Dynamic Modeling of Thyristor Controlled Series Capacitor in PSCAD and RTDS Environments

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***Abstract*—Fast development of power electronics have enabled wide utilization of Flexible AC Transmission System (FACTS) devices for increasing electricity transmission capacity and stability of power systems. Among others, Thyristor Controlled Series Capacitor (TCSC) has been found to have great potential as a device capable of damping small signal oscillations in the power system. In addition, also noticeable voltage support and transient stability enhancement of the power system can be achieved using TCSC.**

In addition to the great possibilities of FACTS technology increase of these nonlinear and complex devices emphasizes the importance of extensive power system analysis to verify the overall stability of the power system. Consequently, in this paper research concerning operation of TCSC as a part of power system is presented. Main targets of the research are to develop new modeling techniques for TCSC and to study the effect of control system structure and surrounding network on operational characteristics of TCSC.

***Keywords*—Thyristor Controlled Series Capacitor, transient analysis, real-time simulation, small signal stability**

I. Introduction

EFFICIENT and reliable electric power transmission have got more and more attention due to continuous increase in electric power consumption and electricity dependency of the society. Consequently, new solutions for increasing the electricity transmission capacity and stability of the transmission system have been developed. Flexible AC Transmission System (FACTS) devices have become respectable alternative for construction of new transmission lines since by utilizing FACTS devices the existing transmission system can be utilized more effectively. This can be considered beneficial especially because construction of new transmission lines is coming increasingly restricted and expensive in the future. On the other hand, global targets aiming for increasing energy efficiency of the society can also be considered to have positive effect on FACTS development projects.

Because of nonlinear nature of FACTS devices structure of power system is becoming constantly more and more complex as number of FACTS devices increases. Furthermore, as main purpose of installed FACTS devices is to improve the overall performance of the transmission network and thereby to increase the reliability and stability of the network extensive power system analysis should be executed always as new FACTS devices are installed in the network. Therefore, need for new extensive but at the same time user friendly analysis tools can be seen obvious. Increase of FACTS devices in the power system emphasizes also the importance of system development in FACTS industry. Especially concern should be taken already in early state of the design project of the device on interaction phenomena between FACTS devices of the power system and between FACTS devices and other power system components.

In this paper research, which main target is to develop new modeling techniques for Thyristor Controlled Series Capacitor (TCSC) and to investigate the interaction phenomena between TCSC and surrounding network, is presented. Paper includes also presentation of main characteristics of TCSC and results of the studies executed at the early state of the project.

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II. Thyristor Controlled Series Capacitor (TCSC)

After introduction of TCSC in the late 1980s TCSC implementations have been installed in several locations in the world. As controllable series compensation device and with flexible control possibilities TCSC has found to be effective especially in damping electromechanical and subsynchronous oscillations. [1,2] Therefore replacing the existing fixed series compensation device or part of it with TCSC may become of interest especially in a case where controlling of series compensation degree of the transmission line and new control possibilities for stability enhancement of the power system are desired.

In Fig. 1 basic structure of single TCSC module is presented.

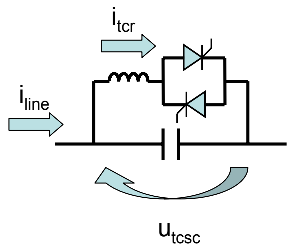

Fig. 1. TCSC main structure

TCSC utilizes controllable TCR branch parallel with series capacitor to enable fast and flexible variation of effective fundamental reactance of the device. Depending on the firing angles of the thyristors both inductive and capacitive control modes can be achieved – though capacitive mode can be considered to be the main control mode.

Boost factor K_b of the device describes the relation between effective fundamental reactance X_{eff} of the device to reactance X_{C0} of series capacitor.

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

According to the above equation positive boost factor refers on capacitive control mode as negative boost factor refers on inductive control mode. Typically in normal operation boost factor of TCSC is in range of 1-3 depending on series compensation degree limits of the transmission line and ratings of TCSC. [2]

Controllability of TCSC can be utilized in various ways to improve the overall stability of the power system. The most common utilization ways are listed in following. [1, 2]

- Damping of electromechanical oscillations
- Damping of subsynchronous oscillations
- Control of transmission line current/power
- Control of series compensation degree of transmission line
- Fault current limiting
- Phase balancing control

As damping of electromechanical and subsynchronous oscillations emphasizes the importance of tuning and design of the control system implementation of TCSC fault current limiting function can be considered to be more related on component ratings and sequencing the control functions.

III. Research Description

With properly designed control system TCSC can be effectively utilized for enhancing both small signal and transient stability of the power system. Therefore, good understanding of the interaction phenomena between TCSC and surrounding network will be demanded to design optimal control structures and at the same time to prevent undesired interactions.

Focus of the research can be divided into three different subtopics:

- Modeling TCSC and its control system in different simulation environments.
- Studying the effect of different structure and control system implementations on operational characteristics of TCSC.
- Investigating the interaction phenomena between TCSC and surrounding power system.

Results of the studies can be utilized in developing new modeling techniques and control structures for TCSC. Special focus of the research is on synchronization method development and studying the subsynchronous response of TCSC with different control implementations.

IV. Modeling TCSC and its Control System in Different Simulation Environments

Despite the development and advantages of linear modeling techniques time domain analysis can be considered always as a mandatory part of studying the effects of designed FACTS devices on stability of power system. Because of that, in research work presented in the paper utilization of time domain analysis tools constitute an essential part of the work. However, because of some definite advantages of e.g. frequency domain modeling of power system components, results of the time domain simulation studies can also be utilized in development of generic frequency domain models of TCSC in later stage of the research work.

A. Transient simulation studies

Because of both discrete and continuous nature of switched device like TCSC transient analysis program as PSCAD can be considered ideal tool for detailed modeling of TCSC. [3] With PSCAD both control system and components of the device can be modeled accurately in connection with relatively large power system models. However, calculation burden by increasing the extent of the modeled network can increase significantly. In addition to transient phenomena studies transient simulation environment can also be found beneficial e.g. parameter tuning of the control systems as it has multiple run options with possibility for parameter variation between cases.

In the research described in the paper transient simulation environment is mainly used for studying the interaction phenomena between TCSC and surrounding power system and in preliminary studies of different control system configurations. Study results of transient simulation can then be utilized in developing the real time control system implementation of TCSC.

B. Real time simulation studies

As another useful analysis tool the real time digital simulator (RTDS) enables fast and flexible testing of real control implementation of the device in real time environment before the device will be connected to the real power system. (Fig. 2) Consequently, operation of the whole control implementation including protection functions can be verified and tested safely in laboratory environment before commissioning of the device.

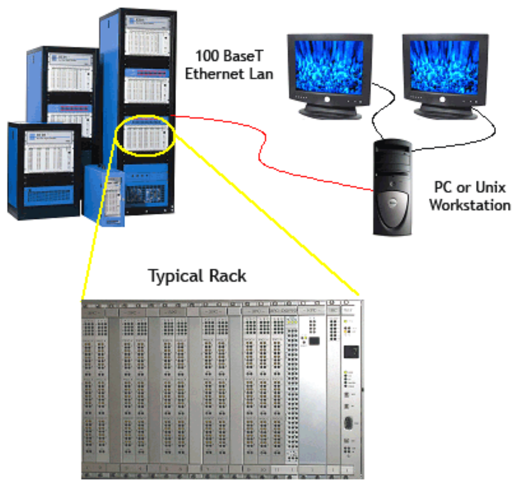

Fig. 2. Typical RTDS configuration [4]

In a case of real time simulation extent of the modeled power system is mainly dependent on the calculation hardware reserved for the simulation.

Structure of real time control system implementation used in research is based on VME bus and customized PLC language. Control system consist three processor cards which can be utilized to calculate the control and protection functions of TCSC in real time basis. Calculation can be done in 4 different time domains depending on time demands of the specific control function. Analog current and voltage data from RTDS is converted into digital format before processing. An independent analog controller card is used to synchronize the thyristor firing pulses to line current.

C. Correspondence between studied time domain simulation models

At the first stage of the research work concern is mainly on TCSC related characteristics and therefore relatively simple power system model, where TCSC is located in the middle of the long transmission line, was utilized in the studies. (Fig. 3)

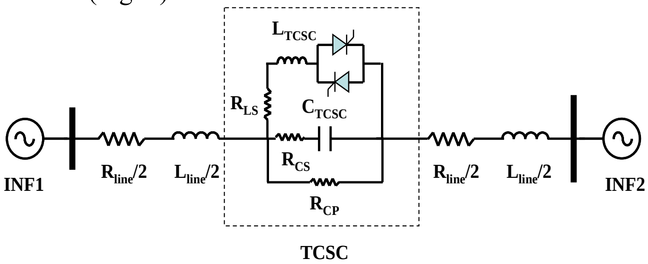

Fig. 3. Structure of the power system modeled in the studies

At the both end of the transmission line equivalent voltage sources were placed to represent the surrounding network. In TCSC model also resistive components describing the losses of reactor and capacitor are included. Data of electrical components of TCSC and surrounding power system can be found in Appendix I.

Operation of the models was analysed using closed-loop fundamental reactance control with PI regulator, common gain and linearization functions. (Fig. 4) PI regulator of the control system was tuned to give satisfying response in whole operation range of TCSC.

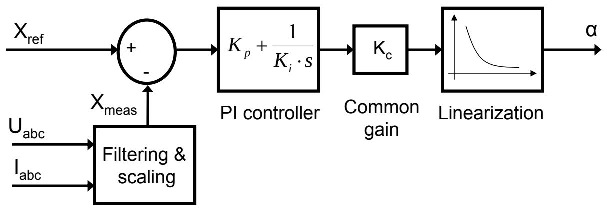

Fig. 4. Structure of fundamental reactance control

Feedback of the system was based on actual fundamental effective reactance of TCSC determined using measured mean voltage and current signals from the system. Both signals were normalized and filtered to extract the fundamental frequency component of the signals.

Network model presented in Fig. 3 was implemented in both transient and real time simulation environments and basic operation of the models was compared to verify the correspondence between the developed models. In Fig. 5 voltage over TCSC in mode switching from blocking mode to bypass mode is compared in both simulation models. In both models switching was executed in a specific time instant respect to voltage over TCSC when closed-loop fundamental reactance control was disabled.

From Fig. 5 can be seen the transient behaviour of the switching event as capacitor of TCSC is short circuited with TCR branch. The system starts to oscillate with the resonant frequency of parallel connected capacitor and reactor of TCSC. Damping of this oscillation is mainly dependent on the resistive component of the system. It can also be seen from the figure that voltage over TCSC decreases significantly as steady state of the bypass mode is reached. This is due to change in reactance of TCSC from about capacitive 80 ohms to inductive 15 ohms. Operation of the studied models can be considered almost identical.

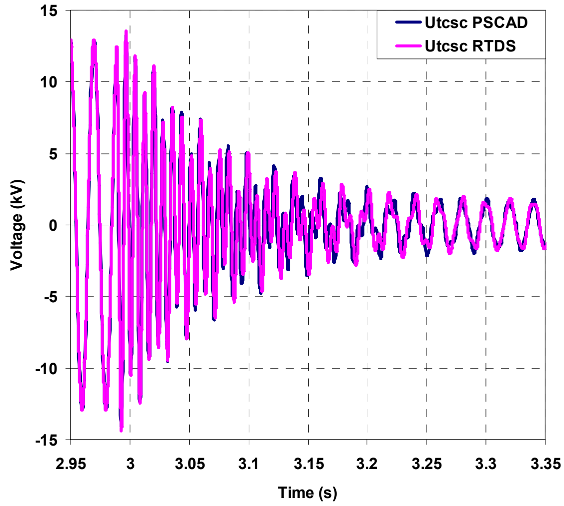

Fig. 5. Mode switching from blocking mode to bypass mode in PSCAD and RTDS

As correspondence between studied electrical systems is compared in Fig. 5, in Fig. 6 correspondence between modeled control systems with closed loop fundamental reactance control (Fig. 4) is presented, when reactance reference is changed from 96 ohms to 200 ohms.

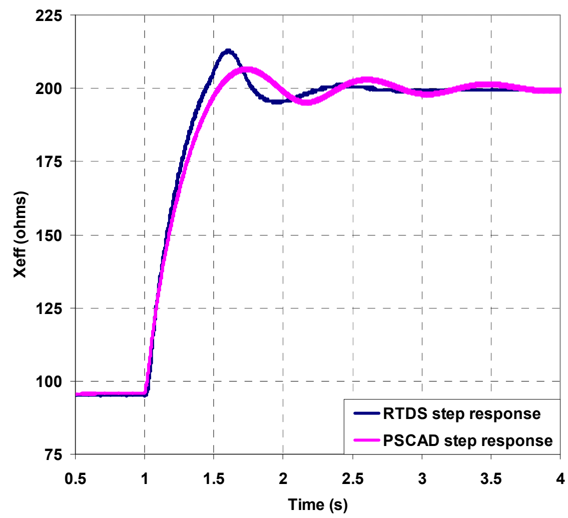

Fig. 6. Step response of closed-loop fundamental reactance control in PSCAD and RTDS

From Fig. 6 it can be seen that responses of TCSC in studied environments differs slightly. Figure indicates that faster response can be achieved with RTDS based TCSC model, however with higher overshoot, than with PSCAD based model. This can be mainly explained by the differences in filtering and synchronizing implementations of the models. Analog synchronization and digital filter implementations of the real time control system was not modeled in detail in PSCAD, though their operation resembled each other closely. In both models synchronization is done respect to line current of the system.

V. Studying the Effect of Different Structure and Control System Implementations on Operational Characteristics of TCSC

Naturally, TCSC control system implementation has significant effect on the operational characteristics of the device. Also, ratings of the device and other structural factors have specific effect on operation of the device. In presented research especially effect of different control system implementations on for example subsynchronous response of TCSC is under examination. [5] Special focus in the research is on measurement and synchronization implementations and their effect on operational characteristics of TCSC. Results of this subtopic are utilized in developing new control structures for TCSC.

A. Effect of synchronization method on fundamental response of TCSC

Synchronization implementation of TCSC determines eventually the actual firing pulse instants of the thyristors respect to waveforms of the electrical system. Therefore, with design of synchronization method of TCSC can be strongly affected on the frequency response characteristics of the device. Consequently, also speed of fundamental reactance response of TCSC is strongly related on implemented synchronization method. In this paper fundamental reactance response of TCSC is studied with 3 generic synchronization methods.

In Fig. 7 step responses of TCSC with different synchronization methods, when boost factor of TCSC is changed from 1.05 to 1.5 and there again to 1.2 in open-loop control, is presented. I_zero refers to synchronization based on zero crossings of the line current, U_PLL refers on PLL synchronization respect to voltage over TCSC and I_PLL refers on PLL synchronization respect to line current. Results of Fig. 7 describe the operation of TCSC in power system presented in Fig. 3.

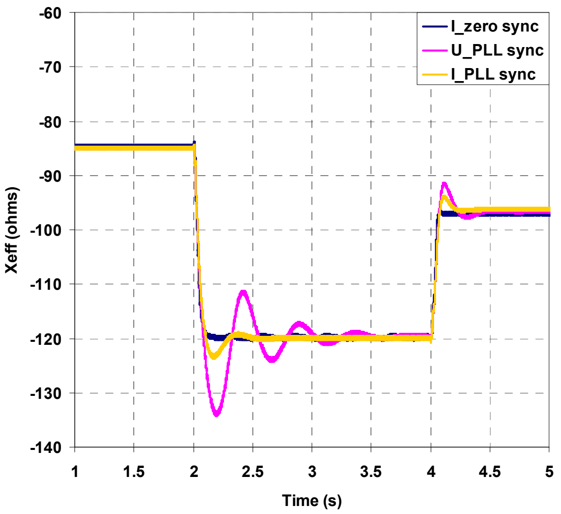

Fig. 7. Step response of different synchronization methods

From Fig. 7 it can be seen that response of zero crossing based synchronization is relatively fast in both step changes. In a case of PLL based synchronization methods responses are oscillatory but I_PLL gives more stable response than U_PLL. In addition, it can be seen that response of PLL based synchronization is related on operation point of TCSC as oscillations are larger with higher boost factor. Responses of current and voltage based synchronizations of TCSC is studied more detailed e.g. in [6, 7].

Based on studies of the fundamental reactance response of different synchronization methods it can be seen obvious that also nonfundamental frequency responses of studied synchronization methods can vary significantly. This fact is important especially concerning the sub- and supersynchronous response of TCSC. Therefore, frequency response of synchronization method used with TCSC should be investigated at least from 5 Hz to twice the fundamental frequency to guarantee the desired response of the device to subsynchronous oscillations. [5, 8] More sophisticated synchronization methods developed to improve the subsynchronous response of TCSC are presented in [9, 10, 11].

B. Effect of proportion of TCSC to fixed series capacitor on subsynchronous damping characteristics

Because of economical and reliability viewpoints TCSC is typically installed only as a part of total series compensation equipment of the transmission line. This layout enables to rate the components of TCSC smaller as at the same time fixed series compensator (FSC) increases the reliability of the series compensation equipment in a case of TCSC breakdown. Despite the smaller proportion of TCSC it can still be utilized effectively in increasing power system stability and flexibility of the series compensation implementation.

In Fig. 8 effect of proportion of TCSC to FSC on subsynchronous damping abilities of total series compensation device is presented. [5]

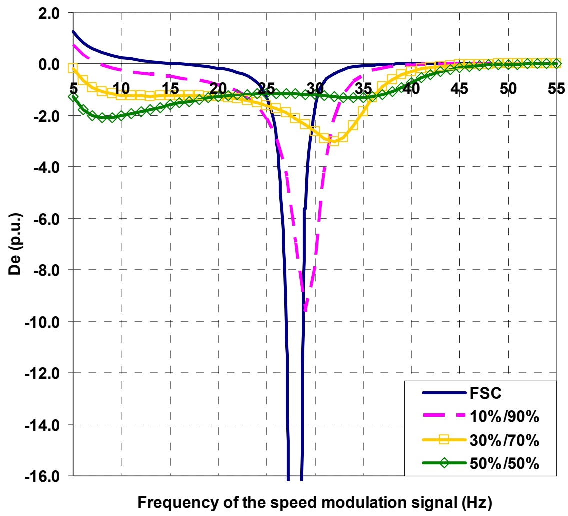

Fig. 8. Damping coefficient with different proportion of TCSC to FSC [5]

From Fig. 8 it can be concluded that by increasing the proportion of TCSC to FSC electrical damping of the system can be increased near the resonance frequency of the original system. Resonance peak moves towards higher frequencies and decreases but at the same time damping of the lowest frequencies decreases. As a conclusion, choosing the proportion of TCSC to FSC can be considered as an optimizing task between stability improving abilities of TCSC and economical and reliability advantages of FSC. Study arrangement, used system model and definitions are explained more detailed in [5].

VI. Investigating the Interaction Phenomena between TCSC and Surrounding Power System

In addition to effect of internal variables of the device operation of TCSC is strongly affected by the characteristics of the surrounding power system. Especially interaction phenomena between TCSC and other nonlinear FACTS devices should be carefully analyzed to avoid undesired interactions in situation where number of installed FACTS devices is increasing rapidly. Also, undesired interaction phenomena caused by other nonlinear components of the power system on operation of TCSC should be recognized and their effect analyzed.

Basically, target of the research is to create new methods for perceiving, illustrating and utilizing the interaction phenomena between TCSC and surrounding power system. One of the most important interaction phenomena between TCSC and surrounding power system is the response of TCSC on subsynchronous oscillations in the power system. In following study effect of surrounding network on sub- and supersynchronous response of TCSC is ignored to illustrate the generic response of TCSC on sub- and supersynchronous oscillations on line current.

Any changes in the state of either the mechanical or electrical side of the power system leave turbine-generators to oscillate at their natural mechanical torsional frequencies $f_{n,mech}$. The mechanical torsional oscillations of a turbine-generator with nominal frequency of f_0 induce sub- and supersynchronous voltages of frequencies $f_{n,sub}$ and $f_{n,super}$ at the stator terminals of the unit.

$$\begin{cases} f_{n,sub} = f_0 - f_{n,mech} \\ f_{n,super} = f_0 + f_{n,mech} \end{cases} \quad (2)$$

As an inherent characteristic of switched device like TCSC subsynchronous voltage component $u_{n,sub}$ induces in terminal of the device both corresponding sub- and supersynchronous current component. Equally subsynchronous current component $i_{n,sub}$ in the network induces in addition to subsynchronous voltage component also counter component into corresponding supersynchronous frequency, assuming that TCSC is operating with firing angle below 90°. [8, 12]

Response of TCSC on subsynchronous oscillations can be illustrated in PSCAD transient simulation with simple test system. As shown in Fig. 9, the system consists of an ideal fundamental frequency current source (f_0=50 Hz) parallel with current source injecting subsynchronous current component into the system including TCSC and ideal voltage source.

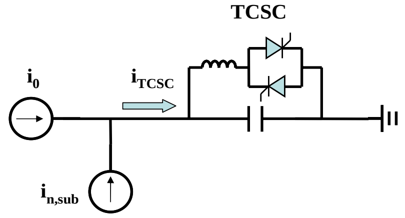

Fig. 9. Test system for illustrating the sub- and supersynchronous response of TCSC

Total current i_{TCSC} is injected into terminal of TCSC:

$$\begin{aligned} i_{TCSC}(t) &= I_0 \cdot \sin(2\pi \cdot f_0 \cdot t + \varphi_0) \\ &+ I_{n,sub} \cdot \sin(2\pi \cdot f_{n,sub} \cdot t + \varphi_{n,sub}) \end{aligned} \quad (3)$$

It should be noted that because of ideal current sources and lack of impedances in the system induced sub- and supersynchronous voltage components do not induce new corresponding current components as in reality. Thus, model presented above can be considered insufficient for modeling the comprehensive interaction phenomena between generators, other linear and non-linear network components and TCSC. Thereby it can only be used to illustrate the frequency coupling phenomena between sub- and supersynchronous frequency components in a case of TCSC.

In Fig. 10 and 11 amplitude of induced voltage component and phase relation between injected current component and induced voltage component with various open-loop firing angles of TCSC are presented, when fundamental current component with amplitude of 1.0 kA and 5 to 45 Hz subsynchronous current components with amplitude of 1.0 A are injected into the system. Capacitor of TCSC was rated based on Appendix I. As main concern is only on sub- and supersynchronous frequency response of TCSC fundamental frequency components are ignored for sake of clarity in the figures.

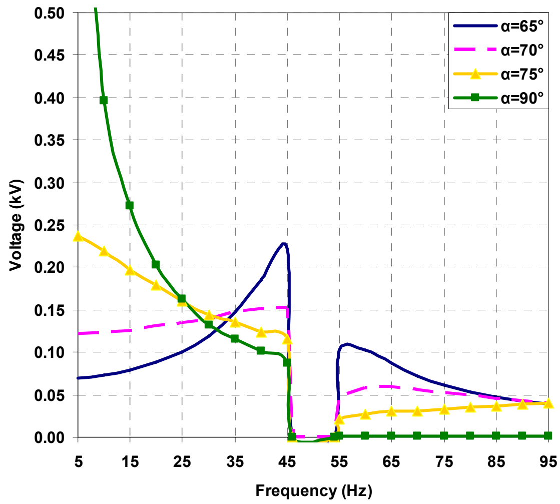

Fig. 10. Induced voltage components with different firing angles of TCSC

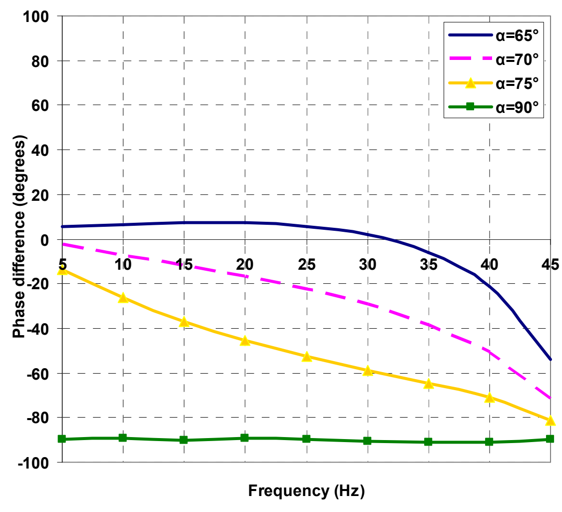

Fig. 11. Phase relation between injected current components and induced voltage components

From Fig. 10 and 11 it can be seen that with constant amplitude subsynchronous current injection amplitudes of the induced voltage components can vary significantly as a function of frequency and firing angles of TCSC. Also, amplitudes of induced supersynchronous voltage components diminish as a function of a growing firing angle of TCSC. In addition to variation in amplitudes of sub- and supersynchronous voltage components also strong variation in phase relation between injected current component and induced voltage components can be detected as a function of firing angle.

In general, response of TCSC on subsynchronous oscillations can be considered to be related on both TCSC and AC system operation conditions, which can be explained mainly by nonlinearity and inherent frequency modulation characteristics of TCSC. Because of frequency modulation characteristics of TCSC, TCSC affects voltage phase angles and thereby realized firing instants of thyristors. In spite of small effect on fundamental behaviour of TCSC these changes in firing instants of thyristors could affect significantly subsynchronous characteristics of TCSC. Therefore effect of studied AC system conditions should always be taken into account in determination of sub- and supersynchronous impedance of TCSC.

VII. Conclusion

In this paper research concerning controlling and modeling aspects of TCSC was presented. Research can be divided into three different subtopics, which include modeling TCSC in different modeling environments, studying the effect of different structure and control possibilities on operational characteristics of TCSC and investigating the interaction phenomena between TCSC and surrounding power system.

Purpose of the studies presented in this paper was to illustrate some main problem specifications included in the research. Future study targets are concerning especially the sub- and supersynchronous response of TCSC and synchronization and control system development of TCSC.

Appendix I

Table 1. Network parameters

R_{line}	12.17 Ω
L_{line}	0.8646 H
C_{TCSC}	39.5 μF
L_{TCSC}	41.0 mH
R_{LS}	1.0 Ω
R_{CS}	0.02 Ω
R_{CP}	1.0E6 Ω
Uinf1	539 kV∠4°
Uinf2	539 kV∠0°

Table. 2. Closed-loop fundamental reactance control parameters

Kp PLL	35
Ki PLL	350
Kp PI	0.5
Ti PI	0.1 s
Kc	1

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