POWER SYSTEM DAMPING IN ICELAND BASED ON PHASOR MEASUREMENTS

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Abstract

Phasor measurement signals are used as only input to a wide-area power system stabilizer to increase interarea mode damping of the Icelandic system. Modal analysis and time simulations of a detailed model show that frequency difference as PSS input gives a damping improvement that is robust to drastic changes in system topology. Field data from phasor measurement units indicate high signal quality and that frequency difference is realistic as PSS input. The wide-area PSS is compared against a generic local PSS with shaft speed input. The total performance is comparable, but while the local PSS has better local mode damping, frequency difference appears to give better interarea mode observability. Continued work aims at combining these advantages in a PSS that uses both local and wide-area signals.

Introduction

In weak power systems with remote generation, power oscillations indicating insufficient damping is one factor often limiting the output power of these plants. There are two general ways to increase the line transfer capacity and thereby fully exploit the production resources. The first and most traditional is to build new lines. This is very costly and increasingly difficult due to environmental constraints. An attractive alternative is to move the stability limit towards the thermal limit by introducing power system controls, thus improving the utilization of the transmission system. In the case of insufficient damping, stability is usually improved by continuous feedback controllers [1]. The most common type is the Power System Stabilizer (PSS), which modulates generator output by adding a signal to the voltage regulator setpoint. The input to the PSS is a measured quantity with a high content of the modal frequency that is to be damped. The main task of the PSS is to provide appropriate phase shift in the frequency range of power system oscillations, typically 0.2-2 Hz. Candidate input signals have traditionally been shaft speed, real power output and network frequency, that are all locally available at the power plant [1, 2].

The development in communication systems has made it feasible to also use remote signals as PSS inputs [3, 4]. Signals to be communicated include local signals in other plants, but also signals provided by Phasor Measurement Units (PMUs) [5]. These units primarily provide globally synchronized measurements of voltage and current phasors, but also phase angle, frequency and line flows, all at a rate of 25 Hz or higher. The synchronization makes is possible to create system-wide data sets in a time frame appropriate for damping purposes. Communication makes it possible to separate where to measure and where to control. In contrast to the case of local controllers, the actuator and the measurement points can then be chosen independently so that modal controllability and modal observability are maximized. The latter can be further improved by using signals from multiple locations.

This paper describes the initial results from work on improving damping in the Icelandic power system. Power System Stabilizers are considered for this purpose. The fact that PMUs and a communication system are available offers new measurement signals that are evaluated against traditional local signals. The Icelandic power system and a full model are first characterized leading to a more specific problem formulation. Then the PMU technology installed in Iceland is described including a sample recording. Two Power System Stabilizers are designed using local and wide-area signals respectively. The performance of the designs is quantified using modal analysis and time simulations. Finally conclusions and suggestions for future work are given.

The Icelandic System

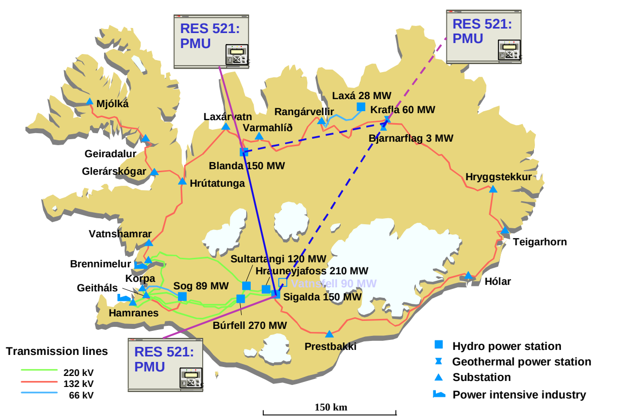

Figure 1: *The Icelandic power system with a 132 kV ring network and a meshed 220 kV network with the majority of the power plants in the south and Reykjavik in the southwest. PMU locations shown are Blanda (north), Krafla (northeast – to be installed) and Sigalda (south).*

A full model of the national Icelandic power system is used for the analysis. This model and the real system are characterized below.

(1) System characteristics

The Icelandic transmission system is owned and operated by Landsvirkjun. The system is based on a meshed 220 kV network and a 132 kV ring around the island, see Figure 1. The 220 kV network connects the load center in Reykjavik in the southwest with the main generation area in the mid-south around Sigalda. Two major generation plants are located in the 132 kV network. These are Blanda (3x50 MW) in the north and Krafla (2x30 MW) in the northeast.

During high load the power flow is from the north to the south along both the east and west coasts. If a fault with line trip occurs on the ring network, it is split and all the power has to go along either of the coasts. Figure 2 exemplifies this with recordings from a disturbance 2001-02-16 when a fault occurred on the line going east from Krafla. The line and one of the Blanda units tripped leading to heavy, undamped oscillations.

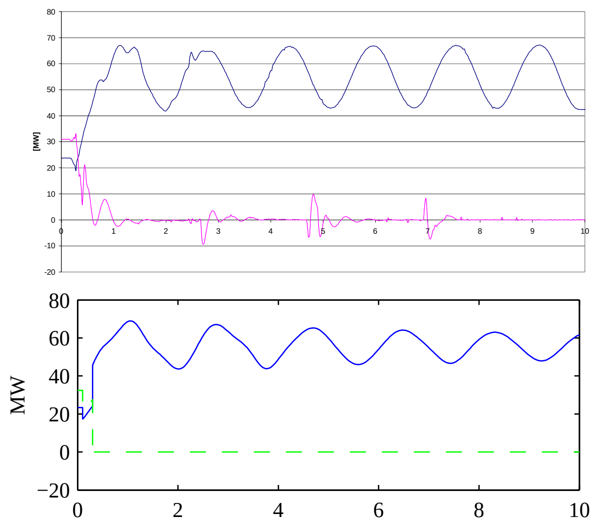

Figure 2: *Recording (top) and simulation (bottom) of disturbance 2001-02-16. Plots use the same scale and show ten seconds of line flow west and east of Krafla, when the latter is faulted and tripped together with one Blanda unit.*

(2) System model

A detailed system model with 37 generators and 202 buses is used for the analysis. Generating units are represented as fifth order models with governors, excitation systems and PSS as appropriate. The model is implemented in the simulator EUROSTAG [6], which also generates the linearized model used for modal analysis in Matlab [7], with a special toolbox [8]. As shown in Figure 2, the model has been successfully validated against the disturbance recording. Splitting the ring gives a longitudinal network and depending on the fault locations listed in Table 1, the configuration of the major plants is very different.

Table 1: *Test cases.*

Test case	Fault location
0	No fault
1	Southwest
2	West
3	Between Blanda and Krafla
4	East of Krafla

The Blanda and Krafla plants can both be feeding Reykjavik from west or east or one from each side. This is very challenging when it comes to finding robust wide-area signals to improve damping. To cover the different situations, five test cases are defined having faults between Blanda and Krafla, west of both and east of both. The cases, listed in Table 1 are all based on the same high-load situation. The troublesome mode is the interarea mode where machines in the north swing against those in the south as illustrated in Figure 3.

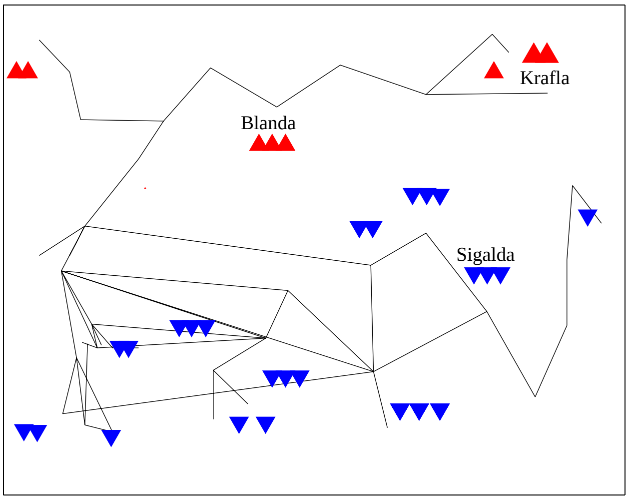

Figure 3: *Mode shape of interarea mode for case 4 shown on simplified network topology. Each triangle represents a machine and those pointing upward swing against those pointing downward.*

The location, in the complex plane, of the interarea mode eigenvalue is strongly affected by the fault location. This is indicated by Table 2, where the interarea mode eigenvalue is shown for the post-disturbance situation for each case. The stabilizer must be designed to manage all five cases. The real parts of all the eigenvalues have to be negative and even have some margin to the imaginary axis. The stabilizer is also explicitly tested on the 2001-02-16 disturbance, which is similar to case 4 with different load situation and additional tripping of a Blanda unit.

Table 2: *Interarea mode eigenvalues for the test cases.*

Test case	Eigenvalue
0	–0.2±j4.50
1	0.09±j2.99
2	0.18±j2.61
3	–0.07±j3.90
4	0.09±j3.43

PMU technology

A Phasor Measurement Unit samples instantaneous values of currents and voltages. Time signals from the GPS satellites are used for synchronisation of the sampling [5]. Figure 4 shows an example of a PMU that is based on a modern protection terminal, with great flexibility and good user experience. By using this well-established and accepted base, all requirements such as CT-/VT-connections, binary inputs and outputs are immediately fulfilled. This reduces the development cost and time to market for a full system.

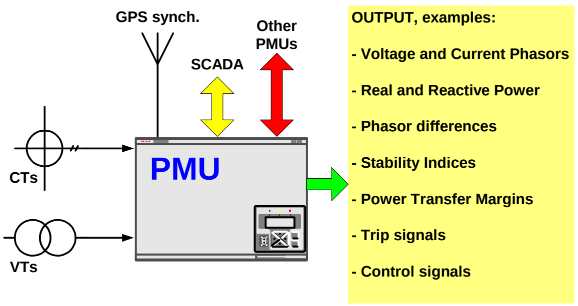

Figure 4: *PMU terminal interfaces and outputs.*

In 2001 two PMUs were installed at Sigalda and Blanda and a third will soon be placed at Krafla. Figure 5 shows a sample recording from a breaker closing between Blanda and Krafla thus closing the ring network.

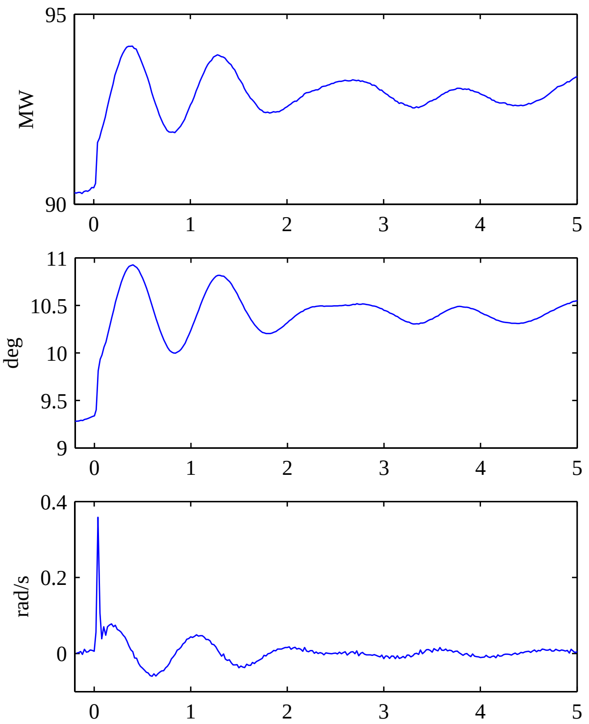

Figure 5: *Recording from closing of line between Blanda and Krafla showing line flow east of Blanda (top) phase angle difference Blanda-Sigalda (center) and frequency difference Blanda-Sigalda (bottom).*

The angle difference signal is smooth and very similar to the line flow signal as expected. As further described in the next section frequency difference is an attractive signal for damping purposes. It is obtained by differentiating the angle difference. The phase angle jump at t=0 reflects the change in load flow caused by the breaker closing. The spike in the frequency difference signal is thus not an error, but rather a direct consequence of the phase angle jump.

Stabilizer Design

As shown in Figure 2 and in Table 2, damping is insufficient when the ring network is opened, since some of the eigenvalues have a positive real part. By communicating PMU signals to PSS, new measurement signals are available for damping. As a first step a PSS using PMU-signals only is compared to one using the local signals speed and power. This is done to investigate the properties of the generic signals. A natural next step is to combine them like in [3]. The design procedure used here involves eigenvalue scan, detailed analysis of selected mode(s) followed by time simulations, which is in agreement with recommendations in [1].

(1) Siting

By comparing the modal controllability [2] of the voltage regulator setpoint signal for the different generators it can be concluded that Krafla is the generator where a PSS has the greatest impact on the interarea mode. The facts that there is no PSS in operation at Krafla and that these machines are heavily involved in the interarea mode further contributes to select Krafla as best PSS location.

(2) Candidate input signals

Robust tuning of a local PSS aims at producing an electrical torque component that is in phase with shaft speed for the frequency range where oscillations are expected [9]. *Shaft speed* is thus a generic input signal to a local PSS and will be analyzed further here. In thermal plants with long and weak shafts torsional oscillations must be considered when placing the speed transducer, but this is not an issue in this case.

It is fully realistic to measure shaft speed, but it may be more desirable to avoid measuring a mechanical quantity. In this case, *real power output* is a nearby alternative. The disadvantage is that turbine output variations will lead to unwanted changes in terminal voltage. It is straightforward to produce the real power output signal. For damping purposes its dynamic performance is comparable to shaft speed and will therefore not be studied explicitly here.

Bus frequency at any side of the step-up transformer can be used as PSS input. This signal is sensitive to interarea oscillations [2], but it is also sensitive to changes in system frequency. The small Icelandic system often exhibit large frequency excursions and it is thus inappropriate to use this signal relative to a fixed reference as PSS input here. An alternative is to use a reference signal such as the frequency near a very large machine. In the Icelandic system, the strong 220 kV network connecting most generators behaves like such a machine. The *frequency difference* between the Krafla and Sigalda PMUs is therefore chosen as the wide-area PSS input signal to be analyzed further.

Note that remote signals must be very carefully chosen. Closing a feedback loop around a large part of the system makes the controller react to all changes within the loop. Previous work on use of remote signals for damping purposes [3,4] does not involve large changes in network topology. In a system with highly varying network configuration it may be difficult to find wide-area signals that provide robust damping improvements with fixed gain. This is a challenge with the Icelandic system.

(3) Phase compensation

Having selected a local PSS with shaft speed input and a wide-area PSS with frequency difference input, the next step is to select the appropriate phase compensation.

The task of the phase compensation in the speed input PSS is to cancel the phase shift between the voltage regulator setpoint and the electric torque. If this is properly done, the phase shift between the measured speed signal and the electric torque is zero in the frequency range of interest. Closing the feedback loop then gives a torque component in phase with speed, which acts as viscous damping and adds damping to all modes. The phase characteristic to compensate is obtained from the linearized model as described in [9], by studying each Krafla generator with fixed speed and rotor angle. The result is shown in Figure 6 in the range 0.5-15 rad/s. A typical PSS with p.u. input and output as follows, has the phase characteristic also shown in Figure 6:

$$G_{Local}(s) = \frac{V_{ref}(s)}{\omega(s)} = K_{Local}\frac{1+s0.167}{1+s0.0238}\frac{1+s0.167}{1+s0.0185}$$

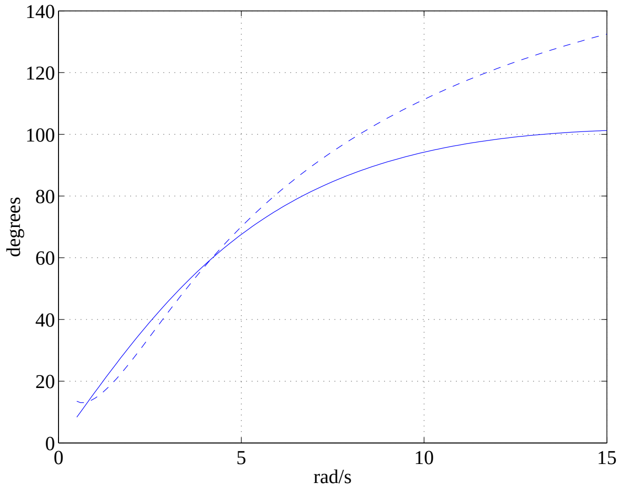

Figure 6: *Desired (dashed) and resulting (solid) phase characteristic of speed input PSS at Krafla.*

It is not as simple to find the desired phase compensation of the wide-area PSS with p.u. frequency difference between Krafla and Sigalda at 132 kV as input. A simple approach is chosen where the phase compensation of a lead-lag filter is selected such that the interarea mode eigenvalue will move straight into the left half plane when increasing the gain from zero. A first-order low-pass filter is then used to reduce the gain at higher frequencies. Finally a gain factor is introduced to give both PSS the same gain at 3 rad/s which is an approximation of the frequencies of the interarea mode.

$$G_{Wide-Area}(s) = \frac{V_{ref}(s)}{\Delta f(s)} = K_{Wide-Area} \frac{1+s0.67}{1+s0.33} \frac{0.79}{1+s0.02}$$

(4) Gain selection

Plotting the eigenvalues as the gain is increased from zero to 20 in steps of 2 gives the root locus plots in Figure 7.

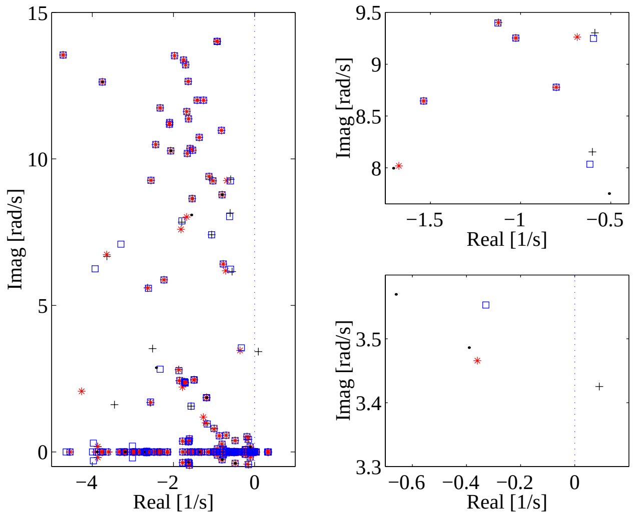

Figure 7: *Root locus plots with gain ranging from zero (+) to 20 in steps of 2 for case 4 with overview (left) and details (right). Selected gains are indicated for local PSS (*) and wide-area PSS (square).*

As can be seen in Figure 7 the interarea mode is successfully damped by both PSS types (lower right diagram). The main difference is that the damping of an 8 rad/s mode mainly involving Krafla and the next plant to the west is decreased by the wide-area PSS while it is increased by the local PSS (upper right diagram). This limits the gain of the wide-area PSS. A design using both local and wide-area signals is expected to combine the high damping of the local mode with high interarea mode damping.

With a design based on simulations and involving phase lead, it is important to consider measurement noise. To minimize its influence controller gains should be kept low. The gain should therefore be limited to the smallest value that gives the required damping. One criterion used in the damping controller design for the synchronized Nordel system is that the oscillation magnitude should be reduced by 50% in 10 s. This corresponds to an eigenvalue having a real part less than –0.07. To fulfill this criterion in all five test cases, the following gains are chosen:

$$K_{Local} = 18 \text{ and } K_{Wide-Area} = 12$$

These gain values give interarea mode eigenvalues as shown in Table 3. It is clear that it is possible to provide robust damping with both types of PSS. The resulting damping is very similar.

Table 3: *Resulting interarea mode eigenvalues with Blanda mode in case 3 in italics.*

Case	Local	Wide-area
0	–0.90±j4.26	–0.88±j4.74
1	–0.11±j2.98	–0.12±j3.05
2	–0.08±j2.60	–0.09±j2.67
3	–0.97±j3.07	–1.06±j4.18
	–0.51±j4.36	*–0.71±j4.27*
4	–0.36±j3.47	–0.33±j3.55

Case 2 is the limiting case with imaginary part of the eigenvalue closest to the imaginary axis. Case 1 is just slightly better, whereas there is considerable margin in the other cases. In case 3 Blanda and Krafla sit at each end of the system, and form two separate modes where they swing against Reykjavik. This new Blanda mode is also shown in Table 3. With wide-area PSS the frequency of these modes may be close. If the gain of the wide-area PSS is further increased, the modes will interact as the connection between Krafla and Blanda via Reykjavik is strengthened. With reasonable PSS gains, however, this interaction is not troublesome.

Time Simulations

The linearized model used for the PSS design is valid only for small deviations from the linearization point. Power system oscillations are usually triggered by a short-circuit followed by tripping of the faulted line. To analyze PSS performance for this event, time simulations are needed. This makes use of the full model with output limits and other non-linearities represented. Figure 8 shows the outcome of the disturbance 2001-02-16 if the proposed PSS designs would have been in place and can directly be compared to Figure 2.

The bus voltage near Krafla drops when the short-circuit on the east-going line occurs, but recovers when the fault is cleared 0.1 s later. One full cycle of oscillations and associated limiting of the PSS output is followed by a quick reduction in amplitude. No dynamics remain visible 10 s after the fault. Short-circuit faults and associated line tripping was simulated also in the five test cases. All cases were stable with settling times in agreement with the eigenvalues in Table 3.

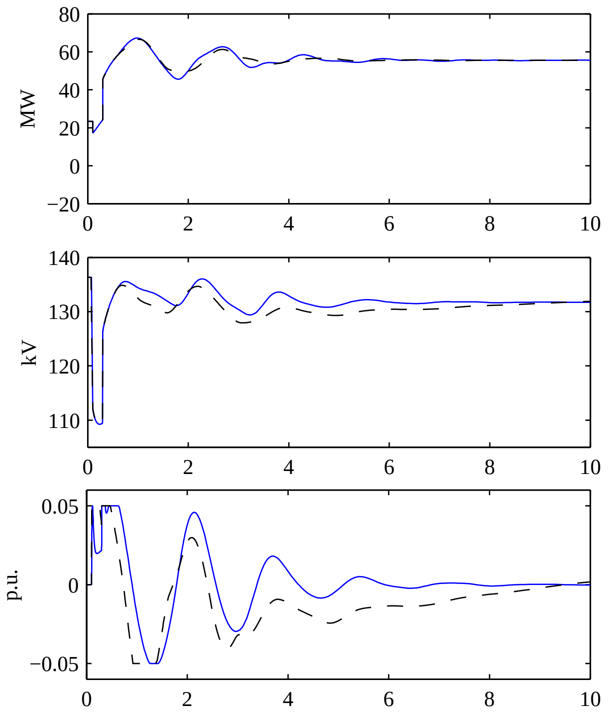

Figure 8: *Simulation of 2001-02-16 disturbance with speed-input (dashed) and with wide-area PSS (solid). Plots show real power on line west of Krafla (top), voltage near Krafla (center) and PSS output (bottom).*

Conclusions

This paper gives improved understanding of how frequency difference performs as PSS input for interarea mode damping. Previous sections indicate that PSS damping in the Icelandic system based on frequency difference is effective. Time simulations verify the results from modal analysis that this wide-area PSS is robust to a number of very drastic, but realistic, changes in network configuration that may occur in a high load case. Data from phasor measurement units in place is illustrated and exhibits high signal quality thus proving that it is realistic to use the proposed signal for damping.

A well-tuned local PSS with shaft speed as input is used as a reference and exhibits robust behavior, which is similar to that of the wide-area PSS, but some differences are noted. The careful choice of transfer function gains makes it possible to state that the wide-area PSS needs a lower gain than the local PSS to provide the same interarea mode damping. Since the control signal is the same in both cases, this indicates that the mode observability of the frequency difference signal is higher than that of shaft speed. The local PSS on the other hand improves damping of a local mode.

The next and very important step is to combine – in one PSS with local *and* wide-area input – the superior local mode damping of the local PSS with the higher interarea mode observability of the wide-area PSS.

Future work

A number of issues for future work can be identified:

A combined PSS will make possible the natural comparison between the resulting PSS and a local PSS. After that it is possible to draw conclusions about the added value of wide-area signals for damping in the Icelandic system, something which is too early to do today.

Large loads in a weak system may cause disturbances that are picked up by frequency signals [2]. Lowpass filtering of the remote signal reduces this problem, but also reduces damping efficiency. As the field measurements continue, they are expected to provide more information about the influence of loads.

A well-functioning communication system is central to the wide-area solution and deserves a few comments. The low frequency of power system oscillations makes it possible to handle some communication delays, but simultaneousness is more critical [4]. Communication interruptions can partly be handled by a proper introduction of the wide-area signal, so that the local PSS acts as a backup. The choice of communication system and the resulting performance will be further studied.

Implementing any of the PSS designs presented here will increase the transfer capacity of the Icelandic network. The resulting further increase in transfers leads to a new maximum load case that will be used in the work to further increase transfer capacity. The transfer limits in this new case are most likely still imposed by insufficient damping or by transient instability. As indicated already, further PSS damping is possible. If transient stability is limiting, new controls can be introduced to improve system security for example through generator dropping. Just like for a PSS, these controls can use local measurement signals or remote signals provided by PMUs. The fact that the number of characteristic disturbances in the Icelandic system is limited makes it realistic to classify the situation and to choose strategy accordingly. This applies to control actions, as well as controller parameter sets.

References

[1] CIGRE, Cigre technical brochure “Control of Power System Oscillations”, Final report by TF 38.01.07, July 1996.

[2] P. Kundur, *Power System Stability and Control*, McGraw-Hill, New York, 1994.

[3] I. Kamwa, R. Grondin and Y. Hébert, ”Wide-Area Measurement Based Stabilizing Control of Large Power Systems—A Decentralized/Hierarchical Approach,“ *IEEE Trans. on Power Systems*, Vol. 16, No. 1, Feb 2001, pp. 136 –153.

[4] J. H. Chow, J. J. Sanchez-Gasca, H. Ren and S. Wang, “Power System Damping Controller Design using Multiple Input Signals, “ *IEEE Control Sys. Mag*., August, 2000, pp. 82-90.

[5] A. G. Phadke, "Synchronized Phasor Measurements in Power Systems", IEEE Computer Applications in Power, Vol. 6, No. 2, pp. 10-15, April 1993.

[6] *EUROSTAG user’s manual – Release 3.1*, Tractebel – Electricité de France, September 1997.

[7] *Using Matlab*, The Math Works, Inc., Natick, MA, USA, 2000.

[8] O. Samuelsson and B. Eliasson, “Damping of Electro-Mechanical Oscillations in Multimachine System by Direct Load Control,” *IEEE Trans. on Power Systems*, Vol. 12, No. 4, Nov. 1997, pp. 1604 –1609.

[9] G. Rogers, *Power System Oscillations*, Kluwer Academic Publishers, Boston, 2000.