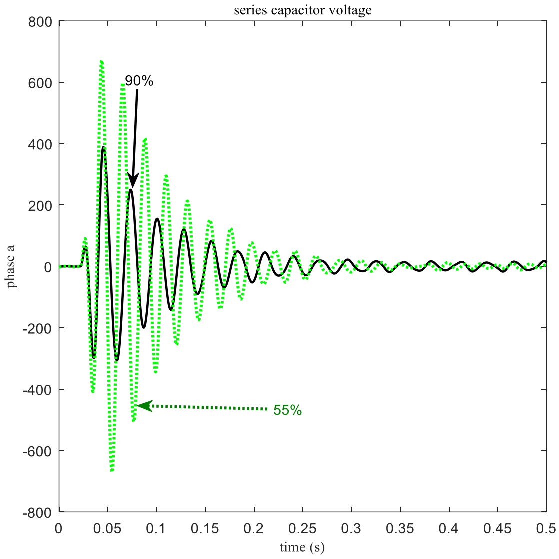


Fig. 10 Effect of changing the compensation percentage on series capacitor voltage

The changes in the speed of different masses are shown in Fig. 6. The series capacitor compensation voltage in different phases is shown in Fig. 7.

Fig. 5 shows the fault current passing through the fault impedance. It is natural that during the fault there is only current and after the fault is cleared the current will be cut off. But in Fig. 3 the phase current is shown. Phase a is in the circuit before and after the fault. After the fault is cleared the current in phase a progresses towards damping and will reach a permanent state.

The effect of varying the compensation on the velocities of the different masses is shown in Fig. 8. As can be seen, in general, increasing the compensation percentage will increase the size of the velocity fluctuations in the three masses, and will not have much effect on the period of the fluctuations.

Figures 9 and 10 show the current in phase a and the series capacitor voltage in phase a, respectively. As can be seen, increasing the compensation percentage has reduced the magnitude of the phase current and the magnitude of the series capacitor voltage.

4- Conclusion

One of the methods to increase the efficiency of existing power systems is to use a series capacitor as a series compensator in the transmission system. Sub-synchronous resonance in series-compensated transmission systems is a phenomenon in which electrical and mechanical oscillations at frequencies below the synchronous frequency can lead to instability and possible damage to turbine generators. This phenomenon occurs when the electrical system (including series compensation) and the mechanical system (turbine-generator) exchange energy at the resonant frequency.

References

[1] Yaghoubi, S., Dehghani, M., Moazzami, M., Zanjani, M.A., Moradian, M.R. (2024). A review on the classification of operating modes in microgrid systems. *Journal of Simulation and Analysis of Novel Technologies in Mechanical Engineering*, 16, 27-34.

[2] Pagard, E., Shojaeian, S., Rezaei, M.M. (2023). Improving power system low-frequency oscillations damping based on multiple-model optimal control strategy using polynomial combination algorithm. *Energy Reports*, 10, 1228-1237.

[3] Liu, Z., Li, D., Wang, W., Wang, J., Gong, D. (2024). A review of the research on the wide-band oscillation analysis and suppression of renewable energy grid-connected systems. *Energies*, 17(8), 1809.

[4] Sharifiyana, O., Dehghani, M., Shahgholian, G., Mirtalaei, S.M.M., Jabbari, M., Non-isolated boost converter with new active snubber structure and energy recovery capability. *Journal of Circuits, Systems and Computers*, 32(5), 2350084.

[5] Gu, K., Wu, F., Zhang, X.P. (2019). Sub-synchronous interactions in power systems with wind turbines: A review. *IET Renewable Power Generation*, 13(1), 4-15.

[6] Haghshenas, G., Mirtalaei, S.M.M., Mordmand, H., Shahgholian, G. (2019). High step-up

boost-flyback converter with soft switching for photovoltaic applications. *Journal of Circuits, Systems, and Computers*, 28(1), 1-16.

[7] Vyas, B., Maheshwari, R.P., Das, B. (2014). Protection of series compensated transmission line: Issues and state of art. *Electric Power Systems Research*, 107, 93-108.

[8] He, K., Tang, Y., Hu, M., Guo, L. (2024). Sub-synchronous oscillation suppression strategy for virtual synchronous generators based on dual-loop sliding mode control. *Sustainable Energy Technologies and Assessments*, 65, 103794.

[9] Liu, Y., Guo, G., Wang, X., Wang, H., Wang, L. (2022). Sub-synchronous oscillation suppression strategy based on impedance modeling by attaching virtual resistance controllers for doubly-fed induction generator. *Electronics*, 11(14), 2272.

[10] Sewdien, V., Wang, X., Torres, J.R., Meijden, M. (2020). Critical review of mitigation solutions for SSO in modern transmission grids. *Energies*, 13(13), 3449.

[11] Jewel, A.S., Roy, T.K. (2021). A hybrid reaching law based double-integral sliding mode controller design to mitigate SSR effects in a DFIG-based wind farm. *Proceeding of the IEEE/ICEEICT*, 1-5, Dhaka, Bangladesh.

[12] Mohale, V., Sonandkar, S., Chelliah, T.R., Large asynchronous hydro generating systems connected to TCSC compensated transmission lines (Simulation with experimental validation): A review on SSO perspectives. *Electric Power Systems Research*, 219, 109257.

[13] Orman, M., Balcerek, P., Orkisz, M. (2012). Effective method of subsynchronous resonance detection and its limitations. *International Journal of Electrical Power and Energy Systems*, 43(1), 915-920.

[14] Badrzadeh, B., Sahni, M., Zhou, Y., Muthumuni, D., Gole, A. (2013). General methodology for analysis of sub-synchronous interaction in wind power plants. *IEEE Trans. on Power Systems*, 28(2), 1858-1869.

[15] Suriyaarachchi, D.H.R., Annakkage, U.D., Karawita, C., Jacobson, D.A. (2013). A procedure to study sub-synchronous interactions in wind integrated power systems. *IEEE Trans. on Power Systems*, 28(1), 377-384.

[16] Zhou, H., Chen, J., Liu, Q., Hu, Y., Zhu, J. (2017). Sub-synchronous torsional interaction with VSC-HVDC affected by feed-forward compensations in current controllers. *The Journal of Engineering*, 13, 2140-2145.

[17] Venkateswarlu, S., Janaki, M., Thirumalaivasan, R., Prabhu, N. (2018) A review on damping of torsional interactions using VSC based FACTS and subsynchronous damping controller. *Annual Reviews in Control*, 46, 251-264.

[18] Han, J., Liu, C. , Liu, Z., Jatskevich, J., Shang, L., Dong, X., Dynamic-tracking damping controller for dfig-based wind farms to mitigate sub-synchronous control interactions. *IEEE Trans. on Power Electronics*, 40(1), 2248-2258.

[19] Liu, C., Han, J. (2023). Evaluation of the sub-synchronous control interaction based on the elastic energy equivalent system. *IEEE Trans. on Power Systems*, 38(4), 3897-3910.

[20] Islam, S.U., Kim, S. (2023). Design and implementation of optimal control scheme for dfig based wind plant to mitigate sub-synchronous resonance issues. *IEEE Access*, 11, 141162-141171.

[21] Li, G., Chen, Y., Luo, A., Wang, Y. (2021). An inertia phase locked loop for suppressing sub-synchronous resonance of renewable energy generation system under weak grid. *IEEE Trans. on Power Systems*, 36(5), 4621-4631.

[22] Damas, R.N., Son, Y., Yoon, M., Kim, S.Y., Choi, S. (2020). Subsynchronous oscillation and advanced analysis: A review. *IEEE Access*, 8, 224020-224032.

[23] Virulkar, V.B., Gotmare, G.V. (2016). Sub-synchronous resonance in series compensated wind farm: A review. *Renewable and Sustainable Energy Reviews*, 55, 1010-1029.

[24] Perera, U., Oo, A.M.T., Zamora, R. (2022). Sub synchronous oscillations under high penetration of renewables- A review of existing monitoring and damping methods, challenges, and research prospects, *Energies*, 15(22), 8477.

[25] Shi, T., Nayanasiri, D., Li, Y. (2020). Sub-synchronous oscillations in wind farms– an overview study of mechanisms and damping

methods. *IET Renewable Power Generation*, 14(19), 3974-3988.

[26] Le, T.N., Minh, C.L.T., Nguyen, P.N., Minh, V.N.H. (2025). Analysis of sub-synchronous oscillation in grid-connected wind farm and proposed improved solution. *IEEE Access*, 13, 95821-95836.

[27] Zhang, Z., Kou, P., Mei, M., Tian, R., Zhang, Y., Liang, D. (2025). Interaction analysis and damping control of sub-synchronous oscillation and medium- frequency oscillation in HVDC-connected offshore wind farm. *IEEE Trans. on Power Systems*, 40(5), 4336-4352.

[28] Tsebia, M., Bentarzi, H. (2022). Sub-synchronous torsional interaction study and mitigation using a synchro-phasors measurement unit. Engineering. *Proceedings*, 14(1), 8.

[29] Abdeen, M., Li, H., Jing, L. (2020). Improved subsynchronous oscillation detection method in a DFIG-based wind farm interfaced with a series-compensated network. *International Journal of Electrical Power and Energy Systems*, 119, 105930.

[30] Verma, N., Kumar, N., Gupta, S., Malik, H., Márquez, F.P.G. (2023). Review of sub-synchronous interaction in wind integrated power systems: classification, challenges, and mitigation techniques. *Protection and Control of Modern Power Systems Volume*, 8, 17.

[31] Du, W., Wang, Y., Wang, H. (2020). Torsional subsynchronous oscillations caused by grid-connected wind farms in a complex multi-machine power system under the condition of near strong modal resonance. *Electric Power Systems Research*, 179, 106085.

[32] Li, P., Xiong, L., Wu, F., Ma, M., Wang, J. (2019). Sliding mode controller based on feedback linearization for damping of sub-synchronous control interaction in DFIG-based wind power plants. *International Journal of Electrical Power and Energy Systems*, 107, 239-250.

[33] Bizzarri, F., Brambilla, A., Milano, F. (2018). Simplified model to study the induction generator effect of the subsynchronous resonance phenomenon. *IEEE Trans. on Energy Conversion*, 33(2), 889-892.

[34] Jennings, G.D., Harley, R.G. (1996). New index parameter for rapid evaluation of turbo-generator subsynchronous resonance susceptibility, *Electric Power Systems Research*, 37(3), 173-179.

[35] Shahgholian, G. (2013). Modeling and simulation of a two-mass resonant system with speed controller. *International Journal of Information and Electronics Engineering*, 3(5), 448-452.

[36] Ugalde-Loo, C.E., Ekanayake, J.B., Jenkins, N. (2013). Subsynchronous resonance in a series-compensated Great Britain transmission network, *IET Generation, Transmission and Distribution*, 7(3), 209-217.

[37] Tung, D.D., Dai, L.V., Quyen, L.C. (2019). Subsynchronous resonance and FACTS-novel control strategy for its mitigation. *Journal of Engineering*, 2019, 2163908.

[38] Moazzami, M., Fayazi, H., Fani, B., Jalali, S., Shahgholian, G. (2019). Simultaneous tuning of static synchronous series compensator and multi-band power system stabilizers to mitigate sub-synchronous resonances in power systems. *Majlesi Journal of Electrical Engineering*, 13(4), 89-98.

[39] Bostani, Y., alilzadeh, S., Mobayen, S., Skruch, P., Fekih, A., Din, S. (2023). Damping sub-synchronous resonance in DFIG wind farms: An innovative controller utilizing wide-area measurement systems, *Energy Reports*, 10, 333-343.

[40] Shahgholian, G. (2020). An overview of hydroelectric power plant: Operation, modeling, and control. *Journal of Renewable Energy and Environment*, 7(3), 14-28.

[41] Yaghoubi, S., Dehghani, M., Moazzami, M., Zanjani, M.A., Moradian, M.R. (2024). A review on the classification of operating modes in microgrid systems. *Journal of Simulation and Analysis of Novel Technologies in Mechanical Engineering*, 16, 27-34.

[42] Khazaie, J., Mokhtari, M., Khalilyan, M. Nazarpour, D. (2012). Sub-synchronous resonance damping using distributed static series compensator (DSSC) enhanced with fuzzy logic controller. *International Journal of Electrical Power and Energy Systems*, 43(1), 80–89.

[43] Li, G., Chen, Y., Luo, A., Wang, H. (2020). An enhancing grid stiffness control strategy of STATCOM/BESS for damping sub-synchronous resonance in wind farm connected to weak grid. *IEEE Trans. on Industrial Informatics*, 16(9), 5835-5845.

[44] Liu, P., Gui, L., Shair, J., Xie, X. (2022). Development of instantaneous transient torque protection against torque amplification for turbine generators in a series-compensated power system. *International Journal of Electrical Power and Energy Systems*, 134, 107444.

[45] Fan, L., Miao, Z. (2012). Mitigating SSR using DFIG-based wind generation. *IEEE Trans. on Sustainable Energy*, 3(3), 349-358.

[46] Li, R., Zhao, S., Gao, B., Zhang, R., Hu, Y. (2019). Sub synchronous torsional interaction of steam turbine under wind power oscillation in wind-thermal power bundled transmission system. *International Journal of Electrical Power and Energy Systems*, 108, 445-455.

[47] Xu, Y., Zhao, S., Cao Y., Sun, K. (2019). Understanding subsynchronous oscillations in DFIG-based wind farms without series compensation. *IEEE Access*, 7, 107201-107210.

[48] Yaghobi, H. (2021). Precision enhancement of the traditional sub-synchronous analysis by using frequency components of instantaneous magnetic flux. *IET Generation, Transmission and Distribution*, 15(22), 3100-3114.

[49] He, C., Sun, D., Song, L., Ma, L. (2019). Analysis of subsynchronous resonance characteristics and influence factors in a series compensated transmission system. *Energies*, 12(17), 3282.

[50] Yuan, L., Meng, K., Huang, J., Dong, Z.Y. (2020). Investigating subsynchronous oscillations caused by interactions between PMSG-based wind farms and weak ac systems, *International Journal of Electrical Power and Energy Systems*, 115, 105477.

[51] Shair, J., Xie, X., Wang, L., Liu, W., He, J., Liu, H. (2019). Overview of emerging subsynchronous oscillations in practical wind power systems. *Renewable and Sustainable Energy Reviews*, 99, 159-168.