Kjetil Uhlen, 16.01.2019

Resultatrapport

Project no. 246784: Operation of the Smart Grid with Wide Area Information

Summary

This is a collaborative project between the Norwegian University of Science and Technology (NTNU, project leader, Prof Kjetil Uhlen) and Motilal Nehru National Institute of Technology (MNNIT, project leader, Prof. Nand Kishor) in Allahabad, India.

The project has performed research into operation and control of power grids with the objective to meet the future challenges in realizing sustainable energy systems. More specifically, the project has analyzed and developed new methods for *wide area monitoring, protection and control*. The motivation behind this is that power systems are becoming more and more complex. Higher variability and uncertainty in power flows make it increasingly challenging for operators to manage the power balance and consequently the security and quality of supply.

On the other hand there more measurements and information available, as well as new components that can be utilized for control and protection. This project focuses on PMUs (Phasor Measurement Units) and how information from phasor measurements can be utilized to improve operators' situational awareness; and further to improve control and protection systems.

The methods and application areas dealt with in the project include:

- Use of system identification techniques to monitor hydro power plant dynamic performance (PhD-study at NTNU)
- A topology-based scheme for islanding detection and adaptive under-frequency load shedding
- Fault identification in network with coil compensation at transformer neutrals
- Coordinated design of oscillation damping controllers and optimization of power system stability
- Contribution to development and implementation of methods for
    - Detecting limits for voltage and transient angle stability
    - Inertia estimation
- Wide area monitoring of sustained power oscillations using two stage mode decomposition
- Determination of mode shapes in PMU signals using two stage mode decomposition and spectral analysis
- Power system event detection utilizing time-frequency representation of synchrophasor data

Several of the methods for power system monitoring have been tested with real system data and reached a state where they are ready to be implemented as prototype tools. The proposed method for protection and control are at an earlier stage of development, which requires further research.

The project has hosted two workshops at MNNIT in Allahabad and two workshops at NTNU in Trondheim with participation from project partners and external experts.

Another benefit of the project collaboration was the possibility to arrange a five days international course at MNNIT on "*Smart Power Grid Operation and control: Use of PMUs*", where Prof. Kjetil Uhlen was the main lecturer.

1. Background and objectives

This project deals with the development of new methods for monitoring and control of large power systems in the *smart grid* context. Specifically, we look at utilization of system-wide measurements (PMUs/synchrophasors) to provide power system operators with improved information and diagnostics that will be necessary for managing the future power systems dominated by variable renewable energy sources.

The objective is to develop, demonstrate and validate smart and robust solutions for grid operation.

The collaboration between NTNU and Motilal Nehru National Institute of Technology (MNNIT) was initiated with an aim to take advantage of complementary expertise. The group of Prof. Nand Kishor at MNNIT has very good expertise within signal processing and system identification theory, which is necessary to develop the monitoring applications. The project group at NTNU, on the other hand, has better knowledge and more experience related to operation and control of power systems as such.

The Indian and the Nordic power systems are naturally very different in composition and size. It is still a fact that the operational challenges are very much the same. Effective monitoring systems to enhance situational awareness and robust control systems to ensure system stability and security are equally important in both systems.

There are ambitious plans for installation and use of phasor measurement units (PMUs) for improved monitoring, protection and control in both the Indian and Norwegian power grid. A common challenge is to make use of all the information that become available and develop applications that significantly benefit system operation and security. By sharing experiences and knowledge, we are better prepared to address the common challenges in the two apparently different systems.

2. Research plan and main results from Norwegian side

The project was planned with six main work packages:

WP1: Problem definition and Model developments
WP2: System analysis
WP3: Development of monitoring applications
WP4: Development of protection applications
WP5: Development of control applications
WP6: Dissemination

The results from the project are related to development of new methods for monitoring, protection and control. The reporting will therefore focus on work packages 3, 4 and 5. Model developments and system analysis were an integrated part of the developments and verification of all methods. Dissemination activities are described in a separate section.

WP1: Problem definition and Model developments

Models and measurements are needed when developing new methods and tools. The aim of WP1 is to specify the need for development of new models and simulation tools.

Some models were developed for specific applications, but as much as possible the project has used available models that are representative of the Nordic power grid and parts of the Indian transmission grid.

Whenever possible, we chose to use available PMU measurements from the Nordic and Indian power grids for testing and verification of monitoring applications.

WP2: System analysis.

There were no defined task for NTNU in this work package.

Work package 3 (WP3): Development of monitoring applications

The objectives are related to monitoring of dynamic system behavior, including the following tasks:

- ✓ On-line monitoring of voltage stability
- ✓ On-line estimation of important power systems characteristics, such as inertia and frequency drop
- ✓ On-line monitoring of the system stability limits
- ✓ Tools to improve situational awareness and identification of critical operating conditions.

The main results are summarized in the table below:

Task	**Main result**	**Researches and partners involved**	**Refs.**
On-line monitoring of voltage stability	This work has contributed to development and implementation of methods for voltage stability. A results from this is that one method is now implemented at Statnett's prototype Wide Area Monitoring system through a separate project[1].	Dinh Thuc Duong Stefan Polster Kjetil Uhlen	[1]
On-line estimation of important power systems characteristics, such as inertia and frequency drop	The use of system identification techniques is analysed and applied to monitor hydropower plant dynamic performance with respect to frequency control. This has been the main topic of a PhD-study at NTNU. Contribution to development and implementation of a method for on-line estimation of Inertia in the power system.	Sigurd Hofsmo Jakobsen (PhD candidate in this project) Dinh Thuc Duong Kjetil Uhlen Kaur Tuttelberg Kjetil Uhlen Hasala Dharmawardena	[2]-[5] [6]-[8]
On-line monitoring of the system stability limits	This deals with on-line monitoring and estimation of limits with respect to transient stability. A novel method has been proposed and analysed that is based on a Robust Sum-of-Squares Optimization Approach	Lester Kalemba Kjetil Uhlen	[9]

[1] ENERGIx project no. 256334/E20: Control Centre Platform for Synchrophasor and PMU Applications, Integration and Data Exchange (SPANDEx).

Tools to improve situational awareness and identification of critical operating conditions.	This refers to the prototype tools that have been implemented for testing and demonstration purposes: ✓ Methods for voltage instability detection ✓ Scheme for islanding detection and adaptive under-frequency load shedding. This is further described below under system protection.	Dinh Thuc Duong Kjetil Uhlen	[1] [10]

Work package 4 (WP4): Development of protection applications

The planned objectives were stated as to:

- ✓ Identify and demonstrate coordinated approaches for the design and execution of system protection schemes
- ✓ Investigate the possibilities and risks of using system protection schemes to increase transmission capacity

The work focuses on *system protection schemes*. System protection is different from traditional relay protection as the purpose is to protect the integrity of the system as a whole, rather than isolating failures and protecting components. The aim of system protection is thus to reduce the risk of wide spread blackouts or to enable increased transmission capacity. System protection schemes includes a monitoring part to identify critical conditions and a control part to perform corrective actions. Thus, there is a certain overlap between monitoring, protection and control applications.

The main results that address protection issues are summarized in the table below:

Task	**Main result**	**Researches and partners involved**	**Refs.**
Adaptive under-frequency load shedding	Under-frequency load shedding schemes are used in most power system in order to avoid total blackouts when large unbalances lead to critical low frequency or when parts of the grid become isolated. In this task, an adaptive scheme for load shedding has been developed based on continuous monitoring of the network topology. The scheme ensures that a minimum amount of load can be disconnected while reducing the risk of a total blackout.	Dinh Thuc Duong Kjetil Uhlen	[10]
Fault location in “coil-compensated” networks	In some sub-transmission networks (typically 66kV and 132kV in Norway), transformer neutrals are grounded through so-called *Petersen coils* with the aim of reducing fault currents as much as possible. However, when fault currents are small, it is very difficult to identify where the fault is. The result from this task is a new	Dinh Thuc Duong Kjetil Uhlen	Not published

	prototype tool that uses information from PMUs to identify the location of faults. This work is not published yet due to on-going investigation of its commercial value.		
System protection from on-line monitoring of system stability limits	The method for on-line monitoring of transient stability limits based on a sum-of-squares (SOS) approach is included here as the final use of this method is expected to be part of a system protection application.	Lester Kalemba Kjetil Uhlen	[9]

Work package 5 (WP5): Development of control applications

The objectives were stated as to develop coordinated control schemes utilizing phasor measurements for optimum voltage control and power system damping, utilizing available FACTS devices and HVDC converters. Hereunder to develop tools for enhanced transient stability and inter-area oscillation damping control.

The main results that address control applications are summarized in the table below:

Task	**Main result**	**Researches and partners involved**	**Refs.**
Coordinated control for secondary voltage regulation and activation of reactive reserves	This work has developed and analysed a multivariable, Model Predictive Control based scheme for secondary voltage regulation and coordination of reactive power reserves. The proposed scheme is validated using an equivalent model of the Nordic power system. Results show that Model Predictive Control can be effectively applied to improve the management of reactive power reserves in a power transmission network.	Lester Kalemba Kjetil Uhlen	[11]
Coordinated design of power system stabilizers	This work proposes and analyses a two stage methods for coordinating the design and tuning of power system stabilizers when utilizing wide area measurements.	Lester Kalemba Kjetil Uhlen	[12]
Optimal generation dispatch to improve power system damping	Ensuring sufficient damping is one of the stability requirements that must be maintained at all times in power system operation. This work proposes a method, which finds the minimum amount of generation or load to be re-dispatch in order to satisfy stability requirements. Such a solution can for example be implemented in conjunction with the balancing power market.	Thiago J.M.A. Parreiras Kjetil Uhlen	[13]

3. Summary of results from Indian side

Results that were achieved from the tasks led by MNNIT are briefly summarized below. The main contributions from NTNU's side to these tasks were to provide data and case studies of interest, and to supervise the Indian researchers in their work. Further details are reported in the reporting by our Indian partner. Three main areas have been investigated:

Wide area monitoring of sustained power oscillations using two stage mode decomposition.

This activity applied system identification techniques to detect system-wide power oscillations based on PMU measurements. Ref. [16].

Determination of mode shapes in PMU signals using two stage mode decomposition and spectral analysis.

Mode shapes characterize oscillatory modes in the power system. In this activity, signal-processing methods were applied to identify which generators or parts of the grid that contributes to power oscillations. Operators can use this information to decide where actions should be taken to mitigate the oscillations before they cause critical system instabilities. Refs. [17]-[20].

Power system event detection utilizing time-frequency representation of synchrophasor data.

When large amount of synchronized voltage and current measurements are available from PMUs (synchrophasors), a main challenge is to extract information that is useful for operators. In this task, various system identification techniques were applied in order to detect and identify critical grid disturbances, such as short circuits and sudden loss of generation and load. Refs. [21]-[23].

4. Collaboration, exchange visits and workshops

This relates to WP6 Dissemination, and the milestones of the project

Work package 6 (WP6): Dissemination

The objectives are:

- ✓ Demonstration and power system analysis in the smart grid or renewable energy laboratory
- ✓ Reporting and dissemination

Demonstration and verification of results are performed through simulation studies and by off-line testing where the methods were applied to real PMU data that are available from the Norwegian and Indian power grids.

Methods for voltage instability detection and power oscillations have also been thoroughly tested and demonstrated in a laboratory set-up in the Norwegian Smart Grid Laboratory.

The collaboration and dissemination activities have been performed according to the milestones that were specified in the project plan. Further details on this below:

Milestones: The table shows the planned milestones and indication of the work packages they are linked to.

MS #	Milestone	Deadline (Month)	Related WPs
1	Kick-off: Establishment of project plans and Identification of development tools	3	All
2	Workshop on modelling and system analysis in India	12	1, 2
3	Workshop on wide area monitoring, control and protection in NTNU, Norway	24	3, 4, 5
4	Dissemination and final reporting	30-36	6

A particular challenge in a collaboration project between Norway and India is how to deal with the cultural differences and the geographical distance. If not taken seriously from the start this could lead to misunderstandings and different expectations with respect to outcome of the project and the way we carry out and lead the work.

Good communication from the start is therefore essential, and we decided to have regular Skype meetings every 2 weeks in order to maintain regular interactions. We also decided to arrange two of the planned workshops (one in India and one in Norway) during the first year of the project in order to get to know each other better at an early stage.

The first workshop, in November 2015, was held in Allahabad in conjunction with the university's "Conference on Engineering and Systems (SCES2015)". Prof. Kjetil Uhlen was invited as keynote speaker, and we had separate meetings and discussions of joint work.

The second workshops was held at NTNU in June 2016. A delegation with professors and PhD student from MNNIT, Allahabad visited us at NTNU for further discussions and planning of work ahead.

The third workshop was again held at MNNIT, Allahabad during the week 5-10 November 2017. This was arranged in conjunction with a GIAN[2] course on "Smart Power Grid Operation and control: Use of PMUs", where prof. Kjetil Uhlen was invited as main lecturer.

At the final workshop at NTNU, 31 May 2018, the participants gave presentations on status of their work, and in particular, this was important for discussions on further work and exploitation of the results.

5. Project Execution and Resources

The project is carried out mainly according to plan and budget. Costs are slightly lower than budgeted.

The collaboration and communication with the Indian partners were executed through the workshops, as described above, and through work on joint publications.

Regarding resources, the project has fully financed the PhD-study by Sigurd Hofsmo Jakobsen, who is in the process of submitting his thesis. It has also financed part of the post-

[2] Global Initiative of Academic Networks (GIAN): http://www.gian.iitkgp.ac.in/

doctoral work of Dr. Dinh Thuc Duong. Other researchers that have contributed to the project are:

- ✓ Dr. Lester Kalemba contributed significantly in all work packages and specifically to WP5 on control.
- ✓ Kaur Tuttelberg, from Technical University Tallinn, Estonia, spent six months at NTNU during his PhD study.
- ✓ Stefan Polster, from Technical University Graz, Austria, did his master thesis at NTNU and have spent three months with us after starting his PhD study.
- ✓ Thiago J.M.A. Parreiras, from CEPEL and Federal University of Rio de Janeiro, Brazil, spnt three months at NTNU during his PhD study.
- ✓ Hasala Dharmawardena, MSc student at NTNU, contributed to modelling activities and participated at the first workshop and conference in Allahabad.

6. Impact

The research work and results from the project must be seen in conjunction with the ongoing collaboration between NTNU and Statnett within the strategic area of Smart Grids. This project is one in a series of research activities aiming at smarter and more intelligent operation of the power system.

Results from this project have already contributed to implementation of prototype tools that are being tested at Statnett. Applications for voltage stability assessment and power oscillation monitoring are being further developed and implemented within the IPN-project SPANDEx.

One main result attributed solely to this project is the method for on-line monitoring of hydropower plants with respect to frequency control performance. If or when implemented, this will have a major impact on how power plants can more easily qualify for and deliver Frequency Containment Reserves. A collaboration with Statnett and Statkraft has been initiated to develop this further.

The scientific results are disseminated as technical publications and presentations at international conferences. 23 papers were published by the end of 2018 associated to this project. Three more is in process.

7. References

List of publications from tasks led by NTNU:

[1] S. Polster; H. Renner; D. T. Duong; K. Uhlen: “Voltage stability monitoring using a modified thevenin impedance”, Proc. 2017 IEEE Manchester PowerTech, Manchester, UK, 18-22 June 2017.

[2] Dinh Thuc Duong; Kjetil Uhlen; Erik Alexander Jansson: «Estimation of hydro turbine-governor system's transfer function from PMU measurements“, Proc. 2016 IEEE Power and Energy Society General Meeting (PESGM), Boston, MA, USA, 17-21 July 2016.

[3] Sigurd Hofsmo Jakobsen; Kjetil Uhlen: «Vector fitting for estimation of turbine governing system parameters”, Proc. 2017 IEEE Manchester PowerTech, Manchester, UK, 18-22 June 2017.

[4] Sigurd Hofsmo Jakobsen; Kjetil Uhlen; Xavier Bombois: “Identification of hydro turbine governors using PMU data”, Proc. 2018 IEEE International Conference on Probabilistic Methods Applied to Power Systems (PMAPS), Boise, Idaho, USA, 24-28 June 2018.

[5] Sigurd Hofsmo Jakobsen, Kjetil Uhlen: “Development of a test system for identification of turbine dynamics using the dc power flow”, IFAC-Papers OnLine, 2018

[6] Kaur Tuttelberg, Jako Kilter, Douglas Wilson, Kjetil Uhlen: “Estimation of Power System Inertia From Ambient Wide Area Measurements”, IEEE Transactions on Power Systems, Volume: 33 , Issue: 6, 2018

[7] Hasala Dharmawardena; Kjetil Uhlen: “Modeling variable speed wind turbine for power system dynamic studies”, 2015 IEEE Students Conference on Engineering and Systems (SCES), Allahabad, India, 6-8 November 2015.

[8] Hasala Dharmawardena; Kjetil Uhlen; Sverre S. Gjerde: «Modelling wind farm with synthetic inertia for power system dynamic studies“, Proc. 2016 IEEE International Energy Conference (ENERGYCON), Leuven, Belgium, 4-8 April 2016.

[9] Lester Kalemba; Kjetil Uhlen; Morten Hovd: «Stability Assessment of Power Systems Based on a Robust Sum-of-Squares Optimization Approach”, Proc. 2018 Power Systems Computation Conference (PSCC), Dublin, Ireland, 11-15 June 2018.

[10] Dinh Thuc Duong; Kjetil Uhlen: “A topology-based scheme for adaptive underfrequency load shedding”, Proc. 2017 IEEE Manchester PowerTech, Manchester, UK, 18-22 June 2017.

[11] Lester Kalemba, Kjetil Uhlen, Morten Hovd: “A scheme for optimal coordination of reactive-power reserves in a large power system”, PowerTech, Eindhoven 2015.

[12] Lester Kalemba; Kjetil Uhlen; Morten Hovd: «Two-tier approach for the design of multiple power oscillation damping controllers”, Proc. 2016 IEEE International Energy Conference (ENERGYCON), Leuven, Belgium, 4-8 April 2016.

[13] T.J.M.A. Parreiras, S Gomes, Glauco Nery Taranto, Kjetil Uhlen: “Closest security boundary for improving oscillation damping through generation redispatch using eigenvalue sensitivities”, Electric power systems research, 2018.

Publications from tasks led by MNNIT:

[14] Omkar Yadav, Richa Negi, Nand Kishor, Kjetil Uhlen: “Analysing Power Balancing as a Constant Power Source Operation in a MTDC System”, Proc. IEEE EnergyCon, April 4-8, 2016, Leuven, Belgium.

[15] Avinash Kumar; Sanjay Singh Negi; Nand Kishor; Kjetil Uhlen: “Signal processing and classification of synchro-phasor data“, 18th Mediterranean Electrotechnical Conference (MELECON), Cyprus 2016.

[16] Lalit Kumar, Nand Kishor, Ms Shweta: “Frequency Monitoring of Forced Oscillation in PMU data from NASPI”, 18th Mediterranean Electrotechnical Conference (MELECON), Cyprus 2016.

[17] Lalit Kumar, Nand Kishor: “Spectral-based dynamic analysis for estimation of mode shapes”, 12th IEEE Power and Energy Society PowerTech Conference (PowerTech), Manchester, 2017.

[18] Lalit Kumar, Nand Kishor: “Determination of mode shapes in PMU signals using two stage mode decomposition and spectral analysis”, IET Generation, Transmission & Distribution journal.

[19] Ms Shweta, Nand Kishor, Kjetil Uhlen, S. Mohanty: “Time-varying coherency study using TFC”,12th IEEE Power and Energy Society PowerTech Conference (PowerTech), Manchester, 2017.

[20] Ms Schweta, Nand Kishor, Kjetil Uhlen, Mohanty Soumya: “Identification of coherency and critical generators set in real-time signal”, IET Generation, Transmission & Distribution journal.

[21] Sanjay Singh Negi, Nand Kishor, Kjetil Uhlen, Richa Negi: “Post-processing algorithm for damped and step-change events detection in PMU signals”, 12th IEEE Power and Energy Society PowerTech Conference (PowerTech), Manchester, 2017.

[22] Sanjay Singh Negi, Nand Kishor, Avinash Kumar, Kjetil Uhlen: “Signal processing for time-frequency representation of synchro-phasor data”, IET Generation, Transmission & Distribution journal.

[23] Sanjay Singh Negi, Nand Kishor, Kjetil Uhlen, Richa Negi: “Event Detection and its Signal Characterization in PMU Data Stream”, IEEE Transactions on Industrial Informatics.

Prof. Uhlen lecturing at the GIAN course.

GIAN course participants with the Speakers