A PSCAD case study of the main factors influencing the level of subsynchronous torsional interaction caused by HVDC

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Abstract-- This paper analyses the main factors affecting the undamping caused by subsynchronous torsional interaction (SSTI) between HVDC and turbine-generator unit. A model describing simple AC-DC transmission system consisting of a turbine-generator, HVDC CIGRE benchmark model and equivalent sources describing the AC systems connected to converter terminals is used to study the interaction. The paper shows how and in what extent the known main factors effect on the level of undamping caused by HVDC. This understanding is of great value as the risk of growing subsynchronous oscillations in transmission system is considered in connection of major structural network changes in vicinity of existing HVDC and turbine-generator installations. The study results and the simulation model used in SSTI studies will be exploited when the SSTI risk is estimated as a part of long-term network planning of Finnish transmission grid.

Keywords: Subsynchronous torsional interaction, SSTI, damping analysis, HVDC, HVDC control, subsynchronous oscillations, unified interaction factor

I. INTRODUCTION

In 1976 during the commissioning tests of the Square Butte HVDC system subsynchronous torsional oscillations were excited due to interaction between the turbine-generator unit and HVDC [1]. Back then the principle of growing subsynchronous torsional oscillations due to the interaction between turbine-generator and external power system component was quite well known as subsynchronous resonance (SSR), ie. interaction between turbine-generator and series capacitors, had became public knowledge a few years earlier [2]. In subsynchronous torsional interaction (SSTI) caused by HVDC the component causing the interaction with turbine-generator is effectively either the power or the current controller of the HVDC rectifier control system. This is because of the response of the controller on subsynchronous frequency range is such that it may cause negative damping on the subsynchronous frequency range [3].

Still, whether the interaction causes growing or damped oscillations depends on numerous factors related to the structure of turbine-generator, power system and HVDC and its control system. Due to the large number of factors affecting the interaction and the complexity of HVDC system simplified analytical expressions describing the factors effecting on the SSTI are extremely difficult to define. Therefore the principle of subsynchronous torsional interaction is often described using simplified block diagram shown figure 1 [3]. The diagram presents the feedback loop between the electrical system and the mechanical system consisting of the rotating mass of the turbine-generator. In principle the interaction causes oscillations to grow if the total response of the electrical system is such that a change in the generator speed Δω causes an opposite sign change in electrical torque ΔT_e.

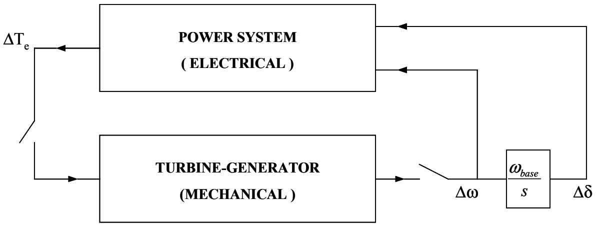

Fig. 1. Principle of subsynchronous torsional interaction

As growing subsynchronous oscillations may lead in extreme situations even to a shaft failure, the possibility of SSTI due to HVDC in the power system must be well-known especially as HVDC system are installed or upgraded in the vicinity of turbine-generators or vice versa. However, as the level of subsynchronous torsional interaction caused by HVDC is affected by several different factors it is very challenging to evaluate without exact system studies. Knowing the effect of the main factors influencing the level of the interaction makes it possible to concentrate on certain network combinations most probable to cause growing oscillations, or even to discard the SSTI studies completely. Understanding the influence of different parameters may also benefit greatly the design process of subsynchronous oscillation damping controller (SSDC) [3] as it is implemented to a HVDC situated in vicinity of several generators which all have different natural frequencies.

This paper targets to create some understanding into the main factors affecting SSTI phenomenon due to HVDC using the results of time-domain simulations. A simple PSCAD

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model is used to study how the main SSTI affecting parameters effect on the level of the. The results gained from simulations are compared with corresponding unified interaction factors (UIF) [3]. This is done in order to obtain some idea of circumstances, under which the threshold level given by UIF can be considered conservative and under which more detailed studies should be performed to ensure that no risk of growing subsynchronous oscillations exists.

II. THE MAIN PARAMETERS AFFECTING THE LEVEL OF SSTI

A. Parameters related to unified interaction factor

During the research project launched after the Square Butte incident a simple method called Unified Interaction Factor was created to be used in estimation of SSTI risk [3]. During last 30 years UIF has been established as an important design factor, which is used as a preliminary study tool in order to decide whether detailed studies of SSTI are needed. Unified interaction factor is based on large-scale interaction studies and it takes into account major SSTI effecting parameters in following way [3].

$$UIF = \frac{S_{HVDC}}{S_{gen}}\left(1-\frac{S_{SC,nogen}}{S_{SC,total}}\right)^2 \qquad (1)$$

where S_{gen} = generator MVA rating
S_{HVDC} = real power transmitted by the HVDC
$S_{SC,nogen}$ = short-circuit capacity (SCC) of the rectifier end AC network without studied generator
$S_{SC,total}$ = short-circuit capacity (SCC) of the rectifier end AC network.

All four parameters included in UIF are closely related to the generators ability to affect the magnitude and especially the angle of HVDC rectifier terminal AC voltage and vice versa. The stronger both the generator and the HVDC can effect on the angle of the system voltage, the stronger the interaction will be. Therefore the parameters and their relations used in UIF can be considered more or less evident.

B. Control system parameters

The control system of HVDC link is the component, which causes the interaction between HVDC and turbine-generator. Especially structure and parameters of the rectifier current controller are decisive in the level of interaction, but also the other controller blocks may have effect on the interaction However, compared to influence of the rectifier current controller their influence on the interaction is minor. [3]

The structures of the HVDC control systems vary between different HVDC installations [4]. The structure and especially the parameters of the control system are defined based on certain performance criteria, which are set to each HVDC scheme depending on the structure of the HVDC and the AC system to which the HVDC is connected [5]. As the different control system structures and parameters change the control system response on subsynchronous oscillations the exact response of the control system on subsynchronous oscillations, is very difficult to predict without detailed studies. Even though the threshold value given by the UIF has been used successfully since it was found, the assumptions made during the large-scale system studies, on which UIF is based on, are not known. Therefore some insight, how the current control parameters effect on the level of torsional interaction, can provide some important information in excess of UIF considering the possibility of subsynchronous torsional interaction due to HVDC.

As the control system, or above all the control principle of the HVDC, is the cause of the interaction, the response of the control system on the critical natural torsional frequencies of certain unit can be affected by using an additional control circuit [3]. This supplementary control is used to affect the transfer function of rectifier control so that control system related phase shift leading to growing subsynchronous oscillation on certain natural frequency is cancelled. These damping circuits have been successfully used to prevent the SSTI caused by HVDC since the Square Butte incident [1]. Nevertheless, their implementation may get complicated as the number of torsional frequencies to be compensated increases in cases there are several turbine-generators with different torsional frequencies located close to HVDC. Basically in such cases due to negligent design of the damping circuit the effect of the circuit may be decreased, or in extreme case even total response of damping circuits may cause amplification of subsynchronous oscillations. In such cases exact knowledge of frequencies, which cannot be excited due to HVDC control system structure, is of great importance as it makes the damping circuit design process more convenient.

C. Structure of mechanical system

1) Natural frequencies and modal inertia

Since the response of the HVDC system on the subsynchronous oscillations can in practice amplify only torsional frequencies below 30 Hz [3], consideration of these modes only is adequate in SSTI related studies. In addition to magnitude of the torsional frequency f_n also torsional frequency related modal inertia H_n has major effect whether the subsynchronous oscillations on certain torsional frequency are increased. Basically modal inertia defines the mechanical system response to the electrical system based excitation. As well as the torsional frequencies also modal inertias are closely related to the turbine-generator structure. Based on the lumped parameter model of turbine-generator both parameters can easily be solved using analytical methods. [6]

2) Mechanical damping

Out of the main parameters affecting the level of SSTI, mechanical damping of turbine-generator is perhaps most difficult to define as it consist of several minor factors, which are practically impossible to determine analytically. Therefore mechanical damping is determined by testing the modal damping of the mechanical system in practise. Only a few such tests and their results are presented in literature and in lack of exact information considering the mechanical damping of the studied generator these literature-based values can be used in analysis. In SSTI studies the mechanical damping can be disregarded completely in order to obtain some conservativeness in simulation results. Alternatively for example following general approximation based on test results presented in literature can be used for mechanical logarithmical decrement [7].

$$\log dec = 0{,}002 \quad (2)$$

In this paper the results considering modal damping are given using modal damping coefficient. Modal damping coefficient can be derived using logarithmical decrement and corresponding natural torsional frequency f_n.

$$\sigma_{mn} = 0{,}002 \cdot f_n \quad (3)$$

III. PSCAD SIMULATION MODEL USED IN SSTI STUDIES

A. Structure of PSCAD model

To study the effect of the known main parameters defining the level of SSTI a PSCAD model (figure 2), including all the parameters presented in chapter 2, was implemented. The model used to study torsional interaction phenomenon consists of a turbine-generator unit, a HVDC link and its control system and AC grid equivalents connected to the HVDC rectifier and inverter terminals. The components of the model used in the study are presented in shortly in this chapter.

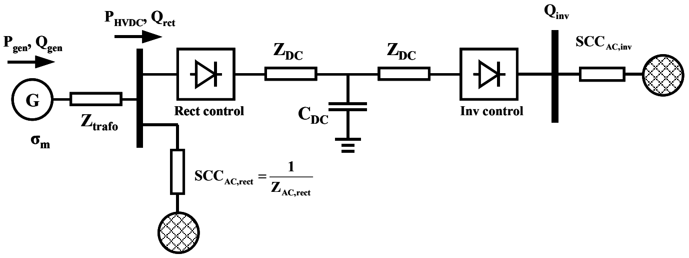

Fig. 2. The structure of the PSCAD model used in SSTI studies

B. Turbine-generator models

As effect of the mechanical structure of the studied generator strongly effects on the level of the interaction it is important to study different turbine-generator structures in order to gain extensive results on the whole frequency range where interaction may theoretically occur. Therefore three different literature based turbine-generator configurations with natural frequencies covering the frequency area from 6 Hz to 22 Hz were chosen to be used in the study. In addition to these three turbine-generators also one turbine-generator connected to the Finnish transmission system was included in the study due to the fact that its lowest torsional mode fits the study perfectly. These turbine-generators and their main parameters affecting the interaction phenomenon are shown in the table I.

TABLE I
THE NATURAL FREQUENCIES AND CORRESPONDING MODAL INERTIAS OF THE TURBINE-GENERATOR MODELS

	TG1 [6]		TG2 [2]		TG3 [8]		TG4	
	f_n	H_n	f_n	H_n	f_n	H_n	f_n	H_n
Mode1	6.7	2.97	8.6	2.53	12.9	2.63	9.8	3.03
Mode2	12.4	3.61	16.2	3.54	22.3	4.25	19.5	2.21
Mode3	15.8	1.62	21.9	8.30	not studied		not studied	

Since the electrical structure of generator is less crucial than its mechanical structure or its rating when SSTI is analyzed, electrical parameters of turbine-generator “TG1” were used throughout the study. Only the rating of the generator was changed in order to affect the level of SSTI. In the simulations the real power output P_{gen} given in table II was defined to be very close to the rated output power.

C. CIGRE HVDC benchmark [9]

A natural choice for the HVDC model used in the study system was the CIGRE HVDC benchmark model, which allows in excess of variation of transmitted power and DC line parameters also variation of the main control system parameters. However, in this study only the effect of the transmitted real power P_{HVDC} by HVDC and PI-controller parameters of rectifier current control block (figure 3) were considered.

As the transmitted power by the HVDC was increased in studies as shown in table II, also the rating of the link was increased by scaling the transformer ratings, filter banks and control system scaling parameters using the relations given by the original model.

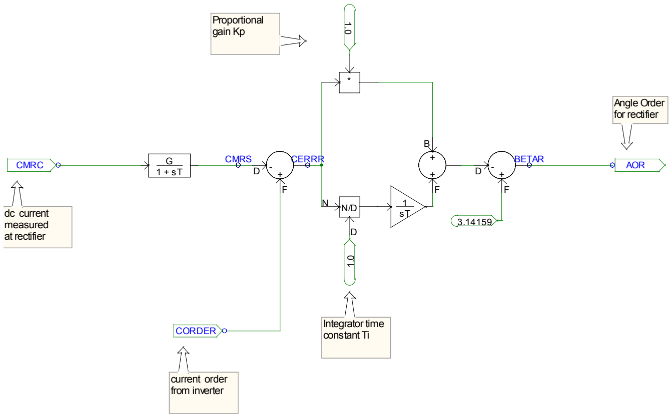

Fig. 3. Structure of the rectifier current controller used in PSCAD model

D. Varied parameters and the structure of the study

The main part of the study concentrated on the effect of UIF related parameters and current controller integrator time constant $T_{i,rect}$. Totally about 900 different cases for each of four turbine-generator models were simulated using different combinations of the parameters given in table II. In table II also some of main constant parameters used in the simulations are shown. The system parameters not given in table are equal to the ones given within CIGRE HVDC benchmark [9] and corresponding PSCAD v4 example model.

TABLE II

MAIN PARAMETERS OF THE GENERAL STUDY

Constant parameters:		Varied parameters:				
$Q_{rct} = 0.55 \times P_{rct}$ Mvar	$Q_{inv} = 0.55 \times P_{inv}$ Mvar	P_{gen} [MW]	750	1000	1250	
$\alpha_{rct} = 15°$	$\gamma_{inv} = 35°$	P_{HVDC} [MW]	600	800	1000	1200
$U_{rct} = 0.98$ p.u	$U_{inv} = 0.98$ p.u	SCC_{grid} [MVA]	2500	4000	5000	
Control parameters except $T_{i,rect}$, see PSCAD v4 example model of CIGRE BM		$T_{i,rect}$	2-40 ms			

In addition to the parameters given in table II also the proportional gain $K_{p,rect}$ of rectifier current control was varied in certain single simulations.

IV. STUDY RESULTS

During the study it was noticed that considering especially the natural frequencies above 10 Hz the stimulus used to invoke subsynchronous oscillations effected considerably on the simulation results in certain cases. If rather small stimulus, like temporary change in current order of HVDC rectifier, was used large divergence in damping results of higher torsional frequencies was noticed when the simulation time step of 50 µs was applied. When the simulation time step was reduced to around 10 µs, the divergence was reduced on a reasonable level. If greater stimulus, like a system fault, was used the divergence of the damping values stayed on reasonable level even if 50 µs time step was applied.

The results presented in this paper are simulated using 50 µs time step and phase-to-ground fault on the HVDC rectifier bus is used as a stimulus for torsional oscillations. The main reason for this choice is the time requirement of simulation. Compared to 10 µs time-step total simulation time reduces to one eight when using 50 µs, which is of great benefit in large-scale studies.

A. Comparison of the simulation results with corresponding unified interaction factors

Study results for torsional oscillation mode 1 of "Gen2" corresponding different combination of variables shown in the table II are presented in figure 4. Similar presentation for mode 2 of "Gen1" is shown in figure 5.

The colored squares describe the damping coefficient as a function of UIF when integrator time constant of the current controller equals 10 ms, which is slightly smaller that the original value given within the CIGRE HVDC benchmark model in PSCAD. The error bar left from the square describes the minimum damping on the integrator time constant range from 5 ms to 10 ms. Similarly the error bar right from the square describes the maximum damping on range from 10 ms to 30 ms.

For each combination of transmitted real power by HVDC and generated real power by generator there are three data points corresponding the three short circuit levels shown in table II. Data point closest to the upper left corner equals to the lowest value of short-circuit rating and respectively the point closest to the lower right corner equals to the highest value.

Like shown in the figure 5, regarding the studied natural frequencies over 12 Hz, increasing subsynchronous oscillations occurred only in few cases for integrator time constant 10 ms or below. A similar example is shown for torsional frequencies below 12 Hz in figure 4. Figure 4 shows clearly that undamped oscillations are common especially in cases where unified interaction factor exceeded the threshold level of 0.1. However, the area of interest in the above-described representation is lower left corner area outlined by zero modal damping axis and UIF threshold value 0.1. In that area, outlined in figures 4 and 5 using red dashed line, there should be no data points assuming that UIF threshold value 0.1 is valid.

If integrator time constant values below 10 ms are disregarded, as they don't seem to improve the performance of the rectifier control considerably, there were no data points in the specified area in any study case. Nevertheless, as UIF seems to be linearly dependent on the damping coefficient as the short-circuit ratio of the parallel network is increased, in two cases (HVDC600_GEN1250 and HVDC800_GEN1250) shown in figure 4 the line drawn via data points crosses through the critical area. Thus, within narrow range of short-circuit ratios of the parallel grid the subsynchronous oscillations increase despite the fact that corresponding UIF is below 0.1. However, as the integrator time constant is slightly increased from 10 ms, the UIF threshold is valid again.

The study results presented in figures 4 and 5 indicate that generator rating and power transmitted by the HVDC affect the damping more or less as expected on the unified interaction basis.

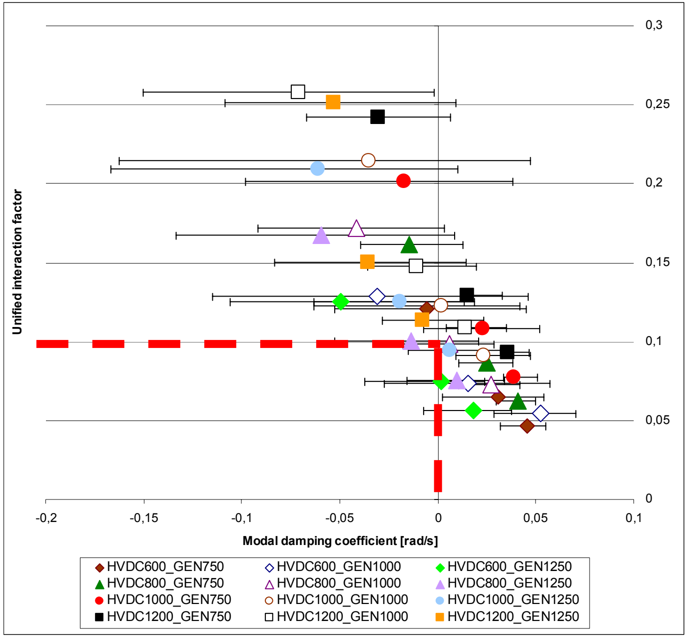

Fig. 4. Unified interaction factor as a function of modal damping coefficient for Gen2 mode 1 (8.6 Hz).

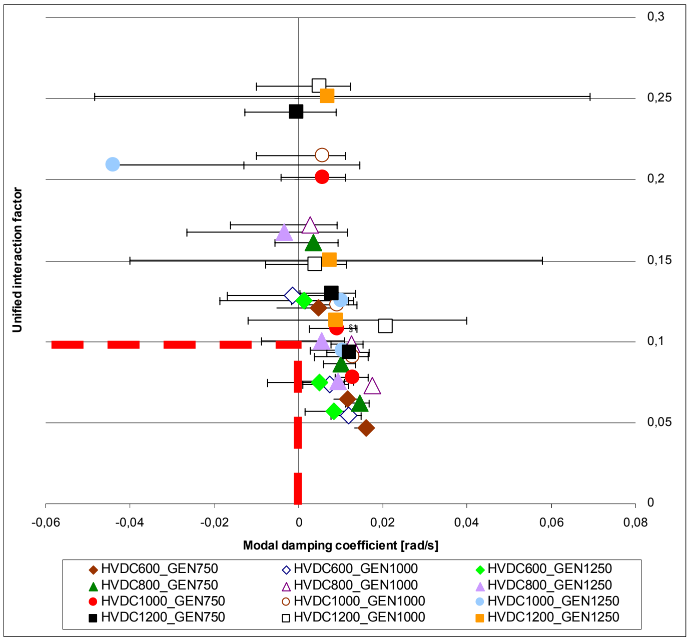

Fig. 5. Unified interaction factor as a function of modal damping coefficient for Gen1 mode 1 (12.9 Hz).

B. *Effect of PI-controller time constant $T_{i,rect}$*

The effect of the integrator time constant of rectifier current controller was already presented in some extent in figures 4 and 5. When behaviour of the modal damping coefficient is presented as a function of the time constant their dependence can be seen more clearly. In figures 6 and 7 this is done for the study case where both the generator output power and the transmitted real power by HVDC are 1000 MW and the short-circuit ratio of the parallel grid is 2500 MVA.

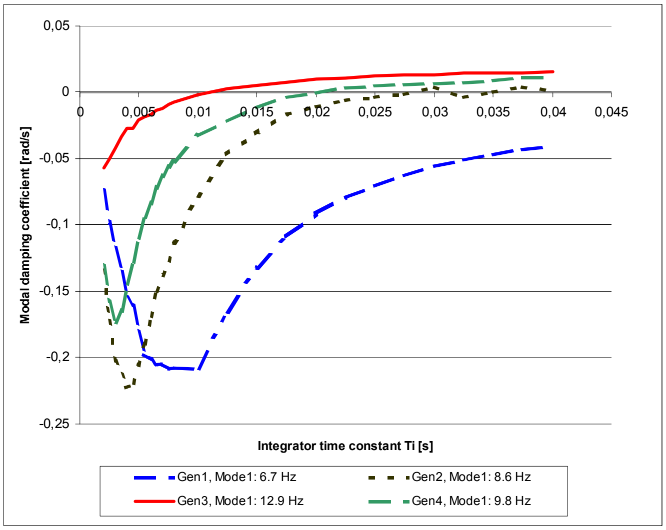

Fig. 6. Modal damping coefficient as a function of integrator time constant for the lowest torsional mode of the studied generators.

Figures 6 and 7 show how the integrator time constant related to the maximum undamping of a certain mode decreases as the natural torsional frequency increases. It's evident that in the simulation model used the undamping is highest on low torsional frequencies as both the level and the maximum value of the damping decrease as the torsional frequency increases. The other varied parameters shown in table II did have remarkable effect only on the maximum value and the level of the undamping. In other words the shapes of the graphs remained same between the different cases, which suggest that there exists a resonance factor analogous to SSR series resonance also for the SSTI caused by the HVDC [10]. In this case the resonance factor seems to be related to the structure of the rectifier current control. However, the resonance-like behaviour occurs on such a low values of integrator time constant that hardly any practical use for the factor exists in transmission system planning.

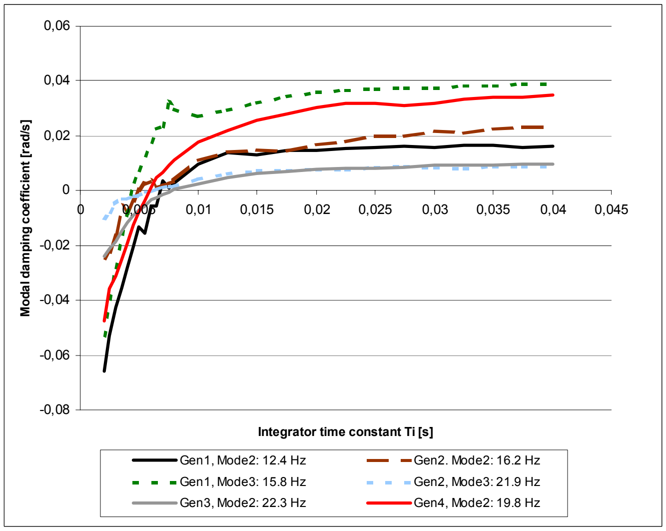

Fig. 7. Modal damping coefficient as a function of integrator time constant for the torsional modes 2 and 3 of the studied generators.

C. *Effect of PI-controller proportional gain $K_{p,rect}$*

The effect of the current controller proportional gain on the modal damping coefficient is presented in figure 8, where coefficient is presented as a function of proportional gain for different constant values of integrator time constant $T_{i,rect}$.

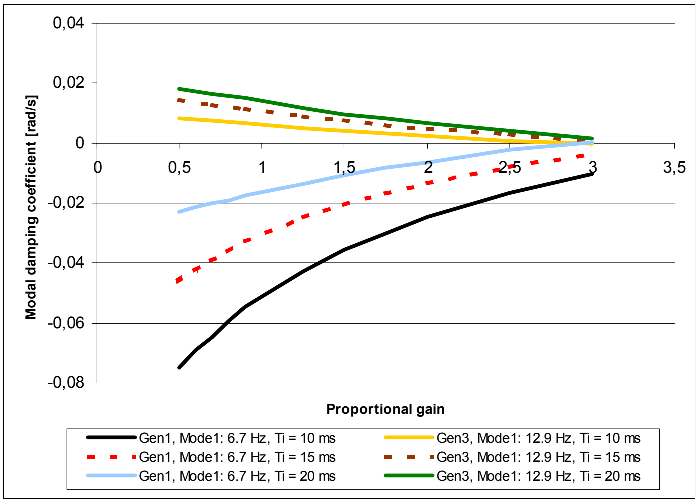

Fig. 8. Modal damping coefficient as a function of proportional gain for Gen1 mode 1 (6.7 Hz).

The graphs in figure 8 are from simulations where generator real power is 1000 MW, transmitted real power by HVDC is 600 MW and parallel AC system short-circuit capacity 2500 MVA. Figure 7 shows the common trend for all the simulation results. For the studied two lowest modes increase in proportional gain improves the modal damping. Instead, for the higher torsional modes increase in proportional gain decreases the damping values.

V. CONCLUSIONS

The results of the PSCAD simulations are in line with the corresponding unified interaction factors. Especially for natural torsional frequencies above 12 Hz unified interaction factor seems to be very reliable. However, if PI-controller integration time of rectifier current controller is around 10 ms for torsional frequencies below 12 Hz, need of detailed study considering the level SSTI can be regarded more useful than if the time-constant is somewhere between 20-30 ms. Also the proportional constant of the PI-controller may have significant effect on the level of the interaction. Nevertheless, this study covers only one representation of the HVDC control system and therefore further studies must be performed before generalization based on the simulation results can be made.

As this study covered only the main parameters affecting SSTI caused by HVDC, further studies considering the effects of other parameters will be performed. Especially the effect of the rectifier control circuit structure and the proportional constant of PI-controller are of interest. Also effect of parameters related to inverter control, such as gamma control parameters and control mode of inverter, will be studied. Studies regarding different electrical structures of the studied generator and some additional mechanical structures can be also considered important, before final conclusions based on the simulations are made.

As long-term network planning of Finnish transmission network is performed the SSTI study model presented in this paper will be used in addition to a more detailed model to analyze the risk of SSTI in order prevent the possibility of interaction. The results of these future studies will be used to further analyze the performance of simplified model compared to the detailed one and also gain more information considering the conservativeness of unified interaction factor.

VI. ACKNOWLEDGMENT

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VIII. BIOGRAPHIES

Tuomas Rauhala was born in Rovaniemi, Finland, on September 11, 1979. He received his Master’s degree in electrical engineering from Helsinki University of Technology, Finland, in January 2004. At the moment he is a research engineer and a post-graduate student in Tampere University of Technology.

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Pertti Järventausta was born in Urjala, Finland, on May 28, 1965. He 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.

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