21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

CIGRE US National Committee
2014 Grid of the Future Symposium

Parameter Sensitivity Analysis for Sub-Synchronous Oscillations in Wind-Integrated Power Systems

M. WU
Texas A&M University
USA

R. SUN
State Grid Jibei Electric Power Co. Ltd.
China

L. CHENG
Tsinghua University
China

L. XIE
Texas A&M University
USA

SUMMARY

This paper is motivated by the recent incidents of sub-synchronous oscillations that occurred in high wind penetration areas such as ERCOT, Oklahoma, and Northern China. In particular, we propose a framework to analyze the root causes of such oscillation, as well as possible remedial actions that operators could take. The theory is based on the eigenvalue sensitivity analysis for series-compensated power network integrated with DFIG-based wind turbine. Studies on eigenvalue sensitivities with respect to system parameters and operating conditions are performed for oscillation modes within sub-synchronous frequency range. Highly sensitive parameters as well as operating conditions for each oscillation mode are identified. Potential parameter adjustment strategies are proposed. Numerical simulations based on realistic DFIG models show the efficacy of the proposed analysis at pinpointing the root causes of sub-synchronous oscillations.

KEYWORDS

Doubly-fed induction generator, sub-synchronous oscillation, wind farm, eigenvalue sensitivity analysis.

marie126@tamu.edu

Introduction

Wind energy has been undergoing significant growth around the world, bringing new challenges to system operators. One of the challenges recently faced by operators is the sub-synchronous oscillation (SSO) due to integration of wind farms through series-compensated transmission lines, which would cause voltage and power oscillations and eventually damage system stability. In October 2009, the Electric Reliability Council of Texas (ERCOT) reported a SSO event in wind-integrated system, triggered by a single line-to-ground fault [1]. A recent National Renewable Energy Laboratory (NREL) report [2] also presents several SSO curves recorded by wind power plants of Oklahoma Gas and Electric Company (OG&E). This type of phenomenon is generally referred to as sub-synchronous control interaction (SSCI) [3], which is primarily caused by fast action of controllers of doubly-fed induction generator (DFIG).

Increasing amount of research efforts has been taken to investigate wind farm SSO. Electromagnetic transient simulations [4], frequency scan [5], as well as modal analysis [6] are performed, qualitative impact of wind speeds, compensation levels and controller parameters are investigated. Several mitigation control strategies are proposed in [7], [8]. However, there has not been rigorous analysis of system parameters and operating conditions' impact on wind farm SSO. In order to optimally mitigate future SSO incidents, it is prudent for system operators to identify important model and control parameters that are likely to induce wind farm SSO.

This paper offers a first-of-its-kind thorough analysis of system eigenvalue sensitivities with respect to parameters in series-compensated power network integrated with DFIG-based wind turbine. Relationship between system parameters and wind farm SSO is clearly presented. This work could potentially help future works in designing mitigation control for SSO in wind-integrated systems.

Proposed Analytical Framework of Parameter-Induced Wind Farm SSO

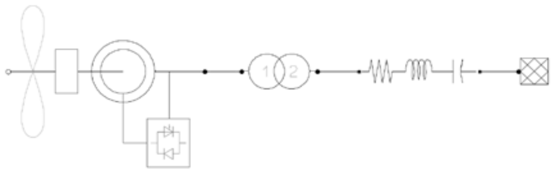

Figure 1. IEEE first benchmark model with DFIG-based wind turbine

In this Section, we propose a rigorous approach to analysing the sensitivity of system eigenvalues with respect to the wind farm parameters and network parameters. We present the framework by using IEEE first benchmark model [9] integrated with a 100MW DFIG-based wind farm, as shown in Figure 1. However, this framework is generalizable towards other systems as well. Five parts of system dynamics are considered: namely drive train torsional dynamics, induction generator dynamics, DFIG converter control dynamics, DC-link dynamics, and network electromagnetic dynamics.

The wind turbine torsional system is modelled by a two-mass system shown as follows [10]:

$$\begin{bmatrix} \Delta\dot{\omega}_W \\ \Delta\dot{\omega}_G \\ \Delta\dot{\theta} \end{bmatrix} = \begin{bmatrix} -\frac{D}{J_W} & \frac{D}{J_W} & -\frac{K}{J_W} \\ \frac{D}{J_G} & -\frac{D}{J_G} & \frac{K}{J_G} \\ 1 & -1 & 0 \end{bmatrix} \begin{bmatrix} \Delta\omega_W \\ \Delta\omega_G \\ \Delta\theta \end{bmatrix} + \begin{bmatrix} \frac{1}{J_W} & 0 \\ 0 & \frac{1}{J_G} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \tau_W \\ \tau_G \end{bmatrix} \tag{1}$$

where J_W and J_G represents inertia of wind turbine and generator, respectively; D and K are system damping and stiffness, respectively; τ_W and τ_G are wind turbine mechanical torque and generator

electrical torque, respectively; ω_W and ω_G are rotating speed of wind turbine and generator rotor, respectively; $\Delta\theta$ is the angle difference between wind turbine and generator rotor.
A 4th order dynamic model [11] is adopted for induction generator dynamics:

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{qr} \\ v_{dr} \end{bmatrix} = \begin{bmatrix} r_s & \frac{\omega}{\omega_b} X_{ss} & 0 & \frac{\omega}{\omega_b} X_M \\ -\frac{\omega}{\omega_b} X_{ss} & r_s & -\frac{\omega}{\omega_b} X_M & 0 \\ 0 & \frac{\omega-\omega_r}{\omega_b} X_M & r_r & \frac{\omega-\omega_r}{\omega_b} X_{rr} \\ -\frac{\omega-\omega_r}{\omega_b} X_M & 0 & -\frac{\omega-\omega_r}{\omega_b} X_{rr} & r_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} + \begin{bmatrix} \frac{X_{ss}}{\omega_b} & 0 & \frac{X_M}{\omega_b} & 0 \\ 0 & \frac{X_{ss}}{\omega_b} & 0 & \frac{X_M}{\omega_b} \\ \frac{X_M}{\omega_b} & 0 & \frac{X_{rr}}{\omega_b} & 0 \\ 0 & \frac{X_M}{\omega_b} & 0 & \frac{X_{rr}}{\omega_b} \end{bmatrix} \begin{bmatrix} \dot{i}_{qs} \\ \dot{i}_{ds} \\ \dot{i}_{qr} \\ \dot{i}_{dr} \end{bmatrix} \quad (2)$$

where v_{qs}, v_{ds} v_{qr}, v_{dr} are generator stator and rotor voltages on q and d axis, respectively; i_{qs}, i_{ds} i_{qr}, i_{dr} are generator stator and rotor currents on q and d axis, respectively; r_s, r_r are stator and rotor resistances, respectively; X_{ss}, X_{rr}, X_M are stator, rotor and mutual inductances, respectively; ω, ω_r ω_b are d-q frame rotating speed, generator rotor speed, and system synchronous speed, respectively.

Series-compensated transmission line is modelled as follows [12]:

$$\begin{bmatrix} L & 0 & 0 & 0 \\ 0 & L & 0 & 0 \\ 0 & 0 & -C & 0 \\ 0 & 0 & 0 & -C \end{bmatrix} \begin{bmatrix} \dot{i}_{ql} \\ \dot{i}_{dl} \\ \dot{v}_{qc} \\ \dot{v}_{dc} \end{bmatrix} = \begin{bmatrix} R & \omega L & 1 & 0 \\ -\omega L & R & 0 & 1 \\ 1 & 0 & 0 & \omega C \\ 0 & 1 & -\omega C & 0 \end{bmatrix} \begin{bmatrix} i_{ql} \\ i_{dl} \\ v_{qc} \\ v_{dc} \end{bmatrix} = \begin{bmatrix} E_q - v_{qs} \\ E_d - v_{ds} \\ 0 \\ 0 \end{bmatrix} \quad (3)$$

where L and C are transmission line inductance and series capacitor, respectively; i_{ql}, i_{dl} are inductor currents on q and d axis, respectively; v_{qc} , v_{dc} are capacitor voltages on q and d axis, respectively; E_q, E_d are infinite bus voltages on q and d axis, respectively.

The following first-order model describes dynamics of capacitor in the dc link between rotor side converter (RSC) and grid side converter (GSC) [6]:

$$P_r - P_g = v_{DC} C_{DC} \frac{dv_{DC}}{dt} \quad (4)$$

where P_r, P_g are RSC and GSC real power, respectively; C_{DC} is the DC-link capacitor; v_{DC} is the voltage across DC-link capacitor.

DFIG converter control loops are shown in Figure 2.

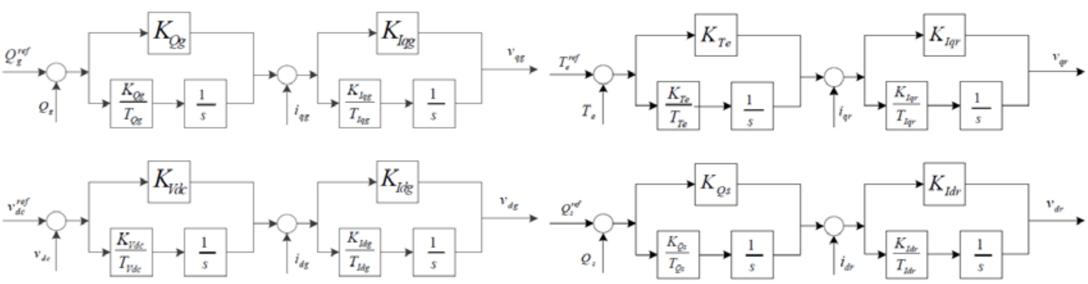

Figure 2. Control loops of DFIG grid side converter (left) and rotor side converter (right)

The complete nonlinear model can be expressed as $\dot{x} = f(x, p)$, which can be linearized as $\Delta\dot{x} = A(x^*, p)\Delta x$, where A is the state matrix of the linearized model, p is the set of system parameters, x^* denotes the steady-state solution of the system, which can be solved from steady-state system equations $f(x^*, p) = 0$. It is clear that change of system parameters and steady-state solutions would affect eigenvalues of state matrix A, and further influence system oscillation behaviour. This paper presents eigenvalue sensitivity study on wind farm SSO in order to explore the relationship between system parameters and eigenvalues of system state matrix.

Eigenvalue Sensitivities and Simulation Results

Since wind farm SSO is related with eigenstructure at sub-synchronous frequency, a powerful analytical tool to trace the impact of different parameters and operating conditions on the oscillation is through eigenvalue sensitivity analysis. The basic idea is presented below.

Let A be an $n \times n$ matrix, and let λ be A's simple eigenvalue with corresponding right and left eigenvectors x and y. Suppose A is perturbed to $\tilde{A} \equiv A + \delta A$, and consequently λ is perturbed to $\tilde{\lambda} \equiv \lambda + \delta\lambda$. If $\| \delta A \|_2 = \varepsilon$ is sufficiently small, then

$$\delta\lambda = \frac{y^T(\delta A)x}{y^T x} + O(\varepsilon^2) \tag{5}$$

This implies that, given left and right eigenvectors of current system state matrix, by perturbing system state matrix through small modifications on system parameters or steady-state operating conditions, one can obtain eigenvalue sensitivities with respect to parameters and operating conditions.

The computational advantage of taking the above approach for eigenvalue sensitivity is obvious: instead of obtaining parameter sensitivities by re-calculating system eigenvalues every time a parameter is perturbed, this approach only needs eigenvalues and eigenvectors of the original system, which saves time on eigenvalue calculation.

The above sensitivity analysis is performed on the test system shown in Figure 1. The following system parameters are implemented: wind farm parameters: current wind speed = 5.6 m/s, current generator rotor speed = 338.5 rad/s, number of turbines in wind farm = 100; Induction generator parameters: rated power = 2 MW, rated voltage = 690 V, R_s = 0.0049 pu, R_r = 0.0055 pu, X_{ls} = 0.0924 pu, X_{lr} = 0.0996 pu, X_M = 3.9530 pu; torsional system parameters: J_W = 209.21 kgm^2, J_G = 41.842 kgm^2, K = 3097.2 Nmrad, D = 1.5 pu; DC-link parameters: C_{DC} = 14000 µF, V_{DC} = 1200 V; series-compensated network parameters: transformer reactance X_{xf} = 0.03 pu, line inductance L = 0.0015 pu, line resistance = 0.0224 pu, series compensation level = 52.38%; RSC controller parameters: K_{Qs} = 0.0001, T_{Qs} = 0.025, K_{Idr} = 0.0001, T_{Idr} = 0.0025; K_{Te} = 0.0001; T_{Te} = 0.05; K_{Iqr} = 0.0001; T_{Iqr} = 0.005; GSC controller parameters: K_{Qg} = 0.1, T_{Qg} = 2, K_{Iqg} = 1, T_{Iqg} = 0.1, K_{VDC} = 0.1, T_{VDC} = 2, K_{Idg} = 1, T_{Idg} = 0.1.

Table 1 shows eigenvalues and natural frequencies related to sub-synchronous modes of the test system. System modes without sub-synchronous frequencies are beyond the scope of this paper and therefore not presented in the table.

Table 1. Test System Eigenvalues and Natural Frequencies Related to Sub-synchronous Modes

Eigenvalue	1.31 + 138.63i	-4.59 + 50.84i	-1.39 + 7.34i
	1.31 - 138.63i	-4.59 - 50.84i	-1.39 - 7.34i
Frequency (Hz)	22.06	8.09	1.17

The eigenvalue sensitivities of three SSO modes with respect to system parameters as well as operating conditions are presented in Figure 3. Eigenvalues corresponding to 22.06 Hz mode is sensitive to network parameters and DFIG grid side controller parameters; eigenvalues corresponding to 8.09 Hz mode is sensitive to DFIG parameters and network parameters; while eigenvalues corresponding to 1.27 Hz mode is sensitive to torsional system parameters, network parameters and

DFIG GSC controller parameters. It can be seen that network inductor and capacitor values are of high sensitivities in all three modes, and parameters in current control loops of DFIG converter controllers have higher sensitivities compared with those in torque control loops. In all three oscillation modes, DFIG rotor speed has significant influence on the corresponding eigenvalues. Since in DFIG-based wind farm, rotor speed is directly related to wind speed, this sensitivity result coincides with the phenomenon that SSO in wind-integrated systems tend to happen under certain wind speed condition.

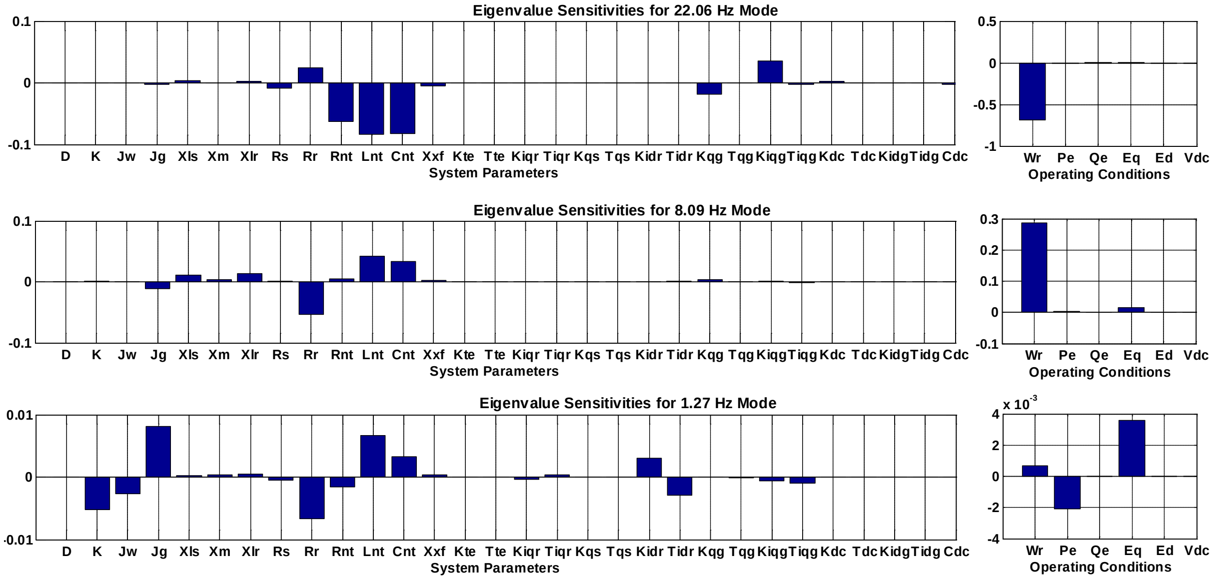

Figure 3. Eigenvalue Sensitivities Related to Sub-Synchronous Modes

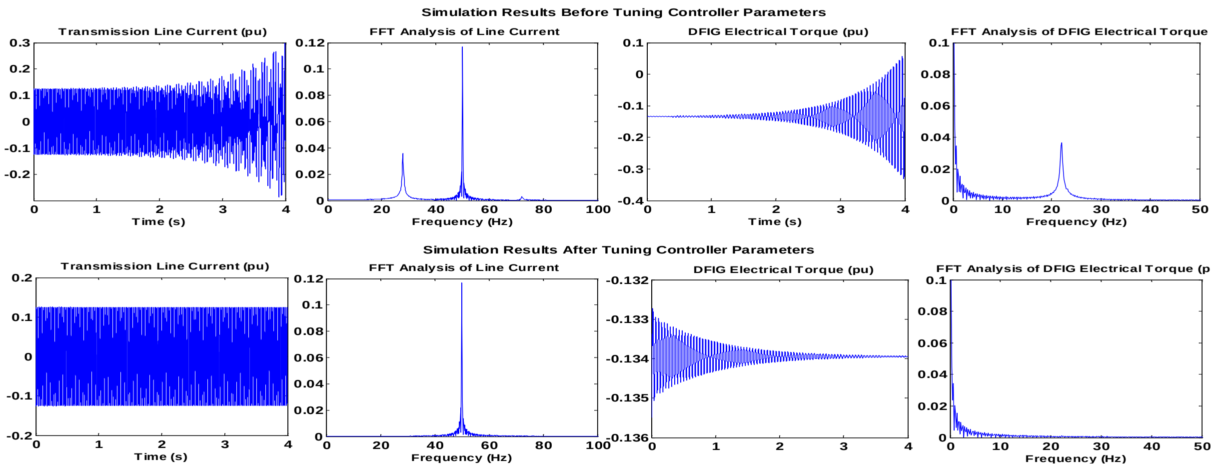

Figure 4. Simulation Results Before and After Tuning DFIG Controller Parameters

This result of sensitivity analysis can be applied to guide system parameter adjustment for SSO mitigation. In Table 1, eigenvalues corresponding to 22.06 Hz mode have positive real parts, indicating unstable oscillations in the test system. According to sensitivity analysis, this mode is highly sensitive to system series compensation level as well as gains in DFIG GSC control loops. Therefore, the oscillation is expected to be damped down by properly adjusting these parameters. Figure 4 shows the simulation results and FFT analysis of the oscillation before and after tuning gains in GSC current control loop. It can be seen that by tuning adjustable parameters which is sensitive to unstable oscillation mode, the corresponding eigenvalue can be effectively moved towards negative direction.

For the purpose of SSO mitigation, system parameters and the amount of adjustment should be selected carefully. According to Figure 3, sensitivities of a certain parameter on different oscillation modes may have different signs, meaning by tuning parameter in a certain direction, eigenvalues of some oscillation modes can be moved left, while eigenvalues of the other modes may be moved right.

In order to keep all the eigenvalues negative and stabilize the system, control strategies which can make well balance among all the oscillation modes should be expected.

Conclusions

This paper presents a framework for analysing the root causes and potential remedial actions associated with SSO in high wind penetration systems. The proposed eigenvalue sensitivity analysis allows for identifying the impact of different model parameters on the occurrence of wind farm SSO. As a direct outcome of this analysis, we propose an intuitive visualization of the parameter sensitivities on system sub-synchronous oscillation modes. This could help system operators to design mitigation control strategies in an optimal way. Highly sensitive parameters as well as operating conditions for each oscillation mode are identified. Potential problems for parameter adjustment strategies are proposed. Simulations are performed in order to verify the results of sensitivity analysis. Future work will focus on the mitigation control for SSO in wind-integrated systems and validation of the control performance in large realistic systems.

Acknowledgement

This work is supported in part by TAMU-NSFC grant, and in part by State Grid Corporation of China (SGCC) (KTB11201301545).

BIBLIOGRAPHY

[1] P. Belkin, “Event of 10-22-09” (CREZ Technical Conference, Jan 2010)
[2] Y. H. Wan, “Synchronized phasor data for analyzing wind power plant dynamic behavior and model validation” (National Renewable Energy Laboratory, CO, Tech. Rep. NREL/TP-5500-57342, Jan 2013)
[3] D. Suriyaarachchi, U. Annakkage, C. Karawita, and D. Jacobson, “A procedure to study sub-synchronous interactions in wind integrated power systems,” (Power Systems, IEEE Transactions on, vol. 28, no. 1, pp. 377–384, Feb 2013)
[4] B. Badrzadeh and S. Saylors, “Susceptibility of wind turbines to sub-synchronous control and torsional interaction,” (Transmission and Dis-tribution Conference and Exposition (T&D), 2012 IEEE PES, Orlando, FL, May 2012, pp. 1–8)
[5] B. Badrzadeh, M. Sahni, D. Muthumuni, Y. Zhou, and A. Gole, “Sub-synchronous interaction in wind power plants- part I: Study tools and techniques,” (Power and Energy Society General Meeting, 2012 IEEE, San Diego, CA, July 2012, pp. 1–9)
[6] L. Fan, C. Zhu, Z. Miao, and M. Hu, “Modal analysis of a DFIG-based wind farm interfaced with a series compensated network,” (Energy Conversion, IEEE Transactions on, vol. 26, no. 4, pp. 1010–1020, Dec 2011)
[7] L. Fan, and Z. Miao, “Mitigating SSR using DFIG-based wind generation,” (Sustainable Energy, IEEE Transactions on, vol. 3, no. 3, pp. 349–358, Jul 2012)
[8] M. S. El-Moursi, B. Bak-Jensen, and M. H. Abdel-Rahman, “Novel STATCOM controller for mitigating SSR and damping power system oscillations in a series compensated wind park,” (Power Electronics, IEEE Transactions on, vol. 25, no. 2, pp. 429–441, Feb 2010)
[9] IEEE SSR Working Group, “First benchmark model for computer simulation of subsynchronous resonance,” (Power Apparatus and Systems, IEEE Transactions on, vol. PAS-96, no. 5, pp. 1565–1572, Sep 1977)
[10] Z. Lubosny, Wind Turbine Operation in Electric Power Systems: Advanced Modeling. (Berlin, Germany: Springer-Verlag, 2003)
[11] P. C. Krause, O. Wasynczuk, and S. D. Sudhoff, Analysis of Electric Machinery. (NY: IEEE Press, 1995)
[12] P. M. Anderson, B. L. Agrawal, and J. E. Van Ness, Subsynchronous Resonance in Power Systems. (NY: IEEE Press, 1990)