The Cell Controller Pilot Project:

Testing a Smart Distribution Grid in Denmark

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ABSTRACT

In order to hit ambitious national targets for the integration of renewable energy sources and the reduction of carbon emissions, the national Danish transmission operator has commissioned the Cell Controller Pilot Project. Coordinated smart control of existing distributed assets such as wind turbines, co-generation facilities and managed loads can support transmission operations during emergency condition, while also enabling enhanced market-based control over these assets during routine operations. The aim of the Cell Project is to develop the controllers and the data-acquisition, command, and communication infrastructure necessary to realize such wide-area control of a distribution grid.

At the time of the first series of comprehensive field tests in late 2008, the pilot solution had been deployed to a 100 km^2 area comprising two co-generation facilities, four 1 MW wind turbines, and approximately 5 MW of residential and commercial load. The 2008 Cell Controller release included two primary functions. The first manages the intentional islanding of the cell from the transmission system, its continued operation under local, distributed generation, and its resynchronization with the grid. The second controls a combination of distributed assets as a virtual generator in grid-connected operation.

This report presents the 2008 Cell Project testing.

1. INTRODUCTION

1.1. Project Goals

Over the last decade, Western Europe has experienced a number of significant power outages. Because of the predominantly vertical generation-transmission-distribution infrastructure, these incidents typically resulted in blackouts for very large groups of customers. That European infrastructure, however, is in a state of flux: the accelerating integration of solar and wind generation and local combined heat and power (CHP) facilities into the system is causing a noticeable decentralization of generation. In theory, it should be possible to leverage these increasingly distributed resources so as to ensure secure supply to the majority of end-users in case of an outage of central generation or transmission. The first major goal and the historical driver of the Danish Cell Project is to move beyond the theory, and demonstrate the practicality of using exclusively local supply during transmission emergencies.

Denmark is ideally suited for such an investigation, since, compared to most other countries, it currently exhibits a high penetration of distributed generation (DG). Over twenty percent of electric demand is already met by wind generation, and in fact, wind-generated power periodically exceeds national power demand. Moreover, the nationwide installed electrical capacity of decentralized cogeneration facilities exceeds the capacity of central power plants. The Cell Controller is being developed in order to tap this vast DG resource for enhanced supply security. Under emergency conditions, it can disconnect a portion of a distribution network from the transmission grid, manage it as a stable, islanded network, and, on receiving a signal from the transmission system operator, resynchronize it with the grid.

Since the Cell Controller is designed to be available for such emergency operation on a continuous stand-by basis, the communication and command infrastructure that its operation requires must also be on-line at all times, thereby creating the opportunity to make use of these resources for market-based operations while the grid is in its normal, secure operating state. For example, the Cell Controller can coordinate operation of available DG resources in such a way as to control active and reactive power flow to the transmission grid at given setpoints, thereby making a virtual generator of its portion of the distribution system.

The second major goal of the Cell Project is to develop and demonstrate such market-based functionality.

The first complete field tests of the Cell Controller and its support system took place during Fall 2008, and the full range of functionality was verified at that time. Those tests are the primary subjects of this report.

1.2. Project Development and Goals met To-Date

The Cell Project is being implemented in a pilot cell on a portion of a distribution grid on Jutland, the mainland peninsula of western Denmark. A prerequisite for operational capability of a central controller is the deployment of the infrastructure necessary to supply the controller with all needed measurements on the one hand, and to convey its setpoints and other commands back to the appropriate power system assets on the other. Accordingly, all assets to be controlled must be equipped with digital interfaces that implement the functionality necessary to decentralize the regulation as much as possible and to supply the Cell Controller with essential data. Figure 1 shows the abstract architecture of the Cell Controller system; the units labeled as Substation Controllers serve as data concentrators.

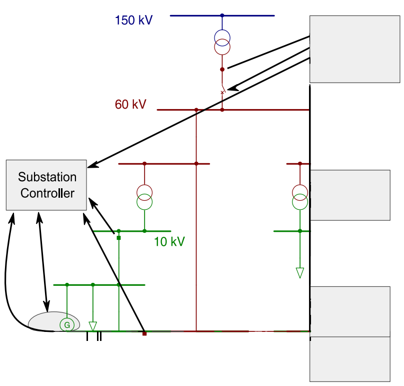

Figure 1: Abstract Cell Controller Architecture

The implementation of the data acquisition and command infrastructure is taking place in three stages. Figure 2 shows the pilot cell and its substations, wind, and CHP plants divided into three areas. At each step of the expansion, one area is added to the previously operational area(s). Currently, the data acquisition system has been commissioned for Areas 1 and 2, and the data are already yielding valuable indications of the distribution system's operating regime. Furthermore, the collected data form the starting point of ongoing simulation work.

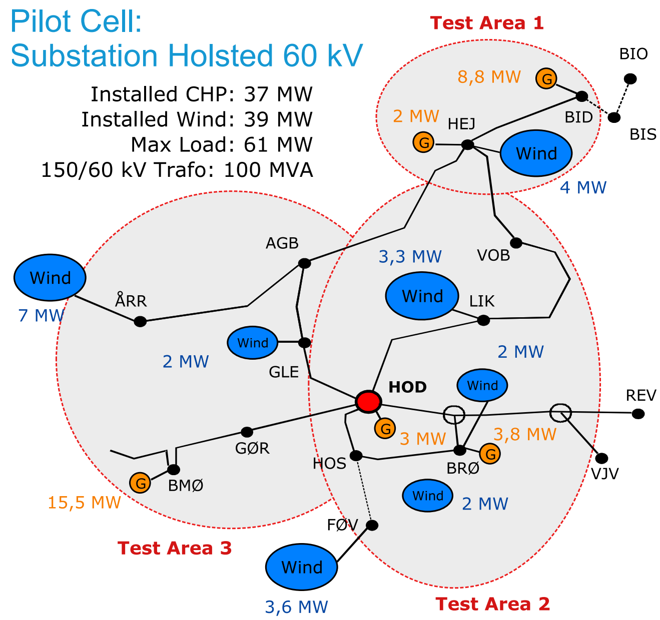

Figure 2: Stages of the Pilot Cell

Initial analysis of available grid data and generation assets showed that both load and wind transients during islanded operations and import/export load flow transients during grid-connected operation could occur at time scales faster than those that the available synchronous machines could respond to. Accordingly, in order to reduce the need to shed loads or generators during islanded operation, a synchronous condenser (SC) and a fast-switching load bank (Secondary Load Controller or SLC) were added to the distribution grid. Furthermore, the SC was equipped with a flywheel to increase on-line rotating mass, thereby improving frequency stability, especially for the smaller grid configurations.

Concurrently with these on-site hardware installations and upgrades, the project team was developing the Cell Controller software and a test and simulation environment. A professional power system simulation platform was selected, which allowed the detailed modeling of both the physical grid as well as the digital asset interfaces required by the Cell Controller. Consequently, it became possible to let the field-destined Cell Controller application control the modeled power system via the field-specified communication protocols. With this set-up, the behavior of the Cell Controller-enhanced grid can be simulated accurately, and in near real time. From the Cell Controller's point of view, there no essential difference between implementation in the field and implementation in the simulation environment.

2. FIELD TESTING

The first field tests of the developed Cell Controller were conducted during Fall 2008. After a variety of grid-connected testing, the smallest test region (Area 1 in Figure 2) was "islanded" 28 times. Prior to live testing, the feasibility of all planned test scenarios was verified by means of static and dynamic simulations.

2.1. Structure of the Tests

Area 1 of the pilot cell comprises two substations (60 kV/10 kV), the 60 kV tie between them and five 10 kV feeders at each of them. Generation consists of two CHP plants with a total of 5 gensets and four wind turbines. All wind systems are stall-regulated, and deliver power via a mechanical transmission and a capacitor-compensated, grid-connected asynchronous generator. Additional major equipment consists of the synchronous condenser and the secondary load controller, and a master synchronizer for managing the reconnection of the pilot cell to the grid at the 60 kV level.

A sequence of eight test cases was developed that would gradually increase the demands placed on the Cell Controller and the islanded power system. In the simplest case, just one synchronous generator was paired with a suitable combination of load feeders, with resynchronization to follow after a minimum of fifteen minutes of islanded operation. For later test cases and runs, islanding time was increased as high as 80 minutes.

For subsequent test cases, load and generation were increased, the SC and SLC were added to the system, and all operating modes were tested. In the penultimate test case, wind generation was gradually added to the grid. The final test case called for operating the cell with wind as the only on-line power source, supported by the SC and the SLC. The relative nominal capacities of the assets made this combination rather ambitious: each of the four wind turbines is rated at 1 MW, while the total controllable variable load (SLC) amounts to only 1 MW.

Individual test cases could be repeated with slight variations of system configuration or under varied external conditions (wind, customer load), so that several test runs were conducted for many of the cases.

2.2. Preparation for Testing

Prior to going to the field, the Cell Controller was tested in a power systems lab environment featuring a variety of generators, an SC and SLC, a wind power simulator, and loads. All control algorithms and communication methods were validated at this reduced scale by running the lab under conditions analogous to each proposed test case.

Meanwhile, detailed load data from the field was analyzed in order to be able to more accurately predict the load flows in the pilot cell during the proposed testing period. The analysis included annual, weekly, and daily load periodicities. Consideration was also given to changes in grid topology, such different configurations of the 60 kV distribution grid or the backfeeding of 10 kV feeders from alternate substations. Fluctuations in wind supply, however, were so strong that even short-term power forecasting could not be achieved on the basis of available data. On the other hand, it was possible to estimate the range of variation.

Based on the predicted customer loads and typical wind variation, all test cases were analyzed in the simulation environment. The complete distribution grid is modeled in software, as are the embedded controllers for generators, the SC, and the SLC. All models were validated with testing conducted at the time of infrastructure commissioning. Load feeders were modeled by composited general loads and were sized based on the analyzed field data.

The Cell Controller has multiple operational modes. In addition to rapid islanding and islanded operation, it can also regulate power import/export from the pilot cell during grid-connected operation. So that the Cell Controller's interactions with the power system can be simulated reliably and repeatably, each modeled asset includes a command interface to the same specification as the corresponding field equipment's. During dynamic studies, the controller can only poll those aspects of the simulated system's state that are analogous to measurements implemented in the field. In addition, operator commands (including those, such as enable/disable, that are issued to the controller) can be executed at specific simulation times via events, meaning that these simulations can be specified precisely and reproduced accurately.

In a first series of simulations, all anticipated operating conditions in both grid-connected and islanded states were run as simple load-flows. Already at this stage, some invalid conditions were detected: for example, in some flows, the necessary reactive power exceeded the on-line generators' abilities to supply it. The test plan was modified to ameliorate these conditions. Then, in a second series of trials, all (modified) test cases were run as dynamic simulations, including variations of load and wind models to represent anticipated field conditions. For each case, the risk of unplanned outages had to be minimized, so simulated voltages, currents, and frequencies were thoroughly analyzed against the distribution network operator's (DNO's) grid codes and protection settings (which were not changed from those used for ordinary, grid-connected operation) .

During this process, limitations in the implemented algorithms for generation- and load-shedding came to light. By adjusting the combinations of assets proposed for the field tests (and rerunning simulations for verification), all such limitations were avoided during the subsequent fields tests. The simulations also yielded valuable results on the limits imposed on the power flows across the grid breaker by the need to reliably switch the cell into islanded operation. The net output of all simulation phases were thorough and detailed recommendations ranges for configuration of the field test scenarios.

On-site preparation for testing was also carried out in several phases. Well before the planned islanding tests, all of the DNO's customers in the affected area were notified in writing of the up-coming work. Also, plans were put in place for the backfeeding of certain critical loads (e.g., a local theme park) during the entire test period, effectively isolating certain customers from the pilot cell's substations. Furthermore, contracts with producers (wind turbine and CHP owners) were put in place to cover the testing period, and short-term insurance to cover the remote possibility of equipment damage was purchased.

Over the course of three weeks, the various communication and remote control pathways were thoroughly verified to assure the full functionality of each asset. Errors were corrected as they were found and tests repeated until correct function was confirmed. This essential preparatory step was very time consuming, since every switch, meter, router, RTU, etc. of the overall system had to be checked in this way.

With a view toward later analysis of successful tests and immediate analysis/debugging of any failed tests, high-speed waveform recorders were deployed to capture the behavior of generating assets, major equipment (SC, SLC, master synchronizer), Cell Controller command timing, and load feeder restoration.

The next phase consisted of grid-connected testing of the Cell Controller. First, mode and setpoint control over single assets was verified. Next, by testing the import/export setpoint control, coordinated command over the cell was verified with CHP plants as the only source of generation in the cell. Finally, import/export control was tested in hybrid mode, i.e., with both CHP and wind generation on-line.

Finally, all islanding test were carried out in a two-week window of November 2008, with higher-risk tests during the second week, in order to confine the inconvenient possibility of multiple, short-term outages to as short a time span as possible. All tests had to be carried out during normal working hours Monday—Friday, in order to ensure maximum availability of DNO's engineers and linesmen in case of a problem.

2.3. Results

The 2008 field testing successfully achieved its major goal: to demonstrate the correct and coordinated operation of the Cell Controller, major equipment (SC, SLC, master synchronizer), and the supporting command, communication and data acquisition infrastructure on a live power system across a variety of test scenarios. In particular, the cell was intentionally islanded from the grid 28 times during testing. For all scenarios, the Cell Controller and its supporting equipment maintained the islanded cell within grid codes, and for all but the wind-only case, the cell was successfully resynchronized with the grid. When necessary, the Cell Controller managed the shedding of loads or generation, and restored customer loads while engaged in "islanded" operation.

Nevertheless, despite the painstaking preparation for testing, several unintentional outages did occur. In each case, the root cause was subsequently identified. For example, some of the low-voltage auxiliary systems at one CHP plant were connected to a feeder different from the one supplied by the plant, and this connection was not documented. A deliberate load shedding operation thereby caused an outage at the plant, resulting in the loss of several MW of generation, causing the cell to black-out. Also, all runs of the wind-only test case eventually resulted in black-outs. Due to the small size of the cell, the relative granularities of available loads and wind generation were low. Furthermore, the capacitive effect of the underground portion of the 60kV tie between the two cell substations could not be fully compensated by the SC. Consequently, taking into account the wind conditions at the time of a test run, there was no combination of available assets that the Cell Controller could have used to keep the active and reactive power balance in the cell.

In the final analysis, none of the outages was the result of a Cell Controller malfunction. One project target was not reached consistently, however: a time gap of at most one second between issuing the command to open the grid breaker and the islanding of the cell. While the measured gap value was under 1 s for the majority of test runs, communication delays and processing times pushed it over 2 s several times. Nevertheless, this is a respectable value that may, in the end, prove sufficient in practice.

In addition to showcasing Cell Controller functionality, the field tests were a valuable opportunity to the efficacy of the major equipment added to the power system as part of the Cell Project. In particular, the synchronous condenser contributed to voltage stability, while the secondary load controller managed active load.

The mini-island test was an ideal way to showcase the SC and SLC: during this test, the (mini-)cell consisted of a single wind turbine (0.69 kV) and the SC and SLC (both 0.4 kV), connected via a 10kV busbar. Figure 3 shows the action of the SLC during this test, and how precisely its load followed the highly variable turbine output, and how precisely frequency was maintained near the 50 Hz setpoint. As the plot shows, winds were highly variable during the test period, and after 5 minutes, a gust pushed production to well over 1000 kW (the maximum load of the SLC). Unsurprisingly, frequency then rose to 51 Hz, at which speed the wind turbine's overfrequency protection kicked in, ending the island.

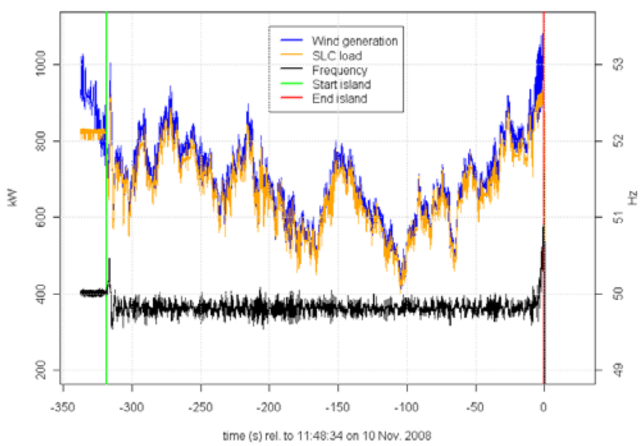

Figure 3: Effect of the SLC During the Mini-Island Test

In the mini-island test, the SC serves as the primary regular of cell voltage, as illustrated in Figure 4. In order to maintain system voltage, the SC must provide exactly the reactive power needed by the turbine's asynchronous generator, which is known to be proportional to the square of its active power production. Comparison of Figure 4 with Figure 3 illustrates the relationship. While the SC is regulating voltage, it maintains its voltage within 10 Volts of its 400 V nominal voltage. The greater deviation at the start of the island period is due to a delay between opening the breaker to form the island, and the SC's switch into appropriate control mode.

Finally, Figure 5 shows the Cell Controller regulating active power flow across the cell's grid breaker to specified setpoint by controlling two CHP units. The exact setpoint cannot be maintained, of course, since the control loop cannot run so fast that the CHPs must react to every variation in net load due to the stochastic changes in wind production and user loads.

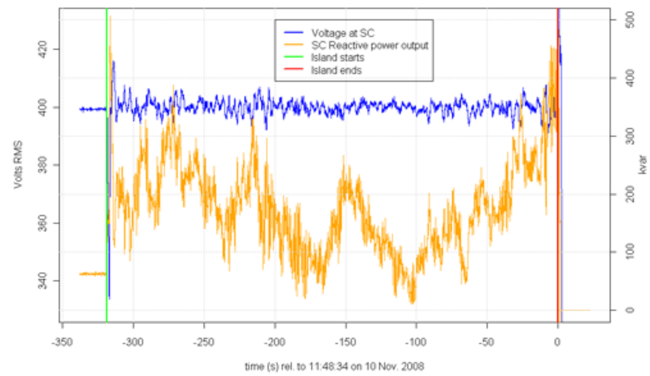

Figure 4: Effect of the SC During the Mini-Island Test

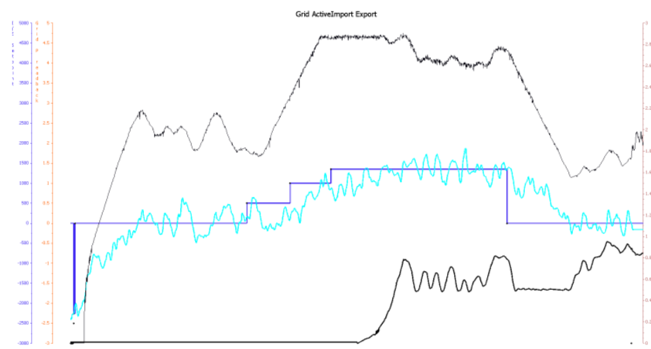

Figure 5: Import/Export Control

3. ONGOING DEVELOPMENT OF THE CELL PROJECT

After the successful testing of a small pilot cell consisting of Area 1 only, additional comprehensive testing for Areas 1, 2, and 3 combined (see Figure 2) is planned for 2009, 2010, and 2011. With the expanded grid, over 40 wind turbines and five CHP gensets will be added to the pilot cell's asset mix. Because the expanded wind portfolio will be widely distributed, one can expect that the fluctuations of individual turbines will balance each other out more completely than during the first phase of testing, so additional synchronous condensers and secondary load controllers are not planned at this time.

In addition to an expanded pilot cell for 2009, 2010 and 2011 testing, the current project phase calls for extensive Cell Controller development. First, the overall architecture continues to evolve with an emphasis on modularity and scalability. Also, existing algorithms are undergoing a thorough review/revision process. In addition, entirely new functionality is being added to the Cell Controller in the form of software modules. For example, an expanded virtual generator control will be implemented in grid-connected mode that will allow multiple arbitrary, independently controlled combinations of a cell's generating units to be made available as virtual generators on a market basis.

Furthermore, a closer coupling of the cell controller with the DNO's SCADA system together with integrated topology management will enhance system reliability and give the Cell Controller the ability to respond dynamically to the changing switch states of the larger pilot cell. Finally, the cell controller will have the ability to manage voltage locally, i.e., on a per-substation basis.

4. WIDER APPLICABILITY

Fundamentally, the Danish Cell Project is about smart distribution grids. While the particular asset mix – heavily weighted toward wind and heat/power co-generation – of the Pilot Cell is probably unique to Denmark, the general mix – distributed generation and managed loads – is not. Whether driven by greater energy independence, reduced carbon emission or the bottom line, photovoltaic production, wind-based production, plug-in electric vehicles, and smart homes, among others, will increasingly become part of a DNO's landscape. The success and continued expansion of the Cell Project establishes how smart participation of increasingly diverse and distributed resources can be leveraged for supply security and market operations.

5. PARTICIPATING COMPANIES

Energinet.dk, based in Erritsø, Denmark, is the national transmission system operator for electricity and natural gas in Denmark and owns the Cell Project. Per Lund and Stig Holm Sørensen manage the project for Energinet.dk.

Spirae, Inc of Fort Collins, Colorado, is responsible for execution of the Cell Project, including design, development, implementation and installation of the Cell Controller (Brendan Keogh, team leader) and the communication and command infrastructure (Nobin Mathew, team leader). Oliver Pacific and Sunil Cherian manage the project at Spirae.

Energynautics, GmbH of Langen, Germany has primary responsibility for modeling and simulation work in the Cell Project, and jointly worked out the project concept with Spirae. Simulations for the project were conducted by Nis Martensen and Eckehard Tröster, and Thomas Ackermann manages the project at Energynautics.

Syd Energi A/S, based in Esbjerg, Denmark, owns and operates the pilot cell's distribution network. At Syd Energi, Niels Graves Christensen coordinates with the Cell Project.

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BIOGRAPHY

Nis Martensen. received his Dipl.-Ing. in Energy Systems Engineering from the Technical University of Clausthal, Germany, in 2002. From 2003 to 2008 he worked as a scientific assistant at Technical University of Darmstadt, conducting research on the large-scale integration of small CHP units into virtual power plants. He plans to submit his doctoral dissertation to Technical University of Darmstadt by the end of 2009. He joined Energynautics in 2008, where he is responsible for modeling and simulation work in the Cell Project. His fields of interest are power system computing and modeling, energy efficiency and usage of renewable energy.

Holger Kley earned a B.A. in mathematics from Dartmouth College and an M.S. and Ph.D. in mathematics from the University of Chicago. After an eleven-year academic career at the University of Utah and Colorado State University during which he conducted research in both algebraic geometry and image recognition, advised graduate students and taught at all levels of the mathematics curriculum, Holger joined Spirae in 2008 in systems analysis. In his time with Spirae, he has conducted and analyzed power system simulations, developed methods to process and analyze test data, developed and implemented algorithms for power system control, and mapped scope and architecture for future platforms.

Sunil Cherian is the founder and CEO of Spirae, Inc. Spirae develops infrastructure solutions for distributed energy and smart grid applications and co-owns and operates the InteGrid Test and Development Laboratory in collaboration with Colorado State University.

Previously, Dr. Cherian founded Sixth Dimension, Inc. for providing networking technologies for the energy industry and served as its CEO from 1997 until 2002. Sixth Dimension was acquired by Comverge in 2003. Before beginning his entrepreneurial activities, Dr. Cherian served as Acting Director for the Colorado Manufacturing Extension Center and as Product Realization specialist for the Mid America Manufacturing Extension Center, both at Colorado State University.

Dr. Cherian has extensive experience in distributed energy applications. He is a frequent speaker at industry conferences and workshops and has been active in establishing the GridWise Alliance that promotes the adoption of innovative IT solutions for the transformation of the power system. He also serves on the Boards of the Northern Colorado Clean Energy Cluster and Colorado Cleantech Industry Assocation.

He earned his M.S. and Ph.D. degrees in Mechanical Engineering from CSU in 1991 and 1995 respectively. He has over fifteen publications in journals, conference and workshop proceedings, and has authored book chapters on software agent technologies and distributed generation.

Oliver Pacific is CTO of Spirae and brings more than 22 years of power generation experience in manufacturing, engineering, and field commissioning to the team. After earning his degree in from Idaho State University in power generation and distribution, he worked for Valley Power Systems for 13 years, where he became operations manager for the power products division. In that capacity, he managed manufacturing and engineering with more than 100 employees and annual sales of $30 million.

Subsequently, Oliver moved to Statordyne Corporation (and its GFI Energy Ventures subsidiary),a manufacturer of rotary UPS systems, where he served as Vice President of Engineering and as a consultant. At Statordyne, he led the use of CPS systems to produce peak efficiency in diesel power plants. He also led the design of a multiple-unit control system that included distributed generation, peak shaving and on-board SCADA.

Per Lund is head of System Design and Development at Energinet.dk. He earned his M.S. and industrial Ph.D. degrees in Electrical Engineering from the Technical University of Denmark (DTU) in 1983 and 1985 respectively. He is currently Senior Member of the IEEE, Danish national member of IEA ENARD Executive Committee and Head of the board for Centre for Energy Technology, DTU-Electro Institute.

In addition to the Cell Controller Pilot Project, the Dr. Lund is responsible for the development of a Phasor Measurement Unit and Wide Area Monitoring System R&D strategy for Energinet.dk and iii) the development of nation-wide technical grid codes for grid connection of thermal power stations, CHP plants and wind turbines.

From his previous employment in the Planning Department of the former Danish Electricity Consortium Elsam A/S and later as Senior Electrical Engineer in the Danish consulting company Techwise, Dr. Lund has a general background in power system planning in large utility-owned systems. He has gained comprehensive international experience in developing and utilizing computer systems for steady state and transient stability analyses used in the design and planning of power systems ranging from regional power pools to wind-diesel systems on small islands.