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Applying TCSC Frequency Response Data Derived Using Electromagnetic Transient Analysis in SSR Frequency Scanning Studies

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***Abstract*—The traditional SSR frequency scanning technique can be generally considered as the most practical and straightforward approach to study the possible instabilities concerning torsional oscillations. However, as the number of controllable and highly nonlinear power system components is continuously increasing, their contribution to the frequency response characteristics of a power system will become more significant. Therefore, the traditional SSR frequency scanning technique can more often be found insufficient for modeling the torsional oscillation related characteristics of a power system with reasonable accuracy.**

In this paper approach for determination of the frequency dependent response of the Thyristor Controlled Series Capacitor (TCSC) to torsional oscillations is presented utilizing the generic signal injection approach. After analysis of the frequency dependent response characteristics of the TCSC with different study approaches suitability of the determined frequency response data in a SSR frequency scanning study is illustrated and analyzed. Finally, the possible benefits and limitations of different approaches to model the frequency dependent response characteristics of the TCSC for SSR frequency scanning purposes are discussed briefly.

***Index Terms*—Thyristor Controlled Series Capacitor, frequency response, SSR, electromagnetic transient analysis, frequency scanning**

I. INTRODUCTION

THE traditional SSR frequency scanning technique has been introduced to represent the response of an electrical power system to torsional oscillations of a turbine-generator shaft [1] and successfully implemented in several papers [2, 3, 4]. The main drawback in the application of the traditional SSR frequency scanning technique is that it is restricted to an analysis of the damping characteristics of networks consisting only linear and uncontrolled power system components. Therefore, due to a constantly increasing number of controllable and highly nonlinear power system components possibly affecting the damping characteristics of the network, the main application of these approaches is to provide background data for more detailed study methods. However, often more detailed study methods, such as the electromagnetic transient (EMT) analysis enabling an accurate representation of any controllable component, require that the model of the studied transmission network have to be reduced extensively to maintain the computational burden within reasonable limits. Nevertheless, in case of meshed, highly series compensated transmission networks extensive reducing may not be possible. In such cases, including the sub- and supersynchronous response characteristics of the controllable components affecting subsynchronous damping to SSR frequency scanning natured study has thus to be considered highly beneficial.

The implementation of a nonlinear and controllable power system component such as the Thyristor Controlled Series Capacitor (TCSC) in a SSR frequency scanning study requires the estimation of the frequency dependent response of the TCSC on torsional oscillations. In [5] both EMT based and analytical approaches are applied to determine the frequency dependent response of the TCSC on frequencies concerning torsional oscillations. In [6] studies are expanded to include, for example, the effect of the synchronization method on frequency dependent response of the TCSC and the scope of the studies is mainly on the resistive behavior of the TCSC in subsynchronous frequencies. Although these studies provide interesting information on the frequency dependent response of the TCSC, they do not provide relevant information that could be applied to an analysis of the effect of the TCSC on subsynchronous damping. This is because the previous studies ignore the fact that to analyze the effect of the TCSC on subsynchronous damping, the response analysis has to be performed considering that torsional oscillations induce simultaneously sub- and supersynchronous components. Consequently, as illustrated in this paper, the ignorance of the effect of either induced sub- or supersynchronous component in a response analysis of the TCSC will result in the data that is irrelevant as regards the subsynchronous damping analysis.

This paper presents an approach to determine the frequency dependent response of the TCSC by considering the inherent characteristics of torsional oscillations in connection with the generic EMT analysis based current injection model. After the comparison of the frequency dependent response characteristics of the TCSC with alternative study approaches,

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the validity of the EMT analysis based TCSC response data in connection with a traditional SSR frequency scanning study is presented and analyzed. Finally, based upon the results, the possible benefits and limitations of different approaches to model the frequency dependent response characteristics of the TCSC for SSR frequency scanning purposes are briefly discussed.

II. Torsional Oscillations in Power System

A. Relation between Mechanical and Electrical Frequency Components

The sub- and supersynchronous oscillations in a power system (with a nominal frequency of ω_{fund}) are most commonly induced by the subsynchronous mechanical oscillations of large turbine-generators. Any changes in the static state either on the mechanical or the electrical side of a turbine-generator act as an impulse to these mechanical oscillation modes. The modal frequencies $\omega_{mech,n}$ are determined based on the mechanical structure of the turbine-generator. Torsional oscillation with frequency ω_{mech} results both sub- and supersynchronous voltage and current components with frequencies ω_{sub} and ω_{sup} at the generator terminals.

$$\begin{cases} \omega_{sub} = \omega_{fund} - \omega_{mech} \\ \omega_{\sup} = \omega_{fund} + \omega_{mech} \end{cases} \tag{1}$$

Damping of these oscillations consists of both the mechanical and the electrical damping of the system. Due to basically only a small contribution of the mechanical damping of the turbine-generator shaft on the overall damping of the system accurate determination of the electrical damping of the system can be seen crucial. Consequently, series compensated transmission lines and a FACTS device located in the vicinity of the turbine-generator are the main components having an adverse contribution on the damping of torsional oscillations.

B. Analysis of the Damping of Torsional Oscillations

Time-domain and frequency-domain study methods for analysis of the electrical damping of torsional oscillations have been developed. Whereas the detailed EMT analysis based time-domain studies enable a torsional damping analysis to be executed with high accuracy, they often require significant amount of computing capacity and are relatively time consuming especially in the analysis of extensive power system structures. On the contrary, the traditional SSR frequency scanning technique allows even large power system structures to be examined with a relatively small time consumption. However, for example in a analysis performed by utilizing SSR frequency scanning technique only linear and uncontrollable power system components can be included. [7]

Based upon these facts, it seems obvious that there is a need to further analyze the limitations and possibilities to implement nonlinear and controllable power system components in a SSR frequency scanning study even with adequate accuracy. Therefore, in this paper the EMT analysis based approach for analyzing the inherent response of the TCSC to torsional oscillations is applied to estimate the possibilities to implement the TCSC as a part of a SSR frequency scanning study.

III. Approach for Studying the Response of TCSC In Presence of Torsional Oscillations

A. Response of TCSC on Torsional Oscillations

To fully understand the factors affecting the subsynchronous damping capabilities of the TCSC the response of the device to torsional oscillations should be determined. Because of the specific switching pattern of a device such as TCSC its operation can be considered to include both discrete and continuous characteristics and therefore the determination of sub- and supersynchronous frequency response of the device is not an entirely straightforward task.

A sub- or supersynchronous frequency component ω in the terminals of the Thyristor Controlled Reactor (TCR) part of the TCSC causes the original frequency component to diverge in multiple frequencies because of the switching frequency being twice the fundamental frequency ω_{fund}. This is illustrated in Fig. 1. [5]

$$\begin{cases} \omega_{TCR,m} = m \cdot 2\omega_{fund} + \omega \\ \omega'_{TCR,m} = m \cdot 2\omega_{fund} - \omega \end{cases} \text{for all integer values of } m. \tag{2}$$

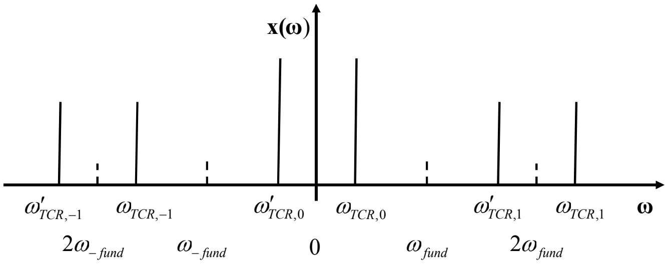

Fig. 1 A portion of the discrete frequency spectrum of the TCR due to a sub- or supersynchronous frequency component

It should be noted that Fig. 1 is only illustrative and in reality all frequency components have their own specific amplitude and phase determined by the inherent characteristics of the device. However, in general it can be considered that the amplitudes of the frequency components decay as a function of $1/m$ [5]. As an obvious consequence of the presented frequency modulation ability of the TCR the sub- and supersynchronous frequency components induced by a turbine-generator are coupled through the TCR switching action. Therefore, it is justified to conclude that the combined effect of the sub- and supersynchronous frequency components have to be considered in studies related to the effect of the TCSC on the subsynchronous damping and its response to torsional oscillations.

B. Generic Open-loop Current Injection Model for Studying the Response of TCSC on Torsional Oscillations

In [5] the current injection model (Fig. 2) and switching functions based on the Fourier series expansion are applied in analytical manner to analyze the response of the TCSC to the injected sub- and supersynchronous current components. To simplify the analytical analysis, the switching instants for the thyristors are determined only based upon the injected fundamental current component. In [6] the main scope of the study is on the resistive behavior of the TCSC on the sub- and supersynchronous frequencies. This analysis includes also the effect of the nonfundamental frequency components on synchronization reference as it determines the sub- and supersynchronous frequency dependent response of the TCSC through analytical equations. However, in both studies the effect of the amplitudes and the phases of the injected current components on the study results are ignored. Furthermore, despite the question of SSR damping abilities of the TCSC is emphasized in both studies, coupling between the sub- and supersynchronous frequency components in case of turbine-generator shaft related torsional oscillations are not discussed.

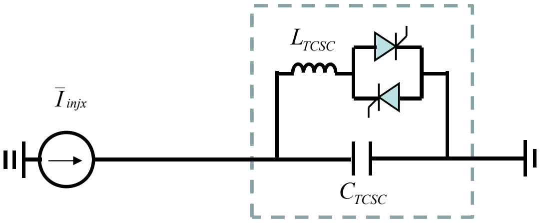

Fig. 2 Generic open-loop current injection model

Due to shortcomings of the previous studies the current injection approach was further analyzed to give a more realistic insight on formulation of the frequency dependent response of the TCSC in connection of a subsynchronous damping related study. Consequently, based upon the relation between the equations (1) and (2) the current injection approaches presented in [5, 6] were expanded to consider the response of the TCSC on the simultaneously injected sub- and supersynchronous current components. In this case the total injected current can be expressed as follows:

$$\bar{I}_{injx} = \bar{I}(\omega_{fund}) + \bar{I}(\omega_{sub}) + \bar{I}(\omega_{\sup}) \tag{3}$$

The main shortcoming of the approach illustrated by Fig. 2 is that it has an open-loop structure. In other words, in reality either any change in the series connected impedances of, for example, a turbine-generator, a step-up transformer, a transmission line, an equivalent network and the TCSC or change in the loading situation of the transmission line would have an effect on the injected current components. This again would change the impedance characteristics of the TCSC as will be further illustrated in this paper. However, the open-loop model can be seen advantageous for example in illustrating on general level the factors affecting the sub- and supersynchronous response of the TCSC excluding effects of the surrounding network components on the response.

The frequency dependent response of the TCSC was studied by applying a constant open-loop firing angle α and generic Phase-Locked Loop (PLL) based synchronization with line current reference. The studied TCSC was rated based upon a 50 % series compensation degree of the transmission line of system described in Fig. 3 by knowing the somewhat oversized ratings of the device compared to any existing applications. However, because of the similar ratings of the previous studies and the strong contribution of such device to the subsynchronous damping characteristics of the studied power system this approach could be seen beneficial concerning the analysis of this paper. The main parameters of the studied TCSC and its PLL circuit are presented in table I.

TABLE I
MAIN PARAMETERS OF STUDIED TCSC

L_{TCSC}	34.59 mH
C_{TCSC}	32.55 uF
ω_{fund}	2π·60 rad/s
α	65°
K_P (PLL)	30
K_I (PLL)	300

IV. COMPARISON OF THE APPROACHES FOR DETERMINING THE FREQUENCY DEPENDENT RESPONSE OF THE TCSC

To illustrate the subsynchronous damping analysis related shortcomings of the generic open-loop current injection model, that is extracted from the surrounding power system and especially from the oscillating turbine-generator, its response characteristics were compared with characteristics obtained by utilizing more complete approach based upon the IEEE 1st Benchmark model for SSR studies [8] (shown in Fig. 3). In addition to the TCSC, the extended approach included a turbine-generator, a step-up transformer, a transmission line and an equivalent voltage source of which parameters were equal to the parameters of the benchmark model.

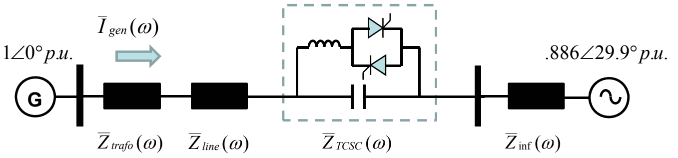

Fig. 3 Studied power system model

By modulating the mechanical speed of the turbine-generator in a frequency range 1-59 Hz corresponding sub- and supersynchronous current and voltage components can be observed in the electrical system as determined in (1).

$$\omega_{mech} = 2 \cdot \pi \cdot k, \text{where}\, k = 1,...,59\, Hz \tag{4}$$

With this approach the subsynchronous damping [9], and thereby the frequency dependent response of each electrical component on these oscillations can be determined with an analysis based upon the discrete Fourier transform of the voltage over and the current through the component.

The frequency dependent response of the TCSC by utilizing the generic open-loop current injection model was studied with two different signal injection approaches. The arbitrary signal injection approach included analysis utilizing both separately and simultaneously injected arbitrary chosen sub- and supersynchronous current components. In connection of the system related signal injection approach the system related sub- and supersynchronous current components were applied in the study.

A. Arbitrary Signal Injection Approach

In approach A1 the response of the TCSC was analyzed by separately injecting the arbitrary chosen sub- and supersynchronous current components related to the studied mechanical oscillation mode. This approach can also be considered as the common approach of the previous studies [5, 6]. The amplitude of the injected current component was chosen arbitrary to be 0.1 % of the amplitude A_{fund} of the fundamental component. Similarly, the relative phase between the fundamental and nonfundamental component was set to 0°. Based upon the proposition of the paper, in approach A2 both the arbitrary chosen sub- and supersynchronous current components were injected simultaneously.

Approach A1:

$$\begin{cases} \bar{I}_{injx} = A_{fund} \cdot \sin(\omega_{fund} \cdot t) + 0.001 \cdot A_{fund} \cdot \sin(\omega_i \cdot t) \\ \omega_i = \omega_{fund} + i \cdot \omega_{mech}, \text{where } i = -1,1 \end{cases} \quad (5)$$

Approach A2:

$$\begin{aligned} \bar{I}_{injx} = A_{fund} \cdot \sin(\omega_{fund} \cdot t) + 0.001 \cdot A_{fund} \cdot \sin(\omega_{sub} \cdot t) \\ + 0.001 \cdot A_{fund} \cdot \sin(\omega_{\sup} \cdot t) \end{aligned} \quad (6)$$

In Fig. 4 the frequency dependent impedance Z_{TCSC} of the TCSC by utilizing the arbitrary chosen signal injection is compared to the frequency dependent impedance of the TCSC determined from the extended power system model.

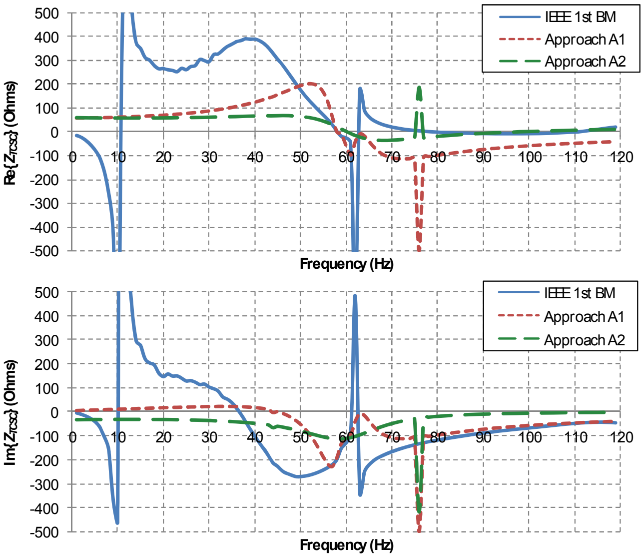

Fig. 4 Frequency dependent impedance of TCSC with arbitrary signal injection approach

As can be seen from Fig. 4 the frequency dependent impedance of the TCSC with the arbitrary chosen input currents differs significantly from the impedance measured from the extended power system model. Even simultaneous injection of the sub- and supersynchronous current components do not produce similar impedance as in the case of the extended power system model.

B. System Related Signal Injection Approach

The system related signal injection approach utilizes the currents signals $I_{gen}(\omega_{fund})$, $I_{gen}(\omega_{sub})$ and $I_{gen}(\omega_{sup})$ measured from the extended power system model. Therefore, the amplitudes and the phases of the applied current signals were basically determined by the frequency dependent impedance seen by the oscillating generator. In approach B1 the measured sub- and supersynchronous current components were injected separately and in approach B2 simultaneously.

Approach B1:

$$\begin{cases} \bar{I}_{injx} = \bar{I}_{gen}(\omega_{fund}) + \bar{I}_{gen}(\omega_i) \\ \omega_i = \omega_{fund} + i \cdot \omega_{mech}, \text{where } i = -1,1 \end{cases} \quad (7)$$

Approach B2:

$$\bar{I}_{injx} = \bar{I}_{gen}(\omega_{fund}) + \bar{I}_{gen}(\omega_{sub}) + \bar{I}_{gen}(\omega_{\sup}) \quad (8)$$

The frequency dependent impedance of the TCSC by utilizing the system related signal injection is presented in Fig. 5. Correspondence between the generic open-loop current injection model and the extended power system based responses improves by utilizing the system related signal injection. In matter a fact, by injecting the system related input currents simultaneously (approach B2), the responses based upon the generic open-loop current injection model and the extended power system model become almost identical. As a conclusion, the effect of the overall response of surrounding power system on torsional oscillations can be seen crucial and cannot be ignored if the effect of the TCSC on subsynchronous damping is of interest.

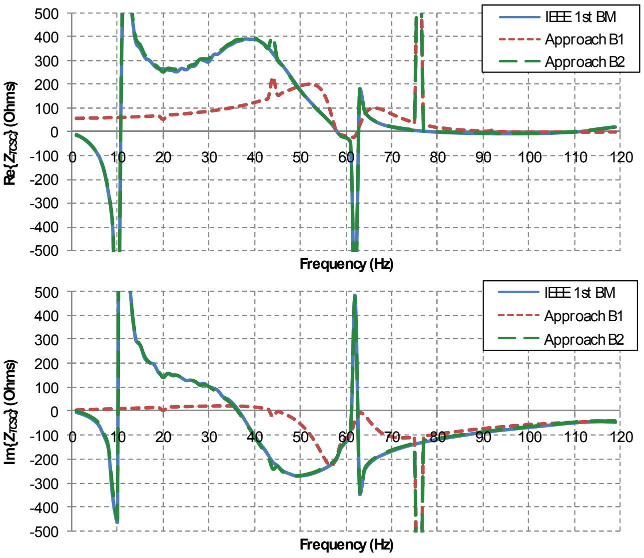

Fig. 5 Frequency dependent impedance of TCSC with system related signal injection approach

V. APPLYING TCSC FREQUENCY RESPONSE DATA IN SSR FREQUENCY SCANNING STUDY

Despite the distinct differences between the frequency dependent response data of different approaches, based upon these results it is not possible to estimate the accuracy, in which they describe the actual frequency dependent response of the TCSC on torsional oscillations. Therefore, the frequency dependent impedance data of all studied cases were applied in a SSR frequency scanning study concerning the network structure presented in Fig. 3. This approach allowed an analysis of the accuracy, in which the applied impedance data estimates the actual effect of the frequency dependent response of the TCSC on torsional oscillations.

The subsynchronous damping of the studied power system in the mechanical frequency range 5-55 Hz was determined with the detailed EMT analysis [9] and the SSR frequency scanning study approach presented in [4]. By determining the total impedance $Z_{net}(\omega)$ of the studied power system the electrical damping $De(\omega)$ for the studied mechanical frequency range can be estimated. [3]

$$\begin{aligned}\overline{Z}_{net}(\omega) &= R_{net}(\omega) + j\cdot X_{net}(\omega)\\ &= \overline{Z}_{trafo}(\omega) + \overline{Z}_{line}(\omega) + \overline{Z}_{TCSC}(\omega) + \overline{Z}_{\inf}(\omega)\end{aligned} \tag{9}$$

$$\begin{aligned}De(\omega_{mech}) = \frac{1}{2\cdot\omega_{mech}}\Bigg(&\omega_{sub}\cdot\frac{R_{net}(\omega_{sub})}{R_{net}(\omega_{sub})^2 + X_{net}(\omega_{sub})^2}\\ &-\omega_{\sup}\cdot\frac{R_{net}(\omega_{\sup})}{R_{net}(\omega_{\sup})^2 + X_{net}(\omega_{\sup})^2}\Bigg)\end{aligned} \tag{10}$$

In Fig. 6 the electrical damping of the detailed EMT analysis is compared to the SSR frequency scanning study results utilizing the TCSC impedance data of the arbitrary signal injection. From Fig. 6 can be seen the relatively poor correspondence between the EMT analysis based and the SSR frequency scanning study based damping curves when the frequency dependent impedance of the TCSC obtained utilizing the arbitrary signal injection was applied in the SSR frequency scan.

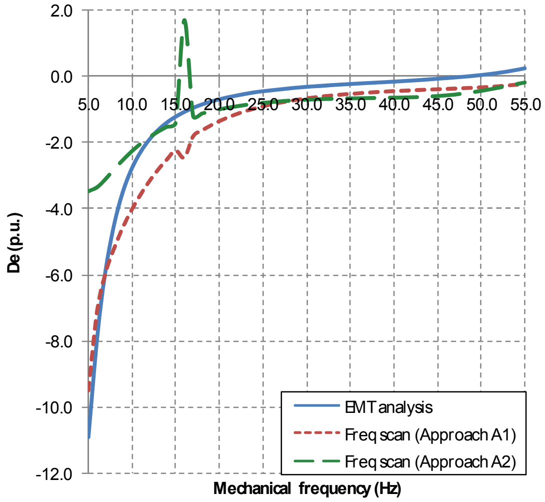

Fig. 6 Electrical damping based upon EMT and frequency scanning approaches with arbitrary signal injection

In Fig. 7 the electrical damping of the detailed EMT analysis is compared to the SSR frequency scanning study results utilizing the TCSC impedance data based upon the system related signal injection. Damping curves in Fig. 7 indicate clearly the importance of considering the coupling between the sub- and supersynchronous frequency components when studying the torsional oscillation related response of the TCSC.

By utilizing the frequency dependent response data of the TCSC related on the approach B1, where the system dependent input currents were injected separately, correspondence between the detailed EMT analysis based and the SSR frequency scanning study based damping curves differs significantly. On the contrary, by considering the coupling between the sub- and supersynchronous frequency components with the simultaneously injected system related current components the damping curves of the EMT analysis and the SSR frequency scanning study based approaches resemble each other with reasonable accuracy.

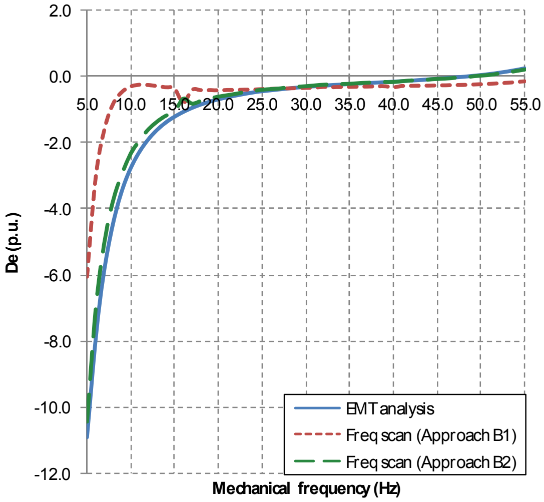

Fig. 7 Electrical damping based upon EMT and frequency scanning approaches with system related signal injection

As a conclusion, effect of a switched device like TCSC on the subsynchronous damping can be estimated with reasonable accuracy by utilizing a SSR frequency scanning technique, if the subsynchronous response characteristics of the TCSC have been determined in valid manner. It is obvious that to be able to determine the subsynchronous response of the TCSC accurately the inherent characteristics and parameters, such as control implementation and synchronization method, of the TCSC must be taken into account correctly. [10] However, the results of the studies indicate that also the effects of the sub- and supersynchronous characteristics of power system surrounding the switched device and the coupling between the sub- and supersynchronous components due to the frequency modulation characteristics of switched devices and rotating machines should be included in the studies. There are two interesting questions here. First, whether that all can be captured by an analytical model. And secondly and maybe somewhat less interestingly, whether an EMT based data set describing the sub- and supersynchronous response under certain selected operating conditions can be applied in a SSR frequency scanning study to present the effect of the TCSC with reasonable accuracy.

VI. DISCUSSION

Whereas the results shown in this paper do not give adequate answers to the questions presented in the previous chapter, based upon the results shown it is obvious that the effect of a switched device like TCSC on the electrical damping of power system is composed of various TCSC and system related parameters. Ideally, the frequency dependent response data of the TCSC in a SSR frequency scanning study would be described with detailed analytical equations that would consider the effect of all the discussed parameters on the response of the TCSC. This approach would allow implementation of a TCSC as a part of arbitrary power system being analyzed by utilizing the SSR frequency scanning technique presuming that required initial information of the power system surrounding the implemented device would be available.

However, because of the variety of the parameters related to the subsynchronous damping characteristics of the TCSC, including the effect of all the discussed parameters on analytical representation, in manner suitable to be included in a SSR frequency scanning study, may obviously become cumbersome. Thereby, it can be considered, that even estimation with adequate accuracy of the frequency dependent response of the TCSC on torsional oscillations could be adequate for modelling the TCSC in connection of the SSR frequency scanning studies especially in case of meshed, highly series compensated transmission networks. In further studies, it could be seen beneficial to estimate the significance and sensitivity of single affecting parameter on the response of the device on torsional oscillations. This again would enable evaluation of the most significant ones to be included in the analytical representation of the subsynchronous damping characteristics of the TCSC. As a final target, successful implementation of this analytical representation into a SSR frequency scanning study would provide a tool to be applied also into transmission networks including nonlinear and controllable devices such as TCSC with reasonable accuracy.

VII. CONCLUSIONS

This paper presented an approach for determining the frequency dependent response of the TCSC on torsional oscillations utilizing the generic open-loop current injection model. The main scope of the study was to analyze the response characteristics in such manner that the results provide relevant information regarding the effect of the TCSC on subsynchronous damping. The frequency dependent response of the TCSC obtained with different study approaches were compared and it was concluded that, in addition to simultaneous injection of the sub- and supersynchronous current components, also the system related amplitude and relative phase between the injected current components should be considered to attain results with reasonable accuracy.

To evaluate the validity of the sub- and supersynchronous TCSC response data obtained by utilizing different study approaches, the TCSC response data was applied in a traditional SSR frequency scanning study to describe the effect of the response data on subsynchronous damping. The accuracy of the SSR frequency scanning was compared to the detailed EMT based damping analysis. Only with the approach, where the frequency dependent response of the TCSC was determined considering fully the inherent characteristics of torsional oscillations, correspondence between the EMT analysis and the SSR frequency scanning study based damping results were achieved with reasonable accuracy. In the paper limitations and restrictions related to development of an analytical model of the TCSC to be applied in SSR frequency scanning study were evaluated and it is concluded that further studies will be required to fully determine the adequate modeling accuracy needed to represent the frequency dependent response of the TCSC on torsional oscillations analytically.

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IX. BIOGRAPHIES

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