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RAISING STABILITY LIMITS IN THE NORDIC POWER TRANSMISSION SYSTEM

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Abstract – The aim of this paper is to present power system stability analyses, which are part of ongoing efforts to raise transmission capabilities in the Nordic power transmission system. The studies focus on the assessment of angle stability limits and the impact of power system stabilisers (PSSs). The paper describes applications and testing of prototype devices for on-line power system monitoring (the Voltage Instability Predictor, VIP and Phasor Measurement Units, PMUs). Utilisation of phasor measurements as input to power system stabilisers is analysed.

Selected results from measurements and computer analyses, using a complete Nordic transmission system model, are shown to illustrate the main benefits from the study. The results indicate that it is possible to raise existing stability limits on important transmission corridors through improved control and better understanding and monitoring of system stability properties. In combination with other ongoing efforts this will enable the system operator to raise present operating limits.

Keywords: Power system security, power transfer limits, power system damping, power system stabilisers, wide area monitoring.

1 INTRODUCTION

Considerable efforts have been made during the recent years to increase transmission capabilities in the Norwegian power system. A main objective is to increase power transfer limits on transmission corridors that frequently constitute bottlenecks.

The efforts have focused on operational procedures, system control and inexpensive grid improvements rather than expensive and often controversial grid reinforcements. The overall motivation is to enable increased utilisation of the grid and still retain a sufficient level of security in operation.

The ongoing work has comprised a range of activities, including:

- Investigations on probabilistic security criteria enabling flexible transfer limits [1].
- Active use of system protection.
- New control centres with advanced EMS tools.
- New devices for on-line monitoring of load flow and stability properties [2].
- Investigations on tuning and implementation of new control devices for stability improvements [3].

The constraints on power transfer capability are generally determined from thermal capacity limits and system stability, including voltage and angle stability limits. Whereas the thermal limits can be efficiently and accurately determined from traditional load flow based security analysis, the stability limits are often more uncertain.

Different innovative solutions regarding system monitoring and system control have been investigated to raise the stability-constrained limits. The aim of this paper is to present the ongoing studies and show main results from various stability assessments and studies in the Nordic power transmission system.

The paper is organised in four main sections. Section 2 provides background regarding practical handling of power system security and determination of transmission limits. On this background the main motivation for stability assessments is discussed. System models and simulation tools that are used for stability analysis are described in Section 3, which also presents results from model validation work. Section 4 discusses the approaches and methods by which stability limits have been assessed. Important results from small signal stability analysis, non-linear time domain simulations and sensitivity studies are presented. Section 5 presents ongoing studies on application of new devices for on-line monitoring of voltage and angle stability. The new devices that are being tested are the Voltage Instability Predictor (VIP) and several Phasor Measurement Units (PMUs). Expected benefits and overall experiences from the studies reported in this paper are summarised in the concluding remarks.

2 POWER SYSTEM SECURITY

The Nordel power system comprises the interconnected power systems of Sweden, Finland, Denmark and Norway. The four countries have a common power market, operated by Nord Pool - the Nordic Power Exchange. Each country has a transmission system operator (TSO). While there is a mix of hydro and thermal power generation within Nordel, the Norwegian power system is characterized by highly distributed hydropower generation. The deregulation of the electricity markets and the geographical differences in generation create an increasing demand for power exchange between parts of the system. In addition to an increasing total demand for electricity, this has lead to larger and more frequent variations in load flow patterns. In this situation the system operators face great challenges in both planning and operation of the system.

Overall power system security is a main responsibility for the transmission system operators (TSOs). A common practice regarding handling of power system security is to determine operating limits on power transfer capacity on a set of (more or less pre-defined) critical transmission corridors. A *power transfer corridor (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 TSO) 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 [1].

The enforcement of PTC-limits, either through market arrangements (price areas, counter trade) or corrective controls, leads to transmission congestions. In total, transmission congestions have a negative economic impact on participants (generators and consumers) in the electricity markets. Thus, there is a main motivation for the transmission system operator to raise power transfer limits while security can be maintained.

The determination of PTC limits is an established part of the operating procedures at Statnett's National Control Centre, and the limits are generally determined based on 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.

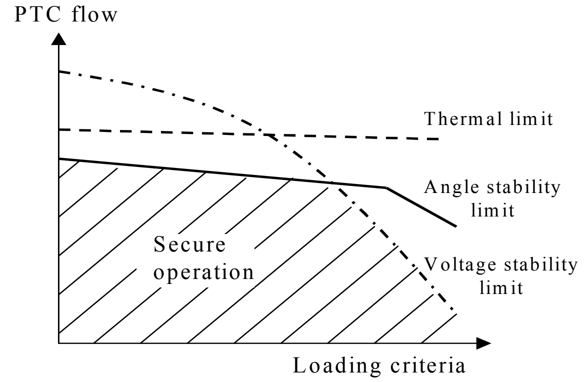

Figure 1: PTC limit defined as a function of system load.

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 the example of Fig. 1 the operating limits will be determined partly by 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:

- Many PTC-limits can be raised if better and more reliable tools are available in order to determine the stability limits more accurately.
- These PTC-limits can be increased towards the thermal capacity limit if automatic control systems were available to raise the stability limits beyond the thermal constraints.

3 POWER SYSTEM MODELLING AND VALIDATION

3.1 Simulation tools and modelling

Power system stability is a complex problem area that may concern single generators, local areas or the entire interconnected system. In order to assess stability problems and to design efficient control systems, it is important to have tools and methods capable of modelling the complex dynamics of a large interconnected power system.

A complete dynamic model of the interconnected Nordel transmission system has been updated and made available for this study. The model is implemented in the Power System Simulator, PSS/E from PTI. This model is used for non-linear time domain simulations, including contingency analysis and sensitivity studies.

A time domain simulator is not the ideal tool when it comes to control design and the understanding of power system oscillations. Small signal stability analysis [4] provides more efficient methods in this respect. Based on the full PSS/E model, small signal stability analyses have been performed using the PacDyn program [5]. Potential stability problems are identified and assessed through modal analysis, and verified by non-linear time domain simulations. One of the goals of this study has also been to demonstrate the feasibility of modal analysis on the very large system model, comprising more than 1000 generators and 11000 state variables.

The studies presented in this paper focus on the "Hasle" corridor, which is a frequent bottleneck for power transfer between Southern Norway and Sweden. The Hasle PTC is depicted in Fig. 2 and consists of the two 420 kV transmission lines "Hasle-Borgvik" and "Halden-Skogsäter". The transfer limit on this corridor is to various degrees constrained by thermal as well as voltage and angle stability limits. As illustrated in Fig. 1

the actual operating limit is determined as a function of a well-defined "load" in the greater Oslo area (depicted in Fig. 2).

Several load flow cases have been established in order to evaluate the possibility of increasing existing transfer limits. The base case model represents a winter load situation with approximately 2000 MW export from Norway to Sweden on the Hasle corridor. By shifting the generation in Norway and Sweden, load flow cases with different power exchange are generated.

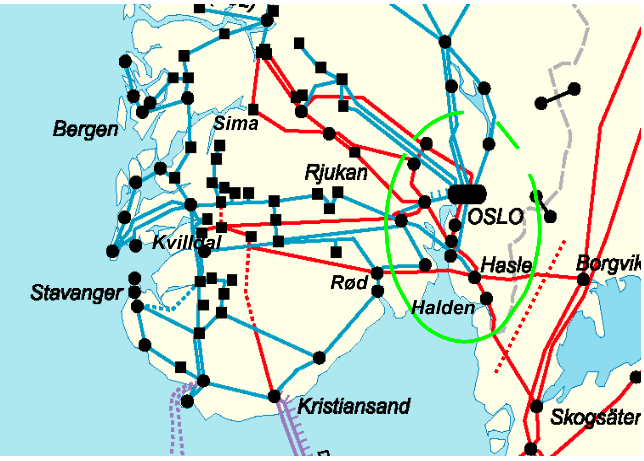

Figure 2. The Hasle PTC and the transmission grid in Southern Norway.

3.2 Model validation

Model validation is an important part of any modelling work, and should not be neglected or underestimated. Validation of large interconnected power system models is an enormous task, dealing with sufficiently detailed representation of hundreds of generators, exciters and turbine models in addition to the load flow model (lines, transformers and loads). Our approach regarding updating and improving of the Nordel power system model can be summarised as follows:

- From more than 20 years of experience and continual improvements, the load flow model is considered sufficiently accurate. However, there is still work to be done in order to validate and improve the load models for dynamic studies.
- By means of power oscillation recorders it has been possible to verify the simulation model when disturbances have occurred during normal operation.
- For selected large power plants, the generator models (including exciters and power system stabilisers) have been validated from special measurement campaigns.

In order to illustrate the performance of the final model, a comparison between measured and simulated response is shown in Fig. 3. It is well known that system disturbances create power oscillations on the Hasle corridor. In Fig. 3 the response in power flow on the line "Hasle-Borgvik" is shown when the other line of this corridor "Halden-Skogsäter" is closed after being disconnected.

As can be seen that the load flow agree fairly well, but more important, the amplitude and damping of the power oscillations are seen to agree very well.

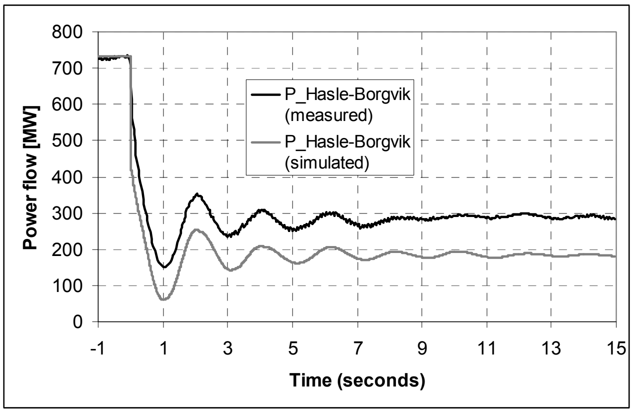

Figure 3: Comparison of measured and simulated response in power flow after closing the 420 kV line "Halden-Skogsäter".

4 STABILITY ASSESSMENTS

The "Hasle" PTC is discussed above regarding transfer limits. This section will focus on angle stability analyses related to this corridor. The aim is to assess the nature of the stability problem and to identify the actual stability limit. The main questions are:

- How does the level of power transfer on the corridor influence on system stability?
- What are the critical contingencies to take into account?
- And what is the impact of power system stabilisers, and to what extent is it possible to increase the transfer limit with proper stabilising controls?

Selected results from computer analyses using the complete transmission system model of the interconnected Nordic power system are shown to illustrate the main findings.

4.1 Small signal stability analysis

The Norwegian power system is to a large extent characterized by distributed power generation. Hydropower plants at different sizes are located all over the country, and many of the larger plants are distant from load centres. This makes it particularly attractive but also difficult to perform small signal (modal) analysis. Attractive because it gives better insight into the nature of the stability problem concerning observability and controllability of critical low damped modes. Difficult because the system model gets very big, and it may in some cases be a problem to identify all critical modes of interest. Model reduction has been considered, but there is always an uncertainty that important information will be lost. It was therefore decided to use a fairly complete system model for the analysis [3].

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 [6]. 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 low damping of several modes for this operating condition. There are two critical inter-area modes that potentially affect the "Hasle" corridor, with frequencies at 0.32 Hz and 0.48 Hz, respectively.

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 1: Summary of critical low damped modes in base case.

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.

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

The robustness of the system is further assessed through analysis of critical contingency cases. Table 2 shows results from corresponding modal analysis after increasing the power transfer by 200 MW and disconnecting the 420 kV line "Halden-Skogsäter" on the "Hasle" corridor.

It is now observed that the system is unstable and pointing to the 0.3 Hz "Finland" mode as being the most critical.

4.2 Contingency analysis and sensitivities

Non-linear simulations, using PSS/E, were performed in order to verify the results from modal analysis, and to perform further assessment of the actual stability limit. In addition to the base case at 2000 MW power transfer on the Hasle corridor, ten load flow cases were established to assess various levels of power transfer. A temporary three-phase short circuit is applied in "Halden" substation to disturb the system, and the responding power flow on the 420 kV line "Hasle-Borgvik" is shown in Fig. 4 for all eleven cases.

It is readily seen from these curves that the low damped "Sweden" mode at approximately 0.5 Hz is most observable, and that the system remains stable even when the total power transfer approaches 3000 MW.

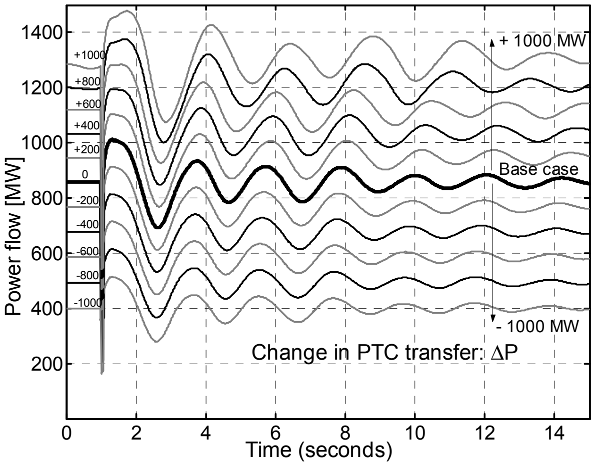

Figure 4: Stability analyses showing the power flow on "Hasle-Borgvik" and its sensitivity to changes in power transfer when the network is intact.

The curves in Fig. 4 show the responses when the network is intact. In practice, the *N-1* criterion is applied when determining the transfer limit for this corridor. Thus, we need to identify the most critical contingency and then assess the stability limit.

The most critical contingency is found to be a three-phase short circuit with subsequent tripping of the line "Hasle-Halden". Fig. 5 shows the corresponding responses in power flow on "Hasle-Borgvik" when this contingency is applied.

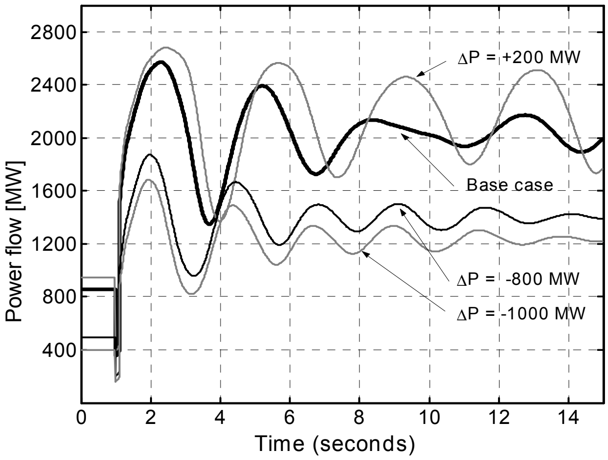

Figure 5: PSS/E simulations verifying the modal analysis. Contingency case

The responses are shown for four different transfer levels. Note that for the two highest transfer levels, the power flow show more or less undamped 0.3 Hz oscillations. This corresponds very well with the modal analysis. It can thus be concluded from these analyses that the *N-1* stability limit is between 2000 and 2200 MW.

4.3 *Impact of power system stabilizers*

Since the transmission system operators in a deregulated environment (like in the Nordic countries) do not own generation, they must rely on various system services to provide important control functions. Power system stabilisers (PSSs) on generating units represent one of these control functions. It is therefore important to know the system benefit from power system stabilisers.

The main results from a study assessing the impact of PSSs on generators in Norway are illustrated in Fig. 6.

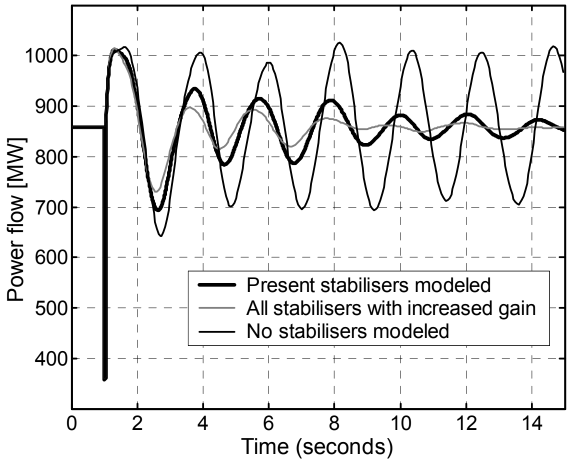

Figure 6: Assessment of power system stabilisers showing power flow on 420 kV "Hasle-Borgvik" with and without PSSs.

The conclusion from the study is that without any PSSs in Norway, the system would be unstable even under normal operation conditions. This emphasises the importance of power system stabilisers. It is also found that there is a potential for further improvements in system damping by retuning and installation of new stabilisers on both generators and SVC units.

5 APPLICATION OF NEW MONITORING DEVICES

5.1 *The voltage instability predictor (VIP)*

As described above, voltage control and voltage instability represent constraints that may influence the PTC limit in Hasle. Despite the fact that voltage instability is a system problem, there is still a place for devices that use only local measurements. The Voltage Instability Predictor (VIP) represents such a device [7]. The goal of the VIP is to determine whether the load connected to a substation is excessive. A fundamental issue is whether the transmission's strength can be "sensed" from local measurements. Once computed, this strength is compared against the local loading to determine which, if any, control actions can be taken.

Fig. 7 shows a load bus and the rest of the system treated as a network equivalent. From circuit theory, maximal power transfer occurs when $|Z_{app}| = |Z_{net}|$.

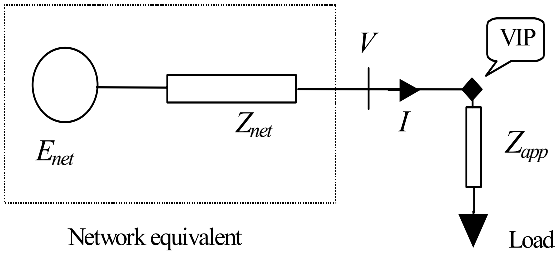

Figure 7: Local bus where the VIP is installed and the system network equivalent.

It is noted that no assumption has been made about the characteristic of the load. The apparent impedance Z_{app} is merely the ratio between the voltage (V) and current (I) phasors measured at the bus. When the loading is normal, the condition $|Z_{app}| >> |Z_{net}|$ holds; while at the inception of voltage instability, the difference between the two impedances approaches zero. Tracking proximity to voltage instability, therefore, becomes tracking the distance between $|Z_{app}|$ and $|Z_{net}|$. This is the essence of the VIP. [2], [7] provide more details on the calculations.

A prototype VIP device has been installed in Hasle substation and initial testing is ongoing. The goal of this VIP is to detect possible voltage instability problems in periods of high power export from Norway to Sweden. In this case, the "load" that is the basis for computing the apparent impedance, Z_{app}, is the net load current on the two lines from Hasle towards Sweden ("Hasle-Borgvik" and "Hasle-Halden"). Thus, the network impedance, Z_{net}, represents the strengths of Norwegian network.

Sample results from the initial testing and performance verification are included on the last page (Fig. 11). The leftmost figure shows measurements from the VIP during normal operation (1850 MW power transfer and an intact network). Z_{app} is seen to be more than three times higher than Z_{net}, which is considered to be a safe margin. In the rightmost figure, the same initial operating condition is simulated in order to verify the VIP results. Ramping up the load in Sweden simulates a steady increase in power transfer, which makes the Z_{app} decrease. Tripping of the line "Rød-Hasle" (the most critical contingency concerning voltage stability) is simulated in order to verify how the VIP is able to track changes in the network.

The initial results indicate that the VIP performs as expected during normal, steady state operation. During transient conditions or when power oscillations occur, the Z_{net} signal is seen to become "noisy". This is an inherent problem of the VIP algorithm and the subject of current research.

Further work will also focus on possible applications and use of the VIP for system monitoring and as input to control actions, e.g. load shedding. Information from one local VIP is in general not sufficient to track the margin to voltage collapse from a system perspective. Ongoing research is undertaken to investigate how improvements can be made by utilizing information from several VIPs [8].

5.2 Phasor measurement units (PMUs)

Along with the installation of the VIP prototype, three phasor measurement units (PMUs) are also being installed for testing and verification purposes. It is expected that wide area measurement systems and PMUs will become important components in the power system of the future. The most promising applications of phasor measurements in the Norwegian power system are listed below:

- Phasor measurements of bus voltages and line currents can be applied as inputs to improve state estimation (which eventually will become linear estimators).
- PMU signals can be applied as input to power system stabilisers.
- PMUs can be applied for general monitoring of voltages and voltage angles in grid operations, including fault location.
- PMUs can be applied for monitoring of special stability problems and possibly as input to system protection schemes.

The present PMUs are installed in Hasle and at the two large power stations, “Kvilldal” and “Sima”, respectively (see Fig. 2). These locations are favourable regarding monitoring and observability of the 420 kV network in Southern Norway.

5.3 Design of PSSs using PMU measurements

One of the studies regarding application of PMUs has been to investigate the potential of using voltage angle measurements as input to power system stabilisers (PSSs).

As shown above, the dominating inter-area modes in the system are characterised by generators in southwest of Norway oscillating against generators in Sweden or Finland. Modal analysis indicates that the difference in voltage angle between the areas would be an ideal measurement to capture these oscillations. By using PMUs as measurement devices, and taking into account the low frequency of power oscillations, it is believed that this approach will become technically feasible in the near future.

The present study has focused on PSS design and verification through time domain simulations. A simplest possible control structure, as shown in Fig. 8, was chosen and tuned by classical frequency domain techniques [6]. The performance was simulated when the PSS models were implemented in the two large power plants, Kvilldal and Sima, which are equipped with PMUs in their respective 420 kV substations. Different remote voltages were tested as input signals.

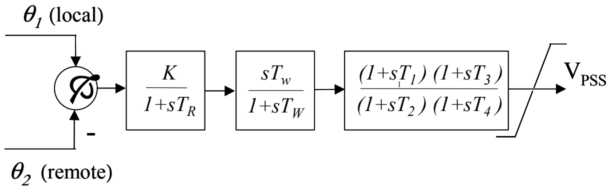

Figure 8: Structure of simple PSS based on measurement of voltage angle difference.

Results from the study are illustrated in Figs. 9 and 10. Fig. 9 shows the response with and without the PMU based PSSs when the system is excited to produce power oscillations on the Hasle corridor. The main conclusion is that significant improvements in damping of inter-area modes can be achieved. It remains to quantify the improvements in terms of increased transfer limits.

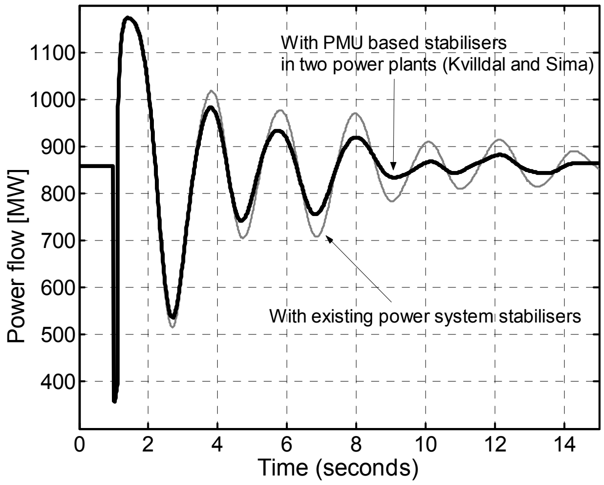

Figure 9: Power flow on the line “Halden-Borgvik” when the system is subjected to a temporary short circuit in “Halden”.

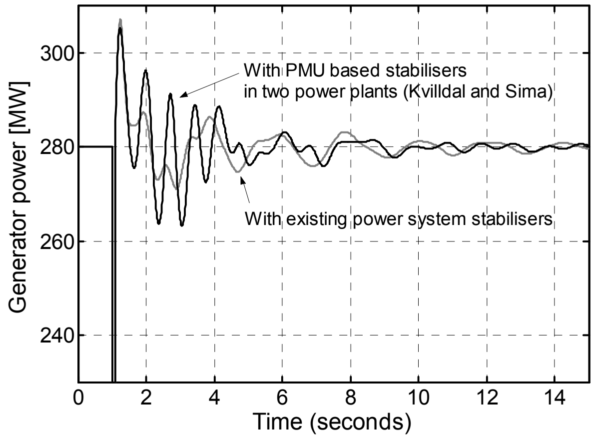

Figure 10: Power output from one generator in Kvilldal illustrating low damping of a local 1.3 Hz mode.

The study has also shown that great care should be taken when designing PSSs based on voltage angle measurements. This has to do with the fact that voltage angles, like rotor angles, have an approximately 90 degrees phase lag compared to bus frequency or rotor speed in the frequency range of inter-area modes. Thus, the PSS compensator needs a corresponding phase lead to provide damping. Using a simple control structure, as shown in Fig. 8, this implies higher gain at higher frequencies and possibly adverse interaction with local modes. This problem was experienced in Fig. 10 where the high gain of the PSSs is shown to excite a local mode at 1.3 Hz.

6 CONCLUSIONS

This paper has presented studies with focus on stability analyses, which are part of ongoing efforts to raise transmission capabilities in the Nordic power transmission system. The studies that are reported in the paper include:

- Comprehensive model development and validation.
- Analyses regarding power system damping and angle stability, including assessments of stability limits and the impact of power system stabilisers (PSSs).
- Implementation and testing of new devices for online monitoring of voltage and angle stability (VIP and PMUs).
- Utilisation of PMU measurements as input to power system stabilisers.

Selected results from measurements and computer analyses, using a complete Nordic transmission system model, are shown to illustrate the main benefits from the study.

- The results indicate that it is possible to raise existing stability limits on important transmission corridors through improved control and better understanding and monitoring of system stability properties (i.e. to reduced uncertainty regarding the actual limits).
- Angle stability is only one of the constraints that must be taken into account when operating limits are determined. However, in combination with existing (and possibly new) system protection schemes, the ongoing efforts will enable the system operator to raise present operating limits.

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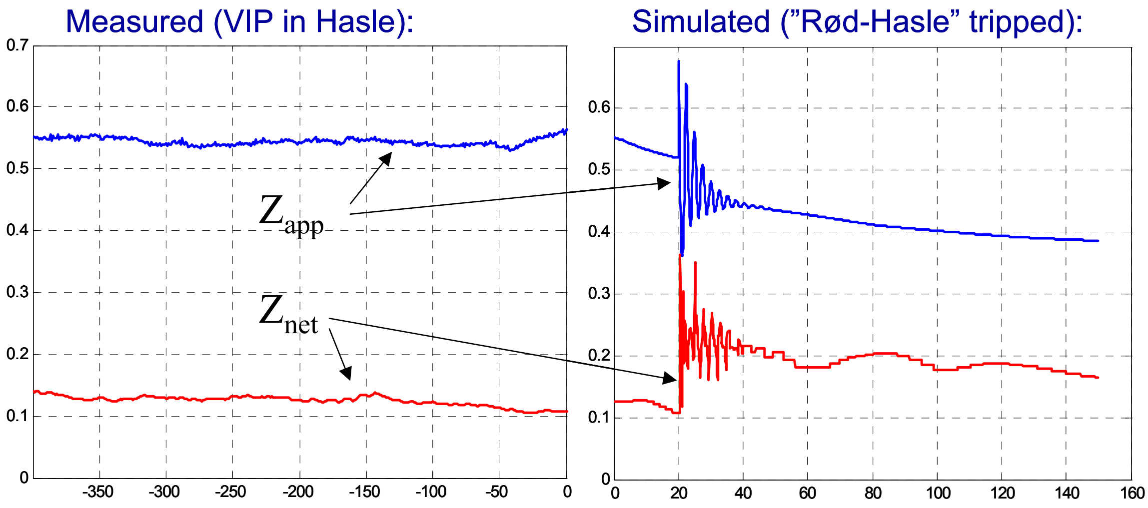

Figure 11: (***X***-axis is *Time in seconds*. ***Y***-axis is *p.u. on 160 ohm base*.) Verification and testing of the Voltage Instability Predictor (VIP): The left curves show 400 seconds of measurements from the VIP prototype in Hasle Substation. The performance of the VIP is verified by simulation studies. The right curves show the simulated network and apparent load impedances when the power transfer to Sweden is gradually increased. After 20 seconds the 420 kV “Rød-Hasle” is tripped, which is seen to increase the network impedance as expected.