Effect of Torsional Mode Coupling on TCSC Related Subsynchronous Resonance Studies

P. Vuorenpää, T. Rauhala, P. Järventausta

***Abstract*--Sustained or growing torsional oscillations of turbine-generator is widely understood problem especially in case the generator is connected in vicinity of long series compensated transmission lines. To verify sufficient damping of torsional modes in all possible operating conditions extensive power system analysis must always be executed as new components possibly affecting the subsynchronous response of the network are installed. To decrease complexity of such studies loosely-coupled or decoupled torsional modes are generally accepted assumptions. However, noticeable effect of coupling of torsional modes on subsynchronous damping study results has been reported.**

In this paper PSCAD studies concerning torsional mode coupling in a case of Thyristor Controlled Series Capacitor (TCSC) are presented. Firstly, generic all-mode and modal approaches for modeling turbine-generator shaft are presented and phenomenon of torsional mode coupling is shortly discussed. Thereafter, electromagnetic transient (EMT) analysis of subsynchronous damping studies concerning all-mode and modal models of specific turbine-generator shaft are presented. In the studies TCSC and its additional Subsynchronous Damping Controller (SSDC) was applied to increase damping of poorly damped torsional modes. Based on the study results effect of coupling of torsional modes on subsynchronous damping is analyzed and discussed.

***Keywords*: Torsional mode coupling, Thyristor Controlled Series Capacitor, Subsynchronous damping controller, Electromagnetic transient analysis.**

I. Introduction

TYPICALLY, long turbine-generator shafts have several mechanical torsional oscillation modes on subsynchronous frequency range. The torsional oscillations are initiated by any changes in electrical or mechanical torques. Insufficient damping of these torsional oscillations can result for example in disconnection of series compensation bank or generator due to operation of protective devices, which are installed to avoid the worst case scenario that is serious damage to turbine-generator shaft. Therefore sufficient damping of the torsional oscillations must always be ensured in all possible operation conditions by means of extensive power system analysis.

The approaches applied in analysis of subsynchronous oscillations can be divided in two: full order or all-mode models presenting the subsynchronous torsional oscillations in full detail and modal or reduced order models presenting only one or a couple subsynchronous torsional frequencies. The fundamental difference between these two is that only when the full order models are applied in the analysis, the effect of possible torsional mode coupling [1] on subsynchronous damping is taken into account in the analysis. Despite subsynchronous frequency scanning techniques [2], that are based on modal modeling, are extensively applied in SSR and SSTI planning and design studies, the sensitivity of results of modal model based studies to torsional mode coupling has not been extensively studied.

Despite the possible significance of torsional coupling phenomenon concerning SSR damping studies it has been covered only in very few papers. [3, 4] In this paper Thyristor Controlled Series Capacitor (TCSC), as an effective measure for damping subsynchronous oscillations, is utilized in series compensated transmission line and the effects of torsional coupling phenomenon on SSR study results concerning this controllable and nonlinear FACTS device are presented. Paper describes an approach for analyzing torsional mode coupling using all-mode and modal models of turbine-generator shaft and power system including TCSC and its additional Subsynchronous Damping Controller (SSDC). Thereby, the main scope of this study was to analyze, whether the torsional coupling phenomenon may significantly affect the results of TCSC related SSR studies. Against the initial hypothesis the results of the performed, extensive studies indicate that torsional coupling phenomenon had no significant effect on the TCSC related SSR study results. Factors possibly contributing on this unexpected result and as well as recommendations for further analysis required to verify the study results are discussed briefly at the end of this paper.

II. Modeling Turbine-Generator Shaft for Subsynchronous Resonance Damping Studies

A. All-mode modeling of turbine-generator shaft

From subsynchronous interaction analysis point of view, long turbine-generator shaft can be considered to be composed of several separate masses which are coupled to each other by specific shaft dependent spring constants. As the coupled masses can be described with their individual inertia constants, turbine-generator shaft can be modeled in straightforward manner using general second-order spring-mass equation

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describing the basic dynamics of this multimass system.

$$\mathbf{J}\ddot{\theta}+\mathbf{D}\dot{\theta}+\mathbf{K}\theta=\mathbf{T} \tag{1}$$

Equation (1) takes matrix form, in which **J** is a diagonal matrix including inertia constants of the masses, **D** represents the mechanical damping of the system and **K** is a symmetric matrix describing the coupling of each individual mass to next. Vector **T** represents the torques delivered to each mass. In Fig. 1 general representation of six-mass shaft system including generator and exciter masses is presented.

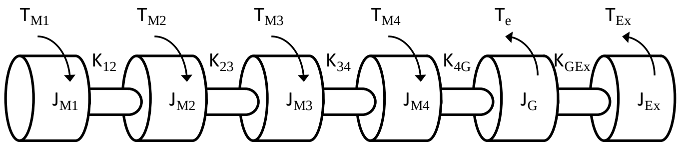

Fig. 1. General representation of six-mass shaft system

Torsional oscillation modes, excited by sudden difference between the electrical and mechanical torques, are constituted to specific subsynchronous frequencies determined by the mechanical parameters of the shaft. If accurate and reliable data of the inertia and spring mass constants of any specific shaft system is available all-mode modeling enables fast and effective approach for studying the characteristics of all the significant torsional modes simultaneously. However, for example lack of accurate mechanical data of shaft system at planning stage requires basically use of more simplified study approaches.

B. Reduced-order and modal modeling of turbine-generator shaft

Despite the straightforward approach of all-mode modeling of turbine-generator shaft, simplified approaches like reduced-order modeling of turbine-generator shaft has been introduced. [5, 6, 7] These approaches are mainly motivated by possible lack of detailed shaft system data or the reduced calculation burden compared to all-mode models especially in eigenvalue analysis. However, reduced-order models are not commonly utilized in EMT analysis based SSR damping studies and therefore they are not included in the scope of this paper.

Another simplified approach for modeling mechanical behavior of turbine-generator shaft is called modal modeling. [8, 9] In modal modeling modal inertia and spring constant related to each individual torsional oscillation mode is determined by eigenvalue analysis of the original spring mass equation or alternatively through field measurements. These parameters can be used to constitute mode dependent two-mass model describing the dynamical characteristics of each individual torsional mode. [2] (Fig. 2)

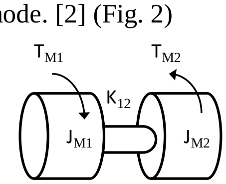

Fig. 2. Two-mass model for modal modeling of turbine-generator shaft

Due to use of this two-mass representation, modal approach leads to simplified representation of spring-mass equation.

$$\begin{bmatrix} J_{M1} & 0 \\ 0 & J_{M2} \end{bmatrix}\ddot{\theta}+\begin{bmatrix} K_{12} & -K_{12} \\ -K_{12} & K_{12} \end{bmatrix}\theta=\begin{bmatrix} T_{M1} \\ T_{M2} \end{bmatrix} \tag{2}$$

As stated earlier, if the accurate data of shaft system is not available, modal modeling enables frequency scanning natured approach for studying the overall SSR damping characteristics of power system in planning state studies. [2]

In general, mechanical damping of torsional modes is extremely difficult to measure even with decent accuracy in extent that would be required for detailed SSR studies and in planning stage such information is not available in practice. Therefore, term of mechanical damping presented in (1) is often ignored in general SSR studies such as in this paper.

III. Coupling Of Torsional Modes

Use of reduced-order or modal models of torsional oscillation modes of turbine-generator shaft presumes uncoupling of torsional modes. This assumption has been used in subsynchronous resonance studies executed in [6, 8, 10] and results of the studies support this assumption. However, strong relation between specific torsional modes, for example in a case where attempting to damp some specific mode the damping of some other mode decreases, has been reported using both eigenvalue and EMT analysis based study approaches. [1] In [1] following conclusions regarding coupling phenomenon of torsional modes were made:

- insufficient modeling of turbine-generator shaft by ignoring coupling phenomenon of torsional modes can lead to incorrect results in studies performed to ensure sufficient subsynchronous damping of overall system
- coupling of torsional modes is highly related to the extent of power system model and control implementations
- coupling phenomenon has most significant effect on amplitudes of the torsional modes and secondary effects on damping of these modes
- only proper control design of torsional oscillation countermeasure device can eliminate the possible insufficient damping due to coupling phenomenon.

Despite the possible significance of coupling of torsional modes on SSR related damping studies subject has drawn only little attention. Because wide utilization of reduced-order or modal models in SSR damping studies nature of torsional mode coupling should fully be understood to verify the correct damping results in such studies. Importance of this subject is emphasized especially in cases where countermeasures for potentially increasing subsynchronous oscillations are of concern. Therefore, in this paper phenomenon of torsional mode coupling in case of TCSC is investigated and discussed based on results of SSR analysis performed using both all-mode and modal turbine-generator shaft models.

IV. Studied Power System

A. Power System Model

Studies concerning coupling phenomenon in a case of TCSC were executed in PSCAD environment using network model presented in Fig. 3. Parameters of the transmission lines, series capacitors, shunt compensators and voltage sources correspond to the ones presented in [11, 12]. However, studied turbine-generator was located in bus H with ratings presented in [1] and generator of bus N was replaced by voltage source originally located in bus H. In addition, transmission line T12 was connected to the transmission system.

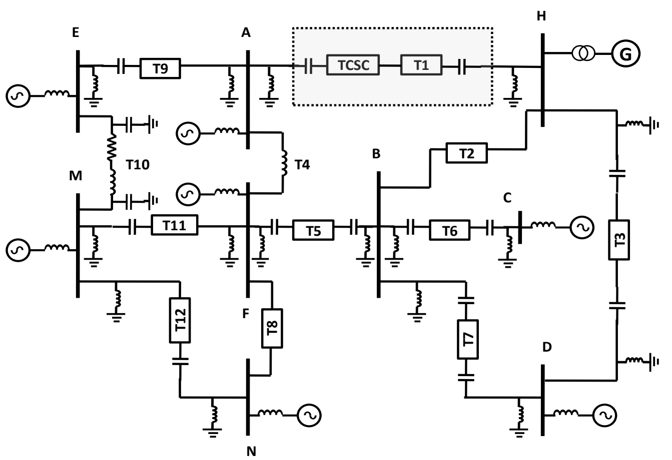

Fig. 3. Single line representation of studied power system

The electromechanical data and modal parameters of studied turbine-generator are presented in detail in [8]. Generator, forming equivalent of three identical generators, was operating on 0.8 p.u. and 0.95 lagging power factor. In all the presented studies 2 ms phase-to-ground fault in bus B was applied to create a small signal natured stimulus for the studied torsional oscillation modes.

B. TCSC model

Three-phase TCSC was utilized to improve the overall damping of system presented in Fig. 3. TCSC was connected in series with transmission line T1 replacing part of the existing fixed series capacitor. In presented studies TCSC without thyristor conduction constituted 30 % of total series compensation capacity of the transmission line T1.

Closed-loop controls of TCSC were assumed not to have any significant effect on subsynchronous characteristics of the device and therefore TCSC was controlled with constant open-loop firing angle. This could be considered as justified assumption because of relatively large time constants of common closed-loop controllers, such as closed-loop fundamental reactance or constant power controllers of TCSC. However, synchronization configuration of TCSC can be considered to have specific contribution to the response of TCSC on torsional oscillations. Generic three-phase Phased Locked Loop (PLL) circuit [13, 14] with line current synchronization was applied to generate the desired firing time instants based on the determined firing angle reference. Main parameters of TCSC and both proportional gain K_P and integrator gain K_I of PLL circuit are presented in Table I.

TABLE I
Main Parameters of Studied TCSC

L_{TCSC}	14.7 mH
C_{TCSC}	76.55 uF
K_P (PLL)	30
K_I (PLL)	300

One of the main advantages of TCSC is related on its inherent positive contribution to subsynchronous damping of generators connected to series compensated network. In some cases though, despite the inherent damping characteristics of TCSC insufficient damping of certain torsional mode may still occur. In these cases additional control circuit, Subsynchronous Damping Controller (SSDC), could be utilized to further improve the effect of TCSC on subsynchronous damping. [15, 16] In the following studies special concern was on possible effects of additional SSDC circuit on coupling of torsional modes. More precisely, target of the paper was not to present the complete design process of SSDC circuit implementation for the studied power system but to illustrate the effect of phase shift φ_{SSDC} and gain G_{SSDC} of the circuit on torsional mode coupling phenomenon.

As a common practice, SSDC circuit is designed using filters and lead-lag blocks to achieve specific phase shift and gain for the designing frequency and thereby improve the damping of this frequency. Effect of any unwanted frequency component is eliminated often using different filtering arrangements. Motivated by the fact that torsional coupling phenomenon is not related on insufficient filtering of input signal or poor design of SSDC circuit [1] generic SSDC circuit (Fig. 4) was introduced to enable more accurate analysis of the coupling phenomenon. Discrete Fourier Transform (DFT) analysis was applied to extract the studied oscillation mode from speed variation signal $\Delta\omega$, which was also used as an input signal in connection of SSDC circuit related studies in [1]. Thereafter gain and phase adjusted modulation signal were added to used open-loop control angle α_0 of TCSC. DFT approach applied eliminates effectively the effect of any unwanted frequency components on modulation signal and therefore enabled more accurate analysis of possible coupling of torsional modes to be executed.

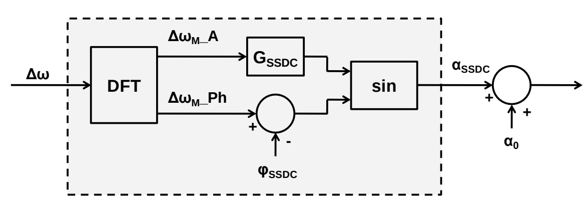

Fig. 4. Structure of the generic SSDC circuit applied in the study

V. Study Results

Studies concerning power system presented in Fig. 3 included various different network configurations, power flow conditions and several turbine-generator shaft configurations.

Following studies were chosen to be presented because they give insight to the executed studies concerning coupling of torsional modes and to some extent comparable results to studies presented in [1]. Consequently, subsynchronous damping is presented applying damping coefficient σ in 1/s, which can be derived using logarithmical decrement δ and natural oscillation frequency f_n of the studied torsional mode. [17]

$$\sigma = 2 \cdot \pi \cdot f_n \cdot \delta \qquad (3)$$

In studies, where mechanical damping of the system is neglected, damping coefficient σ can be considered to describe the required mechanical damping for the studied torsional oscillation mode.

Results of the paper consist of a case, where power system without any controllable FACTS devices was studied and cases, where TCSC and its additional generic SSDC circuit designed to damp torsional oscillations of mode 1 were applied in the studies. Analysis of cases, where generic SSDC circuits designed to damp oscillations of modes 2-4 were studied, indicated similar behavior concerning torsional mode coupling as in case of mode 1 related studies and are therefore not presented in the paper.

A. Base Case

Firstly, subsynchronous characteristics of the studied power system was studied without TCSC to give insight on effect of series compensation degree of transmission line T1 on damping of the torsional modes of studied turbine-generator. Although, figures in the paper mainly illustrates the effect of coupling phenomenon on damping of torsional modes studies concerning amplitudes of torsional modes showed similar behavior, which is also illustrated further in the paper.

In Fig. 5 damping of modes 1-4 as a function of series compensation degree of transmission line T1 using all-mode and modal models is presented.

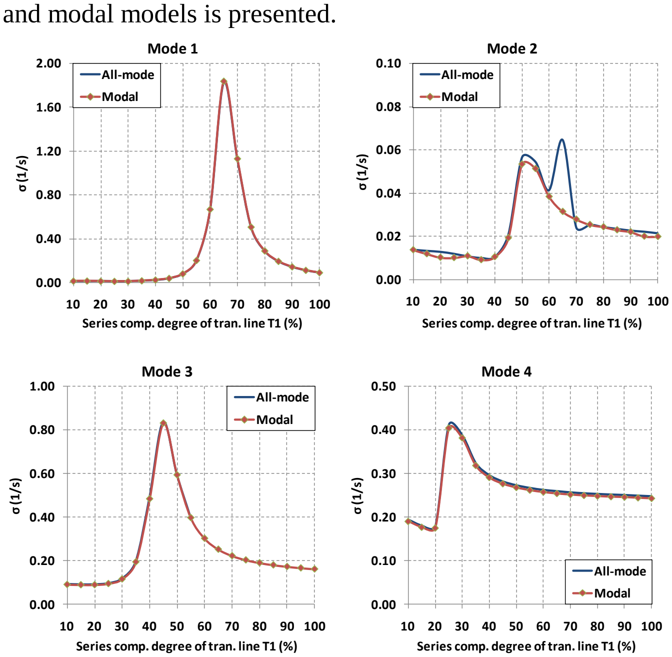

Fig. 5. Damping of modes 1-4 with all-mode and modal models

From Fig. 5 can be seen clearly the critical series compensation degrees for the modes. Electrical damping of mode 1 decreases substantially with series compensation degree of 65 % as mode 2 is relatively well damped with all the studied compensation degrees. Modes 3 and 4 have their own critical series compensation degrees with approximately 45 % and 25 % compensations, respectively.

Fig. 5 shows good agreement between study results executed using all-mode and modal models of studied turbine-generator shaft. Only some differences were observed in mode 2 damping, which can be explained by significantly lower amplitude of mode 2 compared to amplitudes of other modes. This leads to incorrect damping estimates with all-mode model in cases where damping of mode 1 or 4 decreases and consequently amplitude of these modes increases substantially. As a conclusion though, differences in all-mode and modal damping of mode 2 cannot be considered to have any significance concerning the studied torsional mode coupling phenomenon. Series compensation degree of 70 % was chosen to be used in following studies.

B. System with TCSC

With series compensation degree of 70 % of transmission line T1 especially damping of modes 1, 3 and 4 can be considered insufficient in studied loading condition. Therefore 30 % of series compensation of transmission line T1 was replaced with TCSC to improve the electrical damping of the system. Inherent subsynchronous damping capability of TCSC was studied with both all-mode and modal models. In Fig. 6 subsynchronous damping of modes 1-4 with open-loop firing angles of 65°-90° is presented.

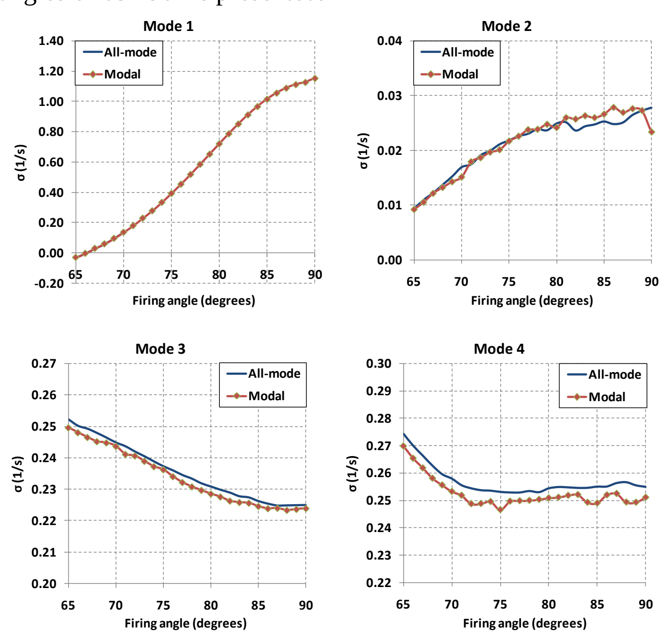

Fig. 6. Damping of modes 1-4 with all-mode and modal models when TCSC is utilized

From Fig. 6 it can be concluded that the strongest effect TCSC operating with open-loop control mode has on electrical damping of mode 1. Damping of mode 1 increased almost linearly with decreasing firing angle of TCSC. Whereas damping of mode 1 can be increased significantly damping of modes 2-4 TCSC cannot be influenced almost at all. In fact, damping of modes 3 and 4 even decrease slightly with decreasing firing angle of TCSC.

In presented studies no significant differences between results of all-mode and modal models of turbine-generator shaft was observed. In choosing the steady-state operation point of TCSC both increasing stresses on components of TCSC and improvements in damping abilities of TCSC with decreasing firing angle should taken into account. Therefore, firing angle α_0=75° was chosen to be used in following studies. From Fig. 6 can be though observed that firing angle of 75° do not give satisfactory electrical damping especially conserning modes 1, 3 and 4.

C. System with TCSC and SSDC

Effect of TCSC on electrical damping of the system was further improved by implementing additional SSDC circuit in control system of TCSC. Proper design of SSDC circuit is though needed to guarantee the satisfactory output of the control loop in presence of any possible steady-state or transient phenomenon occurring in the network. With approach presented in Fig. 4 effect of any unwanted frequency components, mainly other torsional mode frequencies could be eliminated completely on SSDC output signal.

Determining correct phase shift of output signal of SSDC circuit respect to input signal could be considered one of the most significant design aspect regarding the SSDC design process. In Fig. 7 electrical damping of modes 1-4 is presented as phase shift between input and output signals of SSDC for mode 1 is varied between 0° and 360°.

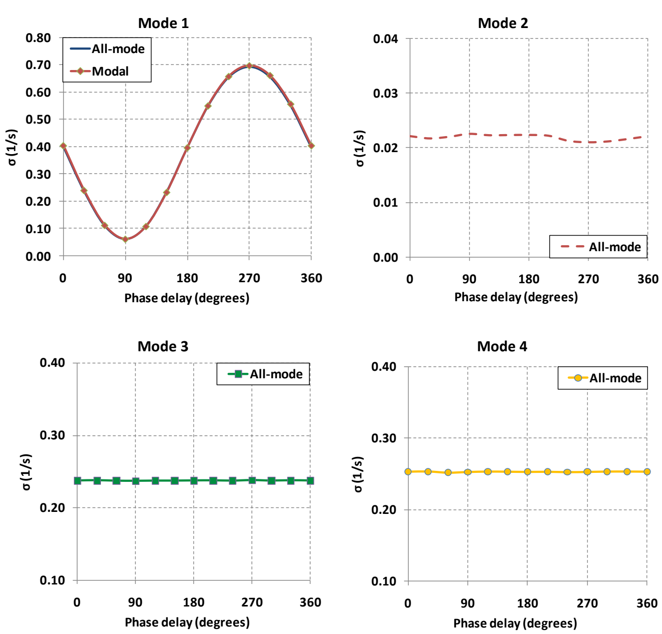

Fig. 7. Effect of phase shift of mode 1 SSDC on oscillations damping with all-mode model

From Fig. 7 can be seen clearly the effect of phase shift φ_{SSDC} of the generic SSDC circuit on damping of mode 1. However, damping of modes 2-4 remains almost constant as a function of studied phase shift variable. This indicate relatively weak coupling between studied torsional modes. Also results executed using all-mode and modal models showed almost identical damping for mode 1.

In addition to analyzing the damping of torsional modes also amplitudes of the torsional oscillations were analyzed. In Fig. 8 oscillation amplitudes of modes 1-4 is presented when SSDC for mode 1 is utilized with optimal phase shift φ_{SSDC} presented in Fig. 7 and with increasing gain G_{SSDC}. Fig. 8 indicates clearly that by increasing the gain G_{SSDC} of SSDC circuit damping of mode 1 can be increased substantially. Even the highest gain used does not lead to instability of the control circuit. However, amplitudes and thereby damping of modes 2-4 seems not to have any relation to gain of SSDC of mode 1. As a conclusion, results presented in Fig. 8 indicate that coupling between studied torsional modes appears insignificant and therefore applying modal model of turbine-generator shaft would be justified in the studies.

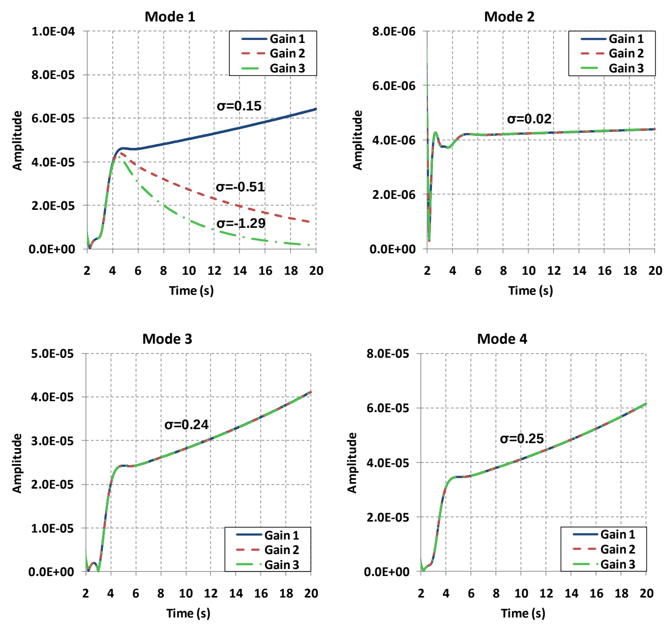

Fig. 8. Effect of gain of mode 1 SSDC on oscillation amplitudes

VI. Discussion

Despite extensive EMT analysis based studies any significant differences between study results executed using all-mode or modal modeling of turbine-generator shaft were not observed. In particular, neither by connecting TCSC and its generic SSDC circuit into the system any relation between their parameters and coupling phenomenon was discovered.

On the contrary, in studies concerning Power System Stabilizer (PSS), Static Var Compensator (SVC) and its additional SSDC circuit notable coupling between torsional modes were observed in both eigenvalue and EMT based studies. [1] By comparing those results and results of this paper it could be easy to make a conclusion, that TCSC basically decouples the torsional modes in studied power system. However, there are several discrepancies in the papers which make them incomparable and therefore final conclusions shall not be made only based on the study presented in this paper.

The most significant difference between the papers is in study approaches whereas in [1] studies were executed using eigenvalue analysis based power system models and control structures as in this paper studies were executed completely using EMT analysis. Although, in [1] EMT analysis based results were also included, presented results do not introduce comprehensive analysis of coupling of torsional modes in EMT environment. Also, comparable results concerning reduced-order or modal models would have clarified even more the nature of coupling phenomenon. To give more insight on the possible effect of torsional coupling phenomenon on TCSC related SSR studies, comparable studies between eigenvalue and EMT based approaches should be executed including analysis of both damping and amplitudes of torsional modes.

In addition, in [1] it was emphasized that neither PSS, generator excitation system nor main controller of SVC have any significance concerning the torsional mode coupling in the system. Due to lack of parameters of these controllers this could not be verified with EMT analysis in this paper. However, because any contribution of these controllers on damping of torsional modes could not be seen to be related on the original phenomenon of torsional mode coupling, they were not included in the studies of the paper. Furthermore, open-loop control approach of studied TCSC and presented generic SSDC circuit applied in this paper enabled elimination of possible effects of TCSC main controller and poorly designed SSDC circuit on the torsional coupling phenomenon. This again enabled more accurate determination of the significance of possible torsional mode coupling phenomenon in connection of TCSC related SSR damping studies.

It should also be noticed that the power system models presented in [1] and in this paper were not completely identical. This can be considered to be due to few unknown parameters of the original system used in [1]. As the structure of transmission network is concluded to have effect on coupling of torsional modes discrepancies of the studied power system models could have effect on detecting the coupling phenomenon. However, these discrepancies can be considered relatively small and are not likely to cause complete disappearance of the studied phenomenon.

VII. Conclusions

In this paper SSR damping studies taking into account the possible coupling of torsional modes in the case of TCSC controlled series compensation were presented. The significance of possible torsional mode coupling in SSR damping studies, firstly introduced in [1], was revised and EMT based approach applied to analyze the torsional mode coupling phenomenon was presented. Thereafter, EMT analysis on effects of coupling of torsional modes on TCSC and its generic SSDC circuit related SSR studies were presented and study results discussed briefly.

The results of the subsynchronous damping and oscillation studies indicated no torsional mode coupling of any significance as the results obtained using all-mode and modal models were identical in practice. Based on only minor differences in damping and amplitudes of torsional modes in presented studies, applying modal model of turbine-generator shaft in connection of TCSC related SSR studies seems justified. As the final conclusion, for final verification the study results of the paper studies including both EMT and eigenvalue based study approaches with identical power system configurations should be executed.

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IX. Biographies

Pasi Vuorenpää received his Master's degree in electrical engineering from Tampere University on Technology, Finland, in December 2006. Since then he has been research engineer and post-graduate student at the Department of Electrical Energy Engineering in Tampere University of Technology.

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