On Effect of TCSC Structure and Synchronization Response on Subsynchronous Damping

P. Vuorenpää, T. Rauhala, P. Järventausta, T. Känsälä

Abstract—This paper illustrates the effect of thyristor controlled series capacitor (TCSC) structure and synchronization response on subsynchronous damping. In spite of various studies concerning subsynchronous behaviour of TCSC, effect of these factors on subsynchronous damping are rarely discussed. Studies have been executed using PSCAD transient simulation program with general power system and TCSC simulation models. Studied system consisted of first IEEE benchmark model for subsynchronous resonance studies and TCSC model controlled with open-loop control mode. Open-loop control mode was used in order to isolate the effect of TCSC structure and synchronization from the effect of closed loop controls of TCSC on subsynchronous damping. It's evident that this approach has only minor significance regarding the effect of real TCSC installations on subsynchronous damping. Nevertheless, together with the results of similar analysis performed using different closed-loop control and firing pulse generation approaches, the results presented here will provide more insight on the effect of TCSC on subsynchronous damping and its subsynchronous response.

Keywords: Thyristor controlled series capacitor, TCSC, subsynchronous oscillations, SSO, time-domain analysis.

I. Introduction

INFLUENCE of conventional series compensation on the risk of SSR phenomena has been well understood since early 1970's. The electrical resonance created by series capacitor can cause growing subsynchronous oscillations between electrical power system and nearby turbine-generator unit. Introduction of thyristor controlled series capacitor (TCSC) has made it possible to improve the overall performance of series compensated electrical power system due to fast and flexible control of the effective reactance produced by TCSC [1]. In addition, ability of TCSC to effectively damp electromechanical and subsynchronous oscillations makes it a versatile electrical power systems stability controller [1].

Since first introduction of TCSC its behaviour in subsynchronous frequency range has been studied extensively using theoretical analysis [2], [3] and actual field tests [4], [5], which have proven ability of TCSC to damp subsynchronous oscillations both in theory and practice. Analytical models [6], [7] are often used to explain the subsynchronous damping behaviour of TCSC on subsynchronous frequency range. However, analytical models never represent exactly the detailed operation of TCSC main circuit. Detailed EMTP based studies concerning the subsynchronous damping ability of TCSC focuses often on damping enhancement on specified frequencies defined by the natural modes of nearby turbine-generator [8]. Effect of different control implementations on subsynchronous damping seen by the nearby turbine-generator has also been studied for example in [8], [9].

In this paper detailed TCSC simulation model with PSCAD transient simulation program was created to illustrate the effect of TCSC structure and synchronization response on subsynchronous damping seen by the nearby turbine-generator. Paper illustrates the effect of boost factor K_b, λ parameter of TCSC and the proportion of TCSC to fixed series capacitor (FSC) on subsynchronous damping. Also the effect of synchronization response of TCSC on subsynchronous damping was analyzed with detailed simulation cases. Test signal method [10] was used to analyse the electrical damping created by the modelled power system and TCSC in frequency range from 5 Hz to 55 Hz.

Detailed subsynchronous behaviour of TCSC is strongly related to firing pulse generation method of TCSC. Examples of firing pulse generation methods improving the subsynchronous damping of TCSC are presented in [11], [12]. Because of general literature based [13] modelling of firing pulse generation method and open-loop control approach, the results of this paper can not be assumed to correspond well with subsynchronous behaviour of actual TCSC implementations. However, together with further studies considering the effect of different closed-loop control and synchronization approaches they will provide insight on the subsynchronous response of TCSC.

II. Effect of TCSC on Subsynchronous Damping

When TCSC is operating in blocking mode without thyristors conduction, it can be compared to traditional fixed series capacitor bank. In that case subsynchronous behaviour of TCSC is also similar with fixed series capacitor with same ratings. Consequently operation of thyristor branch of TCSC is required to change the subsynchronous behaviour of TCSC compared to fixed series capacitor. Specified subsynchronous behaviour of particular TCSC implementation is defined by

This work was supported by compensation equipment and FACTS system manufacturer Nokian Capacitors Ltd.

P. Vuorenpää, T. Rauhala and P. Järventausta are with Tampere University of Technology, Institute of Power Engineering, P.O. Box 692, FIN-33101 Tampere, FINLAND (e-mail of corresponding author: pasi.vuorenpaa@tut.fi).
T. Känsälä is with Nokian Capacitors Ltd., P.O. Box 4, FIN-33331 Tampere, FINLAND.

Presented at the International Conference on Power Systems Transients (IPST'07) in Lyon, France on June 4-7, 2007

various structural and control system related factors. This paper focuses on effect of basic TCSC structure and synchronization related parameters of TCSC on subsynchronous damping.

By controlling the firing angle α of thyristors effective reactance of TCSC can be boosted substantially. Boost factor K_b is defined as a quotient of fundamental effective reactance X_{eff} and capacitive reactance X_{C0} of TCSC without thyristors conduction [13]:

$$K_b = \frac{X_{eff}}{X_{C0}} \quad (1)$$

λ parameter of TCSC determines the relation between the capacitor and reactor of TCSC. When X_L is fundamental reactance of reactor, λ is defined as follows [13]:

$$\lambda = \sqrt{\frac{-X_{C0}}{X_L}} \quad (2)$$

When operation point of TCSC is defined using boost factor K_b operation of TCSC with different λ parameters can be compared on the ground of fundamental effective reactance X_{eff} created by TCSC. In practical TCSC implementations λ parameter is typically between 2 and 4. [13]

Effect of TCSC on subsynchronous damping was studied in the paper using test signal method based on damping torque coefficient D_{en} calculated for the system at subsynchronous frequency range [10, 14]. Damping torque coefficient D_{en} is often defined using block diagram shown in Fig. 1 [15].

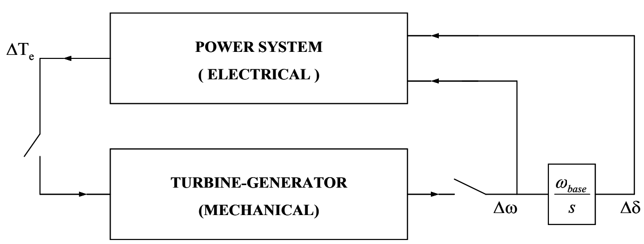

Fig. 1. Block diagram of relation between variations of generator speed and electrical torque.

Impulses like power system faults can cause generator-turbine shaft to oscillate on its natural frequency modes. These oscillations can be detected in generator speed and thereupon in power system frequency, voltages and currents etc.. When mechanical structure of the turbine-generator is ignored, response of the electrical power system on these oscillations can be perceived directly in electrical torque T_{en} of the generator. Damping torque coefficient D_{en} is defined as a quotient of variation of electrical torque ΔT_{en} and generator speed $\Delta\omega_n$ [10].

$$D_{en} = \mathrm{Re}\left\{\frac{\Delta T_{en}}{\Delta\omega_n}\right\} = \frac{|\Delta T_{en}|}{|\Delta\omega_n|} \cdot \cos(\arg(\Delta T_{en}) - \arg(\Delta\omega_n)) \quad (3)$$

As defined in (3) negative damping torque coefficient D_{en} indicates insufficient electrical damping for the studied subsynchronous frequency. Studies in this paper are executed by modulating the speed of the generator and thereafter by measuring the following variation in electrical torque.

III. System Model Used In Subsynchronous Damping Studies

A. Power system model

Effect of TCSC on subsynchronous damping of electrical power system was studied with modified first IEEE benchmark model for SSR studies [16], presented in Fig. 2.

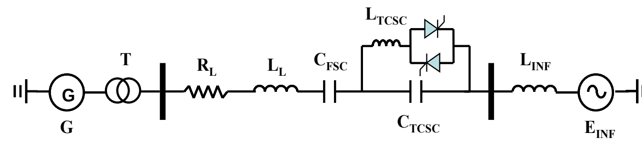

Fig. 2. Circuit diagram of studied power system model.

All or part of the fixed series capacitor of the original model was replaced by controllable TCSC segment. Subsynchronous behaviour of TCSC was studied with no-load situation where active power transfer of the system was negligible. Generator mechanical moment T_m was set to 0.03 p.u., U_{GEN} to $0.98\angle 0°$ p.u. and E_{INF} to $0.9556\angle 29.5°$ p.u.. Detailed parameters of the power system model are presented in [16].

B. TCSC model

Effect of TCSC on subsynchronous damping was studied with general literature based TCSC simulation model. Operation of the simulation model was studied using open-loop control mode, which enables relatively accurate control of effective reactance in stable power transfer situation [13]. Open-loop control approach was chosen to allow analysis of structural characteristics of TCSC on subsynchronous damping without the fast acting closed-loop controls affecting the results. Additionally, typically closed-loop effective reactance control of TCSC is used with relatively slow time constant (> 1 s) therefore having no significant effect on subsynchronous response of TCSC in studied system. Described radial power system representation can also be considered insufficient to model accurately e.g. operation of closed-loop current control of TCSC realized in actual power system.

According to the effective reactance reference corresponding firing pulses were created to achieve demanded fundamental effective reactance X_{eff} for TCSC. To define the realized boost factor K_b of particular study fundamental effective reactance X_{eff} was formulated by means of quotient of measured fundamental voltage over TCSC and fundamental line current. Fundamental values of measured variables were created with proper low-pass and band-pass filters.

Firing pulses were created by comparing the reference firing angle α to output of synchronization circuit. General three phase Phase Locked Loop (PLL) circuit was used to create individual synchronization signals to the thyristors. Band-pass filtered phase currents of the transmission line were used as an input signal to PLL circuit.

Firstly subsynchronous behaviour of TCSC was studied in cases where series compensation of the transmission line was created completely with TCSC. 35 %, 50 % and 65 % series compensation degrees of the transmission line without thyristor conduction were studied and capacitances C_{TCSC} of these situations are listed in table I. L_{TCSC} with different λ values were calculated using equation (2). In addition operation of TCSC was studied in situations where TCSC replaces only part of the traditional fixed series compensation of the transmission line. 10 %, 30 % and 50 % proportions of TCSC to total series compensation were studied with total series compensation degrees listed in table I.

TABLE I

CAPACITANCES OF TCSC WITH DIFFERENT SERIES COMPENSATION DEGREES

	Series compensation degree		
	35 %	**50 %**	**65 %**
X_{C0} (Ω)	56.7	81.0	105.3
C_{TCSC} (μF)	46.78	32.27	25.19

IV. STUDY RESULTS

A. Effect of boost factor K_b of TCSC on subsynchronous damping

Effect of boost factor K_b of TCSC on subsynchronous damping was first studied by changing the boost factor K_b of TCSC between 1.1 and 2.0. Capacitor of TCSC was rated to 35 % series compensation degree and reactor of TCSC was rated based on λ=2.5. In Fig. 3 the effect of boost factor K_b of TCSC is presented with various K_b values in frequency range 5-55 Hz. Also the electrical damping achieved with fixed series capacitor is presented with series compensation degree of 35 %.

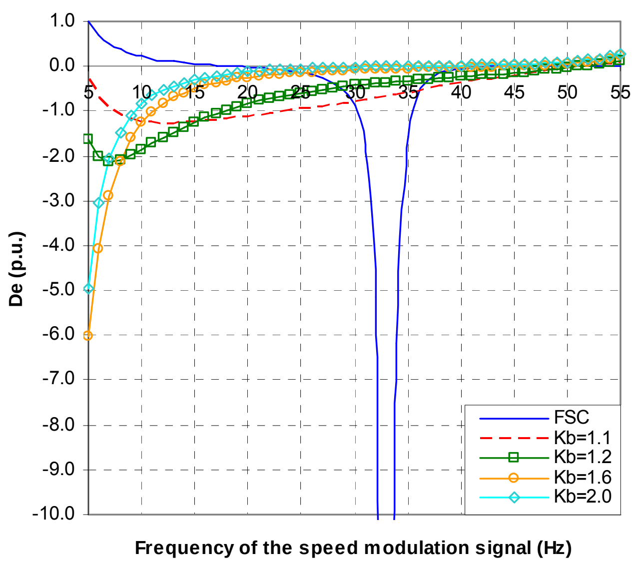

Fig. 3. The damping torque coefficient for various K_b values of TCSC.

From Fig. 3 can be seen that even small boost factor of TCSC improves the electrical damping of the system in vicinity of resonance frequency created by the fixed series capacitor. Also with increasing boost factor K_b it can be seen evidently that the electrical damping of the system in resonance frequency increases whereas electrical damping of the lowest subsynchronous frequencies decreases. Notice that the effective series compensation degree of the transmission line increases in consequence of increasing boost factor.

In Fig. 4 the electrical damping of the studied system is presented with different ratings of TCSC and with fixed series compensation of 70 %. In all cases the boost factor K_b is chosen so that the effective series compensation degree of the transmission line corresponds to 70 %. From the Fig. 3 and 4 can be concluded that the electrical damping of the system in vicinity of resonance frequency of fixed series compensation is improved with increased boost factor. On the other hand electrical damping of the lowest subsynchronous frequencies decreases with increasing boost factor with the studied TCSC implementation. From Fig. 4 can also be noticed that by increasing capacitor rating of TCSC the damping of the lowest subsynchronous frequencies decreases rapidly even with relatively low boost factor.

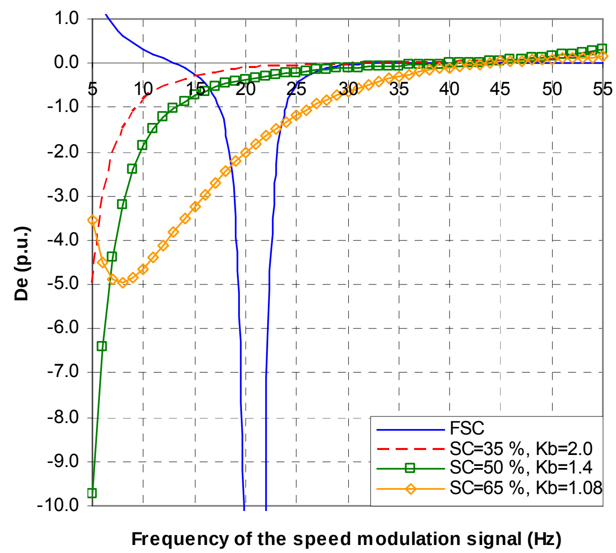

Fig. 4. The damping torque coefficient for series compensation degree of 70 % with various TCSC rating and K_b values.

B. Effect of λ parameter of TCSC on subsynchronous damping

Also the effect of λ parameter of TCSC on subsynchronous damping was studied with various situations. In Fig. 5 subsynchronous damping of TCSC with λ=2, λ=3, K_b=1.1 and Kb=1.2 is presented when TCSC was rated to series compensation degree of 35 %. In Fig. 6 the effect of λ parameter is presented with K_b=1.6 and K_b=2.0. In all cases firing angle α of the TCSC was altered based on the studied λ parameter to achieve desired boost factor K_b.

It can be concluded that λ parameter of TCSC has some effect on subsynchronous damping achieved with TCSC. Especially at frequencies below 40 Hz changes in the subsynchronous damping can be observed. With K_b=1.1 and K_b=1.2 subsynchronous damping of the lowest frequencies is decreased with increasing λ parameter but on the other hand at frequencies higher than 20 Hz subsynchronous damping is clearly increased with increasing λ parameter. With K_b=1.6 and K_b=2.0 subsynchronous damping is increased at almost whole subsynchronous frequency range as λ parameter increases. As a conclusion however effect of λ parameter on subsynchronous damping can be considered to be relatively small.

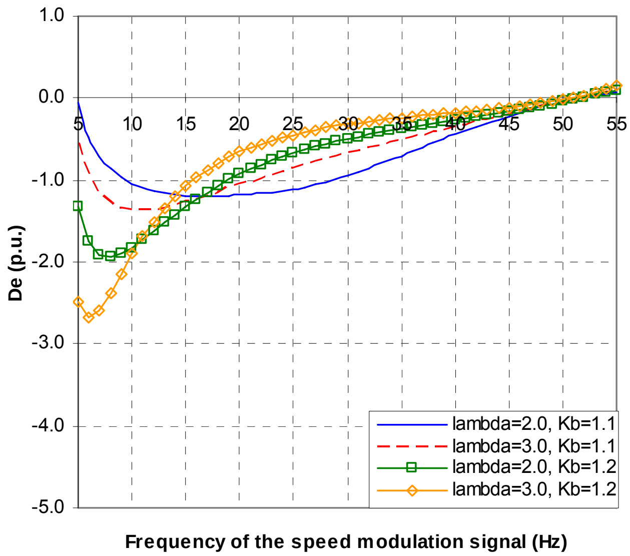

Fig. 5. The damping torque coefficient for λ=2, λ=3, K_b=1.1 and K_b=1.2.

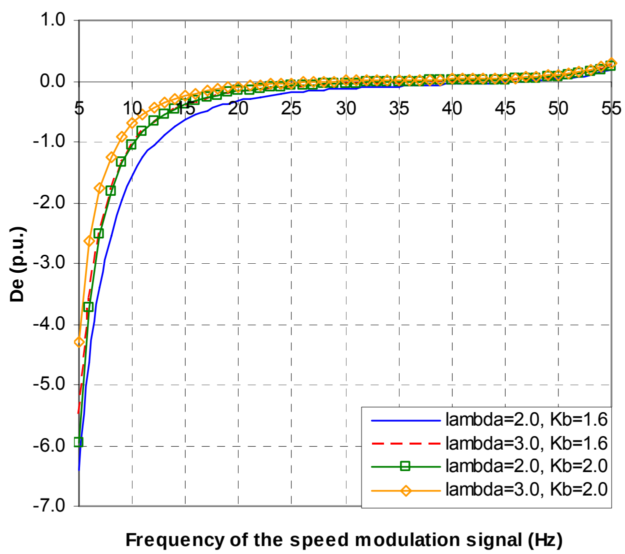

Fig. 6. The damping torque coefficient for λ=2, λ=3, K_b=1.6 and K_b=2.0.

C. Effect of proportion of TCSC to fixed series compensation on subsynchronous damping

In practical TCSC implementations total series compensation degree of transmission line is often formed with combination of fixed series capacitor and TCSC due to economical and reliability viewpoints [1]. Subsynchronous behaviour of the total series compensation equipment is defined mainly by the proportion of TCSC to fixed capacitor and the operation characteristics of TCSC. The effect of proportion of TCSC to fixed series capacitor is illustrated in Fig. 7. TCSC was operating with K_b=1.2, λ=2.5 and the total series compensation degree in all cases was defined to 50 %. Because increasing boost factor K_b also harmonics created by TCSC increases and thus K_b=1.2 is a compromise between subsynchronous damping characteristics of TCSC and harmonics produced by TCSC.

Fig. 7 indicates that subsynchronous damping of specified resonance frequency created by fixed series capacitor is increased substantially when part of the fixed series capacitor is replaced with TCSC. On the other hand the weak subsynchronous damping of the lowest frequencies described in Fig. 3 and 4 can also be perceived with combination of fixed series capacitor and TCSC. When increasing the proportion of TCSC the resonance peak created by the fixed series capacitor decreases and moves towards higher frequencies. With increasing proportion of TCSC the subsynchronous damping of the system approaches the damping behaviour of compensation created purely by TCSC.

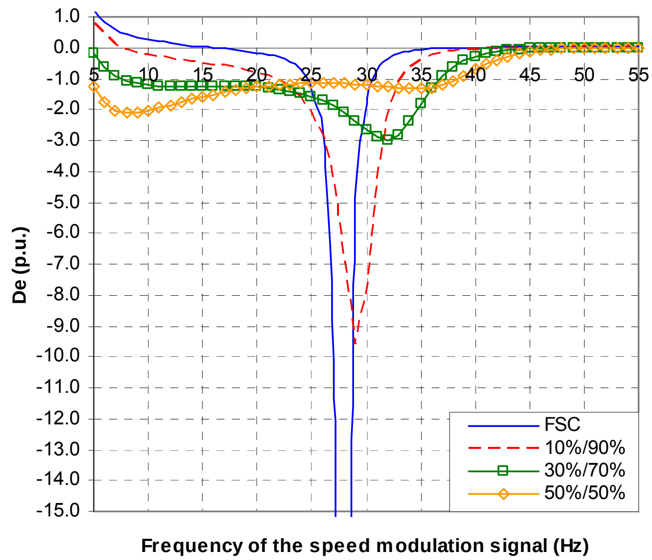

Fig. 7. The damping torque coefficient for combinations of TCSC and fixed series compensation with K_b=1.2.

D. Effect of synchronization of TCSC on subsynchronous damping

It is well understood that firing pulse generation method has a significant effect on subsynchronous behaviour of TCSC [11], [12]. When TCSC is controlled with open-loop control mode and with constant firing angle α, only the boost factor K_b, synchronization and firing pulse generation method of TCSC have influence on the final subsynchronous characteristics of TCSC. Subsynchronous oscillations occurring in the power system create subsynchronous current components and variation in system frequency which can interrupt the operation of synchronization circuit. Because of this, frequency response of PLL circuit especially on subsynchronous frequency range can cause increasing oscillations without existence of any control system. In Fig. 8 is shown the effect of variation of parameters of PLL circuit on subsynchronous damping. In previous studies PLL circuit was used with PI regulator parameters K_p=30 and K_i=300. Subsynchronous damping created by power system and TCSC was studied by varying the common branch gain of PI regulator of PLL circuit. Consequently proportional gain K_p values 10-50 and integral gain K_i values 100-500 were studied. Series compensation degree was defined to 50 % and TCSC was operating with K_b=1.2.

Fig. 8 shows the effect of synchronization response on subsynchronous damping. With faster PLL circuit the subsynchronous damping of the lowest frequencies clearly decreases. This is a consequence of frequency response of the PLL circuit which changes as parameters of the PLL circuit are changed and this affects to realized firing instants of the thyristors defined by PLL circuit output signal.

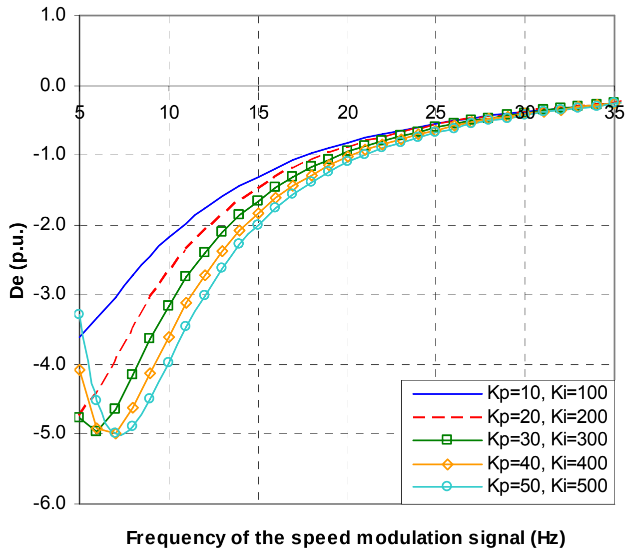

Fig. 8. The damping torque coefficient of the power system with TCSC.

In Fig. 9 the effect of synchronization of TCSC on subsynchronous damping is illustrated in a case of TCSC and fixed series capacitor. Series compensation degree was defined to 50 % and proportion of TCSC to total series compensation was 30 %. Because of smaller proportion of the TCSC compared to previous study the effect of synchronization of TCSC is smaller but still observable.

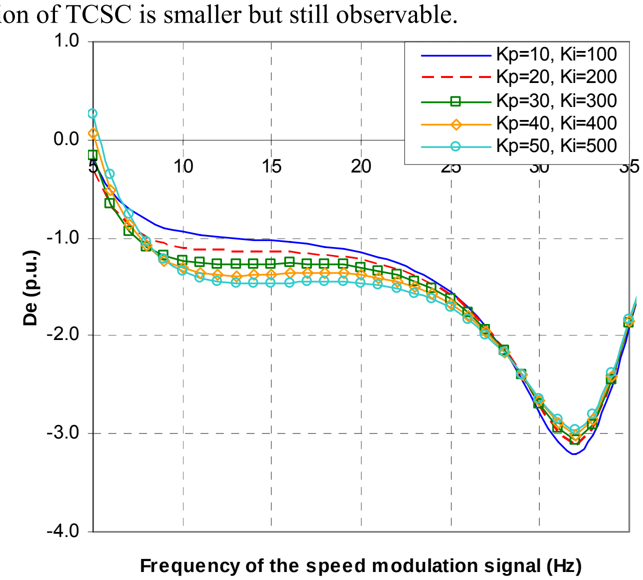

Fig. 9. The damping torque coefficient of the power system in a case of TCSC and fixed series capacitor.

V. Conclusions

In this paper the effect of TCSC structure related parameters and synchronization response of TCSC on subsynchronous damping were analyzed using test signal method. Following conclusions can be made based on studies presented in this paper.

1. With studied simulation model subsynchronous damping created by power system including TCSC increases with increasing boost factor K_b excluding the lowest subsynchronous frequencies.
2. λ parameter of TCSC has relatively small effect on subsynchronous damping characteristics of TCSC with open-loop control mode.
3. With proportion of TCSC to fixed series capacitor can be affected to subsynchronous damping characteristics of the total series compensation. When increasing the proportion of TCSC damping of the resonance frequency of fixed series compensation can be increased. Also the developing resonance peak moves towards higher frequencies.
4. In addition to control system implementation of TCSC also the synchronization response of TCSC affects on subsynchronous behaviour of TCSC.

The results presented here are strongly affected by the generic synchronization and firing pulse generation method. Also, the open-loop control mode applied in the studies can be considered unrealistic assumption with regard the installations where fast acting closed control loops are applied as primary controls of TCSC. However, these results can be considered to reflect the effect of different structural characteristics of TCSC on its fundamental subsynchronous response and subsynchronous damping. As further research will be executed to analyze the effect of different closed-loop control implementations and thyristor firing pulse generation methods, more comprehensive insight to subsynchronous behaviour of actual TCSC implementation will be obtained.

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VII. BIOGRAPHIES

Pasi Vuorenpää was born in Rauma, Finland, on April 15, 1982. He received his Master's degree in electrical engineering from Tampere University on Technology, Finland, in December 2006. At the moment he is a research engineer and post-graduate student in Tampere University of Technology. His main research interests are in FACTS devices and power system dynamics.

Tuomas Rauhala received his Master's degree in electrical engineering from Helsinki University of Technology, Finland, in January 2004. Since then he has been research engineer and post-graduate student at the Institute of Power Engineering of Tampere University of Technology. His main research subjects are phenomena causing high amplitude subsynchronous oscillations and analysis of subsynchronous damping.

Pertti Järventausta received the Diploma Engineer and the Licenciate of Technology degrees in electrical engineering from Tampere University of Technology in 1990 and 1992, respectively, and the Dr. Tech. Degree in electrical engineering from Lappeenranta University of Technology in 1995.

At present he is a professor at the Institute of Power Engineering of Tampere University of Technology. His research activities focus on electricity distribution (e.g. distribution automation, power quality and new business models), distributed generation, transmission systems, and electricity market.

Tarmo Känsälä is a senior R and D Engineer working for Nokian Capacitors since 1975. He received the M.S. degree in Electrical Engineering from Tampere University of Technology, Finland, in 1971. During 35 years he has worked in many compensation projects including static var compensators and series capacitor banks. He is mainly involved in development of control systems, thyristor valves and related equipment.