Combining forces to provide stability

Statnett, Sintef and ABB act together to tame the large Norwegian electric grid

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Electric grids like the one in Norway can extend over thousands of kilometers, connecting generators and end users of electrical energy via countless substations and a wide network of cables and overhead lines. In a well managed grid, disturbances are damped out smoothly and a collapse of the system can be avoided. With increasing utilization of the grids, due to the growing need of electric power everywhere, the limit of stable operation is almost reached.

In this regime of operation the grid as a whole has to be balanced and wide area monitoring and control is required. This sounds easy but due to the nature of a complex, oscillating system like an electric grid, it turns out to be a major technical challenge. Statnett, the Norwegian system operator, SINTEF, the scientific and industrial research group in Norway and ABB, the supplier of technical solutions to the problem have joined forces to keep a tighter rein on the grid.

A typical case for a grid with large geographic extension is Norway. The Norwegian system is subjected to large quantities of power transfer on its transmission network because the large capacity hydro power generation units are located in the western part of the country while the bulk of consumers are situated in the east 1. The large distances between power generation and consumption is one reason the grid system is under stress [1]. For the Norwegian transmission system operator Statnett, it is vital to identify critical operating conditions and to take corrective action before disturbances or local instabilities develop into wide spread blackouts. Besides a net of measuring devices, algorithms to determine unstable situations, mitigation strategies and decision support for the operators must be available.

Research collaboration between ABB, Statnett and SINTEF dates back many decades and has resulted in the introduction of new technologies into the Norwegian system.

What is possible in theory

An extended grid with thousands of substation knots, generating units and wide spread consumers is a highly complex system that requires a wide area view of the manifold oscillations. Various solutions for the stability issue have been proposed and described in the literature, and a number of functions related to monitoring, control and protection have been studied.

So far, such automatic control explorations have mainly been academic in nature. However, ABB Corporate Research and SINTEF, the Foundation for Scientific and Industrial Research in Norway, have acquired a deep insight into this area.

Linking needs and technology options

Research collaboration between ABB, Statnett Factbox 1 and SINTEF Factbox 2 dates back many decades. There are

Factbox 1 Statnett

Statnett is the national Transmission System Operator (TSO) in Norway, responsible for a balanced amount of power generated in Norway and its consumption. Statnett also has the nationwide responsibility to create conditions conducive to an efficient electricity market, providing reliable transmission of electricity through cost-effective development of the electricity grid infrastructure. Statnett owns approximately 85 percent of the facilities in the Main Grid. In 2005 the number of employees was 630 with operating revenues of 5244 million NOK.

www.statnett.no (May 2007)

Factbox 2 The SINTEF Group

The SINTEF Group is the largest independent research organization in Scandinavia. The abbreviation stands for *The Foundation for Scientific and Industrial Research* and employs 1800 researchers located mainly in Trondheim and Oslo. The partner in this project has been *SINTEF Energy* Research Ltd., a division of SINTEF located in Trondheim and acting as a recognized consulting company having the required deep expertise on the Scandinavian power system, and the challenges and limitations associated with large power exports.

www.sintef.no (May 2007)

1 The Nordic transmission grid and installed PMUs, indicated with red circles

Power collaboration

many examples where, as a result of such a collaboration, new technologies were successfully introduced into the Norwegian system. Perhaps one of the more well-known ones is the HVDC (High Voltage Direct Current) installations from the 1970s. Since 1999, ABB has been cooperating with Statnett and SINTEF in several R&D projects focused on using Wide Area Monitoring Systems (WAMS) and control to raise the energy transfer limits of the Norwegian 420 kV transmission grid. The work was structured in two main phases:

1999 to 2004

"Norwegian Intellectric" project with the mission to increase transmission system utilization and operational security by intelligent monitoring applications and control concepts based on new measurement and communication technologies.

2005 to present

"Secure transmission" project to deploy a WAMS in the 420 kV grid and demonstrate new concepts for secure operation of the power network.

ABB's Voltage Instability Predictor (VIP), which provides a transmission system operator with a local measure of the power margin before voltage collapse at a particular substation is encountered, was one of the first monitoring concepts relying on new measurement technologies to be tested [2]. The phasor measurement was developed later. Phasor Measurement Units (PMU) provide time-synchronized values of the local magnitudes and angles of sinusoidal signals with high resolution in time domain [3]. The PMU signals are then evaluated by an adequate processing algorithm, thus enhancing the functionality of the operator's Energy Management System. A threatening instability can then be quickly assessed by a direct connection to FACTS (Flexible AC Transmission Systems).

> A significant benefit of a WAMS is its ability to detect dynamic wide-area phenomena in real-time, thereby allowing for direct counter measures.

Further cooperation

Every large grid has its characteristic inter-area oscillations. In the Scandinavian power system the main oscillatory modes are between 0.3 and 0.5 Hz. Such oscillations are known to the planning departments of system operators from off-line studies. Oscillations can be quantitatively characterized by several parameters in the frequency- and time-domain, such as modal frequency and damping, amplitude and phase. One of the significant benefits of a WAMS is the possibility to detect dynamic wide-area phenomena such as electromechanical oscillations in real-time, allowing for direct countermeasures.

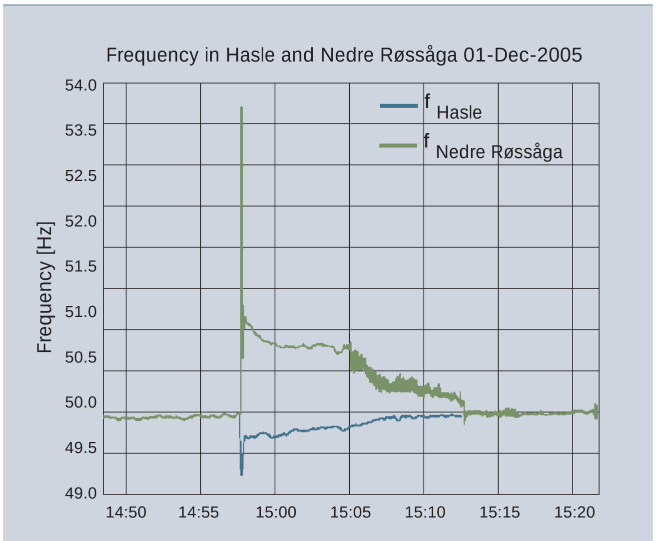
To get a comprehensive overview of the oscillations with as few measuring sites as possible, the first step was the selection of appropriate sites for those few PMU installations. To successfully do this, the following had to be considered:

- The possibility of detecting the characteristic swing modes
- Access to line voltage and current measurements from metering devices
- Access to existing Ethernet communication links to rapidly disseminate the rich information from a PMU to a data processing unit

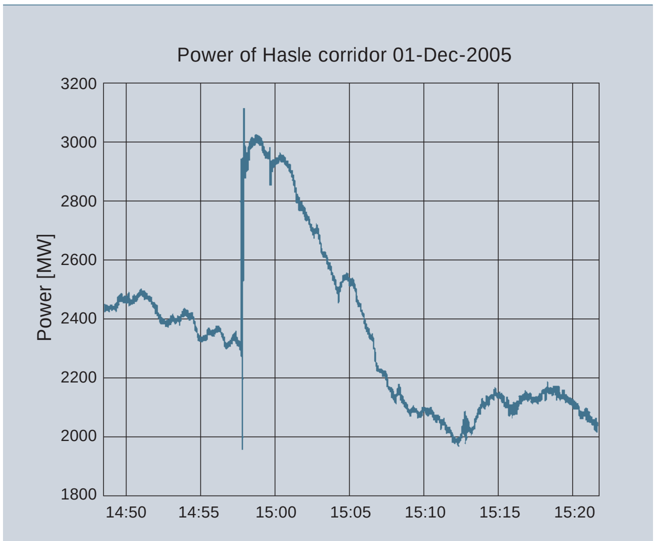
A detailed analysis together with the customer and his profound knowledge of the system led to the selection of four sites: Hasle, Fardal, Kristiansand, and Nedre Røssåga substations 1.

Countless measurements were collected at these four PMU stations and analyzed in order to demonstrate system information in normal operating conditions, and the dynamic response during more critical system disturbances. For example, on December 1

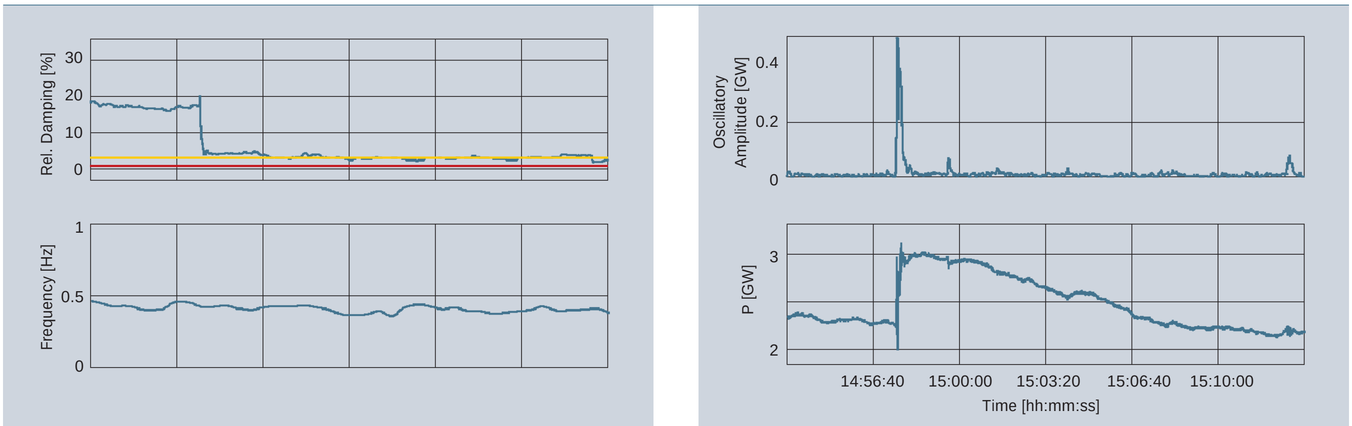
2 Captured system frequencies in Southern Norway (Hasle) and Mid Norway (Nedre Røssåga)



3 Power flow on 420 kV lines from Hasle towards Sweden



4 Monitoring results: the relative damping, frequency, and oscillatory amplitude are the real-time estimates of the most dominant oscillatory mode contained in the measured response P



2005 a large disturbance occurred in the Nordic power system. The disturbance was initiated by a fault in Northern Sweden. Transfer trip schemes, which should have shed generation in Norway, failed, leading to surplus generation and subsequent overloading of remaining power transmission lines in Northern Norway. This led to an uncontrolled collapse and the formation of several islands in Northern Norway.

The wide area impact of this local disturbance is clearly seen – in real time thanks to the time synchronized recording – in the PMU measurements shown in 2 and 3[1]. 2 shows the system frequency as derived from voltage phasor measurements in Hasle (Southern Norway) and Nedre Røssåga (Northern Norway), respectively. The time of network separation and resynchronization are easily detected. The system imbalance due to a cut-off of a significant generation surplus area in the north of Scandinavia led to the activation of primary reserves in the rest of the system. The sudden increase in power flow on the Hasle corridor (power flow towards Sweden indicates that a large amount of the power deficit is compensated by generation in Southern Norway.

To estimate the stability of the complete, widely extended grid in real-time, carefully selected PMU signals are run through an analysis which employs a model-based approach[2]: An autoregressive model with time-varying coefficients and Kalman filtering techniques optimally identifies the best suited model parameters [4]. This method, for the on-line detection of oscillations, was applied to the measured response of power transfer

5 Controller tuning for 0.33 Hz mode regulating the SVC in Sylling using angle measurements from Nedre Røssåga and Kristiansand

Footnotes

[1] In the past, such a wide-area dynamical view would have been difficult and time-consuming to assemble and would only have been possible after the event had occurred.

[2] Its extension to a model-based controller design is possible in the future.

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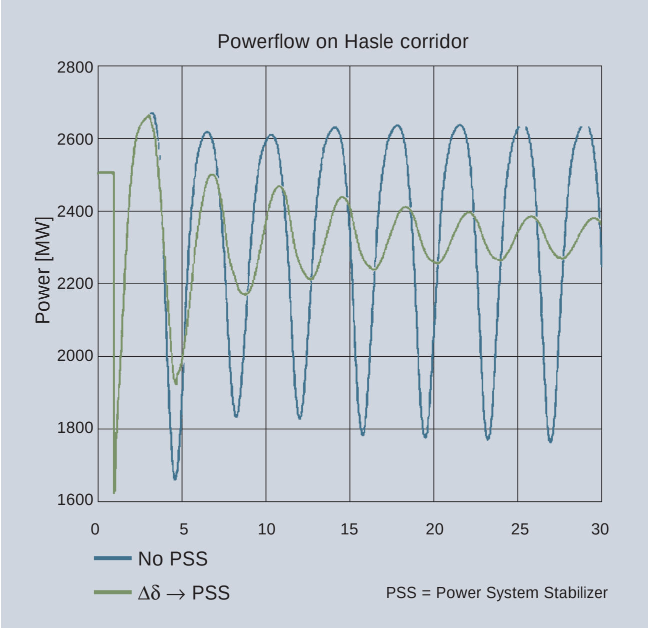
across the Hasle interface 3 during the December 2005 disturbance.

The resulting estimate of the dominant oscillatory mode is shown in 4. The step-like change in relative damping from approximately 15 percent before the initiating event to between 4 and 7 percent during the period after the disturbance can be clearly seen. The modal frequency, which is a function of the network topology and connected elements, remains more or less unchanged; it hovers around its mean value, changing only slightly after the disturbance from 0.39 to 0.42 Hz. Similarly, the estimated oscillatory amplitude increased temporarily in the first 15 seconds after the event. By appropriately choosing alarm thresholds, this type of information can easily be used to automatically trigger operator warnings.

6 Power flow on Hasle corridor with and without damping controller



> Close cooperation such as that between ABB and Statnett is the only feasible way to develop solutions for the challenges of a complex system like a power grid.

Once these warnings are received, the operators have to take corrective action to stabilize the system. At present, several SVC units (Static Var Compensator – a FACTS device) in the Norwegian system are equipped with Power-Oscillation Damping (POD) functionality, using local measurements (eg, bus voltage or power) which contribute to the damping of inter-area electromechanical oscillations as input. While this works well, local measurements may not in all cases provide adequate mitigation of critical inter-area modes.

The aim of the current common project between Statnett, SINTEF and ABB is therefore to investigate how remote measurements from PMUs can best provide input signals to damp the critical modes in the extended grid using the existing SVC actuators.

As a first step towards this objective, a computer simulation study was conducted on the PMU measurements at Hasle, Kristiansand, Nedre Røssåga, and Fardal. To obtain the optimal damping controller parameters, several existing automatic control approaches (lead-lags, robust H∞ design, and adaptive methods) were tested. of the 5 and 6 show how the SVC unit in Sylling, close to Oslo, can be tuned to damp oscillations around 0.33 Hz using voltage angles from PMUs in Kristiansand and Nedre Røssåga.

The resulting damping of the low frequency mode clearly demonstrates the benefit of WAMS technology in that it is possible to take informed as well as timely control and protection actions based on high resolution PMU measurements.

Lessons learned

The close cooperation of technology providers such as ABB, and technology users like Statnett is the only feasible way to develop solutions for the challenges of a complex system like a power grid. The technical problems addressed here are very similar for many other energy systems and operators. The unique experience ABB gained in this joint R&D collaboration provides critical feedback and direction for development of new products, which in turn leads to improved utilization of existing grids in a reliable manner.

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