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APPLICATION OF SMALL SIGNAL STABILITY ANALYSIS TO THE NORDEL POWER SYSTEM

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SUMMARY

This paper deals with transmission system operation and stability control in a deregulated environment. The main objective of the paper is to illustrate how proper tuning of damping controllers can contribute to raising transmission capacities, and thereby reduce operating costs. An example from a main transmission corridor in the Nordel power system is used to illustrate how congestion costs depend on the applied transfer limit. A small signal stability analysis is carried out on a full Nordel transmission system model. Main stability problems are identified, and it is shown that existing SVC units in Norway can be utilized to improve damping of main inter-area modes. It is concluded that power transfers on critical corridors may be increased by improved stability control.

Keywords: Small signal stability, Transmission system operation, Power transfer limits, Congestion cost, Power oscillation damper design.

1. INTRODUCTION

The Nordel power system comprises the interconnected power systems of Norway, Sweden, Finland and parts of Denmark. Several factors and trends motivate a thorough assessment of the stability properties of the system. These factors include deregulation and a steady load increase, which demand for higher utilization of the power generation and transmission system. Several new HVDC links are planned, including three links between southern Norway and the UCPTE system (Germany and The Netherlands). It is of particular interest to study the effects of these links on stability and operation of the Norwegian power system, and also how HVDC converters or other new technologies (like FACTS) can be utilized and controlled for stability improvements.

As a starting point, this paper focuses on modeling aspects and initial results from stability analyses. Small signal stability analysis is introduced in order to assess potential stability problems and to investigate design of damping controllers. The main objective of the paper is to illustrate how proper tuning of damping controllers on SVC units (often referred to as power oscillation dampers or PODs) can contribute to raising transmission capacities, and thereby reduce operating costs.

The paper is organized as follows. Section 2 describes main challenges for transmission system operators from a stability control point of view. The potential benefits that can be gained by improved stability control are discussed in section 3, which gives an example on congestion costs related to a particular transmission corridor in the Nordic power system. Section 4 deals with system modeling and results from initial stability assessments. Further results are presented in section 5, focusing on controller design and tuning of PODs for existing SVC units in Norway.

2. POWER SYSTEM OPERATION

Fig. A1 at the end of the paper provides an overview of the electric power system in the Nordic countries. The energy production capacities in each country are shown together with the main transmission connections between the countries and the interconnections to systems outside Nordel. The Norwegian power system is characterized by distributed power generation and long transmission distances to load centers. The deregulation of the electricity markets and the distributed nature of generation create large variations

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• SINTEF Energy Research, N-7465 Trondheim, Norway in daily load flow patterns, and thus the system operator has great challenges related to both planning and operation of the system.

A main challenge in system operation, which is the topic of this study, is related to the possibility of increasing transfer capacity. This is very much related to congestion management and handling of bottlenecks for efficient and secure operation [1]. One of the main tasks in daily operation planning is the determination of *power transfer corridor (PTC) limits*. A PTC is defined as a set of circuits (transmission lines or transformers) separating two portions of the power system (closed interface), or a subset of circuits exposed to a substantial portion of the transmission exchange between two parts of the system (open interface). In this context, the power flow on a PTC represents the net power flow from a sending end area to a receiving end area. At present, Statnett SF (the Norwegian transmission system operator) applies the deterministic (N-1) criterion as the main operational security criterion. The (N-1) is a simple, technical criterion which states that the system should be designed and operated in such a way that it is able to withstand any single contingency, e.g. outage of a line or generator, without resulting in unacceptable consequences. For some PTCs a relaxed, weather dependent version of the (N-1) criterion is applied.

The determination of PTC limits is an established part of the operating procedures at Statnett's National Control Center, and the limits are generally determined from three different criteria:

- Thermal capacity limits (the steady state N-1 limit)
- Voltage constrained limits (stability or steady state)
- Angle stability limit (transient or power oscillations)

In reality, these limits are functions of the state of the system (i.e. the load flow and network topology). Based on some loading criteria, the various limits may be as illustrated in Fig. 1.

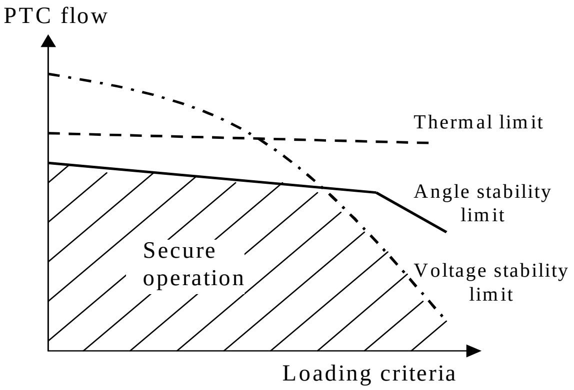

Figure 1 - PTC limits

A typical situation is that the thermal capacity limit is fairly constant (when the network topology is unchanged), while the voltage stability limit is strongly dependent on system loading and reactive reserves. The angle stability limits may take different forms, but a loading limit will always exist. In Fig. 1 the operating limits will be determined by the voltage and angle stability constraints. A fundamental problem concerning stability limits is that they are generally difficult to determine with sufficient accuracy and reliability. This implies that limits are often set conservatively.

On this background, the main motivation for this study can be expressed in the two goals below:

- The transfer limits could be raised if better and more reliable tools were available in order to determine the stability limits more accurately.
- The transfer limits could be increased towards the thermal capacity limit if automatic control systems were available to increase the stability limits beyond the thermal limit (within some operating range).

3. BENEFITS FROM IMPROVED CONTROL

The main benefits that can be gained from the use of dynamic security assessment tools and improved stability control can be summarized as follows:

Benefits related to transmission operation:

- Higher utilization and increased transfer capacity can be achieved through improved stability and load flow control. The benefit is related to reduced congestion costs and in sum higher profit for the actors on the energy market.
- Improved security and less uncertainty with respect to operating limits and consequences of critical outages. The benefit is lower interruption costs.

Benefits related to transmission planning:

- Higher utilization of existing grids requires less network reinforcements. The long-term benefit is lower investments.

In practice, it is difficult to give exact numbers on either of these benefits. The approach that is chosen in this study, has been to focus on congestion costs based on available data from Statnett's National Control Center. Our aim is to show that there is a potential for reducing congestion costs by increasing present transfer limits. The final questions are then:

- Is it technically possible to raise existing transfer limits by improved control?
- And is the potential cost reduction sufficient to cover the cost of developing and installing the necessary control systems?

The work presented in this paper attempts to indicate some answers to the first question. Whether the proposed solutions in the end will be cost-effective, depend on several factors that need further assessment.

The present study focuses on the "Hasle" corridor, which is a frequent bottleneck for power transfer between Southern Norway and Sweden. Throughout 1999 the main problem was power exports to Sweden. Based on data from the National Control Center, for the period from January to September 1999, the accumulated socio-economic cost resulting from the congestions was found to be approximately NOK 27 millions. This includes power export, only, and at times where the network was intact (meaning that no revisions or maintenance were on-going, which might influence the transfer limits).

The congestion cost and the corresponding average transfer limit on the corridor are indicated in Fig. 2. Based on a simple assumption [2] of linear dependence between area price differences and amount of congestion (in MW), the curve of Fig. 2 shows the expected congestion cost as a function of the applied transfer limit for this PTC.

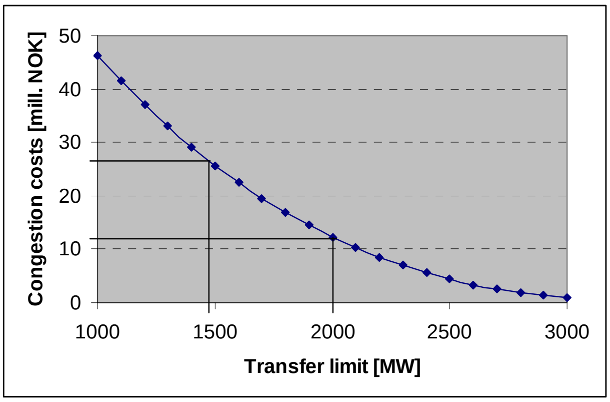

Figure 2 - Accumulated congestion costs computed as function of transfer limit (export only) on Hasle PTC. Based on Statnett data from January – August 1999.

The curve indicates that if the PTC limit was constant 2000 MW, the accumulated congestion costs would have been NOK 12 millions, i.e. a total saving of approximately NOK 15 millions during 8 months of operation. A main objective of this paper is thus, to show that a 2000 MW transfer limit on the "Hasle" PTC is a realistic goal.

4. SYSTEM MODELING AND STABILITY ASSESSMENT

Power oscillations and angle stability is a problem area that may concern single generators, local areas or the entire interconnected system. In order to install efficient controls to deal with these problems, it is important to have tools and methods capable of identifying and assessing stability problems from a system perspective.

Small signal stability analysis [3] provides efficient methods in this respect, and a main purpose of the study presented below is to illustrate the use of such tools for stability assessment and control design. The second aim is to illustrate that improved stability control can contribute in order to raise transfer limits, and thus provide system benefits.

4.1 System modeling

The "Hasle" PTC is discussed above regarding transfer limits and congestion costs. The remaining parts of this paper will focus on technical analyses related to this corridor. It is well known that system disturbances create power oscillations on the Hasle corridor. The aim is here to assess the nature of this stability problem. What is the current impact on the PTC limit, and to what extent is it possible to increase the transfer limit with proper control on generators and SVC / FACTS devices?

A complete dynamic model of the interconnected Nordel transmission system has been made available for this study. Two load flow cases, denoted *base case* and *contingency case*, have been established in order to evaluate the robustness of the system, and the possibility of increasing existing transfer limits. The base case model represents a winter load situation with 1800 MW export from Norway to Sweden on the Hasle corridor. The contingency case represents a similar load situation, but with a shift in power generation resulting in 2050 MW export on the corridor. Additionally, one of the two transmission lines in the corridor ("Halden-Skogsäter") is disconnected, which represents the most critical contingency in this case.

Based on the full model, a small signal stability analysis is performed using the PacDyn program [4]. Potential stability problems are identified and assessed through modal analysis, and partly verified by non-linear simulations. A main purpose of this study is thus also to demonstrate the feasibility of modal analysis on the very large system model, comprising nearly 1000 generators and 11000 state variables.

4.2 Initial stability assessments

Potential stability problems are identified by modal analysis. The most critical eigenvalues, representing low damped system modes, are identified and further assessed by mode shape analysis [5]. The main results are summarized in Table 1 for the base case model. The table shows frequency and damping of some critical modes, and it is indicated where the modes are most observable. The results indicate very low damping for this operating condition. The robustness of the system is further assessed through analysis of the contingency case.

Table 2 shows results from corresponding modal analysis after increasing the power transfer and disconnecting the 420 kV line "Halden-Skogsäter" on the "Hasle" corridor.

Table 1 - Summary of critical low damped modes in base case

Frequency	Damping	Observability:
0.32 Hz	0.13 %	Inter-area mode, observable as power oscillations between Finland and South Norway.
0.48 Hz	2.12 %	Inter-area mode, observable as power oscillations between Sweden and South Norway.
0.56 Hz	2.15 %	Local area mode, observable in Northern Norway.
0.76 Hz	1.83 %	Local area mode, observable in Western Norway.

Table 2 - Summary of critical low damped modes in the contingency case (outage of "Halden-Skogsäter")

Frequency	Damping	Observability:
0.32 Hz	*-2.50 %*	Inter-area mode, observable as power oscillations between Finland and South Norway.
0.38 Hz	3.13 %	Inter-area mode, observable as power oscillations between Sweden and South Norway.
0.56 Hz	2.22 %	Local area mode, observable in Northern Norway.
0.76 Hz	1.65 %	Local area mode, observable in Western Norway.

It is now observed that the system is unstable and pointing to the low frequency "Finland" mode as being the most critical.

Nonlinear simulations, using PSS/E, were performed in order to verify the results from modal analysis. A temporary three phase short circuit is applied to disturb the system, and the responding power flow on the 420 kV line "Hasle-Borgvik" is shown in Fig. 3. The two curves show the responses when the grid is intact (base case) and when "Halden-Skogsäter" is disconnected (contingency case).

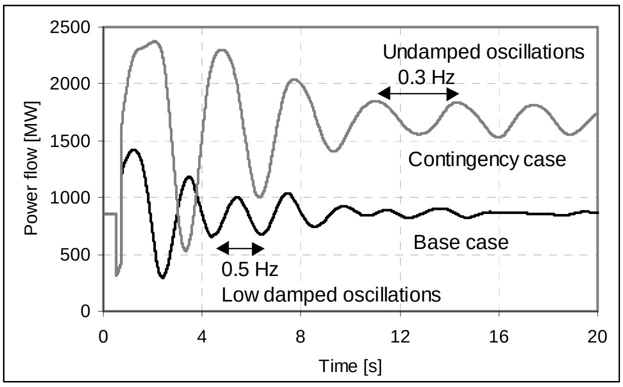

Figure 3 - PSS/E simulations verifying the modal analysis

It is readily seen from these curves that the low damped 0.48 Hz mode is most observable in the base case, and that the system remains stable. The contingency case shows that after an initial transient period, the power flow ends up in 0.3 Hz undamped oscillations. This corresponds very well with the modal analysis.

The results above indicate that there are two critical modes that potentially affect the "Hasle" corridor, namely the 0.32 Hz and 0.48 Hz inter-area modes.

The 0.56 Hz mode is found to be the main cause for stability constraints related to another PTC in the northern part of Norway (The "Tunnsjødal/Kobbelv" PTC). The 0.76 Hz mode (located to the western part of the country) has also been observed in reality. Neither of these two local modes are found to be significantly affected by the critical contingencies related to the Hasle corridor. It is very likely that improved damping of these two modes can be achieved by installation and proper tuning of additional power system stabilizers (PSSs) on generators in the corresponding areas. This will, however, not be further assessed here.

5. CONTROL DESIGN AND MAIN RESULTS

There are two low damped system modes that are found to affect power oscillation damping on the "Hasle" corridor. These are the South-Norway/Sweden mode (0.48 Hz) and the "Finland" mode (0.32 Hz). Both are inter-area modes that to various degrees can be observed throughout the Nordel interconnection. The inter-area modes also show adverse interaction with other local modes, but this aspect needs further assessment.

Since the transmission system operators in a deregulated environment (like in the Nordic countries) do not have direct control of generating units, it is of particular interest to study the effect of stabilizing controls on own equipment, such as SVC units. It is also of interest to study the possible benefits of a TCSC installation, e.g. in Hasle.

There are at present seven SVC units in Norway, primarily installed for voltage control and reactive power compensation purposes. The study below attempts to show that the SVC units can be effectively utilized also for stability control. The aim is thus to locate and tune power oscillation dampers (PODs) on the most effective SVC units.

Controllability aspects are addressed by computing relevant transfer function residues [5] with respect to both inter-area modes. Table 3 shows magnitudes and angles of transfer function residues for all SVC units in Norway. The residues are computed for the transfer functions relating input from the auxiliary voltage controller setpoint, X_{ref}, of each SVC, to the local ac-bus frequency, *freq*. The magnitudes shown are all relative to the “Sylling” SVC. The table also indicates in which part of the country each of the SVCs is located.

Table 3 - Transfer function residues for all SVC units with respect to the inter-area modes

Loca-tion	Name	“Finland mode”		“Sweden mode”	
		Magn.	Angle	Magn.	Angle
South east	Sylling	1.0	210 °	1.0	165 °
	Rød	0.85	215 °	0.88	170 °
	Hasle	0.86	233 °	0.53	179 °
South	Kr.sand	0.45	232 °	0.66	205 °
Mid	Verdal	0.02	263 °	0.04	95 °
North	Kv.dal	0.02	195 °	0.01	10 °
	Røsssåg.	0.01	69 °	0.01	57 °

The results show that all three SVC units located in southeast (the Oslo area) are potentially effective for controlling these modes. Furthermore, it is seen that the residues for these units all points to the left in the complex plane (angles around 180 degrees). This indicates that system frequency would be a good measurement signal for controller design.

However, we have chosen to use local power flow measurements as input to the damping controllers. Frequency deviations will, in practice, be small and therefore difficult to measure properly, while on the other hand, damping problems are seen to be highly observable as power oscillations on the main transmission lines where the SVCs are located (Fig. 3).

PODs for the three SVC units located in “Sylling”, “Rød” and “Hasle” were then designed, using simple control structures (a first order washout filter, a gain and a second order lead-lag filter). The controllers were tuned to provide damping of both inter-area modes, but no proper co-ordination or optimization of the tuning was attempted. The controller design was performed using the *base case* load flow situation as the design model.

In order to illustrate the performance, Fig. 4 shows a root locus plot where the gains of the individual PODs are simultaneously raised. It is seen that all four critical modes move to the left, and the results indicate that by proper control design it is possible obtain significant improvements in system damping. The “Sweden” mode was easily improved to beyond 10 % damping, and the same relative improvement was found for the “Finland” mode. It must, however, be emphasized that there are uncertainties related to modeling of the Finish part of the grid. Initial damping of the “Finland” mode is most likely better than shown in this analysis.

Fig. 5 shows the corresponding root locus plot when the same PODs are applied to the contingency case. The system is easily stabilized, and thus, apparently, it shows satisfactory robustness properties.

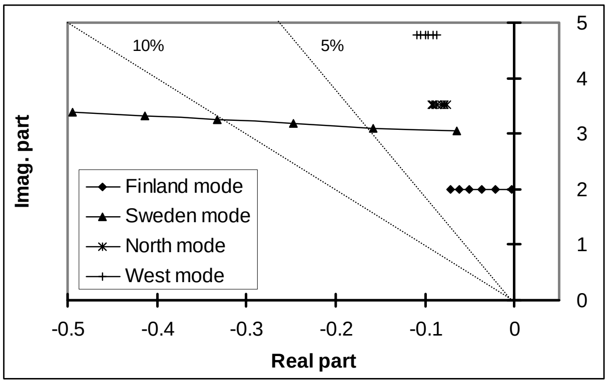

Figure 4 – Root locus for SVC stabilizer design. Base case, 1800 MW export

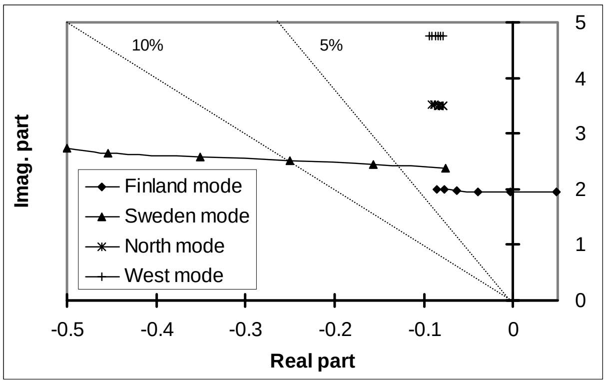

Figure 5 – Root locus for SVC stabilizer design. Contingency case, 2050 MW export

A similar analysis was performed for a possible TCSC installation. The result from this analysis confirms earlier investigations [6], showing that a TCSC in Hasle would be very effective for damping power system oscillations.

The main conclusions from the analysis can be summarized as follows:

- The stability problem of the “Hasle” corridor is mainly related to two low damped inter-area modes.
- These modes can be (and they are to a large extent already) efficiently damped by power system stabilizers on generators throughout the Nordel system. Location, re-tuning and installation of new stabilizers are still recommended actions.
- Power oscillation dampers on SVCs in Sylling, Rød and Hasle provide effective control if properly tuned.
- The study confirms a significant positive effect on system damping from a TCSC installation in Hasle.

6. CONCLUDING REMARKS

The aim of this paper has been to illustrate various aspects of power transmission system operation with the emphasis on stability assessment and control. A main objective has been to show how proper tuning of damping controllers can contribute to raising transmission capacities, and thereby reduce operating costs. A small signal stability analysis is carried out on a full Nordel transmission system model in order to assess main stability properties and to perform controller design.

We have found that SVCs in Southern Norway, as well as HVDC converters and a number of generators and FACTS devices show efficient for damping inter-area oscillations (Sweden and Finland modes). Further studies are, of course, needed in order to conclude how much these improvements in sum may affect the stability constraints related to the “Hasle” PTC. However, this study clearly indicates a potential for increasing the Hasle export limit towards 2000 MW.

7. REFERENCES

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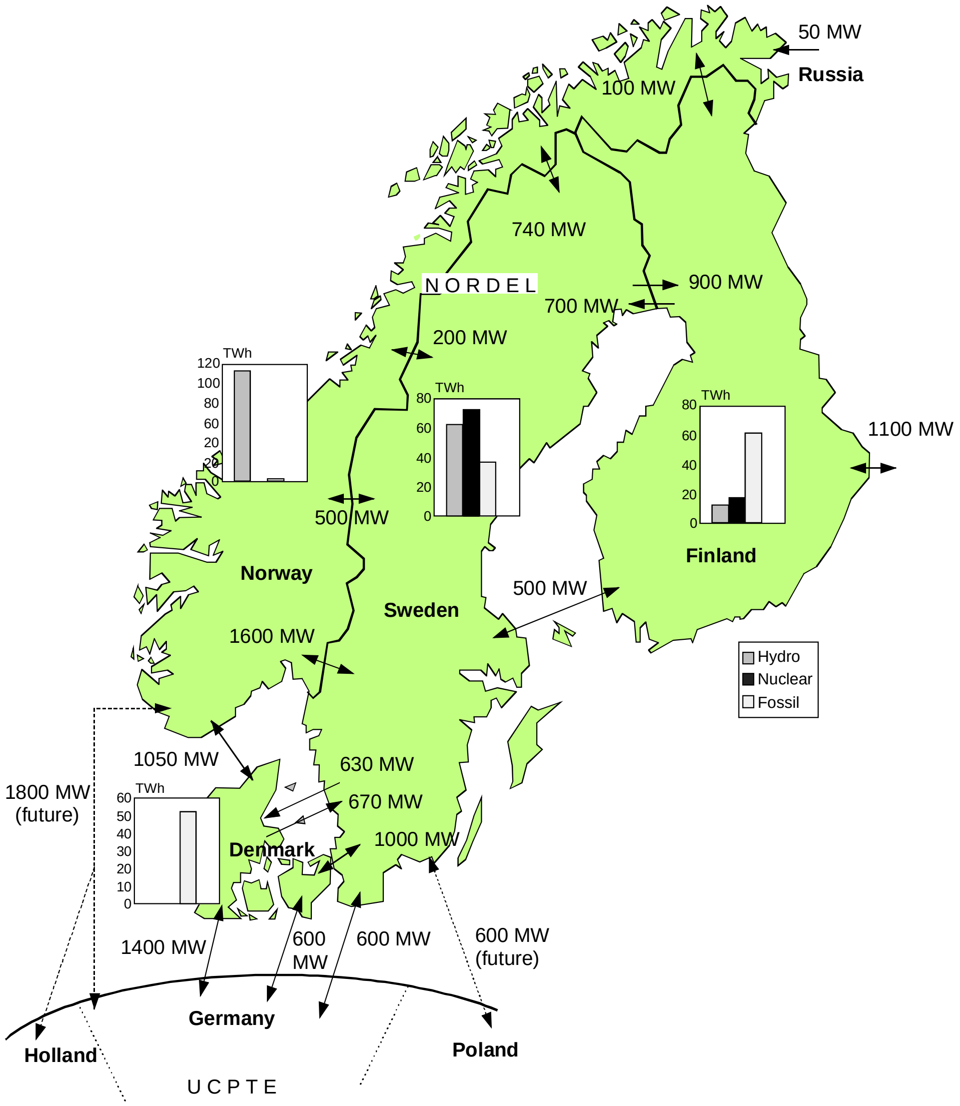

Figure A1 – Overview of generation and transmission capacity in the Nordel power system