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MANAGING THE EFFECT OF PARALLEL HVDC SYSTEMS ON SUBSYNCHRONOUS DAMPING OF NEARBY GENERATOR UNITS

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SUMMARY

It is well known that HVDC converters, especially while operating in rectifier mode, may decrease the damping of subsynchronous torsional modes of nearby generator units. The phenomena is referred typically as subsynchronous torsional interaction (SSTI) and basically, it is due to adverse effect of subsynchronous currents injected by HVDC on the subsynchronous damping of the generator units.

SSTI caused by HVDC has been of interest in Finland since commissioning of 550 MW Fenno-Skan HVDC in 1989, as Fenno-Skan converter station is located in vicinity of generating station consisting of two 950 MVA turbogenerator units. By the end of 2011 a new 800 MW HVDC system, Fenno-Skan 2, will be commissioned in parallel with 550 MW Fenno-Skan. At the same time the capacity of nearby generating station will be doubled via commissioning of a 1980 MVA turbogenerator.

In principle, from subsynchronous damping point of view the situation could become challenging as the subsynchronous damping of three generators, which have with five different subsynchronous modes on torsional frequency range below 20 Hz, will be affected by two different HVDC converters. Large part of this challenge was, however, tackled by the transmission network planners as the network structure on the area basically guarantees very good subsynchronous damping under normal operating conditions and typical contingencies. Nevertheless, due to severity of the risks related to weakly damped subsynchronous oscillations, the adverse effect of HVDC converters on subsynchronous damping will be further addressed by means of additional HVDC controls and SSO protection schemes.

This paper presents the background and the main results of HVDC SSTI feasibility study with main scope in HVDC SSDC and SSO protection performance. Also, the aspects related measures and approaches required to guarantee positive subsynchronous damping and to manage minor risk of increasing subsynchronous oscillations are discussed.

KEYWORDS

Subsynchronous oscillations - Subsynchronous damping - HVDC - Subsynchronous torsional interaction - SSO countermeasures

1 INTRODUCTION

In Finland the effect of HVDC on subsynchronous damping has been of interest since Fenno-Skan HVDC was commissioned in vicinity of the two 950 MVA turbogenerators in 1989. As the relative short circuit capacity under normal operating conditions as well as during common contingencies has been rather high compared to the nominal power of the generating units and Fenno-Skan HVDC connection, the risk of HVDC affecting significantly on damping seen by the units has been minor. Subsynchronous damping controller (SSDC) was implemented as part of the HVDC controls in order to guarantee good torsional damping also during the most severe contingencies. Also a SSO protection scheme based on local frequency measurement was implemented as part of Fenno-Skan control and protection system. The SSO protection scheme is capable to trip the HVDC link in case of high amplitude subsynchronous components is detected in frequency and thus, it serves basically as the last line of protection with respect to extreme amplitudes of torsional oscillations.

Within next few years especially the southwest part of the Finnish 400 kV transmission system will undergo significant structural changes. By the end of year 2011 a 1980 MVA turbogenerator unit will be commissioned and new Fenno-Skan HVDC connection with transmission capacity of 800 MW will be installed in parallel with the existing HVDC connection. There are also plans to uprate the generating capacity of two existing 950 MVA by the year 2012. [1]

After the system reinforcements the effect of Fenno-Skan HVDC schemes on subsynchronous damping seen by the three generating units will further decrease. Thus, even if no countermeasures against low subsynchronous damping would be installed, the risk of low subsynchronous damping can be considered insignificant under normal operating conditions and typical contingencies. Nevertheless, considering the nature of the risk related to increasing subsynchronous torsional oscillations, even the most extreme possible operating conditions should be taken into account in planning. Therefore, feasibility of presently applied SSO countermeasures was analyzed in detail considering especially the effect of two parallel unidentical HVDC converters and the effect of five different torsional frequencies within range from 5 to 20 Hz.

This paper presents the background and main results of HVDC SSTI feasibility study with main scope in HVDC SSDC and SSO protection performance. Also, the aspects related measures and approaches required to guarantee positive subsynchronous damping and to manage minor risk of increasing subsynchronous oscillations are discussed.

2 PRECONDITIONS FOR HVDC SSTI PLANNING

The frequencies of the subsynchronous torsional oscillation modes of generators G1, G2 and G3, which are of main interest from HVDC SSTI point of view, are shown in table I. The values given in the table are obviously preliminary planning values as the effect of uprate on torsional modes of G1/G2 and the true values of torsional modes of G3 will not be available until commissioning of the units. Interestingly, in this case the timing of the former will likely be after the design of the Fenno-Skan 2 controls and the timing of the latter after commissioning of the Fenno-Skan 2. Those schedule related aspects were taken into account in the specification of Fenno-Skan 2 by requiring certain level of flexibility regarding the SSDC structure and its re-parameterization.

Table 1 Approximate planning values for torsional frequencies of the studied units below 20 Hz

Planning values [Hz] for torsional frequencies below 20 Hz				
G1/G2 (950 MVA)		G3 (1900 MVA)		
9.5	19.5	6	10.5	14.5

2.1 Unified interaction factor

Unified interaction factor [2] is the only established, straightforward manner to evaluate, if the risk of HVDC SSTI requires detailed analysis and consideration of countermeasures. As background information for this study UIF was calculated for different combinations of HVDC poles and units in operation. Based on the values shown in the table 2, AC network short circuit capacities (SCC) of 5000 MVA and 7000 MVA were chosen to be applied in planning study in addition to 2000 MVA, that is the specified minimum operating condition for both the Fenno-Skan poles.

Table 2 Approximate short circuit capacity of parallel AC network required to reach UIF threshold 0.1

		Approximate short circuit capacity (MVA) required to reach UIF threshold 0.1	
		G1/G2 (950 MVA)	G3 (1900 MVA)
Active HVDC pole(s)	600 MW	3000	3500
	800 MW	4000	5000
	1400 MW	5500	8000

2.2 The main measures to manage HVDC SSTI related risk

2.2.1 Subsynchronous damping controller

Subsynchronous damping controllers (SSDC) has been applied to cancel deteriorating effect of HVDC system on subsynchronous damping basically since the first time HVDC was shown to have adverse effect especially on damping of subsynchronous torsional modes within frequency range between 5 and 20 Hz [2]. Since then, SSDC has been established basically as the standard additional control feature in all the installations where the HVDC may affect subsynchronous damping of nearby generator units.

Fenno-Skan HVDC has SSDC optimized to improve the torsional damping of the present subsynchronous modes of G1 and G2. The SSDC of Fenno-Skan applies band-pass filter based SSDC structure, which in practice means that SSDC improves torsional damping at and nearby the torsional frequencies of G1 and G2, but decreases the damping on other frequencies on subsynchronous range. Thus, the SSDC must be retuned in connection of each uprate or installation of a new unit in vicinity of converter station. In this case the retuning must be performed considering that the number of subsynchronous frequencies within the critical range 5-20 Hz is increasing from two to five. Obviously, the most intriguing question was whether the SSDC is capable to provide required damping with those building blocks implemented back in late 1980s. Thus, the two main questions that this study was supposed to provide insight were:

1) is it possible to cancel the negative effect of HVDC on damping on five separate torsional frequencies within range of 5-20 Hz and what that requires from SSDC
2) is the new 800 MW scheme capable to compensate the negative effect of existing scheme in case the design target of positive total subsynchronous damping cannot be reached with the present structure of Fenno-Skan SSDC

This document addresses these aspects in chapters 4.1 and 5.

2.2.2 SSO protection scheme

Due to the ultimate risk related to undamped or sustained high amplitude subsynchronous oscillations, implementation of SSO protection scheme can be considered justified, if effect of HVDC, or any network component, may significantly affect subsynchronous damping of torsional oscillations under any possible network operating condition.

In Finland the SSO protection scheme was originally installed as part of Fenno-Skan control and protection system. The SSO protection is based on subsynchronous variations in period time of converter AC side 400 kV voltage and it has been set to indicate an alarm or to trip the pole in case the subsynchronous variation in period time i.e. in locally measured frequency exceeds preset levels.

Although SSO protection scheme has not tripped the scheme during 20 years of operation of Fenno-Skan, it has indicated several SSO alarms throughout the years. After analysis of available disturbance recordings related to certain SSO alarm related incidents, no reason whatsoever for SSO alarms has been determined. As illustrated in chapter 4.2, this may possibly be explained by the nature of sub- and supersynchronous components induced by subsynchronous torsional oscillations.

Due to uncertainties related to SSO protection scheme of Fenno-Skan HVDC and the detected effect of sudden disconnection of HVDC on amplitude of torsional oscillations [3], there was a special need to analyze the fundamentals of the applied SSO protection scheme. Thus, in the main scope of the planning study was to analyze the implementation of HVDC related SSO protection scheme considering especially following questions:

1) how does the strength of parallel AC system affect the selectivity of SSO protection scheme based on subsynchronous components in system frequency
2) do different HVDC systems (rating, primary and SSDC controls, monopole operation) affect on selectivity as they define the effect of HVDC on subsynchronous damping
3) can well-defined alarm/trip levels be found for two torsional frequencies, that have modal frequencies 1 Hz apart and are oscillation modes of two different units with different ratings

In this document these three items are addressed in chapters 4.2 and 5.

3 THE TOOL, TECHNIQUE AND MODELS APPLIED IN THE STUDY

Due to the screening study nature of the analysis and the fact that the manufacturer of the new Fenno-Skan 2 HVDC was unknown at the time the analysis was performed, the analysis was conducted as a sensitivity study. That approach was further justified by the fact that only design values of the subsynchronous torsional oscillation frequencies of the new 1980 MVA generating unit were available during the studies. Furthermore, the possible effect of uprate of 950 MVA units on their torsional frequencies was not known.

The sensitivity analysis was carried out using PSCAD electromagnetic transient analysis software, which allows detailed modeling of HVDC controls and synchronization. The high computational burden required by sensitivity analysis was effectively reduced by applying spectral injection based time domain SSO frequency scanning technique [4]. The applied technique allows subsynchronous damping seen by the studied generator unit to be determined for approximately 20 different subsynchronous frequencies during one single run. By recording also voltage waveforms at the converter terminals, the effect of HVDC related parameters on level of subsynchronous variations in voltage magnitude and angle, and thus also in local frequency, could be analyzed simultaneously with subsynchronous damping.

In this study torsional frequency range from 5 to 25.25 Hz with resolution of 0.25 Hz was covered in two runs using the spectral injection. The injected spectrum was added to generator speed reference to initiate sub- and supersynchronous frequency components at generator terminals. [4] The spectrum consisted of 41 frequency components 0.5 Hz apart from each other. Amplitude of single component was chosen so, that the amplitude of detected subsynchronous frequency variation in locally measured frequency was of same order with those measured in Finnish 400 kV transmission network [3].

To analyze the effect of different HVDC control structures on HVDC SSDC and SSO protection performance, a variety of HVDC control approaches and SSDC structures were applied at the preliminary stage of the analysis [4]. For final studies presented in this document, simple AC-DC network model presented on the left hand side of figure 1 was applied. The basic structure of the implemented SSDC controls is shown on the right hand side of figure 1.

To obtain some insight to the factors that define the way different primary and SSDC controls as well as synchronization affect subsynchronous damping, two different HVDC controls and synchronization implementations were chosen for the final studies. To further illustrate the possible limitations and boundary conditions related to different HVDC control structures, in implementation of SSDC for 600 MW pole only 2nd order band-pass filters were applied whereas for SSDC of 800 MW pole only 4th order filters were applied. The level of total gain of the SSDC circuit was tuned to be of same order.

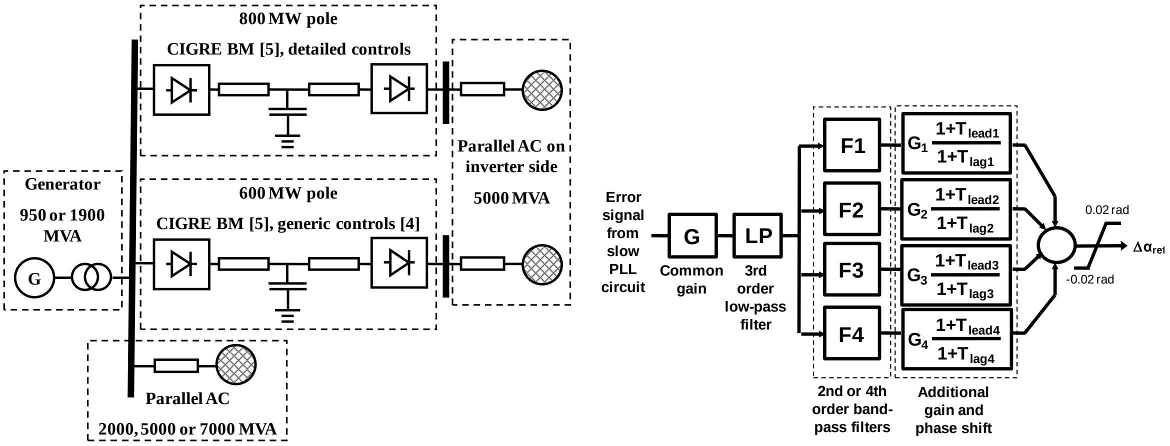

Figure 1 General structure of AC-DC-transmission model applied in the study (on the left) and general structure of the studied SSDC (on the right)

4 THE MAIN RESULTS OF THE ANALYSIS

4.1 SSDC design

The main conclusion of the study related to SSDC structure was, that in studied case SSDC may be applied to improve the effect of HVDC on subsynchronous damping significantly on the studied five torsional frequencies. This is illustrated in figure 2, where the effect of HVDC on subsynchronous damping seen by generator G3 is illustrated in case the short circuit capacity of parallel AC network is 2000 MVA. As shown in figure 2, in case of the studied system structure, design target was obtained although one 2nd order band-pass filter had to be replace by 4th order filter to reach the required positive damping contribution in case of 600 MW pole.

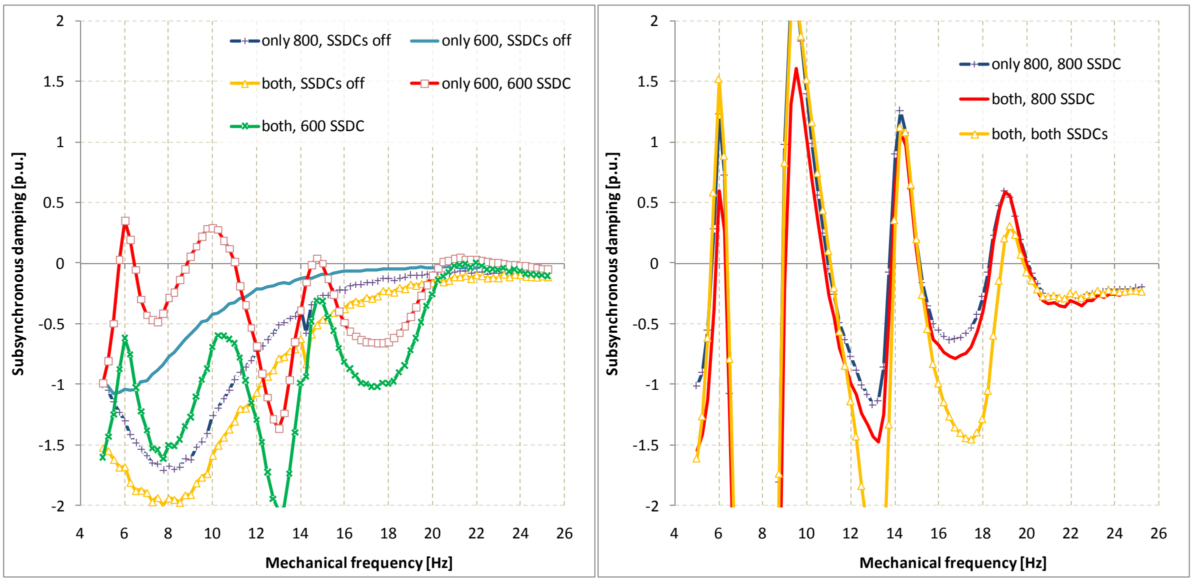

Figure 2 Subsynchronous damping seen by G3 with different combinations of active HVDC poles and controls

Based on the study, high order bandpass filters may be required to improve the damping in case several torsional frequencies are within range of 5-20 Hz. Higher order filters narrows down the range of improved damping that single SSDC "leg" provides, which provides better damping effect and some flexibility in design but makes the SSDC significantly more sensitive to inaccuracies in values applied for torsional frequencies in the design process.

Based on figure 2 it is also obvious that HVDC SSDC can be applied to improve the effect of parallel or nearby HVDC on subsynchronous damping, but the capability of HVDC to improve damping seems to be greatly dependent on the structure of HVDC and thus must be studied case by case. Nevertheless, such approach could prevent the operation with the pole not having SSDC controls.

4.2 HVDC based SSO protection

4.2.1 Effect of strength of parallel AC network on selectivity of SSO protection

The effect of strength of parallel AC network on selectivity of SSO protection is illustrated in figure 3, which presents the amplitude of subsynchronous variation in local frequency measurement as a result of modulation of the speed of generator G1 (on the left hand side) and generator G3 (right) using subsynchronous signal with peak-to peak amplitude of 8 mHz. Amplitude of subsynchronous variation in local frequency is shown as a function of the frequency of speed modulation and subsynchronous variation is shown for three different levels of strength of parallel AC network.

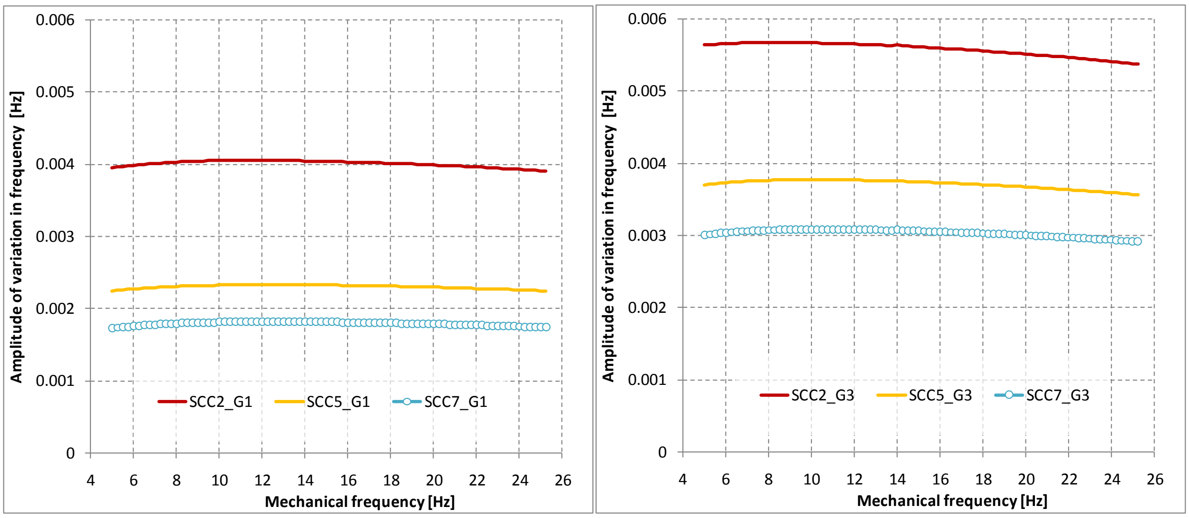

Figure 3 Amplitude of subsynchronous variation in locally measured frequency as the speed of generator G1 (on the left hand side) and generator G3 (right) is modulated using subsynchronous signal with amplitude of 8 mHz.

Based on figure 3 it is evident, that the selectivity of the SSO protection based on locally measured frequency cannot be guaranteed, if the SSO protection is required to operate reliably over range of network switching conditions or over range of different short circuit capacities of parallel network.

4.2.2 Effect of HVDC and its controls on selectivity of SSO protection

Whereas the effect of parallel network on selectivity was basically known before the studies, the effect of HVDC on level of sub- and supersynchronous voltages, and thus also on local frequency measurement was not that obvious. It's a well known fact that as result of frequency modulation characteristics inherent for switched devices in general, also HVDC injects sub- and supersynchronous currents to AC system if its terminal voltage contains sub- or supersynchronous components or both. The effect of injected current components, and HVDC controls in general, on frequency measured at the 400 kV side of converter transformer is illustrated in figure 4 in similar manner as in figure 3.

Figure 4 presents well the effect of HVDC, its controls and especially bandpass filtering based SSDC on the amplitude of subsynchronous components in local frequency measurement. Although the effect of HVDC on subsynchronous variation in frequency appears significant, at the subsynchronous frequencies of interest the effect of HVDC and its controls on amplitude of subsynchronous variations remains moderate. The range within which amplitude of subsynchronous variations alter in figure 4 is summarized in table 3 for the studied subsynchronous frequencies (see table 1). As shown in table 3, around the frequencies on which the SSDC is supposed to improve damping, the effect of HVDC controls, or HVDC in general, is significantly smaller as compared to what the figure 4 indicates. Actually, it seems that the more identical the structure of primary controls and SSDCs of the two poles were, the less the HVDC would affect on amplitude of subsynchronous variation in measured frequency.

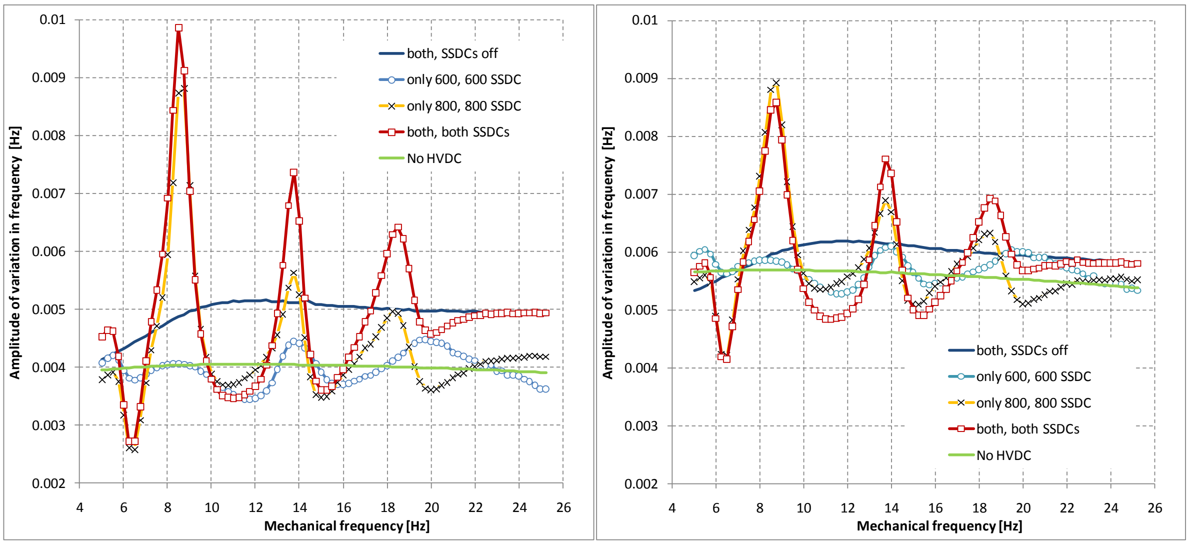

Figure 4 The effect of HVDC and SSDC controls in special on subsynchronous variation in locally measured frequency; G1 on the left hand side, G3 on right hand side, SCC of parallel network is 2000 MVA

Table 3 Range of subsynchronous variation in frequency measurement due to torsional oscillations

		Range of subsynchornous variation in frequency measurement [mHz] due to subsynchronous oscillation of generator speed with amplitude of 8 mHz (peak)				
		G1/G2		G3		
		9.5	19.5	6.0	10.5	14.5
SCC of parallel AC network	SCC2	3.9 - 4.6	3.8 - 4.8	4.8 - 5.8	5.0 - 5.5	5.5 - 5.7
	SCC5	2.2 - 2.8	2.2 - 2.5	3.4 - 3.7	3.5 - 3.8	3.7 - 3.8

5 CONCLUSIONS AND DISCUSSION

Feasibility of different SSO countermeasures depends obviously on several factors related to the structure of HVDC systems, turbine-generators and the surrounding AC network. In following a short summary regarding the feasibility of HVDC related SSO countermeasures is presented with respect the studied. Also, management of the risk related to HVDC SSTI is generally discussed.

The results of analysis indicated that the studied SSDC structures may be adequate measure to manage the inherent negative effect of HVDC on subsynchronous damping of the studied units despite the high number of torsional frequencies within range from 5 to 20 Hz. Based on the study results the main reason for this was the fact, that the five torsional frequencies were located within the range of 5-20 Hz approximately 4 Hz steps apart from each other. This allowed the parameters of the SSDC bandpass filters to be chosen so, that filters designed to improve damping on certain torsional frequency did not have significant adverse effect on damping of other frequencies that required compensation.

In case the torsional frequencies would have been located within the frequency range of 5-20 Hz differently, the SSDC approaches studied here may not have been feasible. Alternative options to improve the effect of HVDC on subsynchronous damping could have been e.g. application of wide-band SSDCs instead of narrow band SSDCs. In this case, however, the studied wide band approaches were not able to improve damping enough at the lower end of the studied frequency range.

Regarding SSDC design it's worth emphasizing that in this document rather straightforward approaches were applied in SSDC design and the performance of the HVDC controls were not analyzed as whole. It seems reasonable to conclude that the manufacturers of HVDC systems are likely to possess more sophisticated approaches in SSDC design allowing more degrees of freedom in design of SSDC circuits and the results of this study shall be applied only for illustrative purposes.

The HVDC related SSO protection based on local frequency measurement proved to be inadequate solution as last line of SSO protection for the studied case. The main reason why the selectivity of the studied SSO protection scheme cannot be considered adequate in this specific case was the relatively large range of system switching conditions under which the HVDC can significantly affect subsynchronous damping (see table 2). Additionally, due to bipolar structure the settings of the protection scheme should be chosen very carefully and likely in very conservative manner, what would eventually increase the risk of unselective operation of the protection scheme. This is obviously due to fact that disconnection of single pole likely causes sudden and rather significant increase in level of torsional oscillations, which could exceed the tripping level of SSO protection of parallel HVDC system or even the fatigue limit of the turbine-generator shaft.

Finally, the different HVDC system and especially SSDC control structures could cause additional uncertainty in the selectivity of the SSO protection. Therefore, in this case it was easy to recommend that the SSO protection scheme should be implemented as a part of the torsional monitoring system. Regarding the studied case this approach is in practice the only approach using which the last line of protection can be implemented so that the settings of protection scheme can be determined in unambiguous manner.

Although inadequate for this specific case, SSO protection based on locally measured frequency could be adequate solution if risk of HVDC SSTI is limited to certain single operating or switching condition and there is only single HVDC system contributing on HVDC SSTI. Additionally, the trip level set for SSO protection should be well-defined with respect to the fatigue limit of turbine-generator shaft.

Planning and design of SSO countermeasures especially in case of HVDC SSTI involves a large number of factors, which may have significant effect on the SSTI risk. Unfortunately, the fundamental problem with many of those factors is that they may be extremely difficult to verify by means of field testing in extensive manner or even in extent that the real risk presented by SSTI could be evaluated in reasonable manner. Therefore, disturbance recording systems capable to capture the attenuation of torsional oscillations of turbine-generator and the operation of HVDC SSDC should be implemented as part of control and monitoring systems in each case where SSO countermeasures are implemented.

Based on disturbance recording data gathered over years the information required for evaluation of true HVDC SSTI risk may be assessed. Based on the assessment the SSO countermeasures can then be re-coordinated by e.g. reconfiguring the SSDC to improve damping on those frequencies that in practice really require improved damping. Based on measurement data even deactivating the SSO protection schemes could be considered, if the inherent mechanical damping of torsional modes of turbine-generator appears to be adequate to cancel the adverse effect of HVDC on subsynchronous damping.

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