THE CELL CONTROLLER PILOT PROJECT: FROM SURVIVING SYSTEM BLACK-OUT TO MARKET SUPPORT

Nis MARTENSEN
Energynautics GmbH – Germany
n.martensen@energynautics.com

Per LUND
Energinet.dk – Denmark
plu@energinet.dk

Nobin MATHEW
Spirae Inc – Colorado/USA
nmathew@spirae.com

ABSTRACT

The Danish Cell Controller Pilot Project aims to develop, construct and test a full utility scale smart grid. The project intends to demonstrate an intelligent mobilization of the relatively large numbers of distributed generators in the Danish MV and LV distribution system. The grid-connected functions implemented in the Cell Controller system have been field tested in November 2010 with success, including market aggregator support, advanced voltage control, and Virtual Power Plant operations. Final field tests in 2011 also include island operation.

INTRODUCTION

The power systems of Denmark are characterized by a high penetration of Distributed Generation (DG) comprised of small to medium scale combined heat and power plants and wind turbines. Today, more than 55% of the total production capacity is dispersed throughout local Medium Voltage (MV) and Low Voltage (LV) distribution grids. The present situation is characterized by the fact that distribution networks have become active power producers. Several distribution companies have today installed DG capacity that outnumbers their total load many times over on windy days. They have become net power exporters. As a consequence, it has become more difficult to predict and to control the total electricity generation. The conclusion reached is that to maintain efficient and safe operation of the Danish power system with an increasing high share of DG aiming at 70% energy consumption produced by Renewable Energy Sources by 2025 it requires the traditional system architecture to be redesigned. One important element of the new system architecture will be closer integration between the national Transmission System Operator (TSO) and the Distribution Network Operators (DNO) which in turn requires a new intelligent communication system encompassing the entire infrastructure. This perception motivated the Danish national TSO to initiate a Cell Controller Pilot Project which aims to develop, construct and test a full utility scale smart grid. The project intends to demonstrate an automated, intelligent mobilization of the relatively large numbers of distributed generators in the Danish MV and LV distribution system.

In full cooperation with the Danish distribution company Syd Energi Net a full scale 60 and 10 kV distribution network below one 150/60 kV transformer substation has been selected as the targeted Cell area. Since 2005 this area has been equipped with a high speed fiber based data communication system reaching all assets in the area via distributed intelligent agent technology. Moreover a prototype of dedicated Cell Controller software has been developed and tested in a comprehensive software environment as well as in a large scale diesel engines laboratory.

The Cell Controller has been developed with a wide range of objectives:

- Providing a platform for market aggregators to operate their distributed generation re-sources in multiple power markets.
- Providing advanced voltage control functionality on both 60 and 10 kV voltage levels for DNO operation
- Providing TSO support by allowing operation of the Cell as a Virtual Power Plant for active and/or reactive power control (independently)
- Surviving transmission system black-out by safely transitioning the controlled distribution system (the Cell area) into automatic island operation

Algorithms for all functions have been developed and implemented in the controller software, and have been tested extensively in simulations. After a first successful field test phase in 2008 followed by extensive data evaluation, algorithm and design improvements, the project is now in its final prototype development and testing phase. As part of this phase all grid-connected functions were field tested in the full Cell area in November 2010. Results of these field tests are presented in this paper.

In order to provide more background, a short description of Cell Controller functions, architecture, and the pilot cell are given in the following sections. The remainder of the paper focuses on the 2010 field test results. An outlook on further field testing in 2011 is given in the conclusion.

CELL CONTROLLER FUNCTIONS

The Cell Controller system provides functions for normal, undisturbed, operating conditions as well as functions for alert or emergency situations. Activation of emergency functions always takes precedence, so that normal operation functions are suspended when necessary.

Market Operations Support

Active power markets support is available under normal operating conditions. Power balance responsible parties can group and dispatch their respective units in different power markets. According to the market specifications, day-ahead dispatch scheduling, merit order dispatch based on price information, and both up- and down-regulation are made available. Support for multiple markets is provided in parallel: Multiple market aggregators can dispatch different units in different markets at the same time, as long as any individual unit is operating in one specific market only. The Cell Controller has full topology awareness and performs load flow validation of dispatch commands to ensure that market commands do not violate power system limits or overloads any individual system component. This feature ensures power system stability and is a key differentiator of the Cell Controller.

DNO Voltage Control

Voltage control within the distribution grid is normally performed by automatic tap changer control at substation transformers. The Cell Controller system extends voltage control by including control of reactive power setpoints of generators. Any synchronous generator available for remote control can be utilized, including all units dispatched by market operators. However, no unit is dispatched for purposes of voltage control exclusively.

The enhanced voltage control thus available can be used to minimize tap changer action in order to reduce wear on the tap changers. When no synchronous machines are available for control, automatic tap changer action is performed as usual at the corresponding substation. The Cell Controller is aware of network topology and generator location; hence tap changer action and reactive power control complement one another on a per-substation basis.

The Cell Controller voltage control function for DNO operation is available under normal operating conditions and can work independently of the market operations mechanism. The Cell Controller is also able to provide voltage control under emergency conditions.

TSO Virtual Power Plant Operation

Operators of the transmission system to which the distribution grid “Cell” is connected may wish to influence active and/or reactive power flow from the distribution grids in certain operation conditions. The Cell Controller implements such virtual power plant (VPP) operation for active and reactive power independently: The reactive power flow to the transmission grid through the 150/60 kV transformer can be influenced by adjusting the reactive power setpoints of the online generators and static reactive power assets like capacitor banks and reactors without violating voltage limits. The TSO only needs to provide the desired setpoint at the point of connection. The Cell Controller automatically adjusts the generators’ reactive power setpoints, at the same time reducing voltage control to pure tap changer control.

In contrast to the reactive power VPP, the Cell Controller active power VPP implementation also dispatches generator units to reach the desired setpoints, bringing additional units online or offline as required. Market operations are suspended while the active power VPP is enabled.

Island Operation

Upon receiving a trigger signal, the Cell Controller can open the circuit breaker to the 150/60 kV transformer and thus transfer the Cell into island operation within a few seconds. Before the breaker is opened, load or generation will be shed in order to bring the active and reactive power balance within a range that can be handled by the online generation units. After opening the breaker, the Cell Controller then ensures that the most capable generation units take over voltage and frequency control. During island operation, additional generation units can be brought online in order to allow restoration of initially shed load feeders. The objective of this function is to maintain uninterrupted power supply to as many customers as possible, and reduce necessary outage of any feeder to the shortest possible time. The island operation function is an emergency function that will disable all other Cell Controller functions. Only a modified variant of voltage control is also applied in island operation.

All functions are implemented in a software architecture that applies distributed agent technology as much as feasible, enhancing portability and scalability of the system.

CELL CONTROLLER ARCHITECTURE

The Cell Controller needs to interact with synchronous generators in order to give setpoints and assign control modes, and to start and stop units as required for the high-level functions. Different interfaces are needed for interaction with wind turbines, substation transformers, load feeder breakers, and any other relevant assets.

On the lowest control level, **asset controls** must provide a set of basic functionality. For synchronous generators found in CHP units, this includes a control mode to operate at a given active power setpoint as well as an independent reactive power setpoint control. All asset controls must be available for remote control.

As the asset control implementation differs between individual generator sets, a thin **interface controller** abstracts away the particular user interface of the asset controller, allowing the Cell Controller to operate with a limited set of object classes without the need to implement interfaces to any possible asset controller. This control level also implements the common logic for starting and stopping the units.

The **Substation Controller** manages the communication to the individual interface controllers and acts as data aggregator towards the Cell Controller. It takes care of substation-specific controls such as 10 kV voltage control.

The **Cell Controller** application is responsible for implementation and coordination of high-level functions.

Parts of the market operation functions are implemented in the highest software layer, which represents the **Cell Controller User Interface**.

Asset controls and mostly also the interface controllers are located on-site at the assets. Substation controllers, Cell Controller, and user interface can run physically distributed across different machines, as long as sufficiently fast communication is available.

THE PILOT CELL

In cooperation with the Syd Energi DNO in western Denmark a suitable 60 kV grid cell was selected and equipped with the necessary metering and communication infrastructure. In addition, local asset controllers have been installed or upgraded where necessary. The full Cell area comprises:

- 5 CHP plant with a total of 15 gas engine driven synchronous generators totaling 32.5 MW
- 47 Danish-style wind turbines all larger than 600 kW with a total installed capacity of 37 MW
- One fast switching load bank of 1 MW
- One synchronous condenser of 800 kVA
- 13 each 60/10 kV substations with tap changer controlled transformers
- One each 150/60 kV substation with tap changer controlled transformer
- All 60 kV overhead lines and cables connecting all 60 kV substations
- 69 each 10 kV load feeders with all load and all smaller production units (CHP and WT) not included above

The full extent of the Cell area is more than 1000 km^2 and includes 28,000 registered power meters in rural areas, villages and small cities.
Prior to going into the field, the Cell Controller system has been tested extensively. This step is essential because failure in the field tests includes the risk of actual consumer black-out. Only after all major issues were resolved the road towards the field tests was cleared.

PRE-FIELD TESTING

Since 2007 the entire pilot cell has been modeled in a professional power system simulation tool. Until summer 2010, models for all dynamic asset controllers were built and have been validated extensively. The simulation model also includes an implementation of the asset interface layer, allowing the Cell Controller development team to test the Cell Controller against a realistic power system with hardly any configuration changes needed. In particular, all test cases planned for the field tests have been run multiple times against the model before.
In parallel, tests against a hardware test environment were performed in the InteGrid Lab at Colorado State University, a laboratory environment with multiple diesel generators, a wind turbine simulator, utility load simulator, fast-switching load bank and synchronous condenser. Also in this environment all test cases have been played through as accurately as possible, but also under varying conditions to identify limitations and worst-case performance.

2010 FIELD TESTS

Initial field tests had already been performed on a small section of the pilot cell in autumn 2008, including tests in island operation. Data gathered during these tests was used for model evaluation and tuning as well as evaluation of Cell Controller design decisions and algorithms. After bug fixes and software improvements, the November 2010 field tests in the full pilot cell mark the first part of the final round of field tests. All grid-connected functions have been tested in a limited number of test cases.

Active Power Market

Via the user interface to the Cell Controller SCADA system, CHP generator sets were to be grouped and dispatched in multiple markets. Note that the test included only the technical side of this process, hence the billing side of market operations was not relevant here. Success criterion for the active power market tests was that all units are brought online as per market operator command, and are brought offline again when scheduled. Any deviation from the expected unit commitment is considered a failure.
Altogether three test cases were run for three different market operation terms. In all cases, units were dispatched as expected. Control modes were always switched where required. All voltages throughout the Cell area was maintained within the desired limits and no power system component was overloaded. Hence, these test cases have been successful.
It should be noted that one test case involved dispatching the units in primary regulation market. Since the grid frequency remained stable during the test, there was no way to evaluate appropriate frequency response of the CHPs.

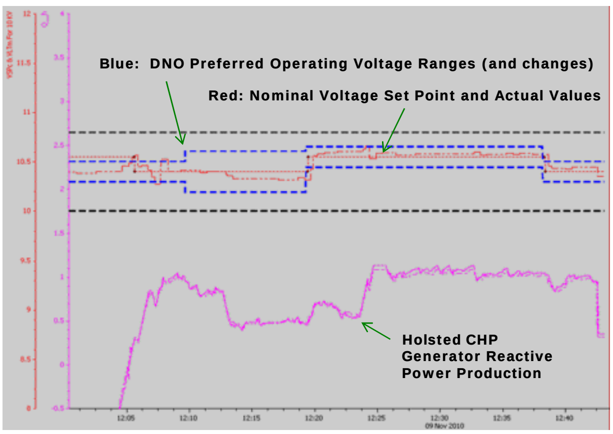

Figure 1: Voltage Control at Holsted 10 kV

Voltage Control

Two test cases were designed specifically to test voltage control. In the first test case, the transformer tap changer of the 150/60 kV transformer was set to manual control. The transformer tap was then hand-controlled up and down in a small number of steps. Expected result was that the Cell Controller adjusts CHP reactive power setpoints and 60/10 kV transformer taps to keep the voltage at the 10 kV level within the desired operating range. In the second voltage control test case, setpoint changes to the voltage control module were issued to the Cell Controller DNO user interface. The Cell Controller was supposed to respond to the modified setpoints by adjusting CHP reactive power setpoints and transformer taps, keeping the voltage at both 60 kV and 10 kV level within the desired ranges at all times.

During the field tests, the allowed voltage ranges were never violated, meaning that the voltage control function was successfully demonstrated. A sample plot from the second test case is shown in Figure 1.

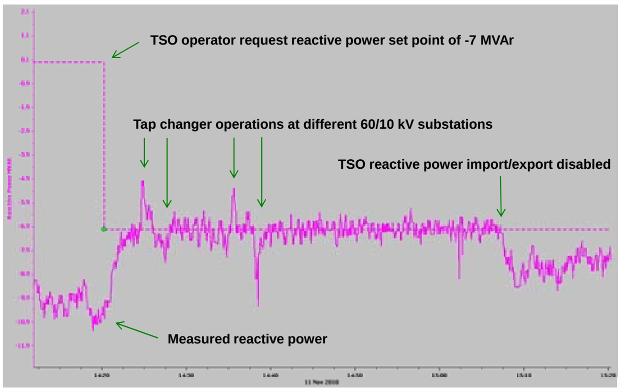

Figure 2: Reactive Power VPP Control

Reactive Power VPP

Reactive power virtual power plant operation was tested in one test case. Reactive power exchange across the 150/60 kV transformer was supposed to follow the given setpoints within the configured accuracy range, while keeping the voltage within the Cell within the allowed ranges at all times.

The reactive power virtual power plant test case was run in a public demonstration on 11 November 2010 – being a day of high wind production – and finished with success. Figure 2 shows the reactive power exchange during the test.

Active Power VPP

Operation of the Cell as active power VPP was tested in one test case. Active power load flow across the 150/60 kV transformer was supposed to follow the given setpoints within the configured accuracy range. Dynamic response to setpoint changes and wind/load fluctuations was considered as an additional performance criterion. During this test case, the voltage control function was supposed to prevent voltage limit violation at all times. Generators were dispatched via the market operation functions at the beginning of this test case and were supposed to return to their market operating point after disabling the VPP.

The result of this field test was a partial success: While the active power control function generally worked and no voltage limits were violated, the originally projected performance targets were not met. The interruption of market operations and handing back control after disabling the active power VPP worked correctly.

The 2010 field tests have been very successful. All tested functions performed as designed, and only minor issues with the active power VPP function were found. Evaluation of these issues has shown that some algorithms must be tuned.

CONCLUSIONS

The Cell Controller system is able to transform a utility scale distribution grid into a new system providing market support for multiple active power markets, enhanced voltage control for the DNO, and virtual power plant operation for TSOs; making use of the distributed energy resources available in a distribution grid today. The system has been field tested in a distribution grid in western Denmark with success. Final algorithmic tuning is necessary in only one tested high-level function. The improved algorithms will be field tested in the final round of field tests in 2011. Island functionality for increased security of supply is included in the system as an emergency function and will also be field tested in 2011.

The Cell Controller system provides a portable and scalable platform to fulfill the demands of the future power system. In distribution grids with high share of distributed generation resources the new platform is able to serve multiple purposes today. Benefits for consumers include increased security of supply; network operators obtain new means for voltage control and virtual power plant operations; and the system supports modern markets aiming to ensure fair consumer prices and steady and reliable revenue for market participants.

Future distribution systems integrating new resources such as demand side management, solar power, modern wind turbines, and other converter-based technologies, possibly even electric vehicles, will provide increased amounts of controllable assets. All of these can be integrated into the Cell Controller system, pushing the function limits beyond what is possible today.

REFERENCES

[1] P. Lund, S. Cherian, T. Ackermann, 2005, "A Cell Controller for Autonomous Operation of a 60 kV Distribution Area", *International Journal of Distributed Energy Resources*, vol.1, No.1, 83-100

[2] P. Lund, 2007, "The Danish Cell Project – Part 1: Background and General Approach", *IEEE Power Engineering Society General Meeting*, Tampa, USA

[3] S. Cherian, V. Knazkins, 2007, "The Danish Cell Project – Part 2: Verification of Control Approach vie Modeling and Laboratory Tests", *IEEE Power Engineering Society General Meeting*, Tampa, USA

[4] N. Martensen, H. Kley, P. Lund, S. Cherian, O. Pacific, 2009, "The Cell Controller Pilot Project: Testing a Smart Distribution Grid in Denmark", *Grid Interop 2009: The Road to an interoperable Grid, Proceedings*, Denver, USA.