

Application of Linear Analysis for Stability Improvements in the Nordic Power Transmission System

Kjetil Uhlen, Stefan Elenius, Ian Norheim, Jussi Jyrinsalo, Jarmo Elovaara, Erkki Lakervi

Abstract –This paper presents research work on stability assessment and stabilizer design that has been carried out for the Finnish transmission system operator, Fingrid. The aim of the work has been to assess observability and controllability of low frequency inter-area modes in the Finnish transmission grid, and to design stabilizing controls to improve damping of critical modes.

Challenges in system modeling are described, and main results from linear analyses are presented and compared with non-linear dynamic simulations. The results are seen to correspond well with real system observations.

Modal analysis and non-linear simulations are applied to verify design of power system stabilizers of some important generators in Finland. Similar methods are also used for retuning and verification of stabilizers on the Fennoskan HVDC link between Sweden and Finland. The stabilizer performance is demonstrated in terms of stability improvements.

A main conclusion is that linear techniques can be of great benefit when designing damping controllers for large power systems. It is also illustrated, with the use of validated models, how linear tools can be used in operation planning for determination of power transfer limits.

Index terms – Nordic transmission grids, stability assessment, modal analysis, dynamic simulation, power system stabilizer design, HVDC, power oscillation control, power transfer limits.

I. INTRODUCTION

Linear analysis techniques have been introduced as a tool for stability assessments of the Nordic transmission grid, and have been applied as a supplement to existing dynamic power system simulators in analysis and design of power system controls [1], [2]. This paper presents research work carried out for the Finnish transmission system operator, Fingrid. The aim of the work has been to assess observability and controllability of low frequency inter-area modes in the Finnish transmission grid as a part of the larger Nordel system, and to find candidate generators for stabilizer retuning.

A main objective has been to assess the potential for stability improvements by redesigning and/or retuning of damping controls for HVDC links.

Power system stabilizer design of some important generators in Finland, which has previously been done by frequency and time domain techniques, is verified by modal analysis. Similar methods are used for retuning and verification of stabilizers on the Fennoskan HVDC link between Sweden and Finland. The performance of the stabilizing controls in terms of stability improvements are demonstrated in the paper.

The paper is organised in four main sections. In Section II, the main objectives of the study are stated and a description of the models used and procedures for the analysis are given. Section III presents main results from the stability analysis and model validation. Challenges in system modeling are described, and the main results from modal analyses are presented and compared with non-linear dynamic simulations. In Section IV, the work on stabilizer design is described, and the main results and potential benefits from the work are presented and discussed in Section V.

II. APPROACH

A. Objectives

The main objectives, in the context of this paper, can be summarized as follows:

- To present the work on stability assessment and stabilizer design that has been carried out in collaboration with Fingrid.
- To show main results and experiences from the work, illustrating how linear analysis techniques have been introduced and applied.
- To show how results from linear analysis compares with corresponding results obtained from analysis based on non-linear dynamic simulations.
- To illustrate how the results can potentially be used to improve utilization of the transmission grid, and finally to illustrate how linear analysis can be applied for operation planning purposes, in determination of power transfer limits.

B. System modeling

Throughout this work the analysis and design have been based on the fully complete dynamic simulation model of the interconnected Nordic power transmission system. This is a model that has been developed over the last two decades, and is presently owned and maintained by the Nordic TSOs. The model is implemented in the power system simulator PSS/E [3] and it is used for transmission and operation planning purposes. More information about the Nordic power system can be obtained from [4].

Two load flow configurations have been studied. The first case represents a high load situation, with limited power exchange between the countries. The second case is a light load condition, but this is characterized by a higher exchange of power. The two cases are denoted *winter load* and *summer load*, respectively. Additional key data for the model and the two cases are provided in the Appendix.

C. Procedure for analysis and limitations

The analysis based on non-linear dynamic simulations is performed with PSS/E. The linear analysis is performed with the computer program PacDyn [5]. This program has the capability of reading PSS/E-formatted model data [2]. A goal has been that the linear analysis and the non-linear simulations shall apply the same model data and basically the same model implementations. For practical reasons some adaptations and modifications of the original model data have been necessary in order to run and perform the linear analysis. This is further commented in Section III.

The basic procedure for the analysis and design carried out can be summarized as follows:

- Overall stability assessments are performed by linear analysis. This is found to be an efficient and practical approach in order to identify the main dynamic characteristics and stability problems.
- The main findings are compared and verified through non-linear simulations.
- Identification of best locations for stabilizer retuning and design of control structures are performed by linear analysis.
- Final design and tuning of controllers involve modal analysis, frequency response computations and verification through non-linear simulations.

III. STABILITY ASSESSMENTS

A. General

This section presents the main results of the stability assessment. The following studies are presented:

- Eigenvalue computation
- Mode shape computation
- Computation of transfer function residues
- Model validation

B. Eigenvalue computation

Eigenvalues were computed using the *Rayleigh Quotient Iteration method* [6]. The procedure was mainly focused on

searching for electro-mechanical system modes in the frequency range from 2 rad/s to 8 rad/s (0.3-1.3 Hz).

Table I lists some of the low damped system modes that were identified from the winter case. A large number of additional eigenvalues were found in the frequency range above 0.8 Hz. These represent mainly local modes. All four modes listed in Table I have been observed in the real network at different times and locations. Such observations, normally in the form of power oscillations following disturbances, contribute to give confidence to the model and the analysis.

TABLE I
Identified low damped modes and their observability

Mode #	Eigenvalue λ	Damping (%)	Freq. (Hz)	Observability
1	-0.0204+ j2.0552	0.99	0.33	Inter-area mode. Most observable in Finland.
2	-0.1530+ j3.0234	5.05	0.48	Inter-area mode. Most observable in Southern Norway.
3	-0.2082+ j3.8121	5.45	0.61	Inter-area mode. Most observable in Northern Norway and Eastern Denmark.
4	-0.2269+ j4.8670	4.66	0.77	Local area mode. Observable in Western Norway.

The complex eigenvalues associated with system modes contain information about frequency and damping of the modes. The term *damping* is here defined from the eigenvalue, λ , such that

$$damping = -\text{Re}(\lambda) / |\lambda| \cdot 100\%$$

A reasonable criterion for required damping of inter-area modes is 3-5%. In this case the damping of the 0.3 Hz mode (mode #1) is only 1%. Thus, exploiting the potential for damping improvements is a main motivation for this work.

C. Mode shapes

The mode shape analysis requires the computation of eigenvectors in addition to the eigenvalues. The eigenvectors are computed from the *Rayleigh Quotient iteration*, and are readily available when the corresponding eigenvalues are found. The mode shape computations have been done with respect to generator speed and generator terminal power.

Fig. 1 depicts the result of the mode shape computation for the 0.33 Hz inter-area mode with respect to generator speed for the summer load case. The overall picture is that the majority of generators in Finland oscillate in phase against the rest of the Nordic system. This mode is most observable in Finland.

Observability information for the different modes is also summarized in Table I. The mode shape computation for the

0.48 Hz mode with respect to generator speed has shown that the generators in Southern Norway (and Finland) oscillate in phase against the rest of the system. The speed variations are most observable in Southern Norway.

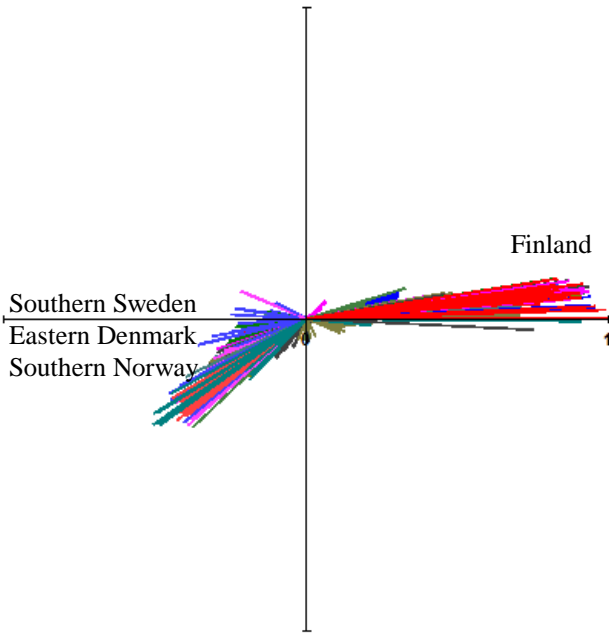


Fig. 1. Graphical illustration of Mode shapes with respect to generator speed for the 0.33 Hz inter-area mode.

From the mode shapes for the 0.61 Hz mode, the generators in Northern Norway are seen to oscillate in phase against the rest of the system and primarily against generators in Eastern Denmark.

The 0.77 Hz mode is a local area mode, mainly observable in Western Norway.

From the mode shapes for 0.33 Hz and 0.48 Hz with respect to generator electrical power for 0.33 Hz and 0.48 Hz, it is seen that the power oscillations are observable in most of the largest generators in Nordel.

D. Transfer function residues

The transfer function residues are also based on the calculations of eigenvectors and eigenvalues. In addition the input and output system matrices, B and C, of the linearized system model must be available.

The transfer function residues have been computed for transfer functions from generator voltage reference (V_{REF}) as input, to generator speed (ω) and generator terminal power (P_T) as outputs. A high residue for an inter-area mode generally indicates that the generator is a good candidate for power system stabilizer placement. In our study the analyses were carried out with the existing stabilizers in service. An interpretation of a high residue can thus also be that there is a potential for improved tuning of that PSS. On the other hand a low residue for a generator equipped with a PSS indicates that there is little potential for improvements. Table II summarizes the observations from the transfer function residue computations.

TABLE II

Summary from the transfer function residue computations (winter load)

Mode #	Damping (%)	Frequency (Hz)	Description:
1	0.99	0.33	Inter-area mode. The largest generators in Finland have the best controllability.
2	5.05	0.48	Inter-area mode. The largest generators in Sweden have the best controllability.
4	4.66	0.77	Local area mode. This mode has the highest controllability at the generators in western Norway.

E. Model validation

The original dynamic simulation model contains a high number of customized component models, including user-defined controllers. Some of these models had to be changed or modified in order to adapt the model for linear analysis. The effects of these changes have been verified by comparing analysis based on non-linear simulations with modal information for the 0.33 Hz oscillatory mode. There are several ways to obtain modal information from (non-linear) time domain simulations. *Prony* analysis [7] is one such method. In this work a similar approach based on a least squares method has been used. Results were obtained both with the complete original model, and with the modified version adapted for linear analysis (labeled “PacDyn changes”). The comparison was carried out using the *winter load* configuration of the system (with 1132 generators in operation). In Fig. 2 a graphical comparisons of the mode shapes for 12 representative generators out of 1119 are shown. Six of them are generators in Finland, four are large generators in Sweden, and two are Norwegian hydro generators.

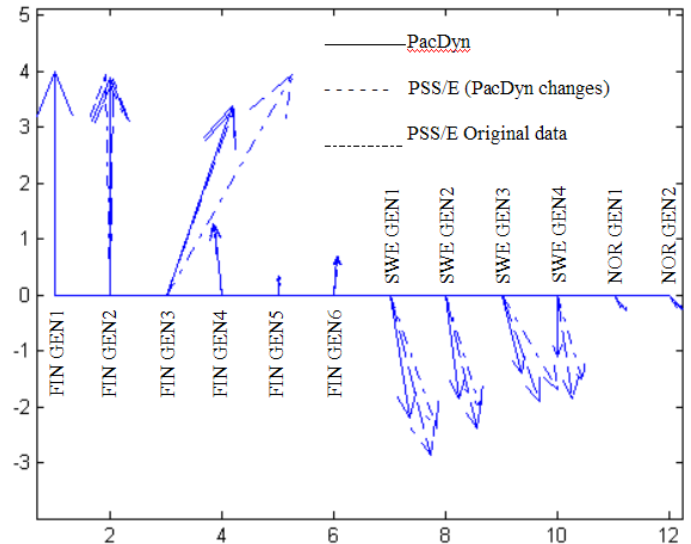


Fig. 2. Graphical comparison of the mode shapes for the 0.33 Hz power oscillations, derived from three different analyses. Two sets of data are used to obtain modal information from non-linear simulations (PSS/E) and one set of data is used for the linear analysis (PacDyn).

From the comparison of mode shapes, shown in Fig. 2, it is seen that despite the model changes the most important system characteristics of the original model are retained. Sec-

only, the linear analysis is seen to reproduce the modal information, and is thus able to provide precise and useful information about the power system dynamics.

IV. STABILIZER DESIGN

A. General

In this section the main results from stabilizer design on generators and HVDC are presented. Benefits in terms of stability improvements are illustrated. The stabilizer design has been illustrated with the summer load configuration. Because there are fewer generators on-line in the summer configuration, the frequencies of the inter-area oscillatory modes are slightly higher than in the winter load configuration presented in section III.

B. Retuning stabilizers on generators

A majority of the large generators in Finland are equipped with power system stabilizers that use active power as input signal. The results based on linear analysis presented in Section III were used as a starting point, in order to identify the potential for stability improvements, and to select the best candidate generators for stabilizer retuning. Frequency response computations of transfer functions from voltage regulator reference to the generators terminal power output were used as a basis for design and retuning of the individual stabilizers. Frequency responses have been obtained both from linear analysis and from non-linear simulations.

It is not the aim in this paper to present details about design and tuning of the individual stabilizers, but some main results of the work are presented in Section V.

C. Modeling and analysis of the Fennoskan HVDC

A relatively detailed HVDC model (CDCAB1) was used for representing the Fennoskan HVDC link in the non-linear simulations. In this model, the DC cable dynamics are well represented, and a fairly complete implementation of the converter controls relevant for system studies is included. The model has a built in power system stabilizer, but in this study we have used a separate stabilizer model that was provided by Fingrid as a basis. Fig. 3 illustrates main modeling features of the Fennoskan HVDC link.

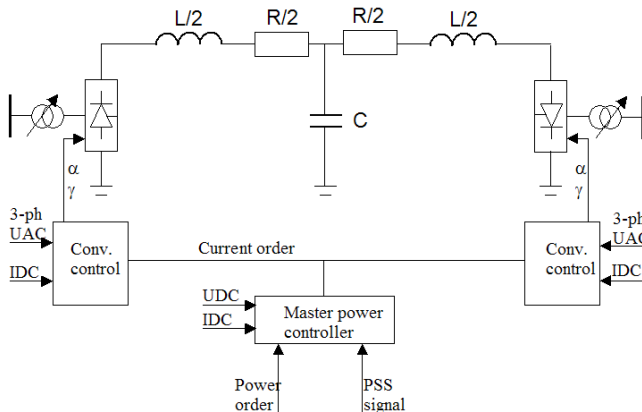


Fig. 3. Diagram showing the main modeling features of the Fennoskan HVDC link.

In the process of designing a stabilizer for the HVDC link, frequency responses of various transfer functions from DC power order to different outputs were computed. The results were used as a basis for selecting control structures and measurement signals. Figs. 4 and 5 show results of these computations where the frequency responses were obtained from non-linear simulations. The DC power order was modulated by a small sinusoidal signal where the frequency is varied from 0.1 to 100 rad/s. The frequency responses could then be obtained by computing relative amplitudes and phase angles between the input and the selected output signals. Fig. 4 shows the transfer function from DC power order to the difference in bus frequency between the converter AC buses in Finland and Sweden.

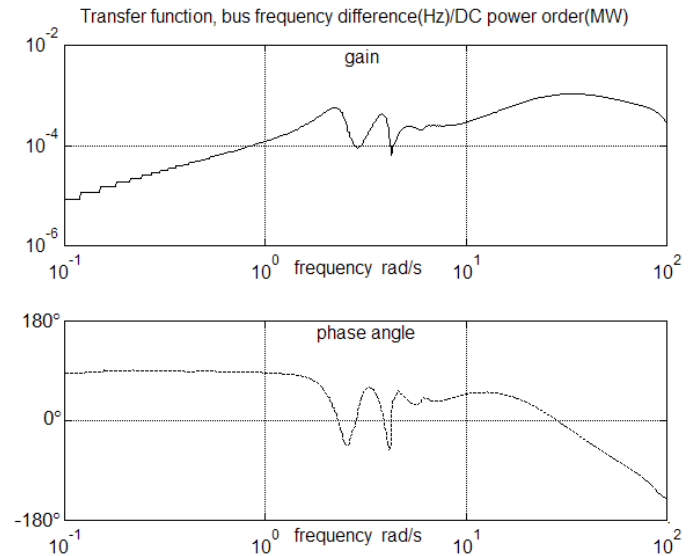


Fig. 4. Frequency response of the transfer function from DC power order (MW) to bus frequency difference Finland-Sweden (Hz) for the Fennoskan HVDC link.

Oscillatory modes at approximately 0.34 Hz, 0.57 Hz and 0.8 Hz can be seen in the response. The phase shift at the two main resonant frequencies is about zero degrees. Thus, the AC frequency difference seems to be a good measurement signal for a stabilizer. An observation of concern is a relatively high gain around 30 rad/s, which is in the turbine-generator torsional frequency range. (It should be noted that there is a separate SSTI/SSR damping control in the link). An alternative input is to measure the difference in AC bus voltage angle on both sides of the link. This can be implemented using Phasor Measurement Units (PMUs) and the already established communication link between the converters. The frequency response of the transfer function from the DC power order to the bus angle difference (Finland-Sweden) is shown in Fig. 5.

D. Linear analysis of the Fennoskan HVDC

For the linear analysis it is not possible, nor necessary, to include all the details of the converter controls in the model. In this study we have retained a dynamic model for the DC cable, but we have implemented a simpler current controller that acts on the converter firing angle. In the non-linear simulations the HVDC stabilizer acted on the power order with a

scaling in MW. In the linear model the stabilizer acts on the current order. Otherwise the models are similar. Fig. 6 shows the corresponding frequency response of the transfer function from the DC current order to the bus angle difference between the converter AC buses in Finland and Sweden obtained from the linear model.

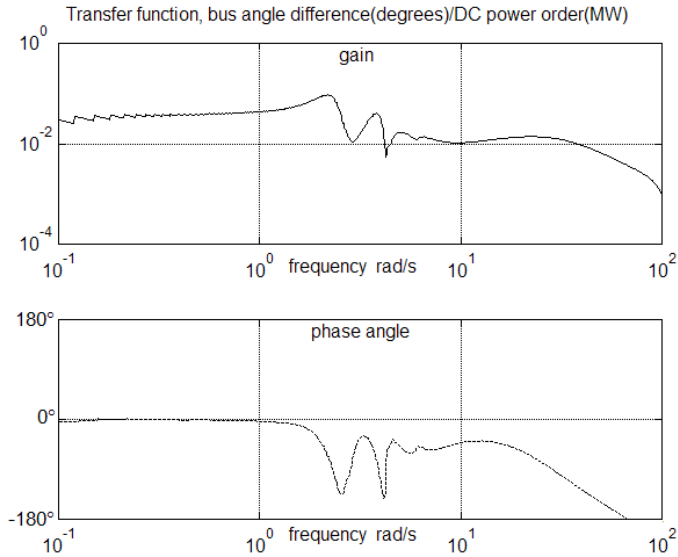


Fig. 5. Frequency response of the transfer function from DC power order (MW) to bus angle difference Finland-Sweden (degr.) for the Fennoskan HVDC link.

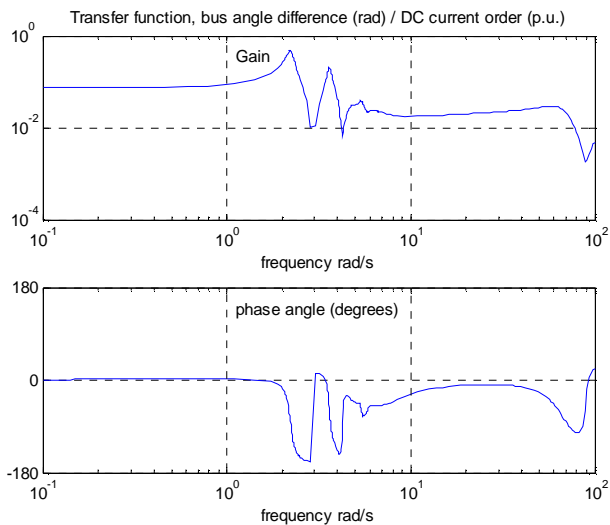


Fig. 6. Frequency response of the transfer function from DC current order (p.u.) to bus angle difference between Finland and Sweden (rad.) for the Fennoskan HVDC link obtained from linear analysis.

By comparing Fig. 5 and Fig. 6 we can conclude that the frequency responses generally agree. The frequency response obtained from the linear model (Fig. 6) has a little sharper resonance peaks, which can be explained by the fact that the oscillatory modes show lower damping in this model. The larger differences are in the frequency range above 10 rad/s. This is partly due to differences in cable modelling, and partly because we have included a low pass filter on the measure-

ment outputs in the non-linear simulations, while no filter was used in the linear analysis.

E. HVDC stabilizer

Based on the analysis and frequency responses presented above a stabilizer was designed with a control structure according to Fig. 7. The two first washout filters convert the bus angle measurements to signals that in the frequency range of the inter-area modes are proportional to bus frequency. The third and fourth washout filters avoid control actions from steady state and low frequency disturbances. The two low-pass filters reduce the gain at high frequencies. This stabilizer gives a phase angle compensation of 90° lead at the inter-area oscillation frequencies.

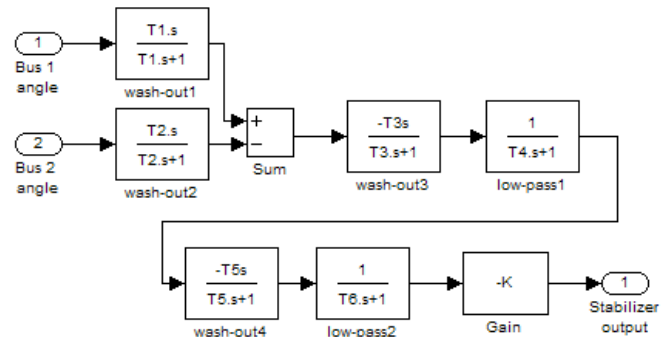


Fig. 7. Controller structure for the stabilizer implemented for linear analysis.

V. PERFORMANCE ASSESSMENTS

A. Potential improvements of retuning stabilizers on generators

Both linear analysis and non-linear simulation tools were used for verification purposes. The aim has been to assess system performance, and to show the impact of the retuned stabilizers in two important power plants in Finland on system stability. Eigenvalue computations are presented for damping assessment, and the results are supplemented with stability assessments based on non-linear simulations. Also in this case the “least squares” method was applied to identify damping of the inter-area modes from simulations.

The system performance was analyzed using the summer load configuration, at different levels of power exchange between Finland and Sweden on the AC interconnections. Figs. 8 and 9 show that the new stabilizers improve damping of the two main inter-area modes at 0.34 Hz and 0.57 Hz. The 0.64 Hz mode is not shown, but the adverse effect on this mode due to the new stabilizers is insignificant.

A main observation from these results is that the relative damping of the modes is equally improved whether the results are obtained from non-linear simulations or from eigenvalue computations. However, the eigenvalue computations indicate that the absolute damping of the 0.34 Hz mode is about 5 percentage points lower than when assessed by non-linear simulations and the “least squares” method. Correspondingly, for the 0.57 Hz mode, the linear analysis compute a damping

that is roughly 2 percentage points lower than obtained from non-linear simulations. A complete explanation of this mismatch has not been found. It is, however, recognized that the damping of inter-area modes is a response of the system inter-connection and interaction of hundreds of generators. Moreover, system damping is sensitive to load representation and line impedances. It is therefore not unlikely that very small differences in model implementations in the tools applied for this study can create such differences, although the same model parameters are used in the two programs.

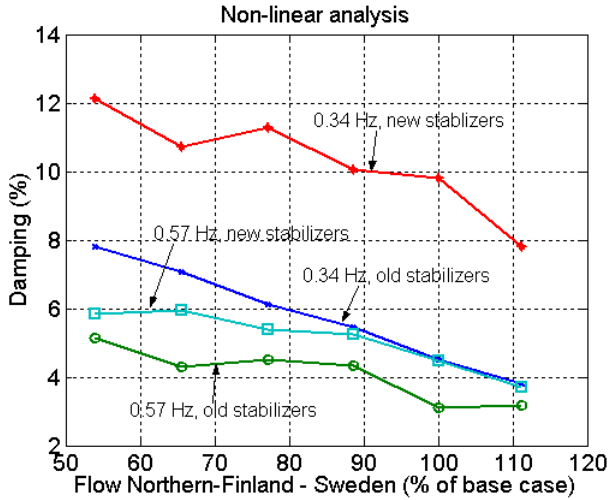


Fig. 8. Curves showing the effect of retuning stabilizers in two large power plants in Finland. Damping of the two main inter-area modes is plotted as function of power flow in the corridor between Northern-Finland and Sweden. All results are based on non-linear simulations and the "least squares" method.

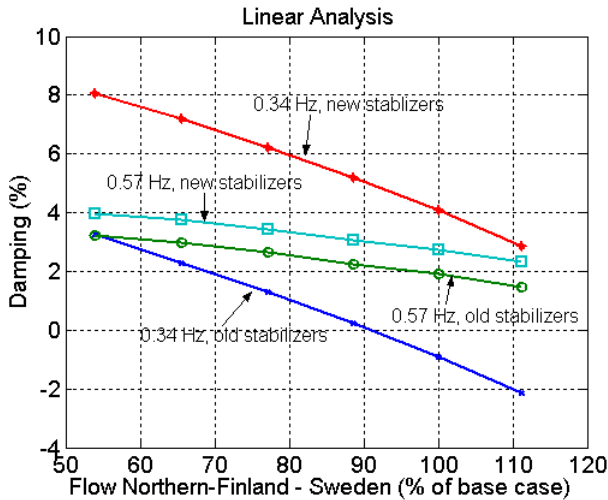


Fig. 9. Curves showing the effect of retuning stabilizers in two large power plants in Finland. Damping of the two main inter-area modes is plotted as function of power flow in the corridor between Northern-Finland and Sweden. All results are based on linear analysis (eigenvalue computations).

A way of assessing the benefit of the new stabilizers is to look at how improved damping can influence the determination of power transfer limits on important transmission corridors. The following examples illustrate how such assessments

can be done. The examples are included for illustration, only. It is recognized that other factors, such as voltage stability or thermal limits after certain contingencies can be equally important when operating power transfer limits are determined:

It is first assumed that the applied security criterion requires 3 % damping of the main inter-area modes at 0.34 Hz and 0.57 Hz, and that the assessments are to be based on linear analysis. Then, by performing eigenvalue assessments for the most critical post-contingency cases at different power transfer levels, as illustrated in Fig. 9, the operating limit can be determined. In the case of Fig. 9 it is seen that the new stabilizers can raise the transmission limit from approximately 60 % to more than 90 % of the base case corridor flow.

B. The new stabilizer on the Fennoskan HVDC link

To illustrate the effect of the designed stabilizer on the Fennoskan link, the root curves for the inter-area modes with respect to the stabilizer gain K is shown in Figure 10. The analysis is carried out using the base case summer load configuration.

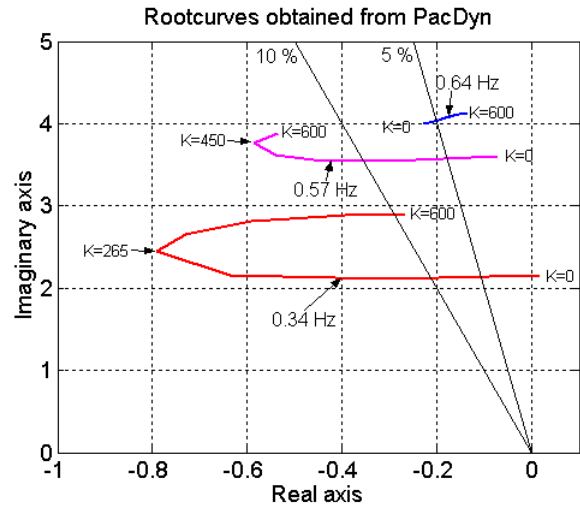


Fig. 10. Root curves dependent of the gain K in the stabilizer loop applied on the Fennoskan HVDC link. The curves are for the 0.34 Hz, 0.57 Hz and 0.64 Hz modes in the Nordic system.

Calculations show that if $K=100$, the damping of all the modes in Figure 10 is better than 5 %. If K is increased to 265 the damping of the 0.64 Hz mode decreases to 4.34 %, while the damping of the 0.34 Hz mode and 0.57 Hz mode increases. However, it is important to be aware of that a high gain may destabilize oscillatory modes in the frequency range where the most critical turbine-generator torsional modes are expected to be found. Thus, the maximum gain with this stabilizer is limited by the gain margin needed to avoid sub-synchronous resonance and possible adverse interaction with the normal power control of the link. A satisfactory compromise is found to be gain $K=30$.

Fig. 11 shows the impact on system stability of the Fennoskan stabilizer with this gain, obtained from linear analysis. Applying the 3 % damping criterion, the transfer limit on the corridor between Northern-Finland to Sweden can be raised from approximately 60 % to 85 % of the base case corridor flow.

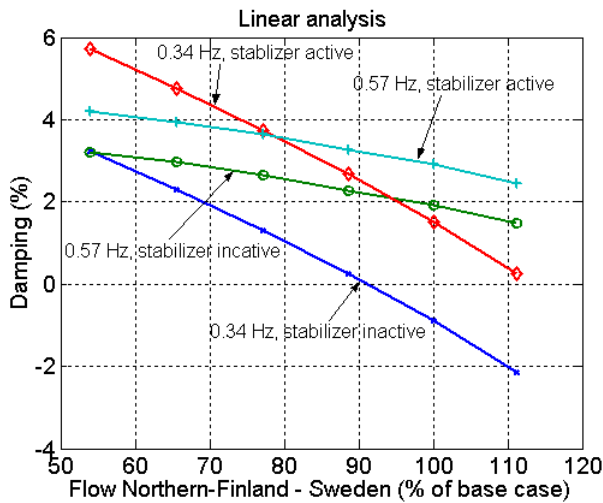


Fig. 11. Curves showing the impact of the HVDC stabilizer on system damping at different power flows in the corridor between Northern-Finland and Sweden. All results are obtained from linear analysis.

VI. CONCLUSION

Main objectives of the work described in this paper have been to assess observability and controllability of low frequency inter-area modes in the Finnish transmission grid, and to find candidate generators for stabilizer retuning. The paper also describes modeling, design and tuning of damping controllers for the FennoScan HVDC link between Sweden and Finland.

The application of linear analysis is demonstrated, and the main results from modal analyses are presented and compared with non-linear dynamic simulations. The findings are seen to correspond well with real system observations.

A main conclusion of the work is that linear techniques can be of great benefit when designing damping controllers for large power systems. It is also illustrated, with the use of validated models, how linear tools can be used in operation planning for determination of power transfer limits.

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VII. APPENDIX

Table III provides some key data describing the size of the model and the base case load flow scenarios that are used in the study.

TABLE III
Base case and model data

	Winter load	Summer load
No. of (on-line) generators modelled:	1119	784
No. of AC buses:	4780	4780
No. of AC branches:	5730	5730
No. of state variables (linear model):	11798	8146
Dimension of Jacobian matrix	66124	50048
<i>Finland:</i>		
Total generation:	11369 MW	7889 MW
Total load:	12211 MW	7267 MW
Power exchange:		
- To Sweden (AC-lines)	338 MW	1176 MW
- To Sweden (DC-link)	-150 MW	550 MW
- From Russia	1283 MW	1310 MW
<i>Sweden:</i>		
Total generation:	26818 MW	15368 MW
Total load:	25559 MW	14980 MW
<i>Norway:</i>		
Total generation:	20922 MW	13591 MW
Total load:	20776 MW	12662 MW
<i>Eastern Denmark:</i>		
Total generation:	2965 MW	2124 MW
Total load:	2901 MW	2031 MW

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Jarmo Elovaara was born in 1945. He received the M. Sc. degree in electrical engineering from Helsinki University of Technology (HUT) in 1969, and is presently a leading transmission specialist and R&D co-ordinator of the Finnish transmission grid owner and independent system operator Fingrid Oyj. Mr. Elovaara is the Chairman of the Finnish National Committee of CIGRE.

Erkki Lakervi (SM 1985) received his MSc from Helsinki University of Technology in 1969 and Doctor of Technology from Tampere University of Technology in 1984. Currently he is working part-time as Professor in Power Systems at Helsinki University of Technology, and running his own company Evaluation Workshop in Tampere.

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