A Review on Sub-Synchronous Resonance Damping with Thyristor Controlled Series Compensators

D. R. Weerakoon, U. D. Annakkage
University of Manitoba
75 Chancellors Cir., Winnipeg, Canada.
rathnayd@myumanitoba.ca, Udaya.Annakkage@umanitoba.ca

C. Karawita
Trans Grid Solutions (Pvt.) ltd.
100-78 Innovation Drive, Winnipeg, Canada.
ckarawita@tgs.biz

ABSTRACT

Over many years, the power industry has used series compensation with fixed series capacitors for long-distance ac power transmission. With the availability of Thyristor Controlled Series Compensators (TCSC), utilities have the option of using them instead of fixed series capacitors to exploit the advantage of their flexibility and controllability. The use of TCSCs for damping electro-mechanical oscillations and Sub-Synchronous Resonance (SSR) has been investigated and reported over the years. This paper presents a review of those techniques to damp SSR problems associated with conventional multi-mass turbine generator systems in series compensated networks. This paper also demonstrates that SSR can be damped out with the proper choice of TCSC parameters and/or control strategies even without an auxiliary damping controller. Sub-synchronous behavior of the TCSC is simulated in both open loop and closed loop controls in the time domain through Electro-Magnetic Transient (EMT) simulations. IEEE 1st Benchmark model for SSR studies is used in this paper to demonstrate the effect of TCSC parameters and control methodology in damping SSR.

KEYWORDS: *Thyristor Controlled Series Compensators (TCSC), Sub-Synchronous Resonance (SSR), time-domain analysis, IEEE 1st Benchmark model for SSR studies.*

1 INTRODUCTION

Series compensation has long been in use to overcome limitations of long-distance bulk ac power transmission. The use of Fixed Series Compensators (FSC) is an economical solution to improve power transfer capability and stability. However, the potential risk of Sub-Synchronous Resonance (SSR) associated with FSC (Anderson, Agrawal, & Van Ness, 1999) makes it undesirable to be used widely in the system. SSR occurs due to the interaction between the generator electrical system and/or torsional system against the network at a frequency below the synchronous frequency. SSR is not limited to series compensated networks or conventional generators but also exists in power electronic-based systems such as HVDC terminals and wind farms, even in the absence of series capacitors (Xu, Zhao, Cao, & Sun, 2019; Karawita & Annakkage, 2009). The first incident of SSR in a series compensated network is reported in 1970 at the Mohave generating station in Southern Nevada which resulted in severe damage to two turbine shafts (Walker, Bowler, Jackson, & Hodges, 1975). A conventional technique to mitigate SSR is to bypass some or all series capacitors. There are many techniques to counteract SSR in FSC networks such as supplementary excitation controls, static filters, dynamic filters etc. (Kundur, 1994).

TCSC is a Flexible AC Transmission Systems (FACTS) device that allows fast and flexible control of transmission line reactance. It is known to mitigate SSR problems and damp power system oscillations (Joshi & Kulkarni, 2009; Nyati, et al., 1994; Piwko, Wegner, Kinney, & Eden, 1996; Urbanek, et al., 1993). However, due to the complexity and costs associated with TCSCs, utilities have the option of placing full or partial TCSCs at optimal locations to exploit the advantages of TCSC after thorough investigations not limited to SSR. Sometimes, it can be for the sole purpose of avoiding SSR issues. This paper reviews SSR damping methodologies with TCSC reported in the literature and explores the inherent damping capability of TCSC with proper choice of TCSC parameters through time domain simulations.

The organization of this paper is as follows: Section 2 reviews SSR damping techniques and TCSC structure and its operation is discussed in section 3. Section 4 demonstrates the inherent damping achieved with the appropriate choice of TCSC parameters when the TCSC is operated in open loop and closed loop configuration with EMT simulations followed by the conclusion in section 5.

2 REVIEW ON SSR DAMPING

SSR damping techniques associated with TCSCs mainly fall under two categories which are, active damping techniques and passive damping techniques. SSR damping with basic TCSC controls such as current and power controls and damping SSR with auxiliary controllers such as Sub-Synchronous Damping Controllers (SSDC) fall under active damping techniques. SSR damping can be achieved with the inherent nature of the TCSC as shown in Piwko, et al,1996; and Nyati, et al., 1994, and this paper includes how inherent damping of TCSC can be utilized in open loop configuration and closed loop current control mode to avoid SSR with the proper choice of parameters.

2.1 SSR damping with basic TCSC controls

The impact of TCSC control methodologies such as constant current, constant power, and constant impedance control on damping of SSR is presented in (Pilotto, Bianco, Long, & Edris, 2003). Simple PI regulators have been used in all control techniques and local feedback signals have been used. Constant current controller with a derivative line current feedback is effectively used to damp all SSR torsional modes in IEEE 1st benchmark model for SSR studies at different compensation levels. It is shown that fast power controllers induce large electromechanical and sub-synchronous oscillations. Therefore, the authors have proposed an enhanced power control methodology where a fast current controller is used in the main control loop and a slower secondary loop is used for power control. It is claimed that the constant impedance control where TCSC operates in an open loop configuration can successfully damp certain torsional modes but is not robust over the range of series compensation levels and may excite other torsional modes.

2.2 SSR damping with auxiliary controls

A supplementary damping controller "TCSC-DC" for TCSC operating in open loop constant impedance control mode is proposed in (Zheng, Xu, & Zhang, 2009, July). This technique uses generator speed deviation which is a remote signal as the input to the damping controller. The damping controller is designed based on wide bandwidth phase compensation technique. An auxiliary signal is added to the original firing angle order as shown in Figure 1. Auxiliary signal will add a supplementary electric torque component so that the net electrical damping torque becomes positive and thus the torsional mode damping is improved. However, controller gain, and phase compensator time constants must be tuned to get the optimal damping effect according to the operating condition. A similar approach has been used in (Dey, Das, & Kulkarni, 2021) along with an eigenvalue analysis, validating the performance of SSDC.

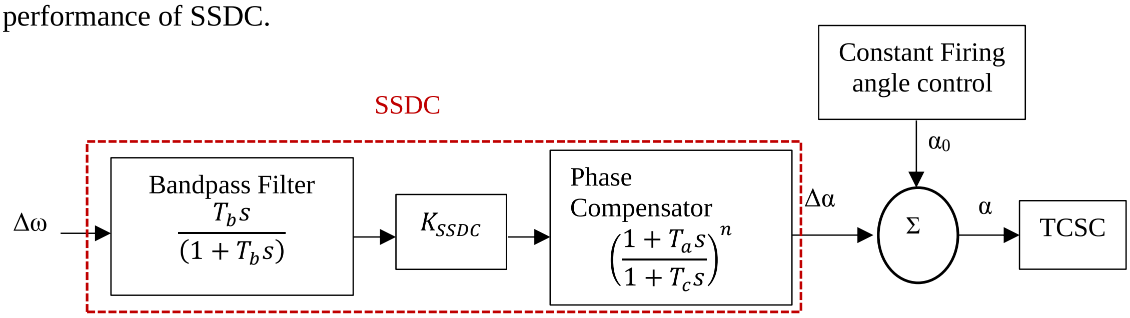

Figure 1: Sub Synchronous Damping Controller block diagram

A novel discrete control strategy based on phase unbalanced concept is introduced in (Subhash, Sarkar, & Padiyar, 2001,November) and applied to IEEE 1st benchmark model. The original phase unbalance concept in (Edris, 1990) which is introduced in FSC networks has been extended to TCSC systems. The basic concept is to have three different inductive-capacitive combinations in each phase so that they produce equal reactances at the power frequency and unequal reactances at the other frequencies. The purpose of having unbalanced reactances is to prevent balanced sub-synchronous currents from entering the generator stator during transients and producing a pure rotating MMF. Phase unbalance is achieved by either inserting or bypassing TCSC modules during a disturbance.

2.3 Passive damping of SSR

Field tests at the SLATT substation demonstrated that the use of TCSCs instead of FSC in vernier control mode avoids possible SSR (Piwko, et al.,1996). In (Nyati, et al., 1994), it is shown that electrical damping of the SLATT system with a TCSC is almost the same when there is no series compensation, claiming that the TCSC is SSR neutral. Although TCSC is known to inherently damp SSR, it is shown in (Pilotto, et al., 2003) that the TCSC is not always SSR neutral especially when the line is composed of both FSC and controlled series compensation. The effect of TCSC parameters on its inherent damping capability is further explored through time domain simulations in section 4.

3 TCSC STRUCTURE AND OPERATION

TCSC is composed of a fixed capacitor in parallel with a Thyristor Controlled Reactor (TCR) as shown in Figure 2. Thyristors are switched at supply frequency (50/60Hz) according to the firing angle delay (α) to control the equivalent reactance of the TCR. The equivalent impedance of the TCSC at a certain firing delay is the parallel combination of the fixed capacitor and equivalent inductance. Firing angles can be synchronized to the zero crossing of either the line current or capacitor voltage. But synchronization to line current zeros is the most effective as the line current is almost sinusoidal.

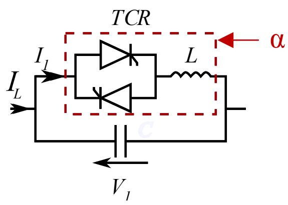

Figure 2: Structure of the TCSC

TCSC can be operated in open loop configuration which is the constant firing angle control mode or in closed loop configuration. In closed loop configuration, the firing angles are generated by upper layer controls such as constant current or power controllers. On top of basic controllers, auxiliary controls such as SSDCs and power oscillation damping controllers will play a role in generating the firing angle orders.

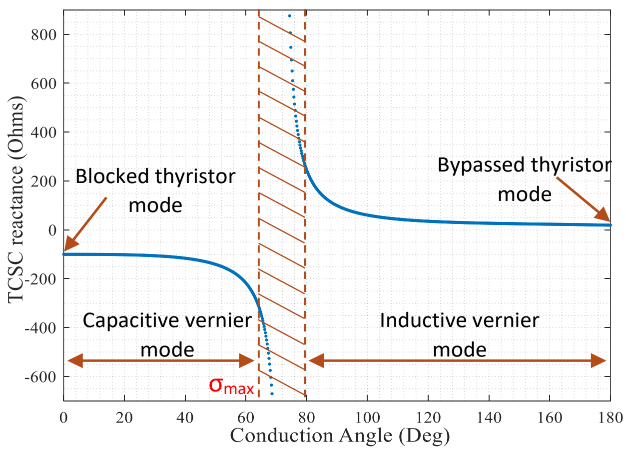

Figure 3: Impedance characteristics of the TCSC

TCSC can be operated in vernier mode, blocked thyristor mode or in bypass thyristor mode. In blocked thyristor mode, the TCSC appears as a fixed capacitor and in bypass thyristor mode it appears as the parallel combination of the fixed inductor and capacitor. When operated in vernier mode, the TCSC can offer either an inductive reactance or capacitive reactance according to the firing angle as shown by the impedance characteristics in Figure 3. TCSCs are generally designed to be operated in capacitive vernier mode with a maximum conduction angle (σ = 2(π-α)) limit to avoid instabilities near the parallel resonance point.

When the required total series compensation level of the transmission line is known, the TCSC inductance and capacitance can be chosen based on three parameters which are, the level of controllable series compensation, boost factor, and the characteristic factor as given in Equations (1) to (3), respectively.

$$X_{FSC} + X_{TCSC} = X_{C,TOT} \quad (1)$$

$$K_b = \frac{X_{TCSC}}{X_C} \quad (2)$$

$$\lambda = \frac{\omega_0}{\omega_N} = \sqrt{\frac{X_C}{X_L}} \quad (3)$$

The total series compensation ($X_{C,\ TOT}$) is composed of both fixed series capacitive reactance (X_{FSC}) and controllable series capacitive reactance (X_{TCSC}) by the TCSC as in Eq. (1). Once the level of controllable series compensation is decided, TCSC fixed capacitive reactance (X_C) can be selected based on Eq. (2) with the proper choice of boost factor (K_b). A high boost factor implies that the TCSC is operating very close to the resonant point. Therefore, even small distortions can change the TCSC impedance drastically, leading to instabilities. Thus, the boost factor is typically chosen to be less than 3 (Zheng, Li, & Liang, 2015). The value of the reactor can be determined by the characteristic factor (λ) defined in Eq. (3). The characteristic factor must be chosen to avoid multiple resonant conditions, limiting to only one resonant point between 0^0 to 180^0 of the firing angles. Typical values of λ are in the range between 2 to 4 (Vuorenpää, Rauhala, Järventausta, & Känsälä, 2007,June).

4 INHERENT DAMPING OF TCSC

IEEE 1st benchmark for SSR studies (IEEE SSR working group, 1977) has been used to demonstrate how the inherent SSR damping capability of TCSC can be achieved with the proper choice of its parameters. Figure 4 shows the IEEE 1st benchmark test system with closed loop current control of TCSC. The generator is modelled with four turbine masses ignoring the exciter. Mechanical damping of turbine masses is ignored to obtain the worst-case scenario.

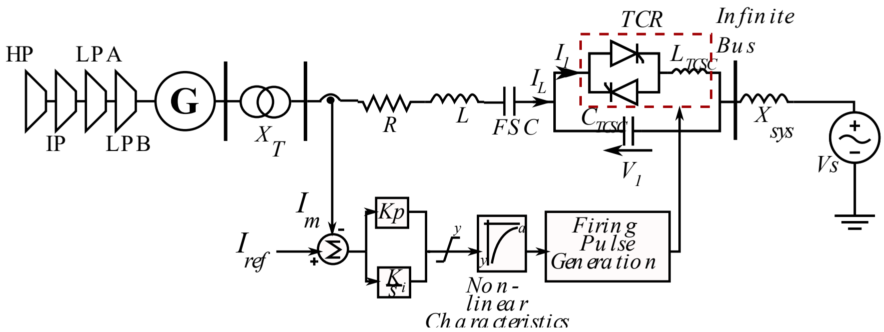

Figure 4: IEEE 1st benchmark test system with TCSC

The generator is operated at 1 pu terminal voltage, 0.9 pu active power and 0.9 power factor at the terminal. Small signal stability analysis of the above system with FSC corresponding to 66% of series compensation reveals four torsional modes, an electromechanical mode, and a sub-synchronous network mode as shown in Table 1.

Table 1: Oscillatory modes in IEEE 1st benchmark test system with 66% FSC

Mode	Frequency	Damping
Torsional mode 1	16.25	-0.12%
Torsional mode 2	25.43	-0.009%
Torsional mode 3	32.19	0%
Torsional mode 4	47.45	0%
Electromechanical mode	1.7	4.7%
Network mode	20.6	2.24%

The most dominant unstable torsional mode is the 16 Hz mode with all turbine masses and generators participating and it is observable in generator speed deviations. Thus, the effect of three TCSC parameters, discussed in Section 3, in damping this 16 Hz torsional mode is explored with time domain simulations.

The level of controllable series compensation is varied in the range from 10% to 100% with TCSC operating in an open loop configuration. The boost factor (K_b) and the characteristics factor (λ) are maintained constant at 1.3 and 2.5, respectively. The proportional and integral gains of the PLL are set to 25 and 900, respectively in all test cases. Table 2 shows the TCSC parameters for each scenario. The firing angle order is maintained to get the same level of series compensation (66%).

Table 2: TCSC parameters for different levels of controllable series compensation

TCSC percentage	C_{TCSC}	L_{TCSC}	Firing angle
10%	285.7 μF	3.9 mH	156.6^0
30%	95.23 μF	11.8 mH	156.6^0
50%	57.14 μF	19.7 mH	156.6^0
70%	40.81 μF	27.6 mH	156.6^0
80%	35.713 μF	31.5 mH	156.6^0
100%	28.57 μF	39.4 mH	156.6^0

Figures 5-7 shows the generator speed variation for a small disturbance of 5% increment to the generator excitation voltage for a period of 1 ms. The unstable 16 Hz mode is clearly visible in Figure 5 when the TCSC compensation level is as low as 10%.

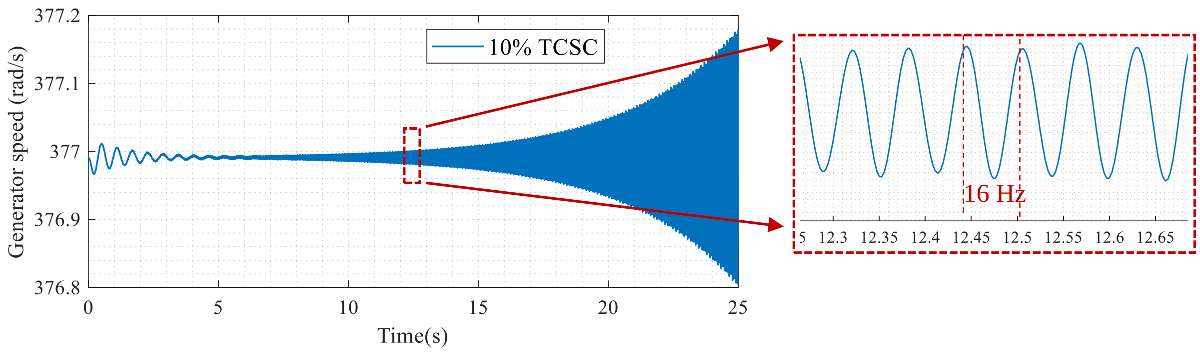

Figure 5: Generator speed variation for a small disturbance when TCSC corresponds to 10% of the total series compensation level

However, it is seen from Figure 6 that, damping of 16 Hz torsional mode is increasing with the increasing levels of controllable series compensation. Even though the torsional mode is fully damped beyond 70% TCSC level in Figure 7, the damping of the electromechanical mode is decreasing with the increasing level of TCSC when the TCSC is operating in constant firing angle control.

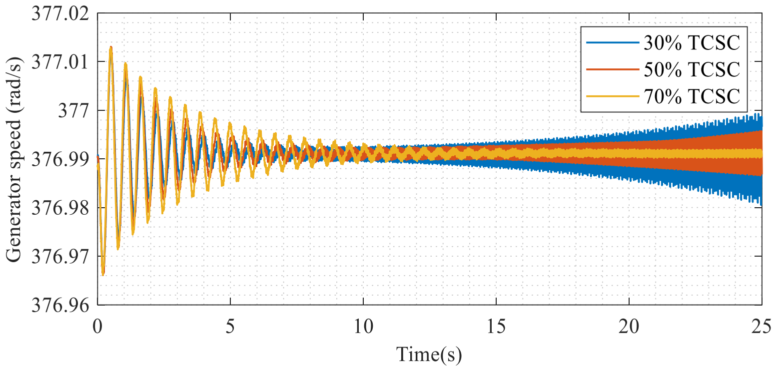

Figure 6: Generator speed variation for a small disturbance when TCSC corresponds to 30%, 50% & 70% of the total series compensation level

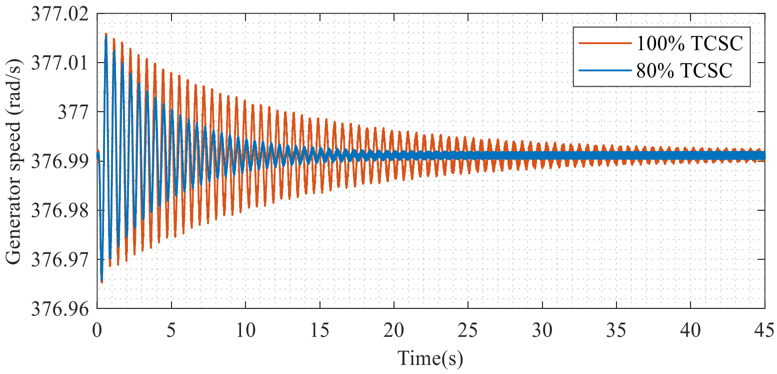

Figure 7: Generator speed variation for a small disturbance when TCSC corresponds to 80% & 100% of the total series compensation level

Figures 8-10 show the generator speed variation when the TCSC is operated in constant current control mode at 70%, 80%, and 100% of TCSC levels, respectively. Current is controlled to maintain the same level of compensation (66%) as in open loop configuration. The proportional and integral gains of the current controller are maintained as 5 and 160, respectively. The damping of electromechanical mode is improved in closed-loop current control mode. However, the controller action did not improve the damping of the unstable 16 Hz torsional mode.

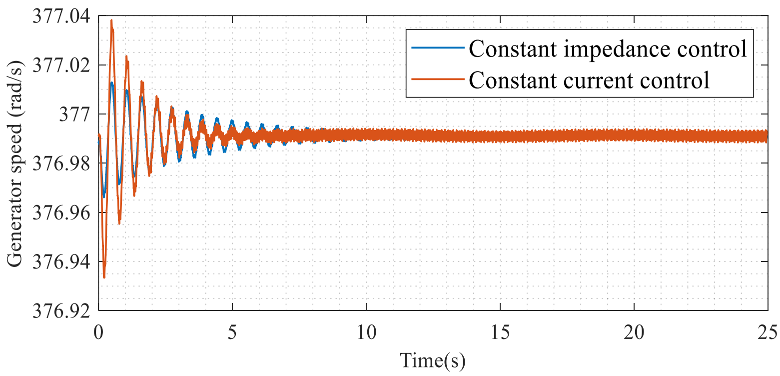

Figure 8: Comparison of generator speed with constant impedance control and constant current control when TCSC corresponds to 70% of the total series compensation level

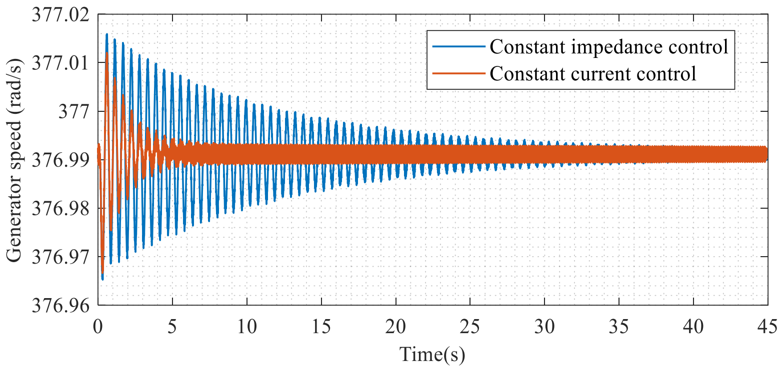

Figure 9: Comparison of generator speed with constant impedance control and constant current control when TCSC corresponds to 80% of the total series compensation level

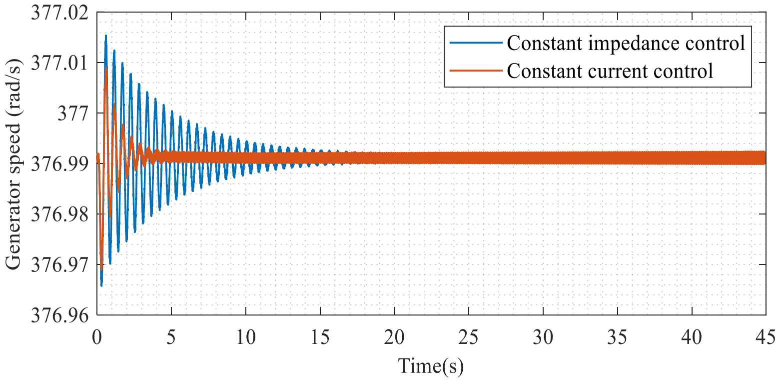

Figure 10: Comparison of generator speed with constant impedance control and constant current control when TCSC corresponds to 100% of the total series compensation level

The effect of operating TCSC at high boost factors (K_b) in open loop configuration is illustrated in Figures 11-13. TCSC parameters for each boost factor are shown in Table 3. TCSC contributes to 80% of the total series compensation level and the characteristic parameter (λ) is maintained constant at 2.5. Firing angles are adjusted to maintain the same total series compensation level of 66%

Table 3: TCSC parameters for different boost factors

Boost Factor (K_b)	**C_{TCSC}**	**L_{TCSC}**	**Firing angle**
1.1	30.218 µF	37.3 mH	162.3^0
1.15	31.592 µF	35.6 mH	160.3^0
1.2	32.966 µF	34.2 mH	158.8^0
1.3	35.713 µF	31.5 mH	156.6^0
1.5	41.207 µF	27.3 mH	153.9^0

As seen from Figure 11, torsional mode damping is improved with increasing boost factor. Boost factor of 1.3 completely damps out the unstable 16 Hz torsional mode as evident from Figure 12, but the electromechanical mode damping is reduced to undesirable values and is almost unable to operate the TCSC at a boost factor as high as 1.5 as seen from Figure 13.

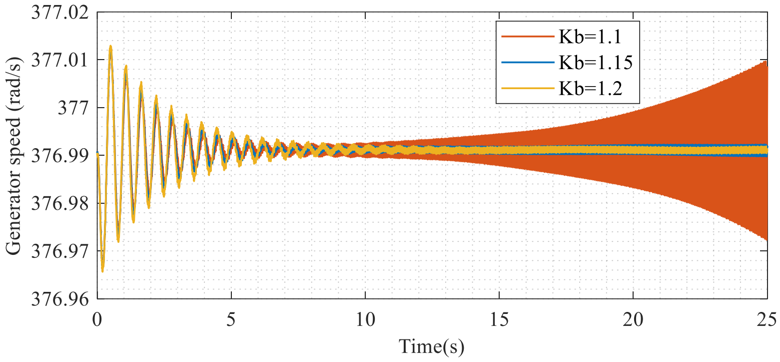

Figure 11: Generator speed variation for a small disturbance when TCSC boost factor =1.1, 1.15 & 1.2

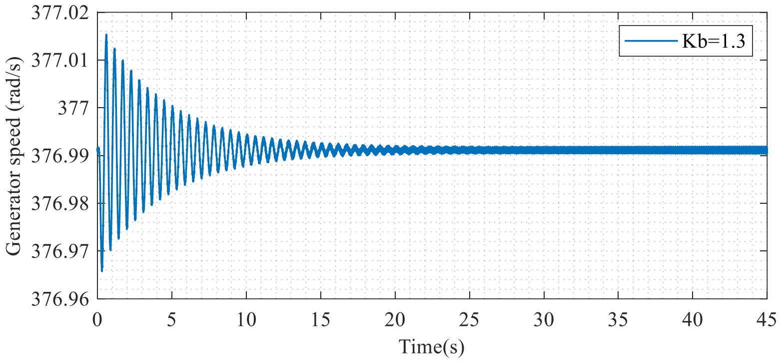

Figure 12: Generator speed variation for a small disturbance when TCSC boost factor =1.3

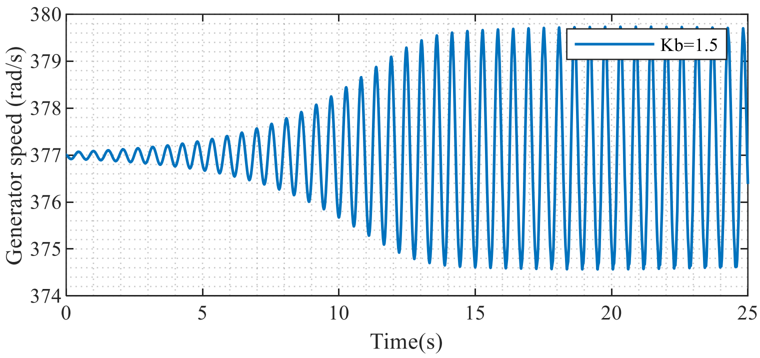

Figure 13: Generator speed variation for a small disturbance when TCSC boost factor =1.5

The impedance characteristics of the TCSC for each scenario in Table 3 are shown in Figure 14. The parallel resonant point is the same in all cases as the characteristic factor is a constant. But the TCSC operating point is moving towards the highly non -linear region with increasing boost factors. The closer the operating point is to the resonant point, the higher the conduction angle and thus better the damping of torsional modes. As seen in Figure 15, electromechanical damping is improved with the addition of closed-loop current control and therefore, high boost factors can be realized in closed-loop control.

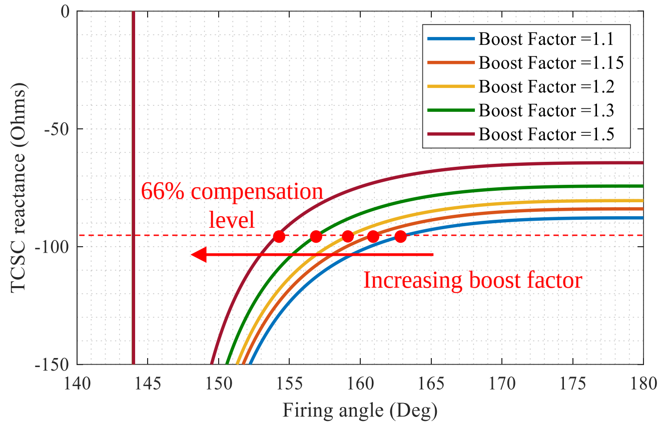

Figure 14: Effect of increasing boost factor on TCSC impedance characteristics

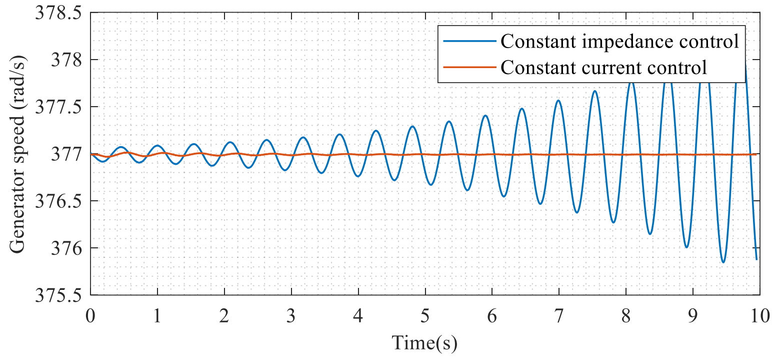

Figure 15: Comparison of generator speed with constant firing angle control and constant current control for a small disturbance when TCSC boost factor = 1.5

Finally, the effect of different characteristic factors on the inherent damping is explored. The TCSC is responsible for 80% of the total compensation level and the boost factor is maintained constant at 1.3. TCSC is fired to maintain a total of 66% series compensation level, all the time. Table 4 shows the TCSC parameters according to characteristic factors.

Table 4: TCSC parameters for different characteristic factors

Characteristic Factor (λ)	**C_{TCSC}**	**L_{TCSC}**	**Firing angle**
2	35.713 μF	49.3 mH	152.2^0
2.5	35.713 μF	31.5 mH	156.6^0
3	35.713 μF	21.9 mH	159.8^0
3.5	35.713 μF	16.1 mH	162.1^0

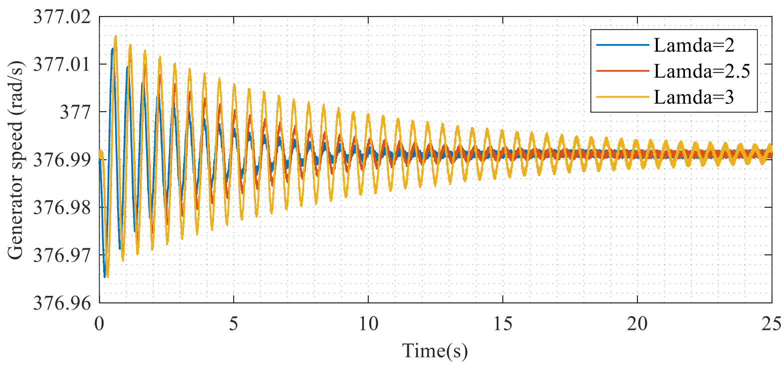

Figure 16: Generator speed variation for a small disturbance when TCSC characteristic factor =2,2.5 and 3

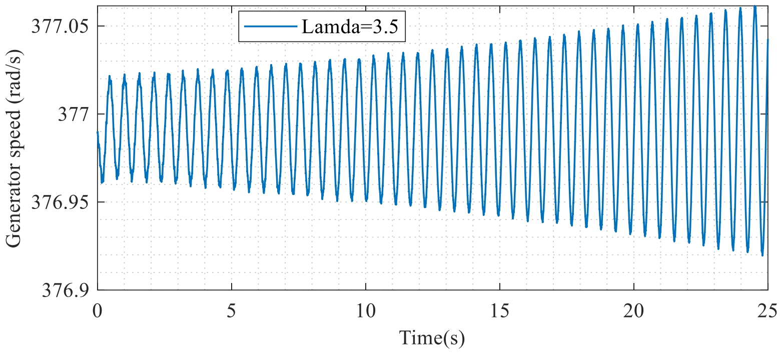

Figure 17: Generator speed variation for a small disturbance when TCSC characteristic factor =3.5

It is seen from Figure 16 that there is no significant effect of changing characteristic factors on torsional mode damping. It only destabilizes the electromechanical mode at high characteristic factors. Therefore, a characteristic factor of 2 or 2.5 is sufficient for most operating conditions.

5 CONCLUSION

SSR damping techniques associated with TCSC are reviewed in this paper. SSR damping can be achieved with basic control topologies such as current and power controllers, or auxiliary controllers such as SSDC or the TCSC can be designed to inherently damp out potential SSRs. It is shown with time-domain simulations that with the proper choice of controllable series compensation level and a boost factor, torsional mode damping could be improved without auxiliary controls. Electromechanical mode instability which occurs in TCSC open loop control is eliminated in closed loop constant current control, which allows a high level of controllable series compensation and boost factors to be realized.

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