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Damping of Sub-Synchronous Resonance by placing Thyristor Controlled Series Compensators (TCSC)

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SUMMARY

Series compensation is a popular solution for improving the power transfer capability of existing transmission lines. However, the presence of Fixed Series Compensators (FSC) in transmission lines can cause Sub Synchronous Resonance (SSR). These resonances can either be purely electrical phenomena or between the electrical and the mechanical system of the turbine-generator system. It may reduce the damping of torsional oscillatory modes of nearby multi-mass turbine-generator sets in the network. In a network with multiple series capacitors, there can be many sub-synchronous oscillatory modes which can excite different torsional modes. It is well known that Thyristor Controlled Series Compensators (TCSC), along with their flexible power transfer capability can be effectively utilized to mitigate SSR [1]. From this point of view, a TCSC is better than an FSC.

Replacing FSCs with TCSCs may not be a viable solution for utilities due to the cost associated with TCSCs. A better option would be to replace a portion of a FSC with a TCSC. Auxiliary Sub-Synchronous Oscillation Damping controllers installed on a TCSC can offer damping to SSR modes. Even without a damping controller, inherent damping of SSR modes can be achieved with properly chosen TCSC parameters [2]. Identifying the location/s and the level of compensation from TCSC, to mitigate the potential torsional mode instabilities is a challenging task. This paper shows that multiple torsional mode instabilities can be mitigated by placing the TCSC at the right location. This paper also shows how the resistance presented by the TCSC varies in the sub-synchronous frequency range according to the choice of TCSC parameters. Knowledge of this is useful in selecting an appropriate operating point for the TCSC to utilize its inherent damping capability.

A test network is developed which includes multiple series compensated lines and multi-mass turbine generator sets. This test network clearly shows SSR at many frequencies, destabilizing multiple torsional modes of nearby turbine-generator sets. The mechanical damping of multi-mass modules has been adjusted to obtain different scenarios of torsional mode instabilities. The torsional modes become most unstable when the network resonant frequencies are close by. The FSCs which excites the most unstable torsional mode is identified as the critical network resonances and is determined through small signal stability analysis. The identified critical FSC is then replaced fully with a TCSC and the minimum level of TCSC required to damp the unstable torsional modes is then determined through EMT simulations. TCSCs used in this analysis do not use any auxiliary damping controllers but utilize the inherent damping capability of the TCSC. The resistive inductive nature of the TCSC at sub-synchronous frequencies contributes to the damping of other torsional modes.

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KEYWORDS

Sub-synchronous Resonance, Thyristor Controlled Series Compensators, Torsional Interactions, Frequency Response.

1. INTRODUCTION

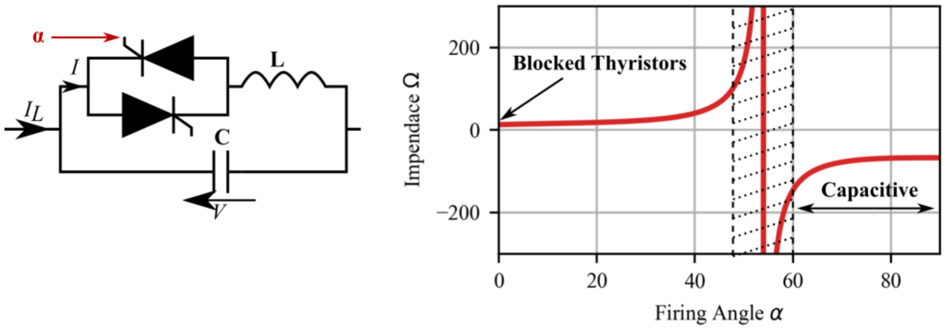
Series compensation of transmission lines have been used to overcome limitations in long distance bulk ac power transmission. It helps to improve the power transfer capability and stability. However, it may increase the risk of Sub-Synchronous Resonance (SSR). SSR occurs when the generator electrical and/or the mechanical system interacts with the network at one or more natural frequencies of the system below the synchronous frequency [3]. Due to the network resonance caused by series compensated lines, amplitude modulated currents can be observed following small disturbances. These currents have a sub-synchronous frequency component at 'ω_n' and a super synchronous component at '$2\omega_0$-ω_n', where 'ω_0' is the synchronous frequency and 'ω_n' is the network resonant frequency. The sub-synchronous current components can interact with the generator electrical system causing Induction Generator Effect (IGE) [4]. It may also interact with the generator mechanical system resulting in Torsional Interactions (TI) [5]. IGE is purely an electrical phenomenon where the synchronous generator acts as an induction generator to sub-synchronous currents. This may lead to growing sub-synchronous oscillations if there is no significant electrical damping provided by the network. TI involves participation of generator masses along the shaft system. If the frequencies of the sub-synchronous currents appearing on the rotor side is close to the torsional frequencies of the multi mass system, there can be sustained or growing torsional oscillations which can damage the turbine-generator shaft system.

Thyristor Controlled Series Compensators (TCSC) is a Flexible AC Transmission Systems (FACTS) device which offers many advantages over Fixed Series Compensators (FSC). The advantages include fast and flexible control of transmission line series reactance, damping of power swings and sub-synchronous oscillations etc. [6]. The first TCSC installation was at Kayenta substation in North-Eastern Arizona, in 1990, where the main purpose was to improve the power transfer capability and voltage support [7]. It has showed that the TCSC in open loop configuration exhibits a resistive-inductive nature providing positive damping to SSR conditions. The second TCSC was installed at SLAAT substation in 1995 [8] and an analogue simulator study has showed that the TCSC operating in impedance control mode makes the electrical system behave like an uncompensated system. The resistive inductive nature of the TCSC has been explored through the frequency responses in [9]-[10]. Damping of SSR with TCSCs can be achieved via active control techniques such as Sub-Synchronous Damping Controllers (SSDC) or its passive damping nature. It is shown in [2] that SSR damping can be achieved with its inherent damping capability even without auxiliary controls.

In networks with multiple series compensated lines and many conventional multi mass generators, there can be many network resonances which can destabilize different torsional modes. In such situations, replacing all FSC in the vicinity with TCSCs may not be a viable solution for utilities due to the cost associated with TCSCs. A better option would be to replace a few FSCs or a portion of it with a TCSC. Placement of TCSCs at appropriate locations is a critical task and there are no significant contributions reported in literature in this area. This paper shows that many unstable torsional modes can be stabilized by placing the TCSC at the right location. TCSC is utilized in open loop configuration and thus the SSR damping is achieved purely due to its inherent nature. The organization of the paper is as follows. Section 2 contains a brief description of the TCSC operation and discuss its impedance characteristics in the sub-synchronous frequency range. A test network with multiple series compensated lines and multi-mass generators is developed in section 3. Section 4 shows damping of torsional oscillations with placement of TCSCs at the right location. Section 5 includes the concluding remarks and future works.

2. FREQUENCY RESPONSE OF A TCSC

TCSC is made up of a fixed capacitor in parallel with a Thyristor Controlled Reactor (TCR) as shown in Fig. 1 (a). Thyristors are fired at a firing angle 'α' in the range from 0^0 to 90^0 with respect to zero crossings of the line current 'I_L'. TCSC will appear as a variable inductor or a variable capacitor depending on the firing angle as shown by the impedance characteristics curve in Fig.1 (b). TCSC is usually operated in capacitive vernier mode or in blocked thyristor mode and operation near the resonant region must be avoided to prevent instabilities. In open loop operation, firing angle is maintained fixed. Otherwise, it can be generated from upper layer controls such as current or power controller together with auxiliary controls such as SSDC. In this analysis, TCSC is always operated in open loop configuration.



(a) (b)

Figure 1: (a) Structure of the TCSC (b) Impedance characteristics of the TCSC versus firing angle at synchronous frequency

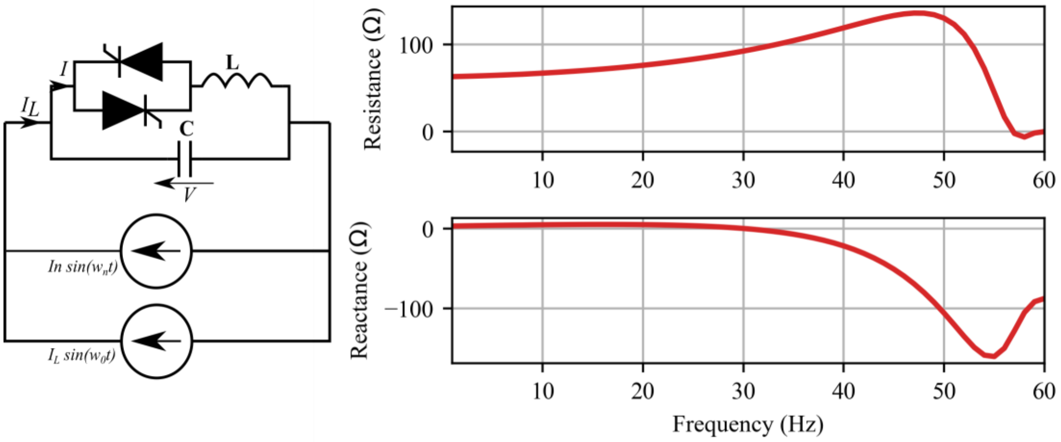
A TCSC can be designed based on three parameters in equations (1)-(3). When the required total series compensation level ($X_{C,TOT}$) is known, the value of 'L' and 'C' can be chosen with a proper choice of TCSC level (X_{TCSC}), boost factor (K_b) (for nominal operating point) and a characteristic factor (λ). Terms X_C and X_L in equations (2)-(3) are the fixed capacitive and inductive reactances of the TCSC at synchronous frequency. Boost factor is limited in the range from 1 to 3 to avoid operation near the resonant region and characteristic factor is limited in the range from 2 to 4 to avoid multiple resonant conditions [11].

$$X_{FSC} + X_{TCSC} = X_{C,TOT} \tag{1}$$

$$K_b = \frac{X_{TCSC}}{X_C} \tag{2}$$

$$\lambda = \frac{\omega_N}{\omega_0} = \sqrt{\frac{X_C}{X_L}} \tag{3}$$

The frequency response of a TCSC designed to provide a capacitive impedance (X_{TCSC}) of 87.5 Ω at Kb=1.3 and λ=2.5 is shown in Fig. 2 (b). Impedance is obtained by injecting small amplitude currents at sub-synchronous frequencies superimposed on the synchronous current source as shown in Fig. 2 (a).



(a) (b)

Figure 2:(a) Current injection technique (b) Frequency response of the TCSC

The TCSC presents a resistance at sub-synchronous frequencies and acts as an inductor in the frequency range from 1-30Hz. Impedance characteristics of TCSCs designed for different boost factors to provide the same capacitive impedance (87.5 Ω) at the nominal operating point is shown in Fig. (3). It is important to note that the TCSC behaves more like a capacitor at sub-synchronous frequencies at low boost factors. Thus, there is a chance of series resonance even though it presents a high resistance. With the increasing boost factor, the resistive nature of the TCSC is decreased at low frequencies and increased at high frequencies. Furthermore, it shows an inductive nature for most part of the sub-synchronous frequency range. This inductive-resistive nature of the TCSC at high boost factors is an advantage in mitigating SSR conditions. Thus, a nominal boost factor of 1.3 is chosen for the analysis in section 4.

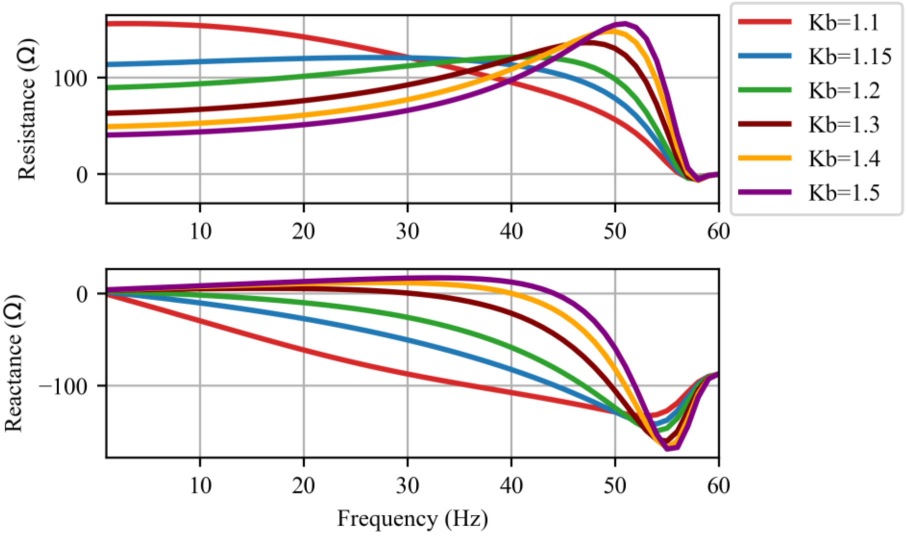


Figure 3: Frequency response of the TCSC at different boost factors

3. TEST NETWORK

A transmission network of radial nature is formed with five series compensated lines and three conventional multi-mass generators as illustrated in Fig. 4. The network and generator data are given in the Appendix. Two scenarios are obtained with different mechanical damping at multi-mass modules.

Table 1: Mechanical damping of multi-mass modules

	Mechanical damping of multi-masses at G1	Mechanical damping of multi-masses at G2	Mechanical damping of multi-masses at G3
Case 1:	0.05	2	2
Case 2:	0.3	0.3	0.3

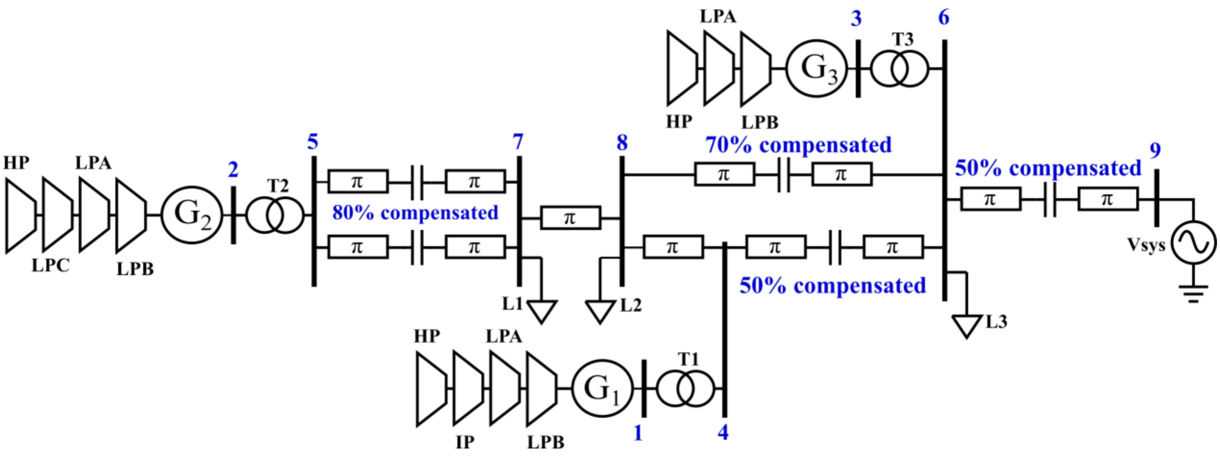


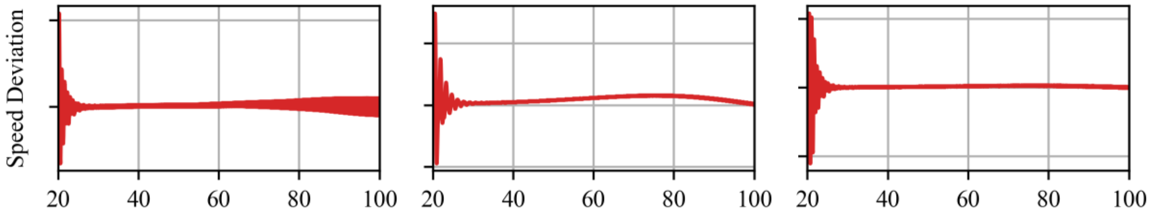
Figure 4: Test network

Results from the Eigen value analysis of the test network is shown in Table 2. Network modes in Table 2 are expressed in rotor reference frame to be consistent with the torsional mode frequencies. Torsional mode instabilities of generators 1 and 2 are observed in cases 1 and 2, respectively. Note that the torsional modes are unstable due to the network mode frequency being close to the torsional frequencies. For example, there are 16.35Hz and 34.11Hz series resonances which destabilize the 16.13Hz and 32.23Hz torsional modes of generator 1 in case 1, respectively.

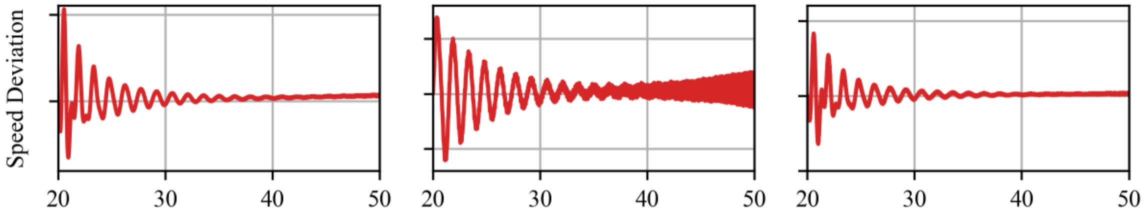
Table 2: Network and Torsional modes from Eigen value analysis

	Frequency (Hz)	**Damping (%)**	**Frequency (Hz)**	**Damping (%)**
Network Modes	43.61	2.17		
	34.11	6.46		
	20.75	8.34		
	16.35	14.52		
	6.51	43.51		
	Case 1		**Case 2**	
Generator 1 Torsional modes	**16.13**	**-0.0158**	16.13	0.175
	25.46	0.038	25.46	0.285
	32.23	**-0.037**	32.23	0.004
	47.45	0.03	47.45	0.182
Generator 2 Torsional modes	8.31	0.84	8.31	0.133
	15.23	0.31	**15.23**	**-0.048**
	20.25	0.0886	**20.25**	**-0.094**
	22.73	0.155	22.73	0.079
Generator 3 Torsional modes	23.64	1.61	23.64	0.24
	29.67	0.735	29.67	0.22
	52.73	0.5	52.74	0.15

Figure 5 shows the EMT results of the generator speed deviations obtained for the two cases following a small disturbance of 5% increment to the generator excitation voltage for 100ms. Torsional mode instabilities are clearly observed in generator 1 and generator 2 in case 1 and 2 respectively, while other generator speeds are stable (A very low frequency oscillation is observed in generator 1 speed deviation in case 1, which damps out eventually when simulated for a long time).



(a): Case 1, G1 (b): Case 1, G2 (c): Case 1, G3



(d): Case 2, G1 (e): Case 2, G2 (f): Case 2, G1

Figure 5: Generator speed deviations following a small disturbance. (a)-(c): Case 1 & (d)-(f): Case 2

4. SSR DAMPING WITH TCSC

Considering the torsional mode instability of generator 1 in case 1, there are two network modes which destabilize the two torsional modes of generator 1. The participation of series capacitors to these two network modes are shown in Figures 6 (a) & (b). The 16Hz network mode has a high participation from the FSC in branch 8-6 and likewise, a summary is given in Table 3.

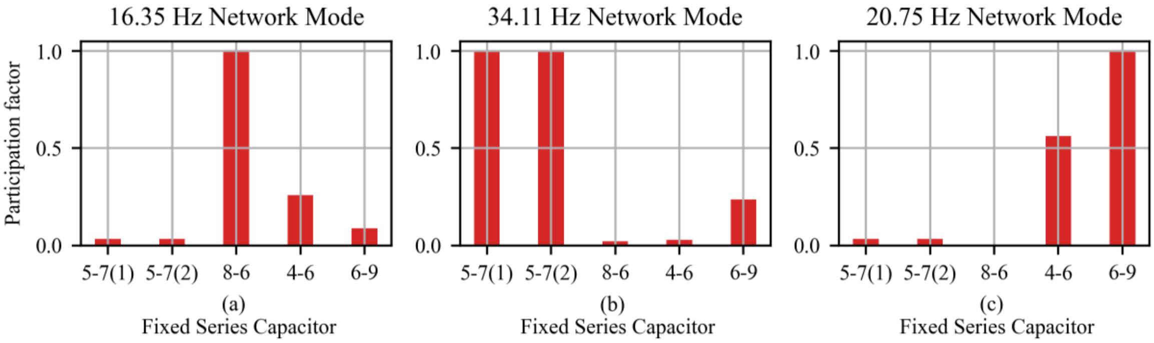


Figure 6: FSC participation to network modes

Table 3: Summary of unstable torsional modes and corresponding FSCs that highly participate in them

	Unstable torsional modes		Critical network modes		Corresponding FSC
	Frequency	**Damping**	**Frequency**	**Damping**	
Case 1	16.13	-0.0158	16.35	14.52	Branch 8-6
	32.23	-0.037	34.11	6.46	Branch 5-7
Case 2	15.23	-0.048	16.35	14.52	Branch 8-6
	20.25	-0.094	20.75	8.34	Branch 6-9

The FSC in branch 8-6 is replaced fully with a TCSC designed to provide the same impedance as that of the FSC at a boost factor (Kb) of 1.3 and λ of 2.5. A small disturbance is applied to the generator 1 excitation voltage and the generator 1 speed deviation is shown in Fig. 6 (a). Note that even though the 16Hz torsional mode is damped, growing 32 Hz torsional oscillation is observed. As per Table 2, 32Hz torsional mode is the most unstable out of the two. When the FSC in one of the branches from 5-7 is replaced fully with a TCSC (designed to produce the same impedance as the FSC at Kb=1.3 and λ of 2.5), both the 16Hz and 32 Hz torsional oscillations are stabilized as seen from Fig. 7 (b). Thus, placing a TCSC in the branch 5-7 can stabilize both the torsional modes. The level of TCSC is decreased from 100% to 30% to choose the minimum level of TCSC required to damp the unstable torsional modes. A TCSC level of 30% was adequate in damping the torsional modes as seen from Fig. 7 (b). Note that replacing an FSC in one of the parallel branches was sufficient to avoid the torsional instability.

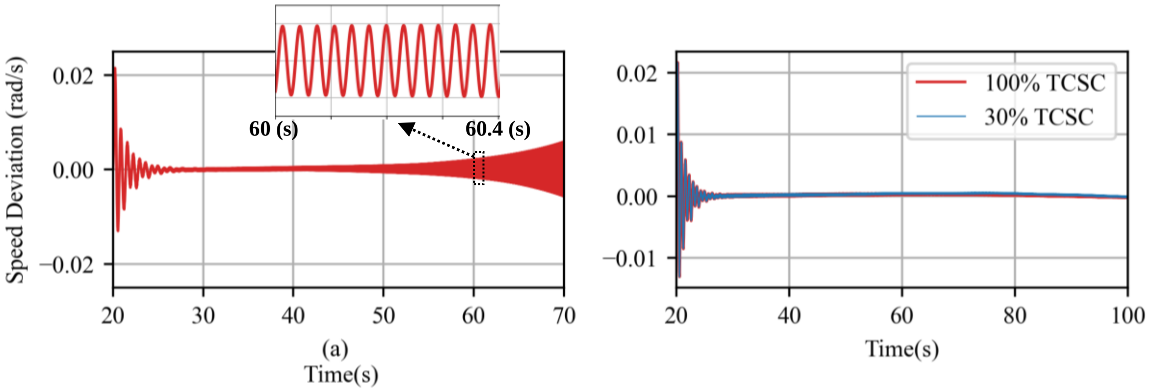


Figure 7: Speed deviation of generator 1 for a small disturbance when (a) FSC in branch 8-6 is fully replaced with a TCSC and (b) FSC in branch 5-7 is replaced with a TCSC

Figure 8 shows the frequency response of the two TCSCs placed in branches 8-6 & 5-7. It also compares the FSC impedance at the same frequency. When the FSC which causes 16Hz network resonance (branch 8-6) is replaced with a TCSC, its impedance at 44 Hz (complement of 16Hz) is capacitive and is different than that of the corresponding FSC and therefore it avoids the series resonance. But the resistance it provides at 28Hz (complement of 32 Hz torsional mode) is less and is insufficient to damp the most unstable 32Hz torsional mode. However, when the FSC which contributes the most to the 34 Hz network resonance (branch 5-7) is replaced with a TCSC, the impedance of the TCSC at 26 Hz (complement of 34Hz network resonance) is inductive and thus the network resonance is avoided. In the meantime, the resistance it adds to the network is considerably high at 44Hz and it is sufficient to provide electrical damping to 16Hz torsional mode. Therefore, it should be noted that, replacing the FSC which relates to the most unstable torsional mode with a TCSC (fully or partially) is more likely to damp other unstable torsional modes due to the resistance it adds to the circuit.

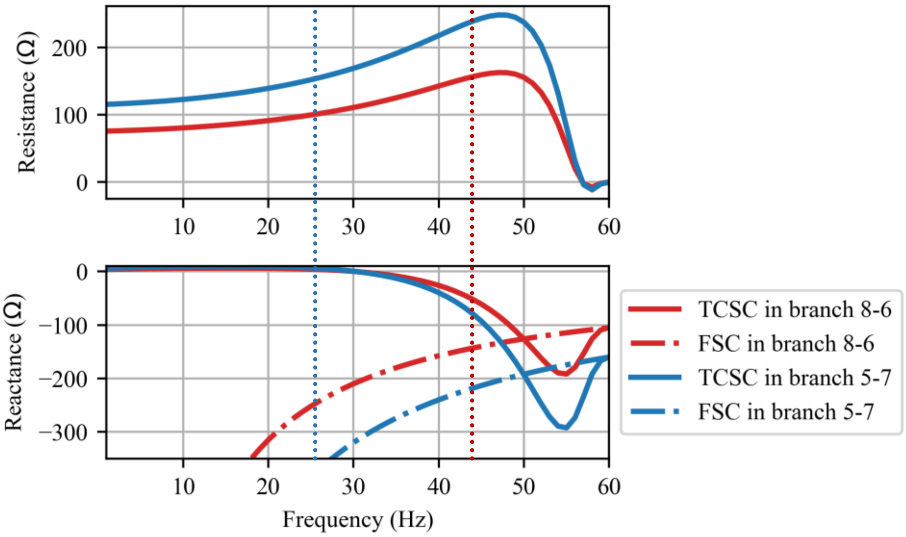


Figure 8: Frequency response of TCSCs placed in branches 8-6 & 5-7

Similar to case 1, replacing the FSC which contributes the most to the 16Hz network mode is not sufficient to damp the 20Hz torsional mode in case 2 as seen from Fig. 9(a). Replacing the FSC in branch 6-9 fully with a TCSC avoids torsional interactions at both frequencies. A minimum TCSC level of 80% is sufficient to damp the two torsional modes.

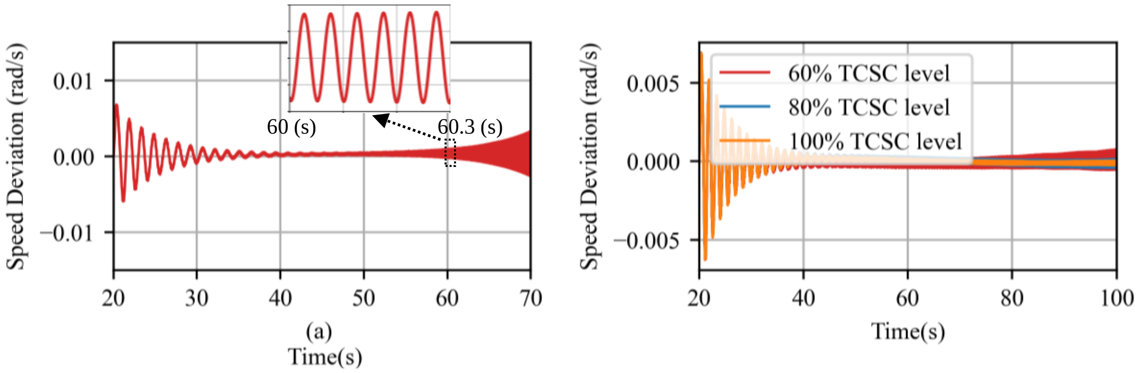


Figure 9: Speed deviation of generator 2 for a small disturbance when (a) FSC in branch 8-6 is fully replaced with a TCSC and (b) FSC in branch 6-9 is replaced with a TCSC

5. CONCLUSION

A test network is developed to demonstrate multiple torsional mode instabilities due to multiple series resonances in the network. Even though replacing all FSC with TCSCs can avoid SSR conditions, it is not a viable option due to the cost associated with it. However, this analysis showed that replacing the FSC which relates to the most unstable torsional mode can improve the damping of other unstable torsional modes as well. The inherent damping capability of the TCSC in sub-synchronous frequencies is utilized to avoid SSR conditions. However, if replacing the chosen FSC does not avoid other torsional instabilities in any case, replacing the FSC which relates to the next most unstable torsional mode may be considered. Furthermore, use of SSDC may also be advantageous. In order to find the optimal solution in such situations, use of small signal stability tools is recommended the authors are currently working in progress to develop small signal models.

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APPENDIX

Branch data (Impedances are expressed on 100MVA base and 500kV)

Branch	R (pu)	X (pu)	B (pu)	Branch	R (pu)	X (pu)	B (pu)
5-7 (1)	0.0074	0.08	0.2	**8-6**	0.004	0.06	0.2
5-7 (2)	0.0074	0.08	0.2	**4-6**	0.002	0.05	0.2
7-8	0.0014	0.03	0.2	**6-9**	0.0036	0.07	
8-4	0.0024	0.025	0.2				

Series Capacitor data (Impedances are expressed on 100MVA base and 500kV)

Branch	X_{FSC} (pu)	Branch	X_{FSC} (pu)
5-7 (1) & (2)	0.064	**8-6**	0.042
4-6	0.025	**6-9**	0.035

Generator Data (Impedances are expressed on generator MVA base)

	Generator 1	Generator 2	Generator 3
MVA rating	892.4 MVA	960 MVA	191 MVA
Terminal Voltage	22 kV	22kV	22 kV
Inertia H (s)	0.868495	0.8684328	0.946
Ra	0	0.0048	0.0026
Xl	0.13	0.215	0.102
Tdo”	0.032	0.032	0.033
Tdo’	4.3	7.9	5.9
Tqo”	0.05	0.055	0.078
Tqo’	0.85	0.41	0.535
Xd”	0.135	0.275	0.171
Xd’	0.169	0.355	0.232
Xd	1.79	1.79	1.651
Xq”	0.2	0.275	0.380
Xq’	0.288	0.570	0.171
Xq	1.71	1.66	1.59

Transformer Data (Impedances are expressed on 100MVA)

	T1	T2	T3
Voltages	22kV/500kV	22kV/500kV	22kV/500kV
Reactance (pu)	0.0224	0.02	0.02

Multi-mass Data

	Inertia Constant (H) (s)				Spring Constant (K) (pu)		
	G1	**G2**	**G3**		**G1**	**G2**	**G3**
LPA	0.884215	1.427	3.68	**Gen-LPA**	26713	14043.478	31192.245
LPB	0.85867	1.4269	-	**LPA-LPB**	19618	11804.201	30879.343
LPC/IP	0.155589	1.4264	0.337	**LPB-LPC/IP**	13168	10428.187	-
HP	0.092897	0.17553	0.099	**LPC/IP-HP**	7277	6701.4729	14306.813
Mechanical Speed (rev/m)					3600	1800	3600
MVA					892.4	960	191