Simulations and Tests of a Danish Smartgrid

The Cell Controller Pilot Project

Eckehard Tröster, Nis Martensen, Thomas Ackermann
Energynautics GmbH
Darmstadt, Germany
e.troester@energynautics.com

***Abstract*— The Cell Controller is an intelligent control system for distributed energy resources (DER) that improves security of supply—by means of emergency island operation capability—and provides a platform for TSO (Transmission System Operator) support operation and market operations. Furthermore, the Cell Controller provides a platform for enhanced automated support of DNO (Distribution Network Operator) operations in medium voltage distribution systems characterized by large amounts of DER. Functions implemented in the Cell Controller system have been field tested with success, including island operation, market aggregator support, advanced voltage control, and Virtual Power Plant operations.**

Keywords-Distributed Energy Resources, Smart Grid, Distribution System, Virtual Power Plant, Island Operation, Voltage Control

I. 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. The present situation is characterized by the fact that distribution networks have become active power producers. Several distribution companies have installed DG capacity that outnumbers their total load many times over on windy days. They have become net power exporters. Consequently, it has become more difficult to predict and 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 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 Energinet.dk to initiate the Cell Controller Pilot Project, which aimed 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 before going into the field. In several test phases followed by extensive data evaluation, algorithm and design improvements, the cell-controller has demonstrated its capability to fulfil the desired features including grid-connected functions as well as islanded operation. In order to provide more background, a short description of the Cell Controller functions, architecture, the pilot cell, and the performed tests are given in the following sections.

II. 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.

A. 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.

B. 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 distributed 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 DGs 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 [1].

C. 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. By monitoring wind speed measurements at the wind turbines, the Cell Controller treats offline wind turbines as a non-spinning reserve and can bring them online as needed. Wind turbines can also be disconnected when the Cell is required to reduce its active power export [2]. Market operations are suspended while the active power VPP is enabled.

D. 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.

III. CELL CONTROLLER ARCHITECTURE

The Cell Controller needs to interact with DGs 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.

IV. 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 controller 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 totalling 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 load and all smaller production units not included above

The full extent of the Cell area is more than 1000 km² and includes 28,000 registered power meters in rural areas, villages and small cities.

V. Testing the System

One of the most significant accomplishments of the Cell Controller Pilot Project was the extensive field deployment, testing and general success of demonstrations on a live power system. The success of the live test highly depended on the accuracy of the utilized model and studies performed prior to the real implementation.

A. Lab test

Before the Cell Controller has been tested in the actual pilot implementation in the selected Danish distribution network, the Cell Controller was tested in detail at the InteGrid Test and Development Laboratory in Fort Collins, Colorado, USA. InteGrid Test and Development Laboratory was designed and built to facilitate the development and testing of the next generation of smart grid control technologies. The initial series of tests for the Cell Controller Pilot Project include setting up a scaled physical simulation of a portion of the selected pilot distribution network in Denmark with four wind turbines, two CHP plants, two substations, and multiple load feeders. The Cell Controller acts as the master controller for the systems using multiple levels of control. Various scenarios have been run to test the capability of the Cell Controller to manage active and reactive power flows at the cell boundary, intentionally island the system and reconnect to the grid on command, and improve the dynamic performance of sluggish generation sources using other compensation equipment.

B. 2008 Field tests

The field testing successfully achieved its major goal: to demonstrate the correct and coordinated operation of the Cell Controller, major equipment (synchronous condenser, secondary load controller, 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.

C. 2010 Field tests

Data gathered during the initial field tests performed on a small section of the pilot cell in autumn 2008, were 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 marked the first part of the final round of field tests. All grid-connected functions were tested in a limited number of test cases.

D. 2011 Field tests

Final multi-function operations were demonstrated in the full Cell area. This also included islanding operations, frequency shedding, voltage control, and load restoration.

E. Simulations

Concurrently with these field tests, 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 modelling 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 modelled power system via the field-specified communication protocols. With this set-up, the behaviour 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. In particular, all test cases planned for the field tests have been run multiple times against the model before the field test took place.

VI. 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 have been 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 has also been field tested in 2011. The Cell Controller system provides a portable and scalable platform to fulfil 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.

For full documentation of the project, please visit http://energynautics.com/en/references/cell-controller-project/ [3].

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BIOGRAPHICAL INFORMATION

Eckehard Troester is CEO and Senior Consultant at Energynautics and manages projects in all areas of grid integration of renewable and decentralized generation, dealing with issues on all voltage levels. His current main working area is related to the modelling of combined heat and power plants for certification purposes according to the German medium voltage directive. He therefore actively participates in numerous working groups related to the development of technical regulations for measurement, simulation, model validation and certification of renewable and decentralized power plants. Furthermore he has many contacts in the energy business and is a lecturer at the International Department of the Karlsruher Institute of Technology (KIT).

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 received his Ph.D. from the Technical University of Darmstadt in 2010. He joined Energynautics in 2008, where he was responsible for the advanced dynamic modeling and simulation work of the Cell Controller Pilot Project. His fields of interest are power system computing and modelling, energy efficiency and usage of renewable energy.

Thomas Ackermann is the founder and CEO of Energynautics GmbH a research and consulting company in the area of renewable energy and power systems. He also lectures at Royal Institute of Technology (KTH), School of Electrical Engineering in Stockholm/ Sweden and. He holds a degree of a Diplom Wirtschaftsingenieur (M.Sc. in Mechanical Engineering combined with an MBA) from the Technical University Berlin/ Germany, an M.Sc. in Physics from Dunedin University/ New Zealand and a Ph.D. from the Royal Institute of Technology in Stockholm/ Sweden. He is the editor of the book "Wind Power in Power Systems" and Co-editor of the Wind Energy Journal, both published by Wiley.