CIGRE-326 **2020 CIGRE Canada Conference**
Toronto, Ontario, October 19-22, 2020

Analysis of Sub Synchronous Resonant Modes in Series Compensated Networks using Multiple Frequency Scans

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SUMMARY

Series compensation of transmission lines is an established method to improve the power transfer capability and stability over long distance ac power transmission. However, protection of turbine generator shaft system against torsional stresses has become a limiting factor in using series compensation. With increased levels of series compensation, Sub Synchronous Resonance (SSR) problems are more likely to occur when the complement of the network natural frequency becomes equal or closer to one of the torsional frequencies of the turbine generator shaft system [1]. This can eventually lead to shaft fatigue and breakdown. Out of many SSR mitigation techniques, the use of TCSC (Thyristor Controlled Series Compensation) has become popular due to its simplicity, controllability and its inherent damping at sub synchronous frequency range [2]. FSC (Fixed Series Compensation) can be fully or partially replaced with TCSCs to avoid SSR. But, as TCSCs are more expensive, replacing all FCS with TCSCs is not a viable option. However, replacing critical series capacitor/s fully or partially with TCSC might solve the problem. Eigenvalue analysis and Electro Magnetic Transient simulation (EMT) can identify critical series compensated line/s, which excites a certain SSR mode. However, such detailed studies are time consuming for large networks as there can be many series compensated transmission lines and multiple resonant points at multiple contingencies at which torsional interactions with the turbine generator shaft can occur.

Frequency scanning, which is a simple preliminary screening technique used for SSR studies, indicates resonant frequencies at which torsional interactions or Induction Generator problems might occur. This paper presents a detailed analysis of SSR modes in a series compensated transmission network and a methodology to use available frequency scanning tools to identify critical series capacitor/s which could be fully or partially replaced with TCSCs to avoid SSR. This study intends to extract as much information as possible from frequency scanning so that time consuming detailed studies could be avoided in the screening stage of a study.

A simple transmission network comprising of 8 busses, three multi mass turbine generators and series compensated parallel lines has been used in the analysis to develop the methodology. Dynamic phasor based small signal stability analysis was also performed using TGSSR software to validate the findings from frequency scanning technique.

Small signal stability analysis revealed that a single series capacitor dominates a certain electrical SSR mode. In this study, Frequency Scanning has been effectively used at multiple locations and at multiple contingencies to identify electrical resonant points and series capacitors which contributes the

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most to a certain electrical mode. Furthermore, two types of sub synchronous resonant modes namely, series resonant modes and intra parallel line resonant modes were identified. Participation factor analysis revealed that intra parallel line modes are purely dominated by transmission line inductances and capacitances and participation of generators to such modes were found to be negligibly small. Electrical SSR modes in the test system and series capacitor/s which dominates critical SSR modes were readily identified with the proper use of frequency scanning

KEYWORDS

Sub Synchronous Resonance, Series compensation, Frequency scanning, Small Signal Stability

1. INTRODUCTION

Bulk ac power transmission over long distances has limitations in terms of loadability and stability due to the excessive inductive reactance in transmission lines. Series compensation has become an economical and viable solution to improve the power transfer capability and stability [1]. Series compensation is preferred over shunt capacitors due to certain major advantages offered by series capacitors [3]. However, series compensation of lines could lead to undesirable effects such as Sub Synchronous Resonance (SSR).

Sub Synchronous Resonance occurs when the generator and transmission system exchange energy at one or more natural frequencies of the combined system below the fundamental frequency of the power network [4]. Unlike in uncompensated transmission networks, transient currents in series compensated networks has an alternating component of frequency equal to the natural frequency (f_n) of the circuit inductance and capacitance and is given by equation 1.

$$\mathbf{f_n = f_0 \sqrt{\frac{X_c}{X_L}}} \tag{1}$$

The natural frequency of the network (f_n) is always less than the fundamental frequency (f_0), as the capacitive reactance (X_c) is usually less than the inductive reactance (X_L). Sub synchronous currents in stator winding of the machine could cause Induction Generator Effect (IGE) or Torsional Interactions (TI) or Transient Shaft Torque (TST) in the machine, which could lead to sustained or negatively damped oscillations. Effects of sub synchronous currents on a generator has been first discussed in 1937, which was later named as IGE [5]. TI and TST could be excited if the network natural frequency becomes equal or close to the complement of one of the torsional frequencies of the turbine generator shaft system. The first incident due to TIs was reported in 1970 at the Mohave Generating station in Southern Nevada [6], where two shafts were severely damaged due to turbine generator interaction with a nearby series compensated line.

Many techniques are reported in literature to counteract SSR such as supplementary excitation controls, static filters, Dynamic filters etc. [1]. A traditional and a temporary solution to protect the power system components against sub synchronous resonance is by relays which bypass some or all series capacitors by closing a circuit breaker [7]. However, such methods are not based on the source of oscillation or the component which excites the oscillations in the network. Use of TCSCs instead of FSC can help mitigate SSR problems as shown in [8] and many studies have been conducted in this regard [9-11]. Although TCSCs are more attractive in terms of its controllability, they are more expensive and therefore, replacing all FCS with TCSCs is not a viable solution. Thus, the requirement of it as a top-up in the series compensation scheme should be carefully evaluated.

To apply a suitable countermeasure, the component which contributes mostly to the excitation of a particular Sub Synchronous Oscillation must be clearly identified. Detailed analytical tools such as Eigen value analysis and EMT simulations can easily identify the contributing component. But such studies could be time consuming for heavily series compensated networks. The analysis presented in this paper intends to capture more information such as locating the component which causes the problem, at the screening stage of the study to avoid doing time consuming detailed studies.

The organization of this paper is as follows. Section 2 of the paper discusses about the analytical tools that have been chosen for this SSR study. Section 3 includes the test system under study and how the analysis is conducted while section 4 presents frequency scanning and small signal stability analysis results along with discussions, followed by conclusions in section 5.

1. ANALYTICAL TOOLS

SSR studies require representation of electromechanical dynamics of generators and electromagnetic dynamics of transmission network components. Identification of SSR problems can be carried out in two steps, namely screening and analysing.

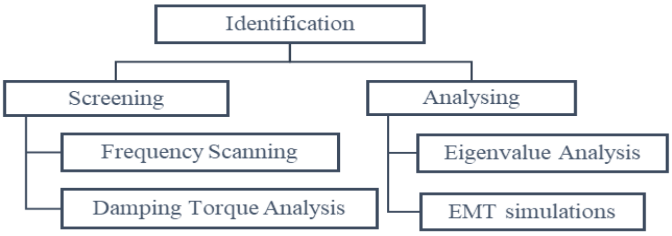

Figure 1: SSR identification

Screening is just an indication of possible SSR problems. It narrows down the regions or contingencies which needs further analysis. Detailed analysis techniques help understand the SSR phenomena and devices contributing to them.

1.1 FREQUENCY SCANNING

Only screening techniques applicable for series compensation related SSR problems are given figure 1. Static and dynamic Frequency Scans (FS) are very popular tools to identify resonant points between conventional or renewable generator and series compensation. It evaluates the impedance seen at a particular point in the network, usually behind the stator windings of the generator. In this analysis, frequency scanning is performed twice separately looking towards the network and the device and the two results are finally combined. Impedance dips in the frequency scan profile indicate network resonant points and if there are any shaft torsional frequencies near the complement of these frequencies, there is a risk of possible TIs or TSTs. The goal of this study is not to identify only the resonant points but to extract more information from frequency scans.

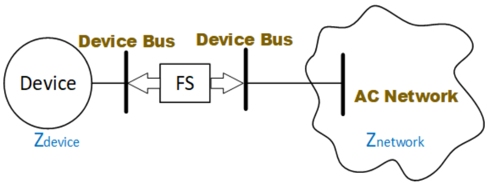

Figure 2: Frequency scanning method

1.2 EIGENVALUE ANALYSIS

Detailed studies using Eigenvalue analysis reveals not only the resonant frequencies, but also the damping of SSR modes, devices contributing to SSR modes etc. However, in conventional small signal stability analysis, transmission system is modelled as a constant admittance matrix and dynamics of generator stator flux are ignored. Therefore, it is only suitable for electromechanical oscillations and is not sufficient for SSR studies as the frequency of interest is much higher. Modelling of network dynamics is important for SSR studies. Thus, Dynamic Phasor (DP) based small signal stability analysis is used for SSR analysis. In DP based small signal stability analysis, AC network dynamics (dynamics of inductor current phasor I_L and capacitor voltage phasor V_C given in equation 2) and stator flux dynamics are modelled as differential equations and appended to linearized conventional machine model and network model [12].

$$\frac{d\,\overline{\mathbf{I}_L}}{dt} = -j\omega_0\overline{\mathbf{I}_L} + \frac{\overline{\mathbf{V}_L}}{\mathbf{L}} \tag{2}$$

$$\frac{d\overline{\mathbf{V}_C}}{dt} = -j\omega_0\overline{\mathbf{V}_C} + \frac{\overline{\mathbf{I}_C}}{\mathbf{C}} \tag{3}$$

2. ANALYSIS

A simple transmission network as shown in figure 3 with 8 busses and 3 generators was used for the analysis. The test system was modelled in PSCAD. Generators 1 and 2 are modelled as single lumped-mass representation of the turbine generator rotor while generator 3 is modelled a with multi mass representation of the turbine generator rotor shafts. Resistance and inductive reactance are taken as 0.0189 Ω/km and 0.189Ω/km respectively. Generator 3 and its multi mass system data were taken according to [13]. Generator 2 and 3 data were taken from [14]. 257.5 km long parallel lines between bus 4 and 5 are series compensated at different values to demonstrate two distinct resonant points. Some resonant frequencies are not visible in frequency scan profiles if the level of series compensation is equal. SC1 and SC2 corresponds to 80% and 20% of the total reactance of the line respectively. Line connecting bus 7 and 8 is compensated for 70% of its total reactance.

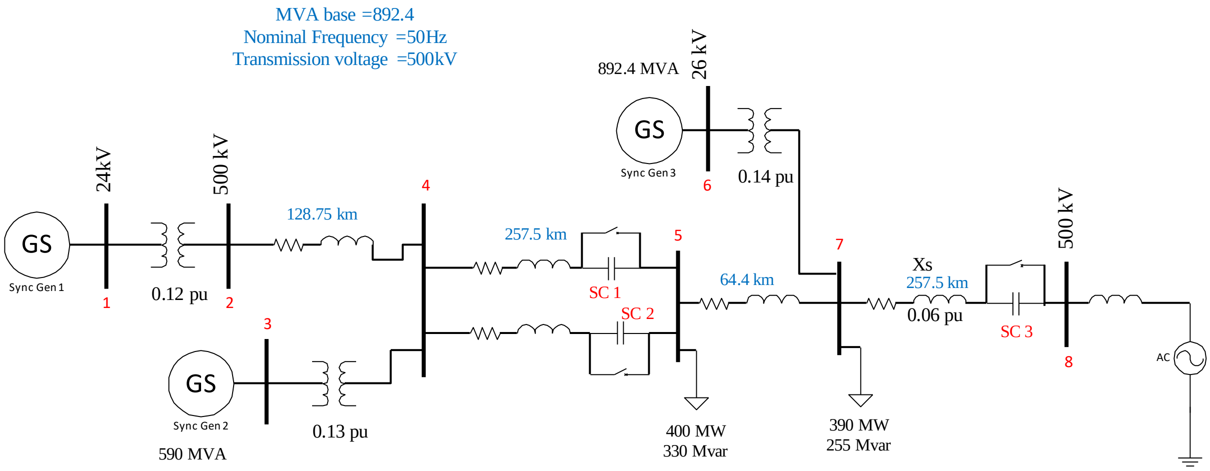

Figure 3: Test Network

In order to understand the SSR phenomena that could arise in the above network, DP based small signal stability analysis was first conducted using a commercial software. Then multiple frequency scans were conducted at multiple locations with capacitors bypassed/in service.

3. RESULTS

Results from DP based small signal stability analysis are given in table 1. Three SSR modes and four torsional modes were identified in the sub synchronous range (frequencies are in synchronous reference frame). Network modes are sufficiently damped while torsional modes are very lightly damped.

Table 1: DP bases small signal stability analysis results

Mode Number	Network Modes		Torsional Modes	
	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
1	8.39	13.5	2.54	0
2	26.75	16.5	19.62	0.0002
3	36.61	17	25.74	0.0003
4			36.92	0.0670

Figure 4 shows the participation of generator stator flux components and infinite bus current to three network modes. It is seen that generator stator flux and infinite bus current contribution to the 3rd network mode is minimal and is almost negligible. According to figure 5, highest contributing devices to that mode are series capacitors and inductances of the parallel transmission line. Thus, network mode 3 can be identified as an intra parallel line network mode.

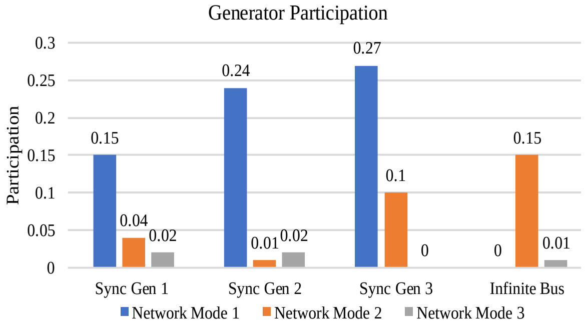

Figure 4: Generator participation on network modes

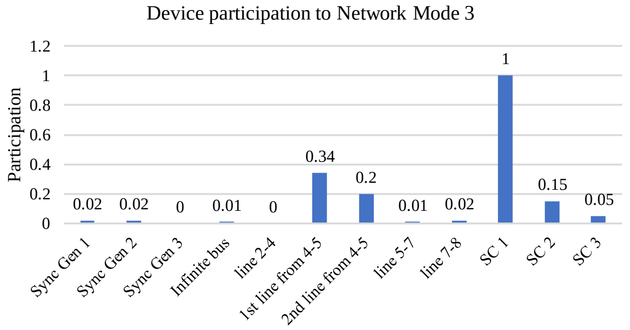

Figure 5: Device participation on network mode 3

Main contributing devices to network resonant modes are series capacitors. When looked at the series capacitor participation in figure 6, it is noticed that there is always one series capacitor which dominates a certain network SSR mode. Identification of the capacitor which excite SSR will help to apply suitable countermeasures, whether to replace the critical series capacitor with TCSC or to bypass it.

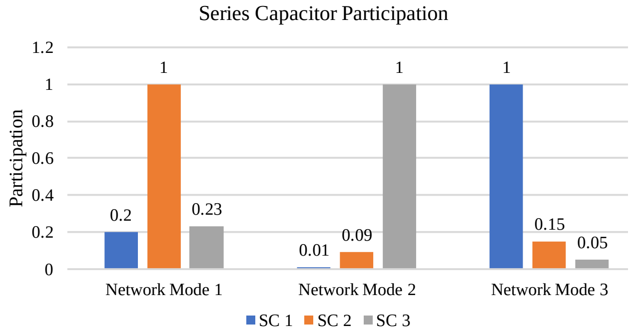

Figure 4: Series capacitor participation on network modes

The goal is to identify the critical series capacitor with proper use of frequency scanning. Frequency scanning was conducted at device busses 2, 7 and 4 with all series capacitors in service and the results are shown in figure 7. According to [15], points which have at least 5% reactance dip within ±3% of the torsional frequency are likely to yield transient torque problems. This theory has found to be generally conservative. FS at a single location doesn't reveal all resonant points in the network as confirmed by the third curve in figure 7, but FSs at multiple locations reveal network resonant points and are recorded as 10Hz, 28Hz and 37Hz. Frequencies of impedance dips are same as obtained in DP based small signal stability analysis. Note that 2^{nd} and 3^{rd} network resonant frequencies are closer to torsional frequencies.

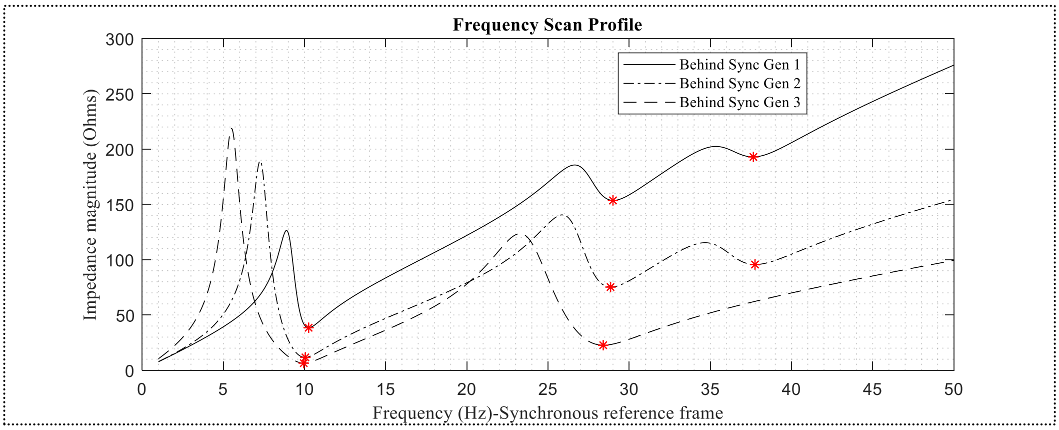

Figure 5: FS profile when all series capacitors are in service

Figures 8,9, and 10 show FS profiles obtained after bypassing SC1, SC2 and SC3 respectively. Frequency of Mode 3 has disappeared when SC 1 is bypassed as seen from figure 8 and mode 2 frequency has remained unchanged. This implies that mode 3 is mostly excited due to SC1 and Mode 2 has negligible effect from SC1. This observation is verified through participation factor analysis in figure 6. However, mode 1 frequency has shifted a little implying that SC1 has some effect on mode 1 but its cannot be quantified unlike other 2 modes.

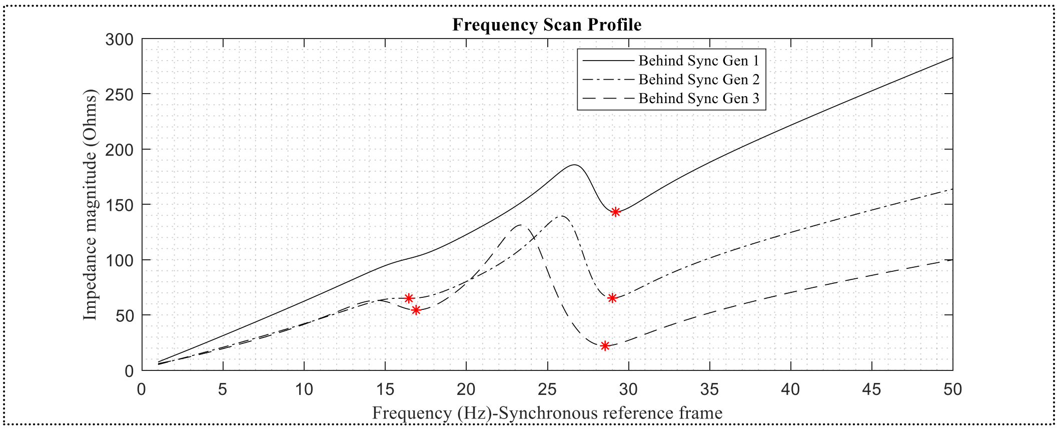

Figure 6: FS profile when SC 1 is bypassed

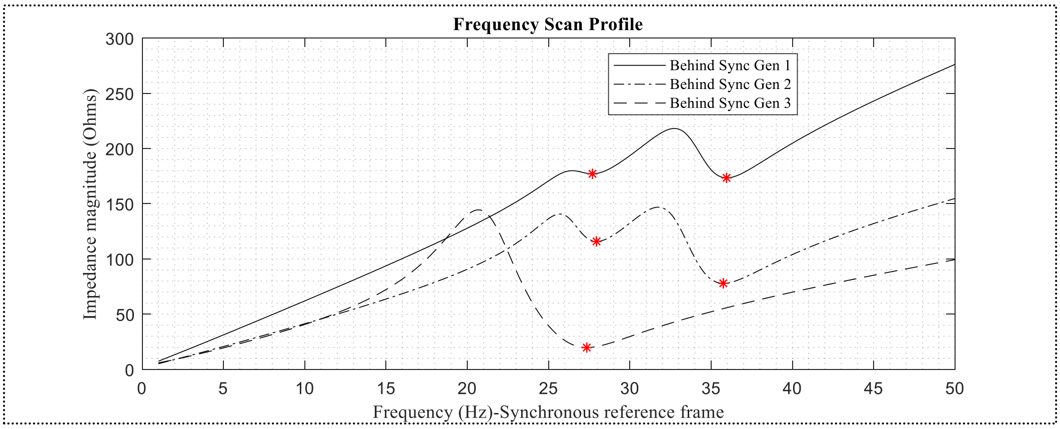

Figure 7: FS profile when SC 2 is bypassed

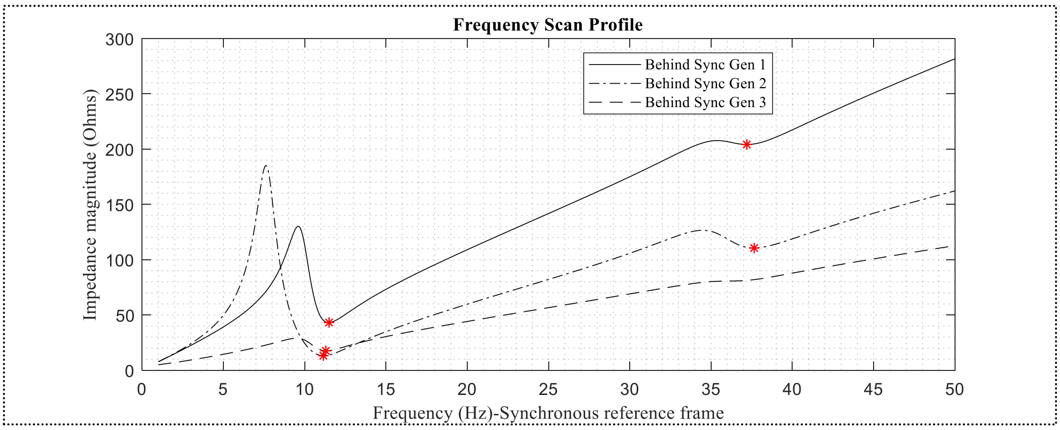

Figure 8: FS profile when SC 3 is bypassed

When SC 2 is bypassed, impedance dip at mode 1 frequency has disappeared and impedance dips at mode 2 and 3 frequencies have shifted a little as seen from figure 9. It implies that SC 2 contributes the most to mode 2. As per figure 10, impedance dip at mode 2 frequency has disappeared when SC 3 has been bypassed and mode 3 frequency remains unchanged. Thus, it can be concluded that mode 2 is mostly excited due to SC 3 and mode 3 frequency does not have any effect from SC 3.

4. CONCLUSION

Analysis of SSR modes in a series compensated test system was conducted using multiple frequency scans at multiple locations of which results are verified through DP based small signal stability analysis. Out of the three network modes identified, one was confirmed to be an intra parallel line resonant mode for which generator contribution is minimal. Intra parallel line resonant mode is visible in FSs if the level of series compensations is different, but if the two parallel lines are at equal levels of compensation, intra parallel line network mode could only be identified through Eigen value analysis.

The critical series capacitor which excites a certain mode can be identified by performing multiple FSs at multiple locations while bypassing the capacitors. Furthermore, network mode which doesn't have any effect from a certain series capacitor can also be identified as that modal frequency is not sensitive to capacitor bypassing. A single frequency scan does not provide enough information to identify the critical series capacitor but multiple frequency scans behind many devices can do the job.

BIBLIOGRAPHY

[1] P. Kundur "Power System Stability and Control New York" ,McGraw-Hill, 1994.
[2] R. M. Mathur and R. K. Varma "Thyristor-Based Facts Controllers for Electrical Transmission Systems", Piscataway NJ/New York: IEEE Press/Wiley, 2002.
[3] E. W. Kimbark "Improvement of System Stability by Switched Series Capacitors", IEEE Trans. Power App. Systems, vol. PAS-85, pp. 180-188, 1966.
[4] "Proposed Terms and Definitions for Subsynchronous Oscillation", IEEE Trans. Power Apparatus and Systems, vol. PAS-99, pp. 506-511, March/April 1980.
[5] J. W. Butler and C. Concordia "Analysis of Series Capacitor application Problems", AIEE Tans., 1937.
[6] D. N. Walker, C. E. J. Bowler, R. L. Jackson and D. A. Hodges "Results of subsynchronous resonance test at Mohave", IEEE Trans. Power App. Syst., vol. PAS-94 no. 5, pp. 1878-1885, Sep./Oct. 1975.
[7] J. Machowski, J. Bialek and J. Bumby "Power System Dynamics: Stability and Control", New-York: Wiley 2008.
[8] S. Joshi and A. Kulkarni "Analysis of SSR performance of TCSC control schemes using a modular high bandwidth discrete-time dynamic model", IEEE Trans. Power Syst. vol. 24 no. 2, pp. 840-848 May 2009.
[9] H.A. Mohammadpour and E. Santi "Sub-synchronous resonance analysis in DFIG-based wind farms: Mitigation methods—TCSCGCSC and DFIG controllers—Part II", Proc. IEEE Energy Convers. Congr. Expo., pp. 1550-1557, Sep. 2014.
[10] Fan Zhang, Zheng Xu "SSR damping study on a generator connected to TCSC", IEEE PES Power Systems Conference and Exposition, pp. 673-678, vol.2, Oct. 2004.
[11] Lei X, Buchholz B and Povh D. "Analysing subsynchronous resonance phenomena in the time-and frequency domain", European transactions on electrical power, pp 203-211, Vol 10, no. 4, July 2000).
[12] C. Karawita "HVDC interaction studies using small signal stability assessment", 2009.
[13] "First Benchmark Model for Computer Simulation of Subsynchronous Resonance", IEEE Trans. vol. PAS-96 no. 5, pp. 1565-1572, Sep/Oct 1977.
[14] P. M. Anderson and A. A. Fouad "Power System Control and Stability", IA Ames:Iowa State Univ. Press, 1977.
[15] B. L. Agrawal and R. G. Farmer "Use of frequency scanning techniques for subsynchronous resonance analysis", IEEE Trans. Power App. Syst., vol. PAS-98 no. 2, pp. 341-349, Mar./Apr. 1979.