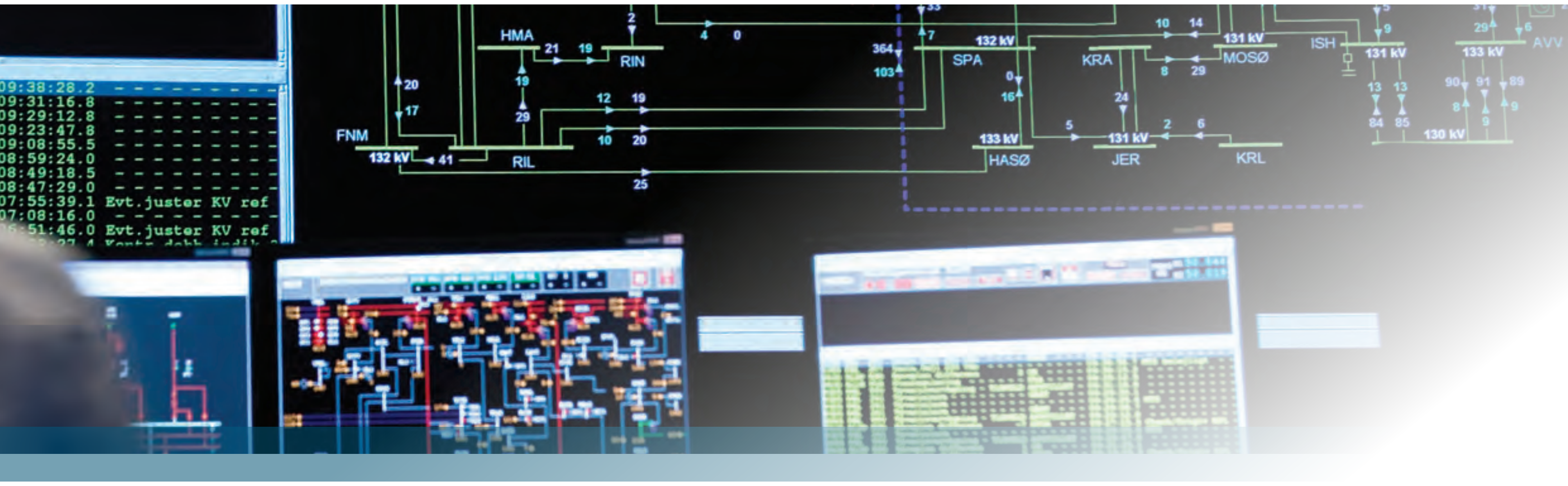

Cell Controller Pilot Project

Smart Grid Technology Demonstration in Denmark for Electric Power Systems with High Penetration of Distributed Energy Resources. 2011 Public Report.

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1. Executive Summary

Over the past twenty years, there has been a remarkable transformation in the generation, transmission, and distribution of electric power in Denmark. Prior to 1990, most Danish electric power was produced at large, centralized generation plants from which it was transmitted and distributed to commercial, industrial, and residential consumers. Since then, thousands of generating assets have been installed throughout the Denmark, including dispersed combined heat and power plants and wind turbines. The Cell Controller Pilot Project (CCPP) was initiated to develop and demonstrate the capability to use distributed generation and other energy resources connected to distribution networks for grid reliability and power-flow related applications. Moreover, it was recognized that the coordinated control of local assets such as combined heat and power plants, wind turbines, and load control could mimic the operation of a single large power plant, and therefore provide ancillary services such as power balancing, import/export of active and reactive power, and voltage control at select locations within the distribution system. Lastly, in the event of a transmission system emergency, local distribution networks (60 kV and below) could be rapidly isolated from the transmission network (150 kV and above) and operated autonomously using local resources, thereby reducing the impact on consumers and contributing to more rapid recovery from the emergency. The CCPP set out with these ambitious objectives and successfully developed, deployed and demonstrated in a 1000 km^2 pilot study region a control system capable of coordinating distributed energy resources (DER), that managed the assets during normal grid operation, supported multiple ancillary services, facilitated participation in emerging DER market opportunities, and was able to safely island the study region, maintain autonomous operation, and resynchronize with the main network.

The CCPP project spanned a seven-year period from 2005 through 2011. During the first three years, the field asset capabilities were evaluated and both monitoring and communication equipment were deployed throughout a portion of the pilot study region; the objective was to better understand the generation and loading demands, and to leverage as much of the in situ capabilities as possible. At the same time, a general control strategy was developed and prototyped on a distributed hardware platform, with the proof-of-concept performed using extensive modelling and simulation techniques and live testing at the InteGrid Laboratory.

During 2008 and 2009, the first fully functional version of the Cell Controller was deployed in a portion of the pilot region. Multiple field tests were performed, including the successful islanding, autonomous operation, and resynchronization of the controlled grid to the main transmission grid. In addition, communication and monitoring capabilities were expanded to the remainder of the pilot region.

From 2010 through 2011, the Cell Controller capabilities were expanded and capabilities were added to allow multiple stakeholders (the transmission system operator, the distribution network operators, and power balancing parties) to perform simultaneous operations. Each new capability was developed and tested both in simulation and at the InteGrid Laboratory before ultimately being successfully demonstrated in the field in Fall 2010 and Spring 2011.

This report describes each of the main phases of the CCPP. It begins by presenting the motivation and planning stages of the CCPP, the pilot project region and the in situ asset capabilities and design constraints. Then follows a complete description of the Cell Controller design requirements, architecture and capabilities. Next, an extensive description of the modelling and simulation efforts is presented followed by a summary of the key field tests performed on the live distribution network (the pilot project region) located in western Denmark. The report concludes with a summary of the major outcomes and lessons learned from the project and its relationship to Smart Grid development activities in Denmark, Europe, and USA.

Figure 1 Cell Controller test team during field test at a 60/10 kV substation November 2010.

2. Initiation of the Cell Controller Pilot Project

The Cell Controller Pilot Project took place in a power system that had been transformed from a classical centralised generation system to a decentralised generation system with thousands of distributed generators during the last 20 years to an extent where the installed generation capacity at the distribution level exceeded the generation capacity at the transmission level.

2.1 The Transformation of the Danish Power System

Due to a constant political wish for environmentally friendly power generation, Denmark has experienced a vast growth in distributed generation (DG). This includes a significant increase in wind power as well as dispersed combined heat and power plants (DCHP). Figure 2 shows this development which was initiated in the early 1980's.

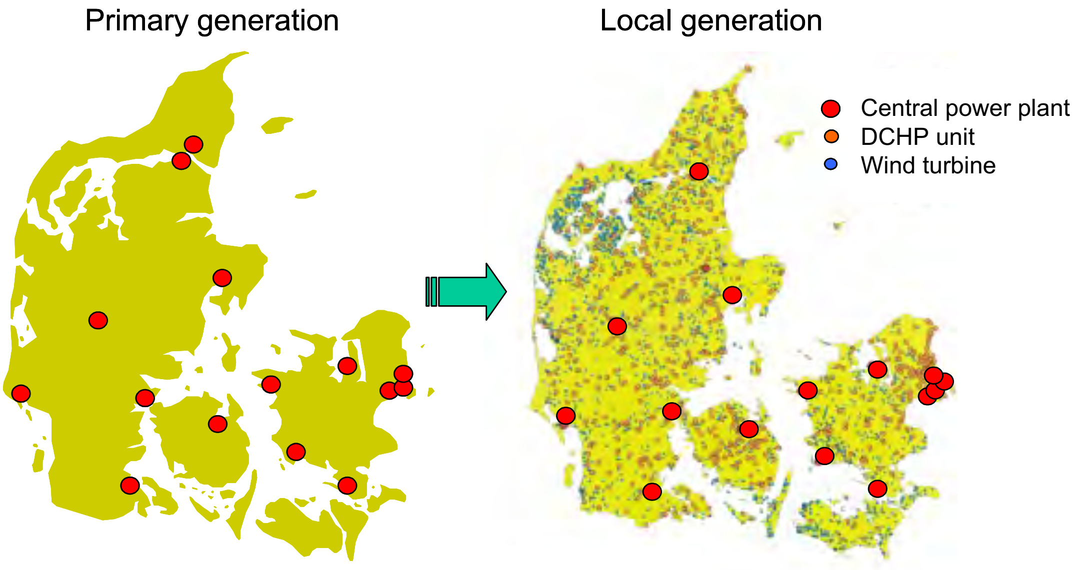


Figure 2 The development in Denmark from centralised to decentralised generation systems.

Already early in this millennium, the amount of installed decentralised generation systems had reached very high relative numbers especially in the western Danish power system as depicted in Figure 3. In 2004 the total installed capacity in this area could be summarised to 3,502 MW central power plants, 1,643 MW DCHP units, and 2,374 MW wind turbines (WTs), totalling 7,519 MW. In comparison, the minimum load of the area was approx. 1,150 MW and the maximum load was approx. 3,800 MW.

All of the DCHP units were primarily built for the purpose of providing local district heating. It follows that the electrical power production from these units were tied to the heat demand and not to the power demand. Hence the area of western Denmark experienced power overflows on a regular basis with close correlation to both wind conditions and outdoor temperature.

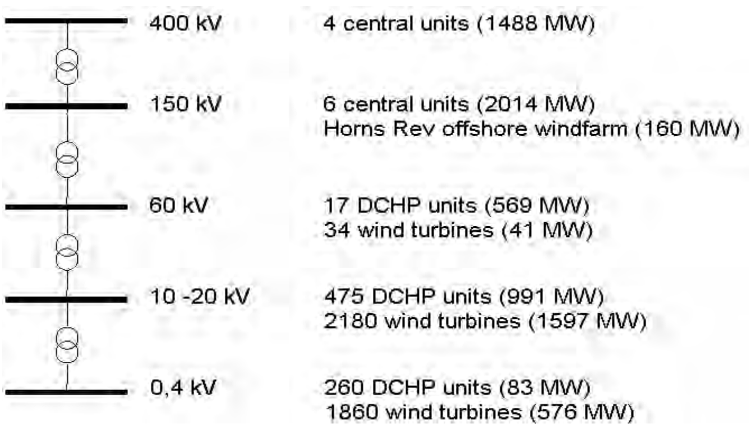


Figure 3 Production capacity per voltage level in the western part of Denmark in 2004.

One of the consequences of this massive build-up of DG was that several 60 kV distribution networks, especially those situated along the coast line to the North Sea with prevailing wind regimes, in fact became net power producers transmitting their excess power up on the 150 kV transmission grid. This is indicated in Figure 4 where the power flow through two similar distribution transformers, but located in different types of areas, is shown.

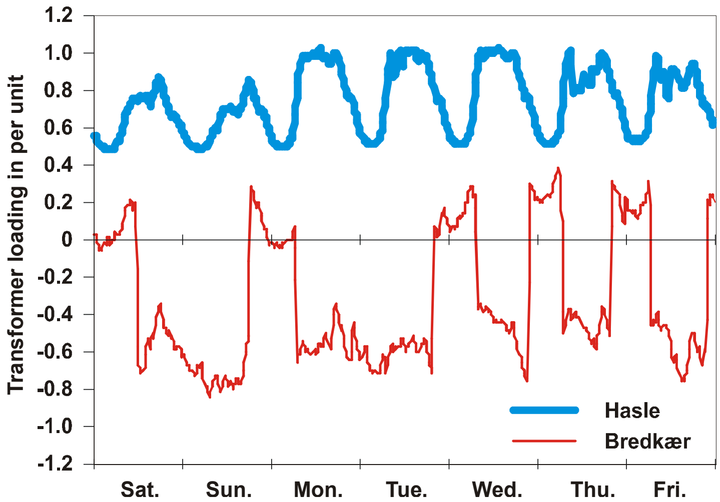


Figure 4 Power flow in two 150/60 kV distribution transformers measured during one ordinary week in 2004.

The power flow depicted in Figure 4 is defined positively flowing from the 150 kV to the 60 kV side of the transformer, which is the normal flow direction for any distribution transformer in a classical power system. The transformer in substation Hasle supplies power to a large residential city area. This curve shows the ordinary well-known daily variation. On the other hand, the transformer in substation Bredkær connects a rural 60 kV area inclusive of villages to the 150 kV transmission grid. This area is characterised by large amounts of WTs in the rural areas and DCHP units in the villages. Particularly at this transformer the start and stop of relatively large DCHP units can clearly be seen in the abrupt reversed power flow from the 60 kV to the 150 kV side.

The 60 kV distribution systems in Western Denmark (the peninsula of Jutland) has been built as a meshed network with at least two supply possibilities to each 60 kV station and with interconnections between neighbouring distribution companies. The 400 and 150 kV transmission system in Jutland serves partly as a transport corridor between the hydro powered systems of Norway and Sweden and the fossil and nuclear powered systems of Western Europe. Hence to avoid that the 60 kV distribution systems take part in any power transit on the transmission system, the 60 kV distribution systems is operated as isolated radial systems beneath each 150/60 kV transformer station.

It is in these radially operated distribution systems that the largest amount of DG units was installed. The DG units are grid connected at 60, 10 and 0,4 kV voltage level and were in most places completely intermingled with the loads on the feeders. The resulting grid situation is illustrated in Figure 5.

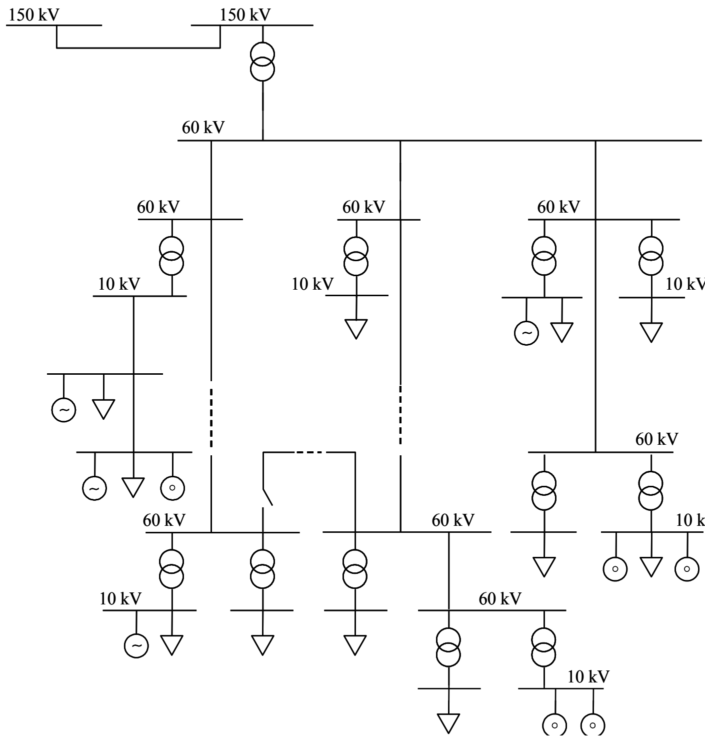
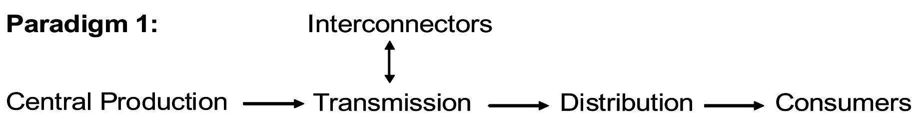
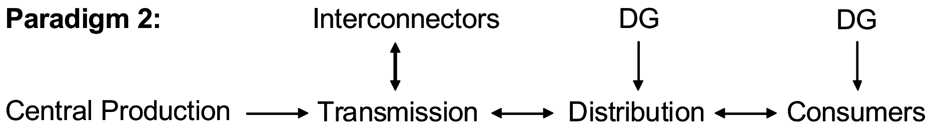


Figure 5 *Simplified section of typical 60 kV distribution grid with DCHP plants (synchronous generators), WTs (induction generators) and 10 kV load feeders indicated.*

Generally before the shift in generation, the power system was characterised by a unidirectional flow of power from a limited number of large central power stations via the transmission and distribution systems through to the consumers at the low voltage side of the system:



After the shift in generation had taken place in the early years of this millennium, the power system was characterised by a massive power production on both the medium and low voltage levels of the distribution system resulting in intermittent bidirectional power flows between all voltage levels:



The control centres, SCADA systems, and operational philosophy of the transmission and distribution system operators were historically designed according to Paradigm 1 while the daily operational realities had shifted to Paradigm 2.

2.2 The Original Cell Controller Idea

Presently, the operation of the power system still relies on the ancillary services provided by the central generation units. But ideally, it should be possible to operate the decentralised power system without any central generation or central control. It is therefore necessary to completely revise the whole operating concept to deal with such a situation. This paradigm shift requires a major effort which can only be implemented gradually in order to uphold the security of supply.

These and similar thoughts were discussed in a small group of employees in the Planning Department of the former Western Danish TSO, Eltra, around 2001-2004 mainly consisting of John Eli Nielsen, Paul-Frederik Bach and Per Lund. Basically the idea of a utility scale active network began taking final shape following an Eltra grid conference in February 2003 where Frank van Overbeeke presented his ideas on active networks (see section References). The resulting original formulation of the Cell Controller idea in 2004 is outlined below.

Generally each local distribution grid connected to the transmission system could form an active network including all local DG assets and all distribution network operator (DNO) facilities. Following this perception the following experiment of thought was devised as the core of the Cell Controller idea:

If the 60 kV distribution grid below each 150/60 kV transformer is defined as an autonomous (self-regulated) Cell with a fully automated Cell Controller with fast data communication to all DCHP plants, WTs, transformers and load feeders within the Cell area inclusive of synchronisation equipment on the breaker in the 150/60 kV grid interconnection point, then this Cell can be given one or more of the following technical functionalities:

1. Automated transfer to islanded operation at the instance of severe faults in the transmission system leading to a blackout. This will ensure power supply to all customers in the widest possible extent during severe national or regional grid faults. This functionality demands for automated control of Cell area voltage, frequency and balancing.

2. Resynchronisation back to parallel operation with the transmission grid.

3. Synchronisation with and powering up of close by parts of the dead transmission grid following a blackout. In a black-start support role each Cell will be able to provide power and voltage support to local parts of the transmission grid during the repowering sequence of the most vital parts of the transmission lines leading to black-start of larger central power stations.

4. Voltage control on selected synchronous machines to acquire voltage profile control within the Cell area. This is handled by the Cell Controller based on knowledge of voltage control

capabilities on each synchronous machine in each DCHP plant. The necessary voltage set-point on each machine is controlled by the Cell Controller in islanded situations. In normal parallel operation a voltage set-point or a request of maintaining a given reactive power import or export set-point with the overlaying transmission grid can be given from a regional control centre. Acquiring this functionality necessitates external access to each machines voltage controller and excitation system and the full agreement of the plant owner probably on commercial terms.

5. Frequency control on selected synchronous machines within the Cell area. This is handled by the Cell Controller based on knowledge of frequency control capabilities on each synchronous machine in each DCHP plant. The necessary frequency set-point on each machine is controlled by the Cell Controller in islanded situations. This ability will also be used for resynchronisation of the Cell area back to normal parallel operation following islanded operation. When the Cell area is in normal parallel operation with the transmission grid all generators are in normal market operation and the Cell Controller will not interfere with the active power control of the machines. Acquiring this functionality necessitates external access to each machines speed governing system in the event of an impending black-out situation and the full agreement of the plant owner probably on commercial terms.

6. Active and reactive power balancing of the Cell area prior to controlled transfer to islanded operation. This functionality is handled by the Cell Controller based on knowledge of the total production and consumption within the Cell area inclusive of knowledge on the available active and reactive power regulating potential of each synchronous machine and wind turbine. It may be necessary for the Cell Controller to disconnect WTs and/or DCHP plants in situations with a Cell area power surplus. Likewise it may be necessary for the Cell Controller to disconnect 10 kV load feeders in situations with a Cell area power deficit.

7. Usage of dedicated 10 kV load feeders within the Cell area for automated under frequency load-shedding. Handled by the Cell Controller based on detailed on-line knowledge of the total active production and consumption on each 10 kV feeder. In this way it will be assured that only pure load feeders are disconnected and not feeders that are in fact net power producers.

2.3 The Cell Controller Pilot Project

In 2002-2004, power systems in North America, Italy, Sweden and Denmark all experienced blackouts of large areas involving millions of consumers in each event. All of these blackouts were caused by voltage collapses due to insufficient reactive power resources available locally.

These blackouts were not seen as isolated events but rather as a consequence of the introduction of market driven power systems indicating that the power systems are operated closer to the limits without timely investment in the necessary reinforcements. Hence it was believed that such blackouts can and will happen again.

This perception, combined with the large DG base already at hand, motivated Eltra, the former TSO of western Denmark, to initiate a Cell Controller Pilot Project (CCPP) with the following ambitions:

- High Ambition: In case of a regional emergency situation reaching the point of no return, the Cell disconnects itself from the high voltage (HV) grid and transfers to controlled island operation.
- Moderate Ambition: After a total system collapse, the Cell black-starts itself to a state of controlled island operation.

The High Ambition aimed at preserving as many cells as possible in island operation, thus securing power supply to as many consumers as possibly during a black-out of the HV grid. Both ambitions aim at having black-start capabilities available in a very short time distributed throughout the power system.

As the CCPP has not been initiated with the sole purpose of securing the distribution systems for very rare although severe black-outs, the High Ambition served as a means to ensure a robust design where new features for normal grid operation can be implemented in the Cell Controller as pure software development without replacement or installation of new hardware. The idea was that if fast automatic transfers to controlled island operation could be accomplished in a severe contingency situation then all other functionalities in normal modes of operation could be achieved within the design.

Therefore a project based on the high ambition was preferred. The outcome of the project aimed at a full utility scale pilot where the envisioned technical functionalities would be developed and tested live. Furthermore the actual pilot implementation could be a future test facility. A general implementation of the new control principles in local grids would require a further development of functional standards and technical concepts.
More specifically, the CCPP aimed to:

- Gather information from the international community about the feasibility and approaches to utility-scale micro grids (Cells).
- Develop requirements specifications and preliminary solutions for a pilot implementation of the Cell concept.
- Implement measurement and monitoring system to gather and analyse data from the targeted pilot area.
- Perform detailed design, development, implementation and testing of a selected utility scale pilot Cell.

In order to ensure a timely stepwise approach towards a fully implemented pilot Cell the CCPP was divided into a number of phases with the following contents and project schedules:

A. This was the initial information gathering phase partly through convening three workshops with invited Danish and international experts and partly through a comprehensive data collection conducted at a distribution company inclusive of DCHP units and WTs of that area. Two of the workshops were held in Denmark and one in the USA. In this phase the requirement specifications and preliminary design of a pilot Cell were worked out. This phase was initiated in November 2004 and was completed in October 2005.
B. Perform implementation and testing of the necessary measurement, monitoring and data communication system in a selected part of the pilot cell. A detailed design and laboratory-scale testing of the prototype Cell Controller was carried out. This phase was initiated in 2006 and was completed in 2009.

C. Here the actual pilot implementation and testing of the Cell Controller in the pilot Cell took place. This phase was initiated in 2006 and was completed in July 2011.

As indicated above one of the progressive distribution companies of western Denmark agreed to be part of the CCPP and a suitable full 60 kV Cell of that company was selected as the pilot cell. The Cell area selected contained a large number of DG equally shared between DCHPs and WTs thus locally attaining 50% wind penetration. The project did not include local grids for lower voltages than 10 kV.

The participants of the CCPP were:

- Energinet.dk (merger between the former Eltra, Elkraft and Gastra companies), Skærbæk, Denmark. The national power and gas TSO of Denmark, which fully initiated, financed and managed the project.
- Syd Energi A/S (now known as SE), Esbjerg, Denmark. Independent Distribution Company and DNO located at the south of Jutland in which grid the pilot Cell was established.
- Spirae Inc, Fort Collins, Colorado, USA. Provides consultancy services and development expertise within smart-grid design and business infrastructure for distributed energy.
- Energynautics GmbH, Langen, Germany. Provides consultancy services to the energy industry focusing on renewable energies and innovative energy applications.

2.4 Cell Controller Functionality

To fulfil the High Ambition of the CCPP the Cell Controller needed to be able to perform a number of functions in a pilot Cell which has been fully prepared for these functions by constructing the necessary data communication, measurement, monitoring and control systems. These functions are briefly listed below:

- On-line monitoring the total load and production within the cell.
- Active power control of synchronous generators.
- Active power control of wind farms and large wind turbines.
- Reactive power control by utilising capacitor banks of wind turbines and grid.
- Reactive power or voltage control by activating automatic voltage regulators (AVR) on synchronous generators.
- Frequency control by activating speed governing systems (SGS) on synchronous generators.
- Capability of remote operation of 60 kV breaker on 150/60 kV transformer.
- Capability of remote operation of breakers of wind turbines and load feeders.
- Automatic fast islanding of entire 60 kV Cell in case of severe grid fault.
- Automatic fast generator or load shedding in case of power imbalance.
- Voltage, frequency and power control of islanded Cell.
- Synchronising Cell back to parallel operation with the transmission grid.
- Black-starting support to transmission grid in case of black-out.

The envisioned functionality of the Cell Controller is partly illustrated in Figure 6. It is important at this point to understand that each Cell will be required to operate in parallel with the HV power system in any normal and stressed contingency situation. Any normal fault on the HV grid must still be handled by the ordinary protection systems like distance relays on the transmission lines etc. This is to ensure that the power system, during contingency situations, does not lose power production, short-circuit power, reactive power, spinning inertia etc. by premature islanding of distribution areas with large amounts of DG in operation. The only exception is that during a regional severely stressed situation as in an impending voltage collapse, where the point of no return has been reached, the Cell Controller can be allowed to transfer the Cell into islanded operation.

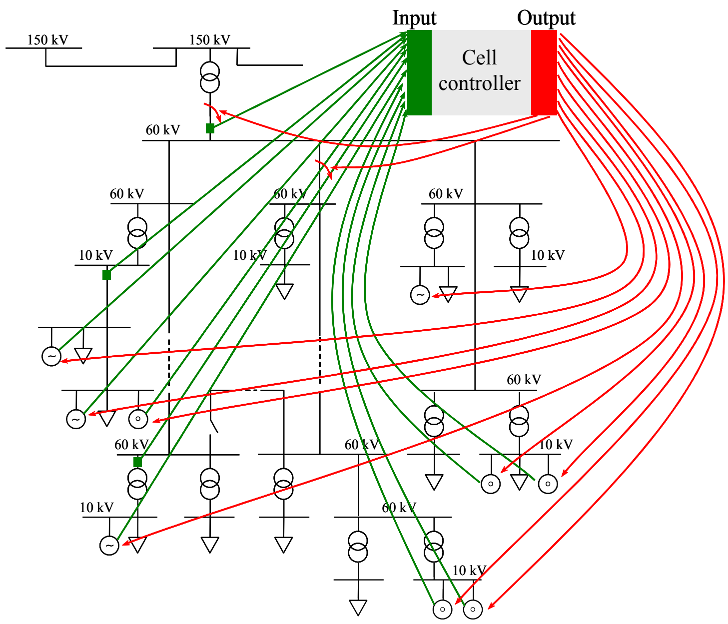


Figure 6 *Cell Controller functionalities. Measuring and monitoring of load and production indicated by (green) arrows pointing towards the Cell Controller. Control actions on generators, load feeders and main power circuit breakers indicated by (red) arrows pointing away from the Cell Controller.*

For the Moderate Ambition the Cell will follow the HV power system into a black-out. But for the Cell to be able to black-start itself to steady-state island operation it can be seen that the Cell Controller needs almost all of the functionalities as listed above for the High Ambition.

In either case, the Cell Controller also needs the ability of communication to/from the DNO and the TSO SCADA-systems. It is from the TSO that an on-line signal of an impending voltage collapse is envisaged to come based on a phasor measurement unit (PMU) based early warning system currently being developed. It is also from either the DNO or the TSO that the request to provide black-starting support will be sent to the Cell Controller.

The advantages for the DNO to be able to communicate with and request services from the Cell Controller are plentiful in a future DG based power system. Firstly the Cell Controller can easily be programmed to minimise the reactive power flow across the Cell boundaries (150/60 kV transformer) and hence automatically ensure that MVAr-limitations imposed by the TSO due to intermittent DG production are kept at all times.

Other obvious advantages for the DNO enabling a high degree of DG penetration are:

- Highly improved on-line monitoring of the area inclusive of all of its main components.
- Remote control and switching capability of all main components.
- Automatic reactive power flow control within the Cell area.
- Automatic voltage control within the Cell area.
- Other automatic control functions as envisioned by the DNO and/or TSO.

- Controlled transfer of the Cell to/from islanded operation.
- In the much more difficult modes of stressed operation of the power system the Cell Controller is envisioned to provide additional possibilities:
- Selective automatic load shedding
- Emergency transfer to islanded operation with preservation of maximum possible power supply.
- Black-starting support for the high-voltage grid.

The division of local grids into highly automated cells will mark a change into a new generation of system control methods. It will allow better utilisation of the grids with optimal and safe operation closer to the capacity limits. The surge of local generation has pushed the development, but a transition into modern control principles in the local grids would be natural sooner or later.

2.5 Long Term Perspectives

Large efforts have been taken in securing a design of the Cell Controller that is general enough to allow for Cells to be combined into larger Cells comprising DNO and even high voltage TSO grid areas. This is illustrated in Figure 7 where the general layout of one Cell Controller is indicated based on a layered control hierarchy using distributed agent technology and high speed fibre in a 60 kV distribution Cell as depicted in Figure 6.

The general design was developed to ensure that distribution companies can obtain control over multiple cells by adding a 4th level agent which could be embedded in the distribution company SCADA system. Furthermore it was envisioned that the national TSO can gain access to all Cells in the Danish power system by adding a 5th level agent which in turn should be embedded in the SCADA system of the TSO enabling the operation of Cells as virtual power plants as seen from the transmission level. This vision for a future roll-out of the Cell concept is also indicated in Figure 7.

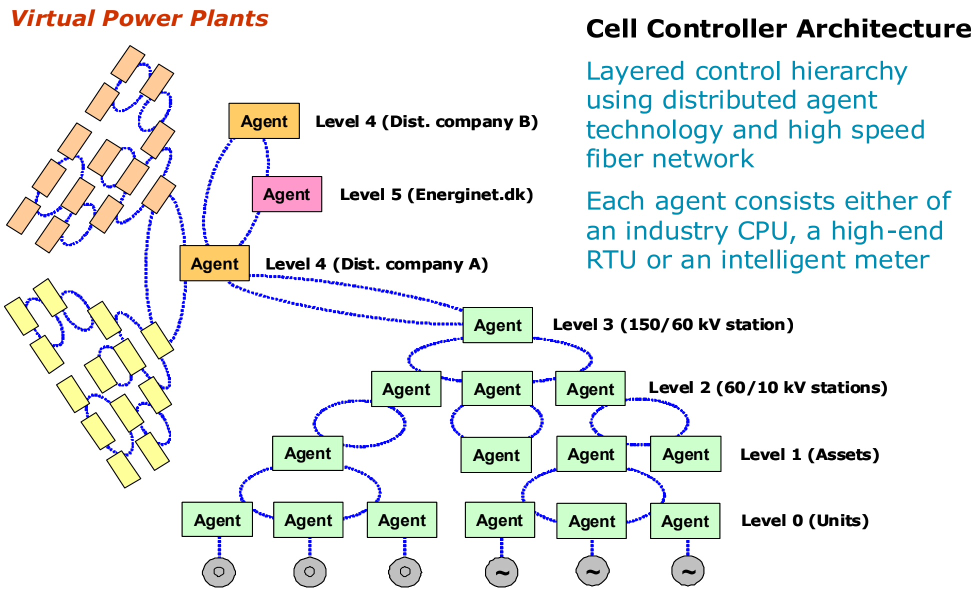


Figure 7 Basic Cell Controller architecture for one cell indicated in green.

2.6 Challenges with Major Cell Assets

The majority of the present Danish DCHP units are either gas engine or gas turbine driven synchronous generators in combination with an exhaust boiler to produce hot water for district heating purposes. All of these units have been designed to achieve very high fuel efficiency rates of 90% or above when operated at full load. Due to large hot water storage tanks most of the DCHP units can meet demands for heat and electricity in a very flexible way. During periods with low heat demand the operation can be limited to hours with high electricity spot prices. The synchronous generators of these units are all equipped with some type of speed governing system (SGS) and automatic voltage regulator (AVR). The latter being operated in power factor control as voltage control of the power system is being done in the classical way by central power plants and automatic tap changers on 150/60 kV and 60/10 kV transformers.

A typical communication system loop of a gas engine based DCHP unit is depicted in Figure 8. Such units have been designed for parallel operation with the grid and furthermore to be operated either at full load to produce hot water for a hot water storage tank or be disconnected. Trying to utilise the existing SCADA system of these units was deemed too slow for the response time needed for the Cell Controller. However investigations carried out at gas engine CHP units during the project revealed that the units are capable of part load operation. Furthermore, it is possible on these units to enter external signals directly into both the SGS and the AVR and hence enabling external control through e.g. dynamically changing the set points of voltage and speed (frequency).

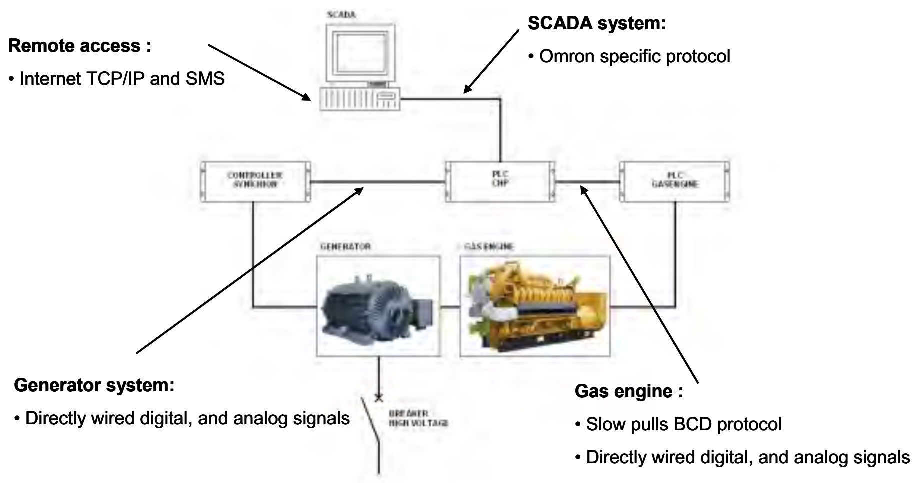


Figure 8 Typical existing communication system loop of a gas engine CHP unit designed for parallel operation with the grid. Exhaust boiler system not shown.

Almost all of the present land-based WTs installed in Denmark are of the so-called Danish concept type (WT type 1), i.e. a three-blade rotor connected through a gearbox to an induction generator which is directly connected to the grid if necessary through a step-up transformer. The WTs came from all of the different Danish vendors from the past 20 years. These WTs are either no-load reactive power compensated or full-load reactive power compensated by switchable capacitor banks. The turbines are either pitch or stall controlled leaving out any hope for the possibility of doing any active or reactive power control on most of these machines except for opening the power circuit breaker in situations with power surplus within the Cell when preparing for islanded operation.

It was also necessary to be able to remotely control the power circuit breakers of dedicated load feeders. This control feature would be needed in emergency situations where the Cell Controller needed to island the Cell in order to preserve it from an unavoidable major system black-out. Prior to such an event – assuming enough lead time can be acquired – the Cell Controller needs to balance out any active and reactive power imbalances within the Cell prior to opening the power circuit breaker in the grid connection point, i.e. at the 150/60 kV transformer station. This can only be done fast enough in lieu of the assumed short lead time (few seconds) by shedding either excessive load or production.

It was the leading idea of the Cell Controller Pilot Project that all of the envisioned functionalities could be made possible by getting access to and actively utilising the already existing distributed generation facilities in the medium- and low-voltage grids of the Danish power system.

Figure 9 CHP plant natural gas engine.

3. CCPP Test Area and Project Considerations

3.1 Cell Controller Pilot Project Test Area

The test area for the Cell Controller pilot project is located in western Denmark (Figure 10) in the Holsted area. This region was selected in consultation with Syd Energi (SE), the DNO project partner, and is referred to as the Holsted Cell. The Holsted substation was the interconnection point between the distribution grid (60 kV and below) and the 150 kV sub transmission grid. Consequently the Cell Controller was configured to leverage assets available in the area and to work within grid constraints associated with the Holsted distribution network. Although the Holsted distribution network contained many of the asset classes found throughout Denmark (and the rest of the world), not all classes were represented. For example, as only Danish-style wind turbines were available within the pilot region, controls for more modern wind turbines with "state-of-the-art" controls (WT type 3 and 4) were not developed during the CCPP.

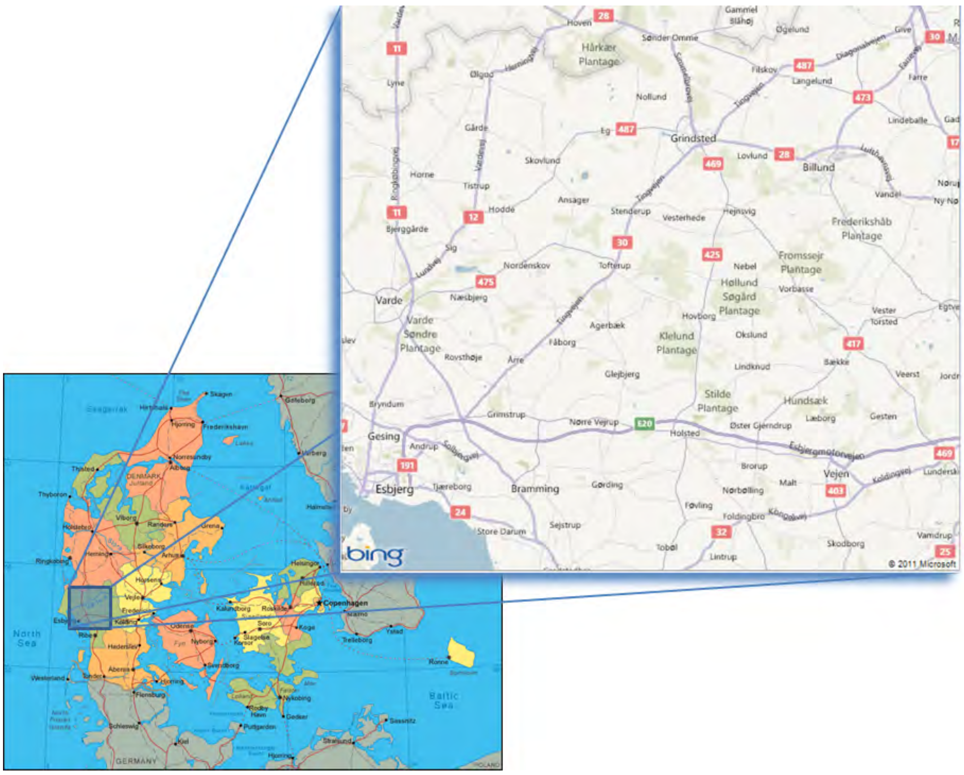


Figure 10 The Holsted Cell (pilot region) located in Western Denmark.

In addition, the topology of the Holsted Cell guided the general deployment strategy of the Cell Controller. Specifically, the Cell Controller master was deployed at the Holsted substation, intermediate control nodes were deployed at substations found throughout the Holsted distribution network, and the end nodes were deployed at each controllable asset such as CHP plants and Wind Turbines. Another major consideration was that since islanding the Cell was one of the objectives of the project, the boundary of the Cell had to be selected such that there was sufficient diversity of controllable assets and their dynamic characteristics supported island operations. This objective was achieved through judicious selection of participating assets, upgrades to existing facilities, and selective installation of new equipment.

Figure 11 illustrates the topology of the Holsted Cell which was divided into three sub-regions, referenced as Test Areas 1, 2, and 3. The three regions were defined to support a staged deployment strategy. Initial deployment and testing was done in Test Area 1 and the final round of tests included all three areas. Table 1 summarises the assets found within the Holsted Cell; the primary interconnect breaker was located at the Holsted substation in Area 2.

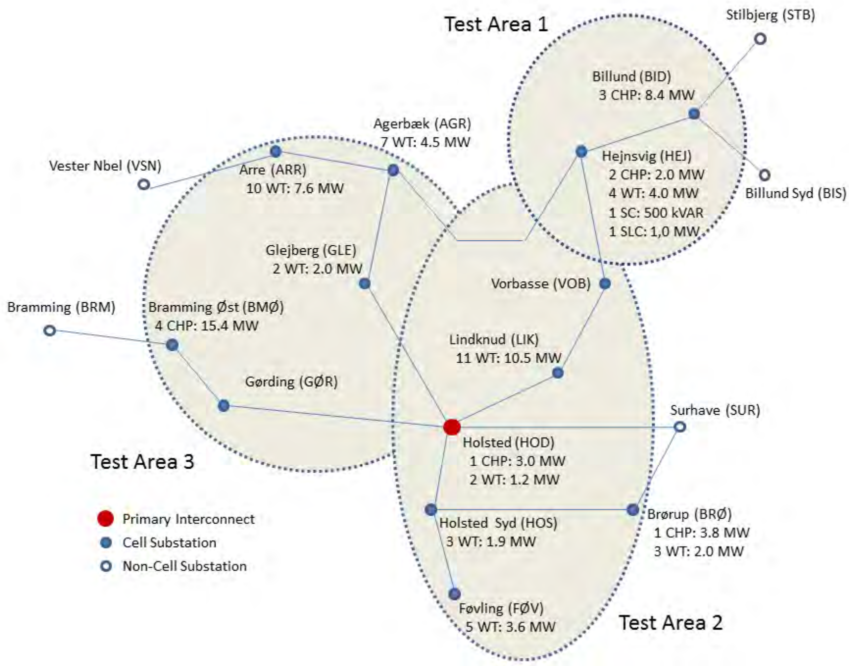


Figure 11 Topology of the Holsted Cell. The cell was divided into three test areas; testing prior to 2008 was performed in Area 1 only; the testing region was expanded to include Area 2 for 2008 and 2009, and all three Areas were involved in the testing done in 2010 and 2011.

Area	Substations	Synchronous CHPs No. × Nameplate	Wind Turbines No. × Nameplate	Load Feeders No. × Total Capacity	Additional Assets
1	2	3 × 2.8 MW 2 × 1.0 MW	4 × 1.0 MW	8 × 5.0 MW	Synchronous condenser (0.8 MVA) Secondary load controller (1.0 MW)
2	6	1 × 3.8 MW 1 × 3.0 MW	24 × 0.6-1.6 MW	26 × 20.0 MW	
3	5	2 × 2.8 MW 1 × 3.8 MW 1 × 6.0 MW	19 × 0.6-1.0 MW	18 × 15.0 MW	

Table 1 Asset Summary for the Holsted Cell.

3.2 Cell Controller Design Considerations

The basic premise of the Cell Controller project was that a distribution network could be successfully operated with a portfolio of local Distributed Energy Resources (DER). However, rapidly transitioning from grid connected operations to island operations by transferring load following responsibilities to local DER without compromising the stability of the local grid poses a challenging problem for the Cell Controller. Successful Cell separation from the transmission grid requires a coordinated effort by all of the energy resources within the cell to balance generation and load within a matter of seconds and coordinated transition of operating modes of major assets from grid-connected mode to island mode.

Three important conditions had to be met to achieve proper cell control: a mechanism to pre-calculate and pre-load the required actions in the event of an island signal, a means to reliably and rapidly communicate the island command to core DER assets, and DER and wide area controls capable of rapid execution. In addition, the system also needed to have enough online capacity to ride through transients caused due to islanding. Once the Cell was successfully islanded, sufficient intelligence had to be distributed within the system to manage a wide range of unpredictable dynamic conditions. The Cell Controller therefore needed fast local controls for DER and wide-area coordination at the substation and Cell levels to meet these requirements.

3.2.1 Enabling DER Benefits for Multiple Stakeholders

Once grid stability and reliability driven requirements were met, the Cell (or portions thereof) could be used to provide ancillary services to many stakeholders. For example, the transmission system operator (TSO) could ask the Cell to operate as a virtual power plant (VPP) to supply active or reactive power to the transmission system, the distribution network operator (DNO) could ask the Cell for automated voltage profile control and/or reactive power control for reducing unmanaged reactive power flows to and from the transmission system. The Cell Controller would also have the capabilities to ensure that local grid operations were not compromised during market-based dispatch and operations of a variety of distributed energy resources.

Hence, a major consideration of the Cell Controller Pilot Project was to develop, test and validate solutions for the challenging technical problem of reliable grid operations using DER while enabling new system capabilities such as rapid islanding and very high renewables penetration. Solving this challenge was expected to yield a robust technical foundation for meeting the ambitious renewables integration and advanced market operations capabilities envisaged by Energinet.dk for future intelligent power system operations. In short, the Cell Controller project had to prove out the technical capabilities needed to foster Smart Grid deployment in Denmark to meet its 2025 goals.

3.2.2 Distributed Assets for Cell Controller Operations

Since the ultimate goal of the project was to develop solutions that could be scaled and replicated in other areas in Denmark in a cost effective manner, one of the major design requirements was that the Cell Controller had to leverage existing assets wherever possible. In addition to major equipment such as generators, the communications infrastructure also had to utilise existing or easily available technologies. The addition of new equipment and the installation of communication equipment were considered ancillary to the primary goals of the project. This approach was taken not only for minimising project costs, but also to represent the situation most likely to be faced as these types of solutions are deployed on a larger scale in the future.

In order to safely perform testing of the islanding capabilities, it was also determined early on in the project that "shock absorbers" would be required for damping the transients during islanding and island operations. This was due to the fact that existing equipment available to the Cell Controller had slow dynamic response characteristics and was installed for grid-connected operations only.

A Secondary Load Controller (SLC) was specified for rapidly varying loads to respond to variations in renewable generation and loads within the Cell. For example, when the breaker at the primary interconnect is activated (either opened to isolate the cell or closed to re-connect the cell), any difference between generation and load will result in a frequency shift; the SLC reduced the magnitude of these deviations thereby acting as a safety net for the "downstream" assets. SLC controls were also developed to rapidly respond to frequency deviations and then to bring in other resources to free up its capacity on an ongoing basis. This allowed natural gas generators with slow response characteristics to be optimally utilised for Cell operations.

A Synchronous Condenser (SC) was specified for voltage and reactive power management during transient conditions. The SC served the same role for reactive power and voltage management as the SLC did for active power management.

A Master Synchroniser (MS) control panel was built and installed to aid the transition to and from grid connectivity at the Holsted substation to separate and reconnect the Cell from the primary grid.

Other assets that were installed for the project in general were meters, communication equipment, and Cell Controller specific embedded controllers (hardened computers). Upgrades to existing sites were done on a case-by-case basis to expose existing asset functionality to external systems and to add capabilities in some instances. A pragmatic approach was taken by the project team to recruit and upgrade assets based on availability, cost, and functionality for meeting key objectives of the project.

3.2.3 Research, Development and Demonstration Project

The CCPP was structured as an RD&D project from which important conclusions could be drawn about technical feasibility, asset requirements, system capabilities and controls, and the potential to service existing and new markets.

Since the capabilities were to be tested in the field using a live distribution network, several tradeoffs were made to accommodate the in-situ network topology, asset availability, and customer impacts. These tradeoffs impacted which assets could be used, how they could be controlled, communication and data acquisition methods and protocols, test types and test durations.

Taking these considerations into account, the main objectives of the CCPP were finalised. The CCPP had to develop and demonstrate a distributed control system that could safely island the cell, maintain the cell while islanded, and re-connect the cell when requested by the transmission system operator *and* demonstrate potential services that could be offered to several stakeholders including the transmission system operator (TSO), the local distribution network operator (DNO), one or more Balance Responsible Parties (BRPs) operating in the Nordic Power Market as indicated in Figure 12, and the asset owners.

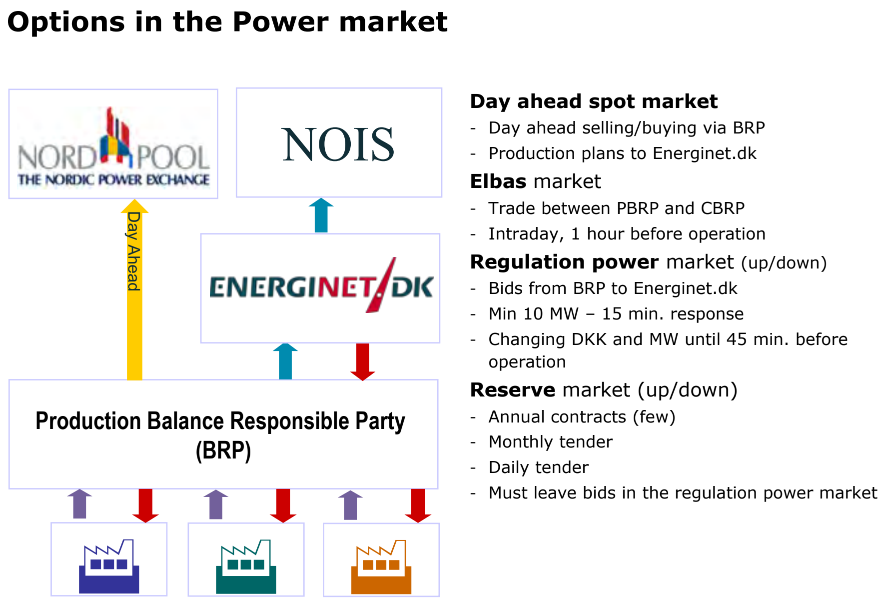


Figure 12 Production Balance Responsible Party operating in the Nordic Power Market.

3.3 Cell Controller Development Considerations

The ambitious scale of the Cell Controller Pilot Project forced the CCPP team to carefully plan a roadmap that would allow the project objectives to be met incrementally. The general approach was to identify milestones that could be reached within a 12 month period. Contingent on the identified milestone, the team constructed and implemented development plans that included (rapid) prototyping, laboratory testing, building representative mathematical computer models and performing simulation studies, acquiring and deploying new field assets, and progress reporting.

The general strategy employed by the CCPP was to expand the capabilities of the Cell Controller incrementally by first testing and validating solutions at a smaller scale (in the laboratory or on an individual asset), then expanding its reach across multiple assets. Only after "proof of concept" was established would additional functionality be added. Each new phase of the project involved incorporating lessons learned from the previous phase, making modifications to the Cell Controller as needed, adding new functionality, and carrying out model-based, lab-based, and field-based tests in that order.

The CCPP can be roughly divided into three major development phases:

- 2005 – 2007: Development and deployment of the Cell Monitoring System (CMS) to Areas 1 and 2 of the pilot Cell area; development of the core Cell Controller operations and laboratory testing; procurement of additional field assets and upgrading of the existing CHP plants.
- 2007 – 2009: Deployment and testing of the Cell Controller in Area 1 of the pilot Cell area.
- 2009 – 2011: Additions to Cell Controller capabilities; expanded deployment and testing to Areas 2 and 3 of the pilot Cell area.

Development of the CMS included the installation of the communication and control infrastructure to collect real-time generation, load, and network status data for cell operation analysis, Cell Controller design and lab testing, and modelling and simulation of field scenarios.

3.3.1 Program Road Mapping and Annual Milestones

Each year a roadmap was designed and implemented to attain the goals set forth by Energinet.dk and the CCPP team. Although the particular roadmaps varied from year to year, each followed the same general outline below:

- Identify goals, build and implement roadmap
- Acquisition and deployment of additional field assets, e.g., SLC and SC
- Acquisition and analysis of field data
- Development of Cell Controller functionality
- Laboratory testing to validate control algorithms and software
- Modelling and simulation
- Field testing and results analysis
- Reporting

Each year, the CCPP team would target a set of specific goals dependent upon the current "state of knowledge" and the "lessons learned" from the previous year. In this way the CCPP team was able to structure the project into manageable development portions and progress incrementally towards the following successful project milestones:

- 2006: Development and initial deployment of CMS. CC proof-of-concept designed and demonstrated in the InteGrid Lab
- 2007: CMS fully deployed in Cell Area 1. Functional version of CC demonstrated in the InteGrid Lab
- 2008: CC deployed and tested in Cell Area 1. Islanding operation, SC and SLC operation demonstrated in Area 1
- 2009: CMS fully deployed in Cell Area 2. Demonstrated distributed agent deployment of CC
- 2010: CMS fully deployed in Cell Area 3. Multi-function operations demonstrated in full Cell area; voltage control, import/export control, state estimation/load flow deployment (SELF)
- 2011: Final multi-function operations demonstrated in full Cell area; islanding operations, frequency shedding, voltage control, load restoration, complete multi-function operations.

3.3.2 The Cell Monitoring System

Development and deployment of the Cell Monitoring System (CMS) was a high priority early in the project lifespan. The obtained data were used to inform the control designers and the simulation models of running conditions, expected loads and generation, response times, etc. Following Area 1 the CMS was deployed into Areas 2 and 3 to further study the field assets and to test the communication infrastructure.

In addition to gaining access to controllable assets it was necessary to establish and maintain (near) continuous communication with all of the substations and assets in order to monitor the system properly and issue coordination commands as necessary. Consequently, a major goal attained in the early years of the project was the construction of a project network compatible with the DNO's existing communications systems and operating policies. Communications capabilities were added to non-DNO locations such as CHP sites and Wind Turbines. The end result was a wide area communications system composed of fiber, DSL, and GPRS as appropriate for individual locations within the Cell. This network was initially used for data collection by the CMS.

The data collected by the CMS was analysed on a regular basis and archived remotely. The sheer volume of data generated by the CMS dictated that data collection, analysis, and archival had to be significantly automated. This capability was also incrementally developed, deployed, and tested during the course of the project.

3.3.3 Modelling and Simulation

The Cell Controller Pilot Project faced two major challenges from the very beginning: i) lack of an established development and testing framework and mature toolset for developing distributed control systems for grid operations and ii) the need to test and validate solutions prior to deployment on a real distribution network.

In order to tackle these two challenges a conventional power system modelling and simulation tool was leveraged to: i) study the operating boundaries of the distribution system in the test area for system design and ii) serve as a test platform for Cell Controller function validation prior to field testing. Both objectives were successfully met during the course of the project.

Figure 13 Hejnsvig CHP plant with hot water storage tank.

4. Cell Controller Design Requirements

The high level design requirements for the Cell Controller were derived from the core project objectives: to be able to reliably island, maintain, and reconnect the cell to the grid, and to demonstrate services that could be offered to several stakeholders including the TSO, DNOs, BRPs, and asset owners.

The design also had to be "forward looking" by being built to accommodate different network topologies, asset types, and operations objectives. In addition, the Cell Controller had to be designed such that it did not interfere with the normal operations of local assets or the electric grid unless its capabilities were explicitly activated.

In addition to these high level design requirements several specific design requirements drove the design, development, and testing process. They are described in Sections 4.1 to 4.7 below.

4.1 Scalable, Portable and Extensible

A key design criterion addressed by the CCPP was the need to be able to configure the Cell Controller to accommodate different cell topologies. Individual cells may have very different sets of (controllable) assets; for example one cell may only have CHP generation whereas a neighbouring cell may contain a combination of both CHP and wind turbine generation. Hence a key design requirement was to develop a control system structure that separated the Cell Controller functionality from the configuration files that inform the Cell Controller of the specific topology and asset capacities of a particular cell to assure portability.

The Cell Controller architecture had to be scalable in the sense that it should be capable of managing larger networks and larger numbers of assets without having to modify the core software.

Extensibility in the Cell Controller context is the ability to add new asset classes, operating modes, etc. For example, the CCPP developed high level capabilities to control Danish-style wind turbines. Future deployments will most likely require control of modern wind turbines which have more controllable functionalities (e.g. control of reactive power within capability limits), thus new asset control interfaces and high level control algorithms will need to be engineered pre-deployment. Even though new asset types may be added to the system, the same overarching control strategy employed by the CCPP should be usable for grid operations with those new assets.

4.2 Distributed Deployment

As the name implies, distributed energy resources are generally geographically dispersed throughout the cell. The Cell Controller was designed with a distributed control architecture anticipating that asset controllers could be co-located with the field assets, substation controllers co-located with the corresponding substations, and the Cell Controller master located at the DNO control room.

This control methodology also enables system intelligence to be located where it is needed, minimising the dependency of system reliability on communication network availability, latency, and error rates. This approach also results in a robust control system that scales well since the majority of data is consumed in close proximity to where it is generated in near real time. The different levels within the distributed controller also carry out control operations at appropriate time scales.

4.3 Continuous Monitoring of a Cell

Islanding of the cell is not possible without (near) complete knowledge of the state of each cell asset, i.e., the Cell Controller must be sufficiently "self-aware". Therefore a necessary design requirement was for the Cell Controller to be able to evaluate its status relative to the transmission grid at all times. Therefore the adopted design allowed continuous access to both static asset parameters (e.g. asset availability, operating mode, protection limits) and dynamic metrics (e.g. active power import/export across key interconnect points). A distinction was also made between data monitoring for analysis and archival purposes and data access for control purposes. Since completely instrumenting a Cell was impractical, the decision was also made to evaluate the use of state estimation for both bad meter detection and to estimate system states where no direct measurements were available.

4.4 Rapidly Balance the Cell When Trigger Issued

The ability to rapidly balance the cell was deemed a critical design requirement. In the event that the cell is commanded to island i.e. hard trigger (or commanded to prepare for islanding, i.e., soft trigger) power exchange at the primary interconnect must be (near) minimal to avoid large, damaging transients to both the distribution network and grid-connected devices when the breaker is opened. Fast balance can be achieved by rapidly shedding generation, shedding load, or a combination of the two.

4.5 Island Operation and Resynchronisation

Successful islanding requires the cell to operate independent of the transmission grid using its own assets to achieve stable voltage and frequency. During island operation the cell must attempt to restore any shed loads when possible. Finally, when commanded to reconnect to the main transmission grid, the cell must resynchronise with the grid prior to closing the primary interconnect breaker. Active resynchronisation requires the ability to vary frequency and voltage within the Cell to bring them within the synchronisation window with the primary grid.

4.6 Maintain Local Control of Assets

The Cell Controller was designed to allow asset owners to freely disable and re-enable assets from the cell. In particular, if an asset was to be temporarily removed from the cell, the owner was able to indicate that the asset was "out-of-service" for a specified time period. In response, the Cell Controller would redeploy the remaining assets as necessary to either maintain or temporarily suspend the current services being provided. Upon the return of the asset to the cell by the owner, the Cell Controller would once again redeploy the available assets as necessary and attempt to restore any suspended services. In addition, if asset capabilities changed during the course of the project due to equipment upgrades, component wear-out, etc., the appropriate system configuration files accessed by the Cell Controller that define each asset's running parameters, capacity, etc. could be updated.

By allowing complete local control of DER, individual asset owners within the pilot region were able to maintain and manage their equipment as needed. If the asset owner disabled his asset for any reason, the Cell Controller could not override that setting under any circumstance.

4.7 Maintain Grid Operation Parameters

To minimise the chance of causing damage to any of the in-situ assets, and per Energinet.dk's guidance, grid operation parameters and protection relay parameters were not to be changed during testing. This resulted in the need for larger "shock absorbers" to hold tighter operating tolerances especially during island operations. The project team decided not to invest in larger equipment than already installed but rather to select network regions and operating conditions for the field tests where the risk of being resource-short was minimised.

4.8 Cell Controller User Interfaces

Since CCPP was an RD&D project, it was decided that only basic User Interfaces were required for the demonstration of technical capabilities. Human factors and usability from the point of view of commercial users were not taken into account. Therefore, while the technical capabilities of the Cell Controller were well developed, only rudimentary Graphical User Interfaces (GUI) was developed for the project in order to reserve available manpower resources for the functional development. Since the Cell Controller was to be operated by skilled personnel during field testing, a high level of familiarity with the system was required for operating the Cell.

It should also be noted that several of the GUI screens that mimicked actions taken by different stakeholders (TSO, DNO and BRP operations) were only intended to showcase the technical capabilities of the Cell Controller.

Figure 14 Billund CHP plant.

5. Cell Controller Capabilities

Cell Controller (CC) capabilities are extensive and can be best described by first separating high level user capabilities, e.g., active power balancing at the primary interconnect, from lower level Cell Controller functional capabilities, e.g., monitoring the status of individual assets. For the former, the capabilities are grouped by the services required of or offered to the (potential) stakeholders, i.e., asset owners, the Distribution Network Operator, the Transmission System Operator, and the Balance Responsibility Party. For the latter, capabilities are grouped by CC functional capabilities.

5.1 High Level User Capabilities

The high level user capabilities overlap with the original project objectives such as islanding the cell and providing active power balancing services to the transmission services operator. A brief description of the final developed capabilities presented to the stakeholders (users) by the Cell Controller is given below.

5.1.1 Transmission System Operator (TSO)

The TSO is presented with a technical virtual power plant (TVPP) view of the cell for monitoring the status of the total spinning and non-spinning reserves (see below for a more complete description of spinning reserves) available within the cell, and both the cell's active and reactive power exchange with the grid. Using the TSO GUI, the TSO can issue active and/or reactive power import/export set points, or issue a hard trigger to island the cell.

5.1.2 Distribution Network Operator (DNO)

The DNO can use their DNO GUI for enabling/disabling voltage control at the 60 kV and 10 kV levels. The Cell Controller will utilise tap changers and the reactive capabilities of online CHPs to maintain the voltages per the DNO's requested set points and preferred operating ranges throughout the distribution network. This is the expected normal mode of operation for the Cell Controller.

5.1.3 Balance Responsibility Party (BRP)

As a necessary field test mock-up a BRP can query the Cell Controller via a BRP GUI for details about the various assets within the cell, such as rated capacities, availability, run time, etc. Based on the details provided by the Cell Controller, the BRP can group sets of assets based on their existing business logic, and issue commands to the Cell Controller to dispatch the groups for performing a particular service.

5.1.4 Asset Owners (AOs)

The Cell Controller provides an interface through which owners can more easily manage their individual assets. Of primary concern to the owner is the ability to (temporarily) remove his asset from the cell during routine maintenance or equipment upgrades. Since the Cell Controller must maintain an active inventory of the assets and their current availability for certain operations/services, the owner is provided with the added capability to flag his asset as either available or unavailable for any of the operations described above.

5.1.5 Multi-Stakeholder Coordination Capabilities

The Cell Controller was designed to accommodate multiple service requests simultaneously. For example, a BRP may request active power support from the CHPs within the cell while the DNO is using the reactive power capabilities of those same CHPs for voltage control. The Cell Controller has the ability to coordinate these operations to occur simultaneously. In the event that two or more requests come from authorised stakeholders, the Cell Controller acts as arbiter using the following priority list (by descending priority) to settle conflicts:

1. TSO Hard trigger, i.e., immediate islanding of the cell
2. DNO voltage control
3. TSO Soft trigger, minimum, and maximum generation triggers
4. TSO active power import/export control
5. BRP market operations
6. TSO VAR control (150/60 kV level)

Thus, if the TSO issues a hard trigger, i.e., the TSO instructs the cell to island as quickly as possible, the Cell Controller will immediately terminate all other operations whereas a soft trigger issued by the TSO will not cause the DNO voltage control operation to terminate.

5.2 Lower Level Cell Controller Functional Capabilities

The lower level Cell Controller functional capabilities are the building blocks from which the high level user capabilities are constructed. For example, if the TSO issues a hard trigger to safely island the cell several specific tasks are executed in parallel and/or rapid succession: (i) the TSO issues the trigger via an interface between the TSO control room and the Cell Controller, (ii) all active assets reset to pre-assigned operating modes and capacities based on the preload plan (continuously updated and distributed by the Cell Controller), (iii) as the assets transition, a mode manager coordinates the DER to achieve (near) power neutrality at the primary interconnect which may require the shedding of loads, wind turbines, etc., and (iv) when and if the conditions to go to island mode are met (within a predefined tolerance range), the breaker at the primary interconnect is commanded to open.

Figure 15 illustrates the topology of a representative cell and a simplified representation of the corresponding Cell Controller. For this particular example the cell includes two substations (SS_1 and SS_2); SS_1 contains the primary interconnect between the transmission grid (150 kV) and the local distribution network (60 kV).

Figure 15 also shows the major control levels of the Cell Controller, L1 through L4. The layer denoted L0 stands for the control system that comes standard with an asset. L1 through L3 are part of the Cell Controller and L4 (during field testing) is a stand-in for third party user capabilities. L1s reside near DER, L2s reside at substations, and L3 resides at the master substation (primary Cell interconnection). For field testing purposes, L4 was also installed at the master substation for the project.

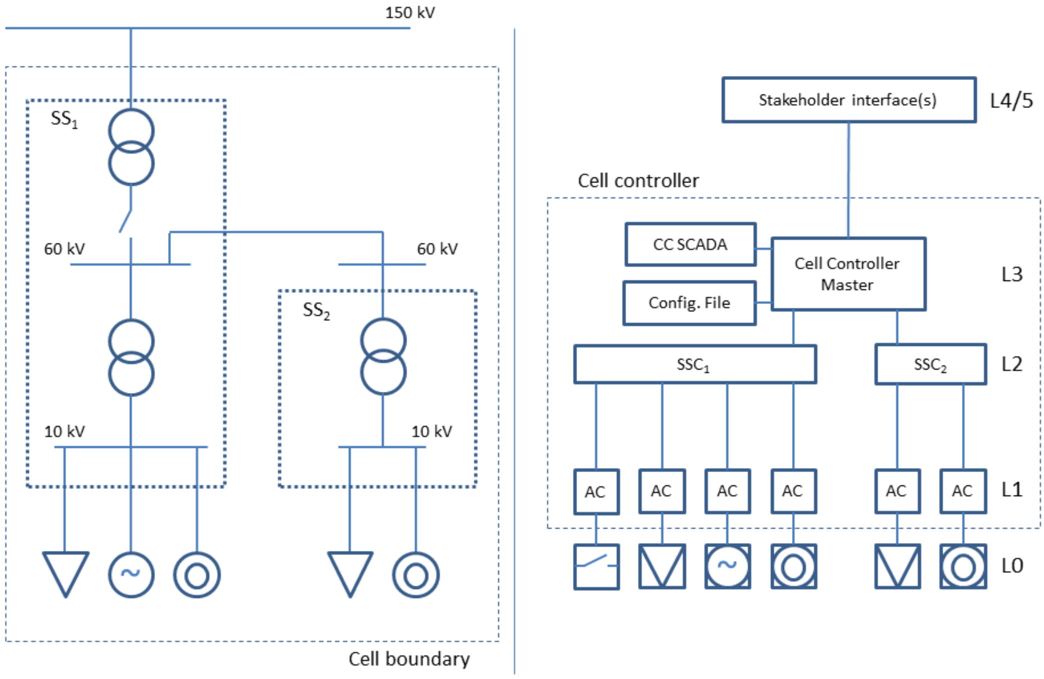


Figure 15 Representation of a Physical Cell side by side with the Cell Controller. The left panel illustrates the basic elements of a distribution network including a breaker on the low voltage side (60 kV) of the transformer at the primary interconnect and downstream load and generation assets. The right panel summarises the Cell Controller architecture with its three distributed control layers, L1, L2, and L3 that approximately parallels the distribution network topology. The stakeholder interfaces reside at the L4/5 level and the asset interfaces reside at level L0.

At the highest level (L3) within the Cell Controller is the Cell Control Master (CCM) from which system wide coordinated control operations are initiated. The CCM continuously accesses the CC SCADA system which acts as data historian, protocol driver, etc. The cell configuration file stores "static" information about the cell such as generator nameplate capacity, asset parameters and default set points. The Substation Controllers (SSCs) are found at the next level (L2); the SSCs act as data aggregators with respect to the CCM, i.e., they report the active and reactive power at the substation, the total downstream generation and load, etc. The SSCs receive commands from the CCM, perform the necessary computations to determine how to deploy the downstream assets, and issue commands to the asset controllers (ACs) at Level L1. Each AC computes new set points for the particular asset it controls and issues direct commands via an existing interface (L0) for that particular asset. Note that the L0 interface is not considered part of the Cell Controller.

All of the high level capabilities are initiated through the human-machine interface (HMI) denoted by L4/5. Each stakeholder has a custom interface with the Cell Controller through which queries about the availability of individual assets, requests for particular operations, and triggers are issued as previously explained.

Below are brief descriptions of the key modules, controls, and functional capabilities developed and tested during the CCPP grouped by the primary level (L1–L4/5) at which the function was deployed within the Cell Controller.

5.2.1 Level 4 Functions

Market Operation (MO): The Market Operation user interface was developed to illustrate some of the potential services that could be provided by the cell when grid connected. In particular, the MO allows (i) the TSO to dispatch assets for kW/kVAR control across the primary interconnect, and (ii) presents the BRP operator with a list of assets from which groupings could be selected for inclusion in day-ahead, power balancing, and primary regulation markets.

Multiple Cell User Interface (MCUI): This feature was developed to demonstrate the Cell Controller's capability to support the selection and dispatch of generation assets across two cells by a BRP while both TSO and DNO controls were active.

5.2.2 Level 3/Level 2 Distributed Functions

Several functions were deployed at both the L3 and L2 control levels. The L3 versions of these control functions performed system wide control (strategic deployment) whereas the L2 versions performed local control (tactical deployment).

For example, after the L3 control accepts set points (e.g. target values for the import/export of active power) from the L4/5 interface, it computes a solution at the substation level, i.e., the L3 control passes unique target values to each substation controller (L2) and not to the individual assets. Each L2 controller, in turn, computes and deploys a solution based on the target values issued by the L3 controller using only the local assets.

There are four critical functions deployed at both the L3 and L2 control levels: voltage control, import/export control, preload planning and frequency shedding. A description of each, at both levels, can be found below; Level 3 and Level 2 functionalities are distinguished by the suffix .L3 and .L2, respectively.

5.2.3 Level 3 Functions

Voltage Control (VC): Voltage control is implemented at both the L3 and L2 control levels. When in island mode, the VC.L3 is responsible to assign an SSC to CELL VOLTAGE MASTER; when grid connected, the VC.L3 is responsible to assign an SSC to LOCAL VOLTAGE CONTROL MODE, and to assign one or more SSCs to VAR SUPPORT MODE to supply/consume VAR as needed.

Import/Export Control (I/E): While grid connected, the TSO is able to command the import/export of power across the primary interconnect. The I/E controller is tasked to maintain (nearly) constant total power import/export in the presence of wind and/or load changes by increasing or decreasing generation as needed. The L3 version set target values at the substation level only.

Preload Plan (PLP): The preload plan is a collection of operations to be executed if a hard trigger command is issued by the TSO, including the strategy for achieving the fast balance of the cell. The Cell Controller continuously updated the preload plan and communicated the plan with the assets (L1, L0) at a regular interval to minimise the time required to deploy the plan.

The PLP.L3 is responsible for initiating, constructing, and broadcasting the cell wide preload plan. First the PLP.L3 computed target values for both active and reactive power for each substation and passes them to the corresponding SSCs (L2). Each PLP.L2 returns one or more preload plans using its local assets. From the collection of PLP.L2 plans, the PLP.L3 assembles the “best” plan based on a configurable priority listing and broadcast the plan to the assets via the SSCs and the ACs.

Frequency Shedding (FS): This functionality is similar to the preload plan, i.e., the FS.L3 constructs a system-wide shedding plan by first collecting shedding plans from each SSC (FS.L2), assembling a “best” master plan and then broadcasting the plan to the assets. Unlike the preload plan, the system-wide shedding plan prioritises the order in which to shed assets.

This functionality is only available in island mode; it is enabled only after a predefined amount of time (configurable) has elapsed after the cell transitions to island mode (e.g. 60 seconds).

*Market Operation Support (MO*S): This function was developed to accommodate multiple and possibly competing market operations. (See Section 5.2.1 above for additional detail.)

Mode Management (MM): The mode management plan calculator is running continuously to assign operating modes to all CHPs, SLCs, and SCs within the cell. For example, a CHP generator may be operating in base-load mode for active power export, but will be switched to isochronous master mode for island operations.

Spinning Reserve Control (SR): This capability was developed to start and stop generation assets. While grid connected, the SR is used to maintain import/export requirements for both active and reactive power. During islanded operation, the SR is used to keep the isochronous master unit(s) operating within their preferred operating range; wind turbines are presently not allowed to start during island control.

Load Restoration (LR): When transitioning to island mode, it is assumed highly likely that loads will be shed in order to balance the cell. The LR capability is designed to restore shed loads, when possible, while in island mode by increasing the available generation. Load restoration is only enabled when commanded by the DNO operator.

Network Topology Module (NTM): The Cell Controller uses the NTM extensively to gain awareness of node connectivity, voltage levels, substation connectivity, and real-time breaker status.

State Estimation and Load Flow Module (SELF): This capability was developed to analyse the distribution network and present limited state estimation for unmetered nodes identified as critical for Cell Controller operation using feedback from the Level 1 field assets. In addition, the SELF module was tested as a means to identify meter failures.

Cell Boundary Limit Detection (CBLD): This function is used in conjunction with the NTM and SELF module to determine the cell operation limits and restrict the Cell Controller from exceeding those limits.

Dynamic Cell Configuration (DCC): The dynamic cell configuration functionality works in conjunction with the NTM to identify rerouted assets and to determine i) whether or not import/export services are possible, ii) whether or not the cell can be islanded, and iii) whether or not the islanded cell can be resynchronised with the transmission grid.

Synchroniser Module (SM): When commanded by the TSO (via a Level 4 user interface), the SM issues frequency and voltage set point commands to the isochronous/voltage master generator to achieve frequency and voltage match with the grid; the master synchroniser (MS) issues a close command to the primary interconnect breaker only when the voltage, frequency slip, and phase difference between the cell and grid is within a predefined range.

5.2.4 Level 2 Functions

Voltage Control (VC): The VC.L2 control is responsible for implementing asset control based on the mode commanded by the VC.L3. In particular, the VC.L2 assigns set-points and voltage ranges to the local CHPs, SCs, tap changers, cap banks, and reactors.

Import/Export Control (I/E): The L2 I/E control is implemented to smooth transition to and from I/E operation. Nearly identical to the L3 I/E control, the L2 I/E control assigns the set points for the local assets.

Preload Plan (PLP): The PLP.L2 control is responsible for (i) computing one or more preload plans using the local assets to meet the target values issued by the PLP.L3, and (ii) passing the necessary information to each local asset as outlined in the system-wide preload plan.

Frequency Shedding (FS): The FS.L2 control is very similar to the PLP.L2 control in that it is responsible for (i) calculating a shedding plan for the local assets and (ii) passing the prioritised list to the local assets as outlined by the system-shedding plan.

5.2.5 Level 1 Functions

Asset Supervisory Interface (ASI): The ASI was developed to manage and control the individual assets as commanded/set by the upper level controls (L3 and L2). For example, if an island command is broadcasted, the L1 controller will immediately place the asset into the mode listed in the PLP without waiting for a communiqué from L3 or L2. The ASI is responsible for basic control functions (e.g. online, offline, reset alarms, etc.), data acquisition, asset integrity checks, safe mode handling, and error handling. Last, an L1 interface was created and deployed to simplify and standardise the communication between all assets and the upper level controls.

Under Frequency Load Shedding (UFLS): If frequency shedding is enabled, the UFLS control will compute and prioritise which 10 kV load feeders to shed if the island frequency falls below a predefined frequency threshold (e.g. 48.5 Hz) to bring the frequency back into the normal band (50.0 ± 0.5 Hz). This information is passed to the upper level controls (FS.L3 and FS.L2) for construction of the frequency shedding plan.

Over Frequency Generation Shedding (OFGS): If frequency shedding is enabled and the island frequency exceeds a predefined (configurable) frequency threshold (e.g. 50.75 Hz), the OFGS control will compute the excess generation to be shed based on the total online CHP generation and the CHP droop characteristic. (Only active power is considered for shedding.) This information is passed to the upper level controls (FS.L3 and FS.L2) for construction of the frequency shedding plan.

5.3 Integrated Control Viewpoint

Figure 16 represents an abbreviated overview of the entirety of the Cell Controller with the interfaces to both the high level user capabilities (L4/5) and the interfaces between the field assets and the asset controllers (L0). In addition, the right panel displays the assets available, by substation, throughout the CCPP. Not all of the functionalities presented above are explicitly listed in Figure 16; instead Figure 16 provides a means to better understand the interplay between the stakeholders, the Cell Controller, and the field assets when performing one or more activities. For example, Section 7 (Cell Controller Field Testing) references Figure 16 highlighting system components and capabilities relevant to the particular activity being presented.

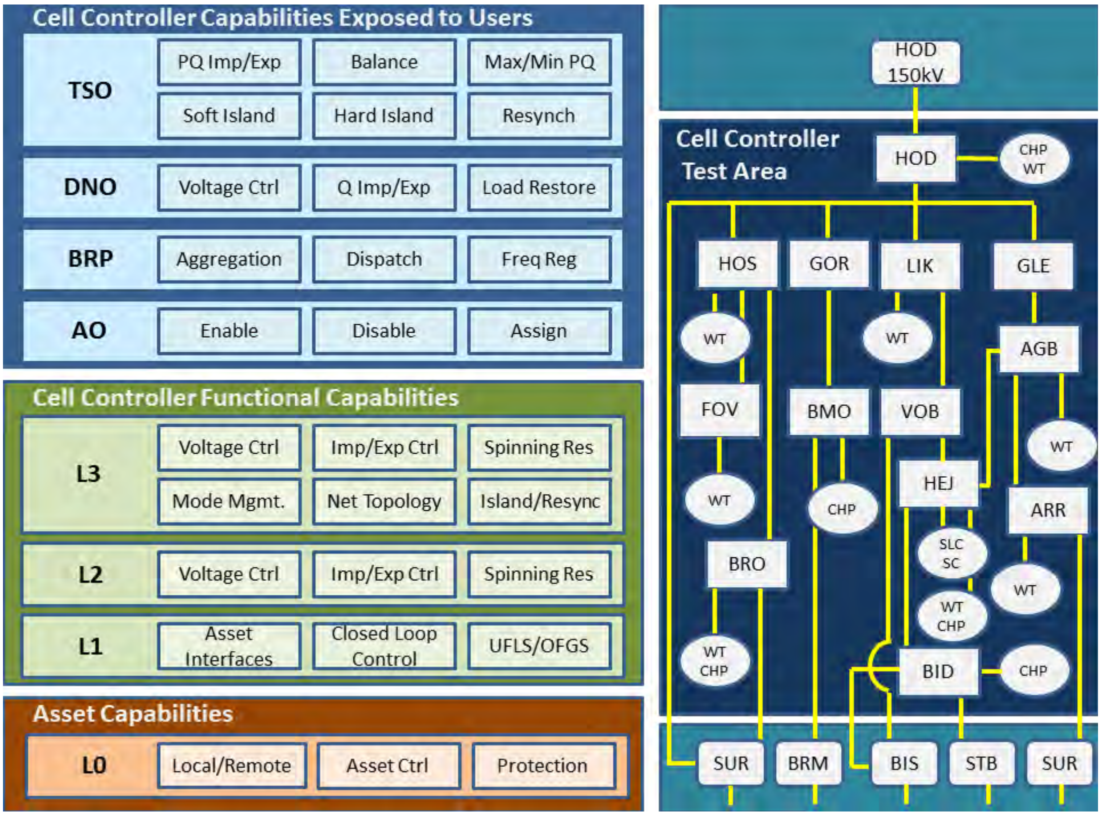


Figure 16 Overview of the Interaction between the User, the Cell Controller and its Capabilities, and the Field Assets. The top left (blue) panel is a simplified representation of the interfaces available to each stakeholder and corresponds to high level user capabilities. The middle-left (green) and bottom-left (red) panels represent key lower level Cell Controller capabilities that are tapped to perform the user capabilities. The right panel is a simplified representation of the actual Holsted Cell area and its assets.

5.4 Cell Controller Development and Testing Methodology

5.4.1 Prototyping of Cell Controller Software and Control Algorithms

The Cell Controller is a complex software application that is distributed across multiple locations and dynamically coordinates the operation of devices and systems at multiple time scales and different geographic ranges to meet specific operational goals. The Cell Controller development team followed a rigorous process of requirements specification, design, development, simulation and lab testing and software release for field testing. The development approach was one of rapid prototyping to develop software modules and control algorithms followed by testing and software improvements to achieve a sufficient level of reliability for field testing. Minimal emphasis was placed on user interfaces and ease of use issues since the objective of the project and resources available were limited to demonstrating technical feasibility.

Every year the Cell Controller's capabilities were successfully expanded, tested in simulation and in the InteGrid lab, and released for field testing.

5.4.2 Laboratory Testing

Each Cell Controller capability was tested and validated in the InteGrid Laboratory, Ft. Collins, Colorado, USA. The lab afforded the ability to fully control the system and isolate particular assets and/or controls with which the Cell Controller could be tested. The lab proved to be an invaluable resource for testing and debugging Cell Controller software and for developing Level 0 asset controllers.

5.4.3 Modelling and Simulation

Cell Controller testing required the implementation of a time-domain simulation model that would behave analogously to the actual distribution network of the Pilot Cell. Such a time-domain dynamic model allowed for deeper insight into the expected frequency and voltage transients when the distribution system was switched to island operation.

PowerFactory from DiGSILENT was chosen as the power system modelling and simulation tool. Custom interfaces were developed to achieve interoperability with the Cell Controller. The integration strategy was such that the Cell Controller could run on separate hardware, including the hardware to be deployed in the field, with communications between the Cell Controller and the simulation occurring across a network. In this configuration, as far as the Cell Controller was concerned, it was operating the target power system.

The development of the simulation model followed the strategy of the field implementation: full functionality was first established in Area 1 of the Pilot Cell, and later extended to include Areas 2 and 3. The total effort to build, test, and validate the simulation models was extensive and it is described in more detail in Section 6.

5.4.4 Field Testing

Field tests were the ultimate goal of each year's roadmap. Since the CCPP was initiated primarily to illustrate that cell control is possible with high penetration DER, it was imperative that the Cell Controller be deployed and testing on a real power system using in-situ assets with their unique characteristics. A roughly similar, staged approach to field deployment was followed each year with equipment installation and commissioning followed by software deployment, communication loop checks, and limited functionality tests.

Great care was taken to prepare for any field test prior to execution; in particular, contingency plans were prepared and protection relay settings maintained to maximise the safety of the field engineers and to protect the equipment. Finally, field tests were performed incrementally by testing individual assets, testing asset groupings and the distribution network as a whole.

Field testing followed a well-defined test plan that had in most cases already been validated in simulation. Section 7 presents some of the major field tests and results.

5.4.5 Reporting

At the close of each year, a series of annual internal reports were produced by the CCPP team. The reports summarised all of each year's activities, including the acquired assets, any software development, testing results (laboratory and field), and the modelling and simulation results. The reports enabled the team to document the successes and failures of the year and to present "lessons learned" to help inform the following year's roadmap.

In addition to the annual reports, quarterly reports summarising the data obtained from the CMS were published for the team to reference. The data sets typically exceeded 1.2 billion records annually (second-by-second meter data at multiple distribution network locations) and were a valuable asset for test planning and modelling & simulation validation.

Figure 17 NEG Micon 1 MW wind turbines.

6. Cell Controller Modelling and Simulation

6.1 Objectives

The Cell Controller implementation in the Pilot Cell area grid represents a challenge in many ways: Not only is completely new distribution grid management software designed and built, but it is also deployed in a real distribution system with many customers. From the very beginning of the project it was therefore seen as necessary to also build and validate a simulation model of the Pilot Cell electricity grid. The main purpose of the model was twofold:

1. To study the operating boundaries of the distribution system in general, like exploring inherent limits of active and reactive power production in terms of allowed voltage profile boundaries and thermal loading limits.
2. To serve as a test platform for Cell Controller function validation, and testing the algorithms that were developed for distributed voltage control, and frequency control in island operation.

These two purposes already define the main objectives that the simulation model needed to fulfil. While the inherent operating boundaries can be adequately explored by means of steady state power flow calculations, Cell Controller testing requires the implementation of a time-domain simulation model that can act analogous to the real grid in the test environment. Such a time-domain dynamic model would also allow deeper insight into what frequency and voltage transients must be expected when the distribution system is switched to island operation.

6.2 Building the Model

The main simulation model was to be suitable for basic load flow studies and symmetric RMS time domain studies (electro-mechanical transients). Variants of the model were also later prepared for certain EMT studies (electro-magnetic transients); however, the changes necessary for these studies were not fed back into the main model.

6.2.1 Strategy

In the course of construction, the development of the simulation model followed the strategy of the field implementation: Full functionality was first established in a small subset of the Pilot Cell, and later extended to cover all further participating substations and the loads and generation assets connected to them.

Basically the whole project was scheduled to cover the full Pilot Cell in three stages, corresponding to the three sub-areas of the Cell area. The first stage, Area 1, covered the substations of Billund and Hejnsvig. In parallel to the commissioning of measurement equipment, upgrading control systems of the CHP plants, and the installation of a synchronous condenser and a fast switching dump load, data was gathered to create a fully functional model of the Area 1 grid by mid 2008.

The data collection process included sending questionnaires to grid operators, power plant owners and operators, and manufacturers. All generator sites and substations were visited to collect one-line diagrams, SCADA screenshots, and name plate photographs. This process was repeated for all three stages of the Cell expansion, until all required information had been obtained.

6.2.2 *The Area 1 Model*

In regards to the network topology representation, the model represents the full 60 kV and 10 kV grid infrastructures to the extent covered by measurement devices. As feeder power measurement was undertaken only at the connection to the substation and not at remote nodes, each feeder could be represented by a single load element in the model. However, for purposes of dedicated protection studies, there were also variants of the model constructed that included further detailed modelling of the 10 kV load feeder topology.

In addition to the network topology, all generation assets of more than 600 kW rated capacity are represented in the simulation model. In the case of Area 1 this includes four wind turbines of 1 MW each, connected to Hejnsvig substation, the 800 kVA synchronous condenser and the 1 MW load bank (SLC) also connected to Hejnsvig substation, and the synchronous generators at the Hejnsvig and Billund CHP plants. All of these assets are complemented by asset-specific models of the control systems and the command interfaces necessary to start and stop assets and operate power circuit breakers.

In order to validate the dynamic models, a series of control system performance tests were conducted at all CHP assets and the synchronous condenser and load bank at commissioning time. The results of the tests were used for model parameter identification, leading to well-validated asset model performance throughout Area 1.

6.2.3 *Area 1 Field Tests*

The first Cell Controller field tests were conducted in Area 1 in late 2008, and were thoroughly prepared by simulations in summer and autumn 2008. After the set of test cases had been specified (determining the set of assets involved in each test, the operating conditions, and the sequence of operation), all scenarios expected during the test were first analysed in load flow calculations. One finding was that the reactive power balance could not be held in all specified cases, so that at least one unit would have had to operate outside its capability area. This test was therefore modified for the field, taking care that sufficient reactive power capability would be available at all times.

The sequence of events of each test case was then investigated in multiple dynamic simulation runs with the 2008 prototype of the Cell Controller. These simulations showed that even in island operation the system would be able to absorb significant load steps, and that the system would be able to safely resynchronise to the transmission grid after several minutes of island operation. While different initial power flow levels across the main grid breaker could be managed, the load shedding algorithm turned out to be too weak for fully automated feeder selection. For this reason, load shedding was manually limited to a suitable set of feeder load at each field test run involving island operation.

During the field tests, extensive data recordings were collected at the substations and the generation assets (and the load bank). The purpose of these data was to allow for detailed analysis in case of test failure, further model validation, and development of improved load feeder models. This data analysis was undertaken over several months in 2008 until late 2009.

6.2.4 *Addition of Areas 2 and 3*

In work conducted in parallel to the Area 1 field test preparation and data analysis, the simulation model was extended to cover the further substations in Area 2 (six additional 60 kV substations) and Area 3 (five more). Dynamic models were built for all 43 additional wind turbines and the six additional CHP generators.

6.2.5 Asset Model Validation

Similar to the asset-level testing already conducted in Area 1, commissioning tests for model validation purposes were carried out at the CHP generator units in Area 2 and Area 3. The scope of these tests was adapted from the previous tests as the controllers of the "new" CHP generators were not equipped with the same functions, and additional functions were added in secondary or tertiary control loops.

The dynamic tests were aimed at testing all possible control loops in the generator controllers:

- Voltage control loops were tested by assigning a sequence of voltage set points in open loop operation
- Speed control loops were tested by applying load steps in a setup where the generator supplies only the connected load bank (Area 1 CHP units only).
- Active power and reactive power control loops were tested by assigning sequences of set points in grid-parallel operation.
- Further tests captured the response to voltage changes on the grid (imposed by tap changes at the substation transformer) and the response of the engine/generator system to a sudden disconnection from the grid. (These were conducted at the units in Area 2 and Area 3 only.)

Despite detailed asset modelling based on manufacturer information, the validation process revealed that significant changes must be made to some controller models, as the measured response could not be matched closely by the model without modifications in the control structure. These changes were applied and the models were re-validated until no further improvement could be achieved from the given set of data recordings.

At this point, after the last CHP model validation in 2010, the model was deemed complete and ready for the preparation of the final field tests in autumn 2010 and summer 2011. This process was started with a series of power system studies, and then continued with extensive Cell Controller testing in scenarios similar to the projected field test cases.

6.3 Power System Studies

The first two studies investigated the limitations of reactive power generation and the potential impact of multiple Cell operation on substations outside the Pilot Cell area. These studies were carried out as steady-state power flow analyses. The further studies were all carried out as time-domain studies using the dynamic model.

6.3.1 Reactive Power Import/Export

Since the Pilot Cell would be able to operate as a virtual power plant for active power and, independently, for reactive power, one question was simply what amounts of reactive power can be injected into the transmission grid. Related to that it can be asked how much can be drawn at maximum in the same scenario, and how much this import/export range depends on external factors such as the wind situation or the consumer load.

Results show that the import/export range that can be achieved at practically any time is smaller than the variations imposed by changes in consumer load and wind generation. Most CHP generators can operate at their reactive power boundaries without causing overvoltage at the substations. The only exception to this is the Bramming Øst substation, where the substation transformer is unable to reduce the 10 kV voltage sufficiently when all generators run at maximum reactive power output. In this case the reactive power capability range of the generators cannot be fully exploited.

6.3.2 Voltage Impact of Multiple Cell operation

One idea for the 2011 field tests was to demonstrate portability and scalability of the Cell Controller system by splitting the Pilot Cell into two parts, which would then be operated independently from each other. These could either be connected together (sharing the single external connection at the Holsted substation) or run disconnected from each other. In the disconnected case, the second sub cell would have to be connected to another external substation for its connection to the high-voltage transmission grid. The question raised towards this scenario was whether circumstances in the second sub cell could cause any unexpected operating conditions at connected substations.

Simulations could only partially address this concern, as the 60 kV grid topology outside the Pilot Cell was not well known and not included in the model. However, taking the assumption that the differently connected second sub cell will form the furthest end ("leaf") of a 60 kV grid branch, it can be determined that the furthest voltage deviations will always occur within the Cell itself and can thus easily be detected during a test run. Generator set points could then be adjusted as necessary to restore more regular power flows and voltage levels.

6.3.3 Impact of Tap Changing on Frequency Control

In island operation it is necessary that the connected generation assets are capable of balancing the active power load and generation within the Cell to keep the frequency within a small band around the required 50 Hertz. This capability is continually exercised by the changing consumer load and the natural fluctuations of the wind in the case when any wind turbines are online. Besides consumer action, the load also varies depending on voltage changes at the substations, as can be observed when the transformer tap changers adjust their position. These effects were studied in a series of dynamic simulations, with different generators online, and tap changers acting at varying substations.

The general concern was confirmed in the simulations, although only determined to be problematic when the frequency was already close to the protection limits of the generation assets. As a result of this finding, the Cell Controller was modified to inhibit tap changes when the frequency would approach these frequency thresholds.

6.3.4 Studying Communication Delays

The transition from grid-parallel operation to island operation of the Pilot Cell especially depends on a sequence of events that must be executed in close succession. This involves the shedding of load and/or generation to achieve sufficient active and reactive power balance within the Cell, then the opening of the Cell grid breaker, and finally the necessary switching of control modes and set points at some generation assets. All of these must occur in the right order and with as little delay as possible to minimise the black-out risk. Delays caused by the communication media used as command channels to the assets can thus significantly influence the transition to island.

The impact of communication delays was studied by first analysing the communication media used at each asset, and determining the delays that must be expected with the given technologies. The second step involved modifying the model to introduce artificial delays of the same order of magnitude wherever possible at the respective signal interfaces. Finally a set of islanding scenarios was simulated with and without communication delays and the results were compared.

The simulation results showed that the configured delay times did not have significant impact on the capability of safe island transition in the given scenarios. Further simulations were therefore carried out without considering the issue again.

6.3.5 150/60 kV Transformer Inrush Study

Future visions of Cell Controller applications include the possibility to contribute to black-starting the transmission system from distribution systems such as the Cell running in islanded operation. For this scenario it would be of interest whether the Cell could survive the transients that would occur during the energization of the 150/60 kV transformer without tripping generator protection and thus blacking out the Cell itself. This problem was investigated in a number of EMT-type simulations using an extended variant of the simulation model.

The result of the inrush study was that the likelihood of failure in such a case must be regarded as very high, although not all sources of uncertainty could be eliminated and there might be a small chance of success. However, the risk was regarded as sufficiently high to cancel this test as part of the field tests. In further Cell applications it is therefore deemed advisable to choose the island breaker on the high-voltage side of the transformer, so that no such energization would need to be conducted from a Cell that had successfully switched to island operation.

6.4 Cell Controller Testing

The choice of OPC as the scheme of communication between the different parts of the Cell Controller architecture was a good choice for the integration of the simulation model, as the simulation software used (DIgSILENT PowerFactory) provides a built-in OPC interface that makes it easy to connect the model to an OPC server. From a testing standpoint, this meant that the Cell Controller could run with practically identical configuration against the field and against the model. The only difference required was a time synchronisation scheme, because the final simulation model turned out to be too slow to run in real-time.

6.4.1 Grid-Parallel Operation

With such a simulation setup in place, Cell Controller testing in simulations focused on the preparation of the field tests. The first round of field tests involving the whole Cell was scheduled for autumn 2010, where grid-connected functions would be tested extensively. Based on the then current draft field test plan a set of test cases was specified for simulation testing in May 2010. The simulations were started a few months before the field tests with a development prototype of the Cell Controller and continued for several weeks; issues found were reported after each test run, and tests were re-run in simulations when bugs in the Cell Controller and in the model were fixed. Issues found in this phase include the failure of independent functions to be enabled in parallel, bad performance of the voltage control function, communication issues between certain parts of the Cell Controller architecture, a few inappropriate configuration settings, and several small issues in the performance of the simulation models.

A new Cell Controller prototype was released after this round of simulations, adding a few new functions targeted at the field tests and incorporating the feedback obtained from the simulations. To test this new prototype and properly prepare the field tests, the simulation specification was updated to incorporate testing of the new functions, and simulations recommenced with test cases almost identical to the final field test plan. In the simulations, it was found that the new prototype deviated from the specified behaviour in how it handled connection and disconnection of assets, and that the built-in state estimator did not work correctly in all circumstances. Both issues could be fixed in an updated prototype before the field tests commenced.

6.4.2 Island Operation

The simulation of island test cases was begun already during the grid-parallel field tests in November 2010, although the island field tests were only scheduled for June 2011. However, island operation involves the risk of consumer black out in the field tests and thus must be prepared extremely carefully. Like for the grid-connected simulation tests, a set of test cases based on the field test plan was specified for island simulation tests. Twelve different test cases were specified, covering different sets of generation assets connected to the grid, and different priorities for choosing the master units that would be responsible for frequency control and voltage control in the islanded Cell.

Over the course of about seven months between early November 2010 and early June 2011, all specified test cases were run repeatedly with multiple Cell Controller updates. This simulation cycle worked out as a stress test not only for the Cell Controller system, but also for the simulation model, and a long list of smaller and larger issues were found in both. Similar to the grid-connected testing, simulations were conducted until the beginning of the field test phase, and new Cell Controller updates were released incorporating the findings.

6.5 Conclusions: Modelling and Simulation

The performance of the Cell Controller system during the field tests represents the benchmark of whether the modelling and simulation work was successful or not. While the field tests also uncovered several problems in the overall system, the Cell Controller application itself performed well in the final field tests in 2010 and 2011. All issues in the Cell Controller that were found in the simulations could either be resolved before going into the field, or suitable workarounds could be applied. The modelling and simulation work has therefore successfully fulfilled its purpose.

However, the failures observed in the field tests also indicate the limitations of the simulation model. By definition, the model contains a simplified representation of the real world system, and limits must be drawn between what should be included and what is to be neglected. Besides the lack of modelling of the non-electrical parts of individual assets, it was observed that even the electrical control models did not fully match the field behaviour in all cases. For example certain CHP control modes were found to perform badly in simulations, but did perform well in the field. This indicates that errors were made in the modelling and validation processes. In most cases, however, the field tests confirmed the results of the simulations.

In summary, the results of the simulations and the field tests confirmed the choices of the simulation software and of the modelling approach. For future projects of similar scope a similar modelling approach is recommended. A few differences should be considered: More attention should be paid to the simulation speed right from the beginning of the modelling process. Controllers with very slow time constants might be implemented as external modules to the simulation software, so that they do not have to be executed at every time step in the simulation. Complex interfaces between different parts of the real-world controller applications should not necessarily be modelled in the same way; even if that means that the model validation process cannot use the signals at these interfaces for validation.

Figure 18 SC and SLC each in a 40 feet container with step-up transformer, protection and control equipment is hoisted on to foundations at Hejnsvig 60/10 kV substation.

7. Cell Controller Field Testing

One of the most significant accomplishments of the Cell Controller Pilot Project was the extensive field deployment, testing and the general success of demonstrations on a live power system. As outlined above, much care was taken by the CCPP team to develop, build, and test both the algorithms and the controls in the InteGrid laboratory; the algorithms and controls were further refined using comprehensive numerical analysis and simulation. The ultimate payoff was the ability to deploy the Cell Controller incrementally into actual field conditions where testing parameters could not be completely prescribed (e.g. consumer demand, wind conditions, etc.).

The CCPP team's approach to field testing closely followed the laboratory and simulation based testing approaches in that the prototype algorithms and controls were tested incrementally: first L0 and L1 capabilities were tested on individual assets, followed by L2 and L3 testing where the coordinated control of multiple assets could be performed, and concluding with L4/5 testing of services involving multiple parties. Progression through the various levels of testing only proceeded if all of the necessary functions and capabilities at the lower level(s) were satisfied. Consequently there were occasions where planned tests had to be postponed until a control was corrected. This conservative approach ensured that the risk of disruption to the consumers in the field was minimised. In addition, the field tests were designed to cover a broad range of operating conditions and usage scenarios and intended to validate technical capabilities that were deemed essential for future power system operations. Since the geographic scale, functional scope, asset diversity, and real world conditions of the CCPP could not be truly replicated in any simulation or lab, the field demonstrations served as the ultimate test for the concept.

The analysis and test summaries that follow are presented to illustrate the general approach employed by the CCPP team, i.e., dividing the project into manageable portions by first prototyping, testing, and refining the algorithms and controls on individual assets, then expanding testing to include multiple assets, before introducing new capabilities. The first two examples illustrate the collection and analysis of field data prior to deployment of the Cell Controller using the CMS. The subsequent two examples illustrate the type of testing performed by the CCPP team to validate the acquisition and deployment of new assets (SLC and SC). The final five examples show a natural progression of testing that complements the CCPP analysis approach: testing of a single L1 control, the successful islanding and resynchronising of the cell with and without wind generation, and two examples illustrating the ability to service multiple parties (e.g. TSO, DNO, BRP) simultaneously.

The tests presented in the following sections are a small subset of the full suite of tests that were conducted over a period of several years. Although they present some of the most important results, it should be noted that they represent less than 10% of the field tests carried out.

7.1 CMS: Pre-Cell Control – Load Analysis

7.1.1 Objectives

Prior to deploying cell control, it was important to gain an understanding of as many of the cell characteristics as possible. These types of analyses were used to verify sufficiency of transient and overall capabilities of existing generation assets, determine the appropriate combinations of assets for field testing, and to reach informed decisions about the types and capacities of additional assets to be acquired and deployed to successfully island the cell.

This example illustrates load data collected at two 10 kV feeders at which different populations are being serviced. Figure 19 plots the measured active load at a feeder that service a mostly residential area; Figure 20 plots the measured active load at a feeder that service an industrial customer base.

7.1.2 Results

Figure 19 and Figure 20 clearly illustrate the difference in load as a function of consumer usage: the residential feeder traces two distinct peaks (one in the morning just before the work day begins and a second peak in the mid- to late-evening hours) compared to the single extended plateau from roughly 08:00 to 16:00 associated with the industrial load.

This type of information is valuable to many different stakeholders. For example, prior to deployment of the Cell Controller, this information was used to inform simulation models from which various scenarios were generated for testing the controller capabilities. A second potential use includes the planning of asset allocation for a BRP which may be interested in participating in one or more active power markets. Furthermore, as data are collected over time, the CMS provides a means with which to monitor trends in both generation and loading, providing evidence for necessary equipment upgrades, available capacity for TSO and DNO services, and the potential or limitations for further penetration of renewables.

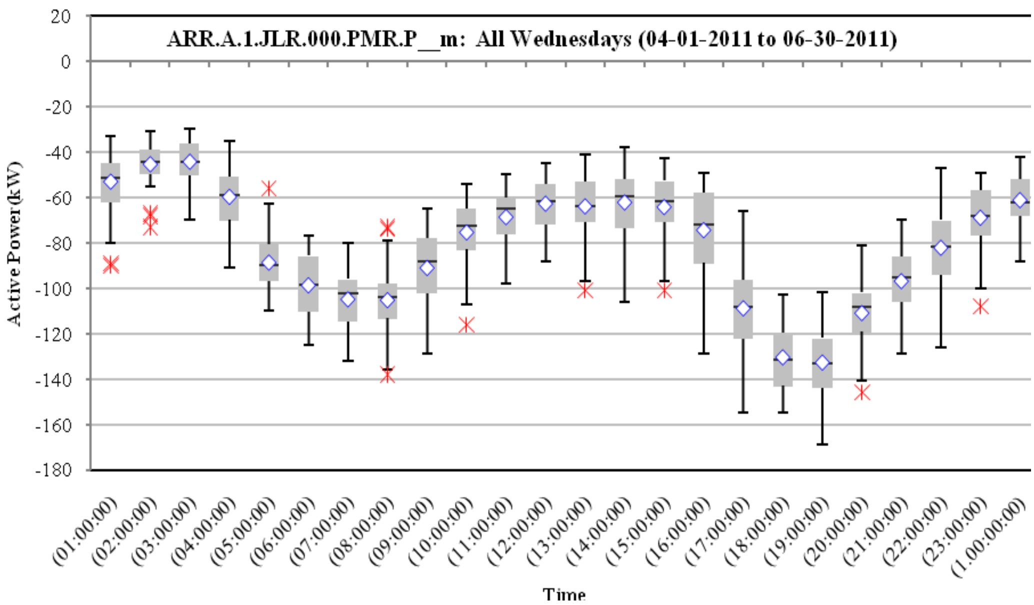


Figure 19 Load as a Function of Hour of Day for a Residential Feeder. The boxplots summarise the quantiles of the observed load (kW), by hour of the day, for all Wednesdays between 2011-04-01 and 2011-06-30; the grey boxes capture the middle 50%; outliers are indicated by red stars.

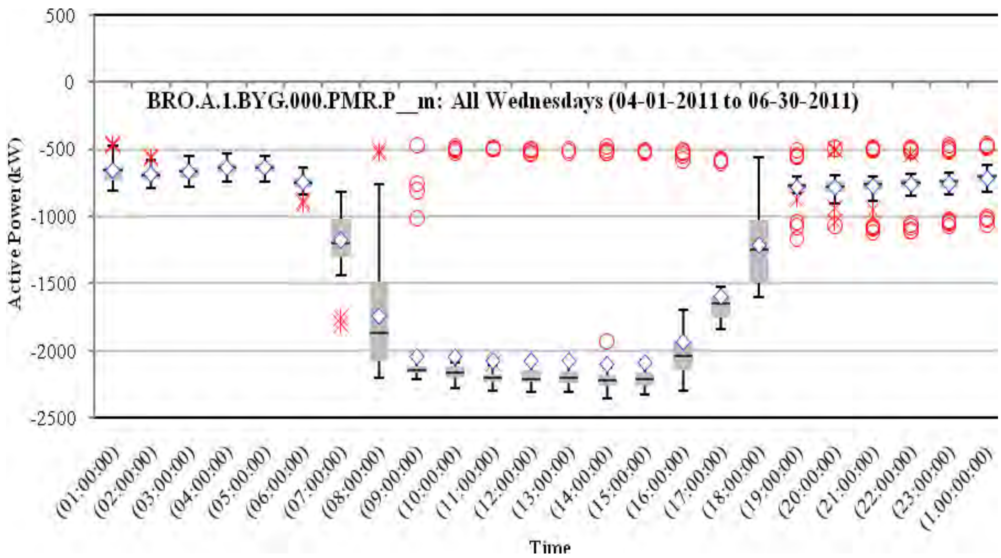


Figure 20 Load as Function of Hour of Day for an Industrial Feeder. The boxplots summarise the quantiles of the observed load (kW), by hour of the day, for all Wednesdays between 2011-04-01 and 2011-06-30; the grey boxes capture the middle 50%; outliers are indicated by red symbols.

7.2 CMS: Pre-Cell Control – Wind Transient Analysis

7.2.1 Objective(s)

This example illustrates the importance of understanding the DER with respect to the existing assets and to what extent new assets may need to be acquired and deployed. Recall that the pilot cell monitors 47 wind turbines of 600 kVA capacity or greater among its controlled assets. To better manage the transient nature of the wind power, the CCPP deployed a secondary load controller (SLC) capable of absorbing active power transients. This study was performed to verify that the SLC had sufficient capacity.

7.2.2 Result(s)

Figure 21 plots the distribution of the aggregated one-second active power transients for the fleet of 47 wind turbines (note the logarithmic scale). Of particular interest is the range and frequency of the extreme transients (both positive and negative). The histogram is nearly symmetric around zero with little more than 2% of the observed transients in excess of 400 kW (in magnitude). The 400 kW limit is significant because with optimal control by the Cell Controller during islanded operation, the 1000 kW SLC installed at Hejnsvig substation can readily absorb active power transients of magnitude 400 kW or less. Note that in the event that the transients could not be fully filtered by the SLC (the most extreme cases), any online CHPs would likely be able to absorb the excess.

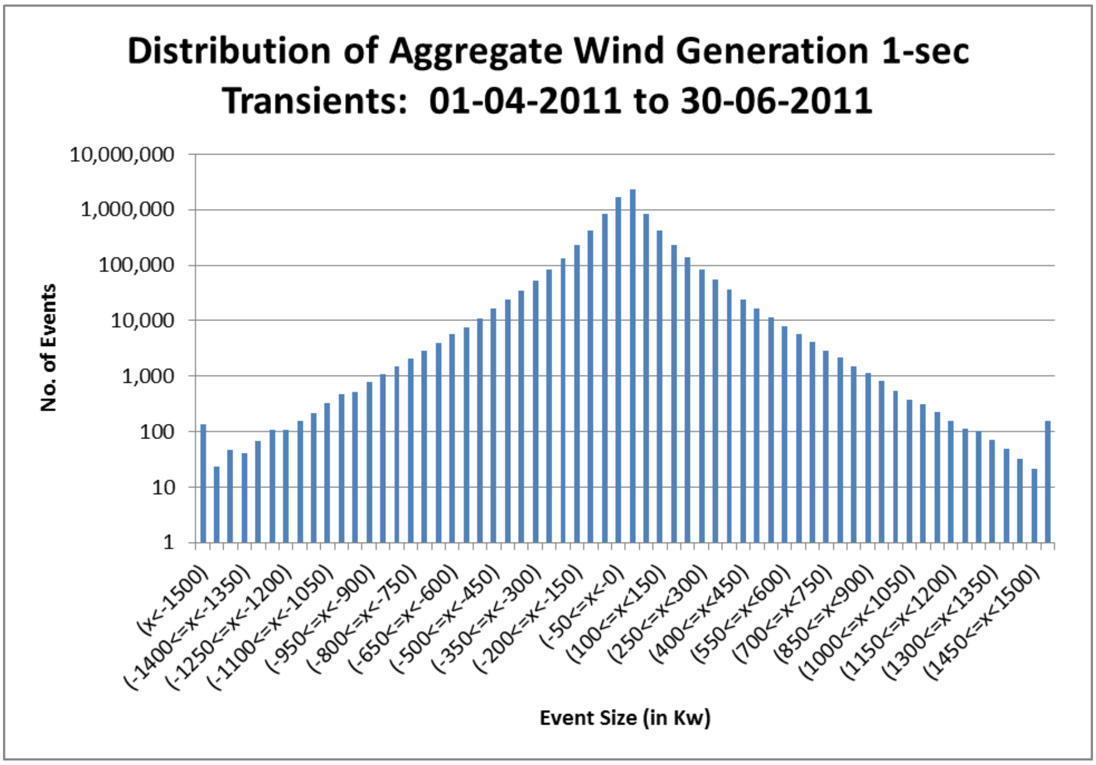


Figure 21 Distribution of Aggregated Wind Generation One-second Transients; the transients equal the second-to-second changes in total monitored wind generation in the Holsted Cell during the second quarter of 2011.

7.3 Secondary Load Controller (SLC) Analysis

7.3.1 Objective(s)

This test was performed to test the impact of the SLC on managing frequency during island operation. Three cases were compared: operation of Area 1 without the SLC, operating with the SLC in baseload droop mode, and operating with the SLC as a frequency (isochronous) master.

7.3.2 Test Setup and Initial Conditions

- Test conducted in Area 1.
- All wind-turbines were offline.
- 1 synchronous generator (2.8 MW) at BID CHP available.
- Sufficient load feeders available to (approximately) balance the cell.

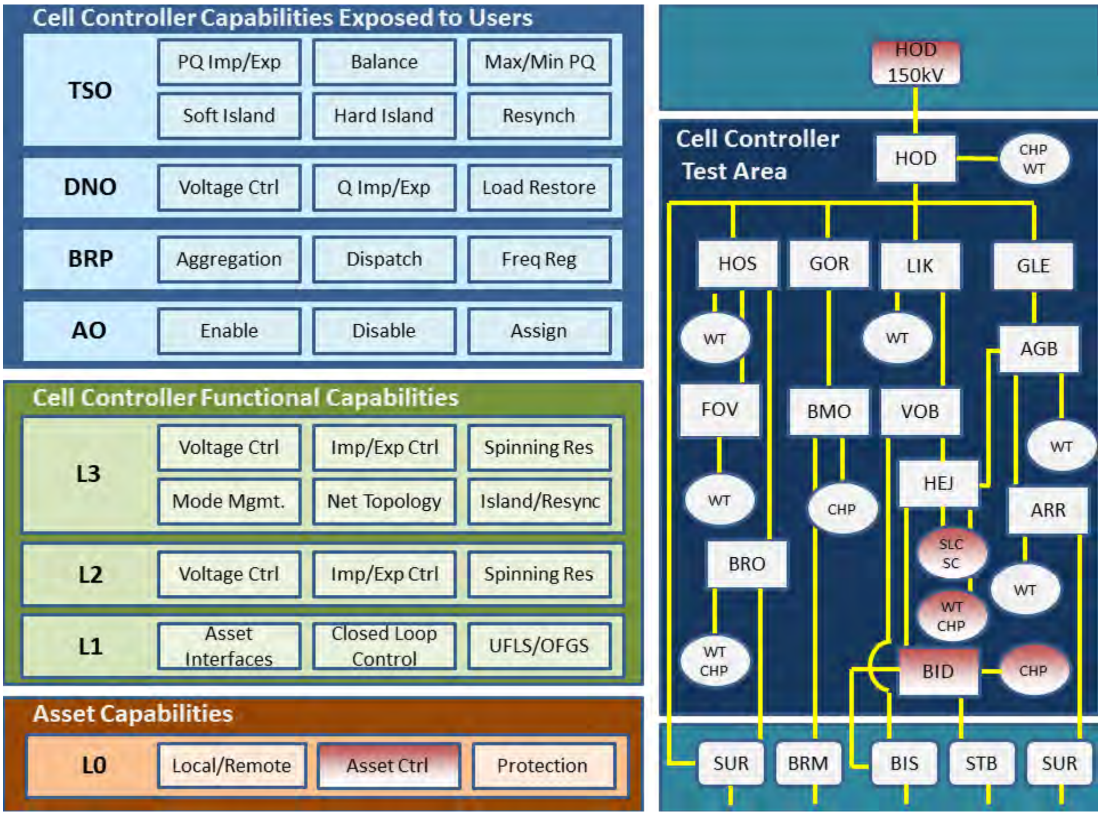


Figure 22 Cell Controller Configuration during SLC performance analysis. The left panels indicate which Cell Controller capabilities were being used during the test (highlighted in red) and the right panel highlights the Holsted Cells assets involved in the test.

7.3.3 Result(s)

Figure 23, Figure 24 and Figure 25 plot the frequency and 500 ms moving average with respect to time for each case. Table 2 summarises the mean and standard deviation (Hz) of the frequencies by case. The SLC significantly reduced the peak frequency swings of the islanded system; spectral analysis (e.g. spectral magnitude) showed that the amplitude of oscillations in the cell frequency was also significantly reduced. This test demonstrated the added benefit of deploying an SLC to better manage an islanded cell's frequency. Future deployments of cell control will likely require similar testing to identify the types and capabilities of assets to be acquired and deployed.

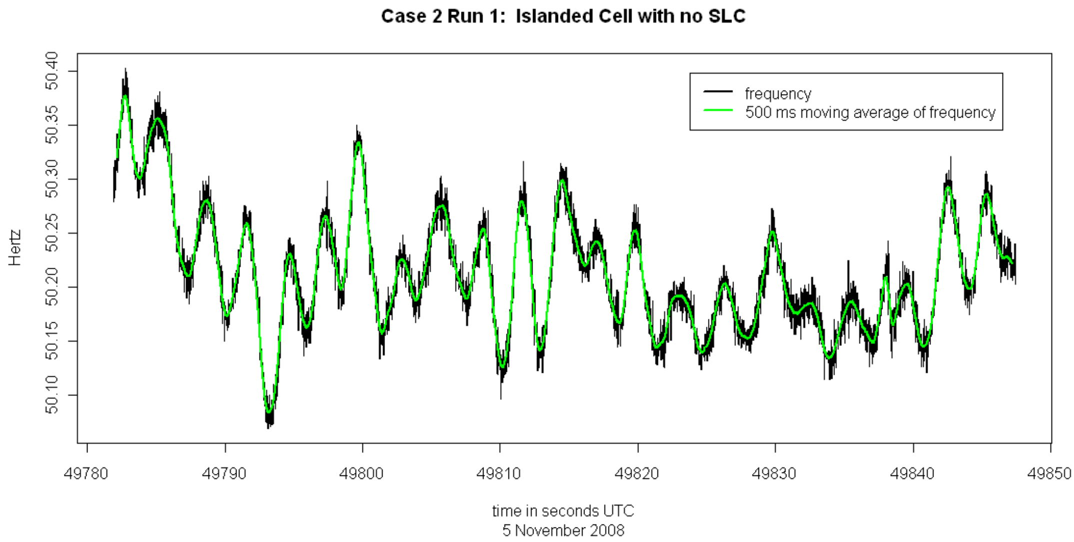


Figure 23 Islanded Cell with Inactive SLC – Frequency Signal. One minute "snapshot" of the entire trace collected during testing. The black trace plots the metered high speed data and the green trace plots the 50 ms moving average. Note the strong presence of periodicity in the time series when the SLC is offline.

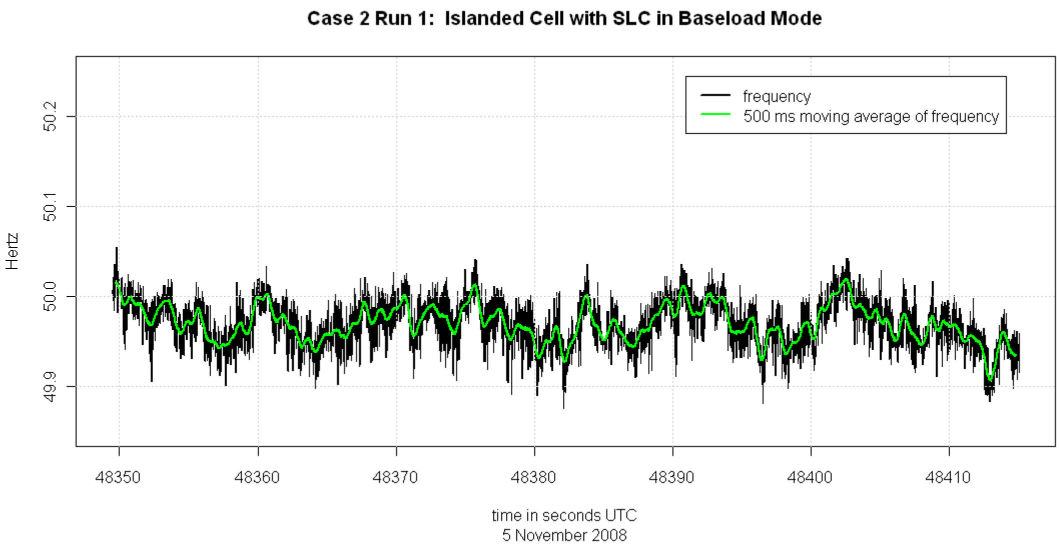


Figure 24 Islanded Cell with SLC in Baseload Mode – Frequency Signal. One minute "snapshot" of the entire trace collected during testing. The black trace plots the metered high speed data and the green trace plots the 50 ms moving average. The periodicity observed when the SLC was offline is significantly reduced.

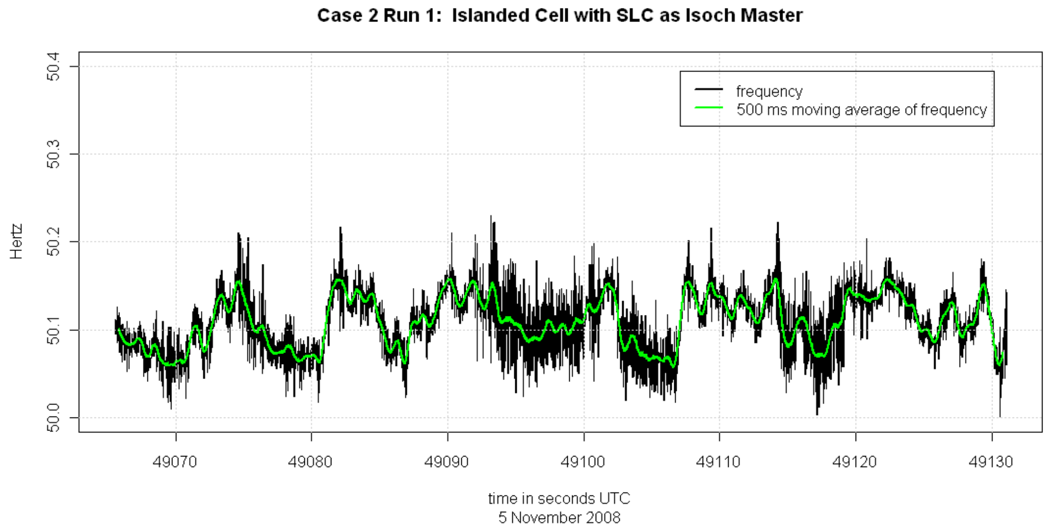


Figure 25 Islanded Cell with SLC in Isochronous Frequency Master mode – Frequency Signal. One minute "snapshot" of the entire trace collected during testing. The black trace plots the metered high speed data and the green trace plots the 50 ms moving average. Similar to the baseload case, the periodicity observed when the SLC was offline has been significantly reduced.

SLC Mode	Mean	sd ($\times 10^{-2}$)	Spectral Magnitude($\times 10^{-4}$)
Offline	50.17	10.8	11.1
Baseload	50.00	3.4	3.7
Isoch	50.11	3.5	1.4

Table 2 Operational Statistics for the SLC in Various Modes of Operation. The spectral magnitude quantifies the oscillatory nature of the frequency relative to the mean frequency; a lower number indicates a steadier frequency.

7.4 Islanded Wind Only Operation

7.4.1 Objective(s)

This test was performed to test the Cell Controller capabilities to transition to island and perform island operations in a wind only state. The test set out to verify the isochronous master operation of the SLC and the voltage master operation of the SC.

7.4.2 Test Setup and Initial Conditions

- The mini-island consisted of a single wind turbine, the SC and the SLC.

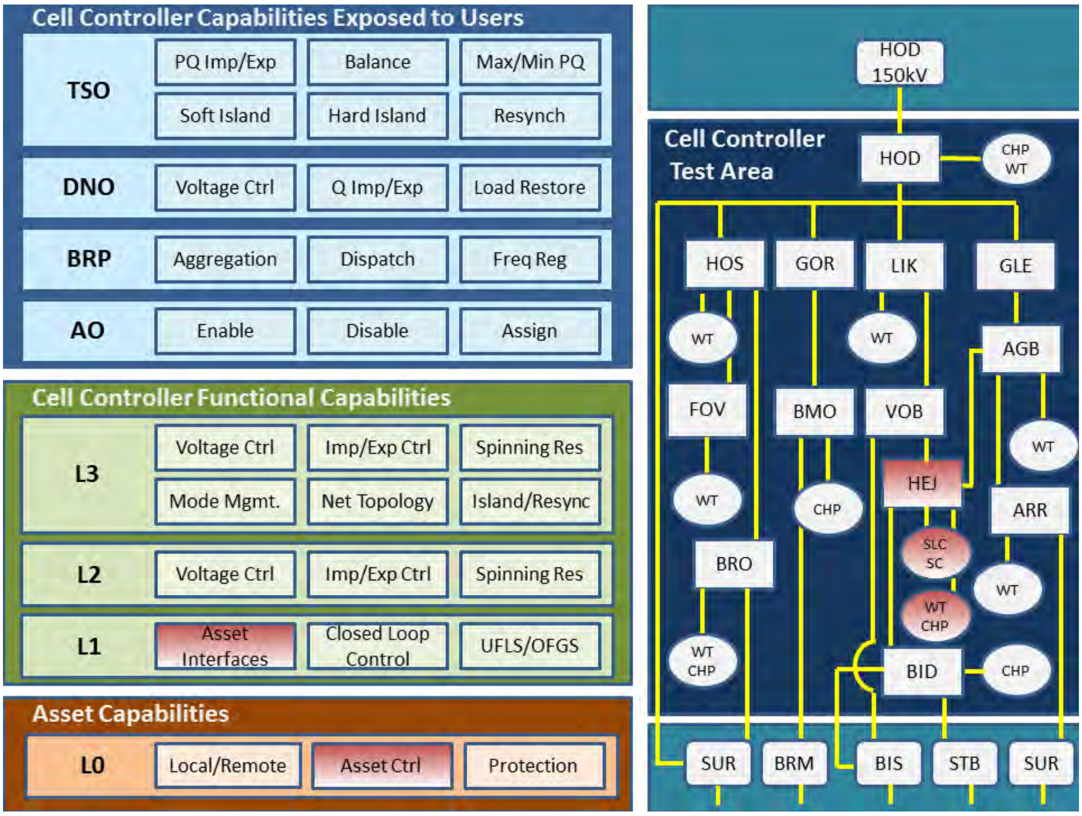


Figure 26 Cell Controller Configuration during Mini-Island Test (Wind Only Operation).

7.4.3 Result(s)

The SLC and the SC were able to support the frequency and voltage of the mini-island for more than five (5) minutes. Figure 27 and Figure 28 illustrate very effective control of the cell frequency (black) and voltage (blue), respectively. Figure 27 also shows that the SLC was able to balance the wind generation during the first 5 minutes during island operation. Hereafter the 1000 kW SLC began to dramatically lag during the very large wind transient then occurring resulting in 1100 kW wind turbine production which ultimately lead to blackout of the mini-island.

The mini-island test matched the SLC to a *single* wind turbine; as soon as sufficient wind energy was put into the wind turbine, the SLC went to its upper limit and stayed there. The SLC had no resources with which to counteract the increasing wind energy and the wind turbine shutdown on turbine over-speed. Analysis of four wind turbines using the data collected with the CMS shows that there can be a significant amount of variation between wind turbine power outputs even when the turbines are geographically close to one another. However the natural variation of the loads typically cancels the variability of generation, thereby implying that the SLC could balance multiple turbines if combined with dispersed loads.

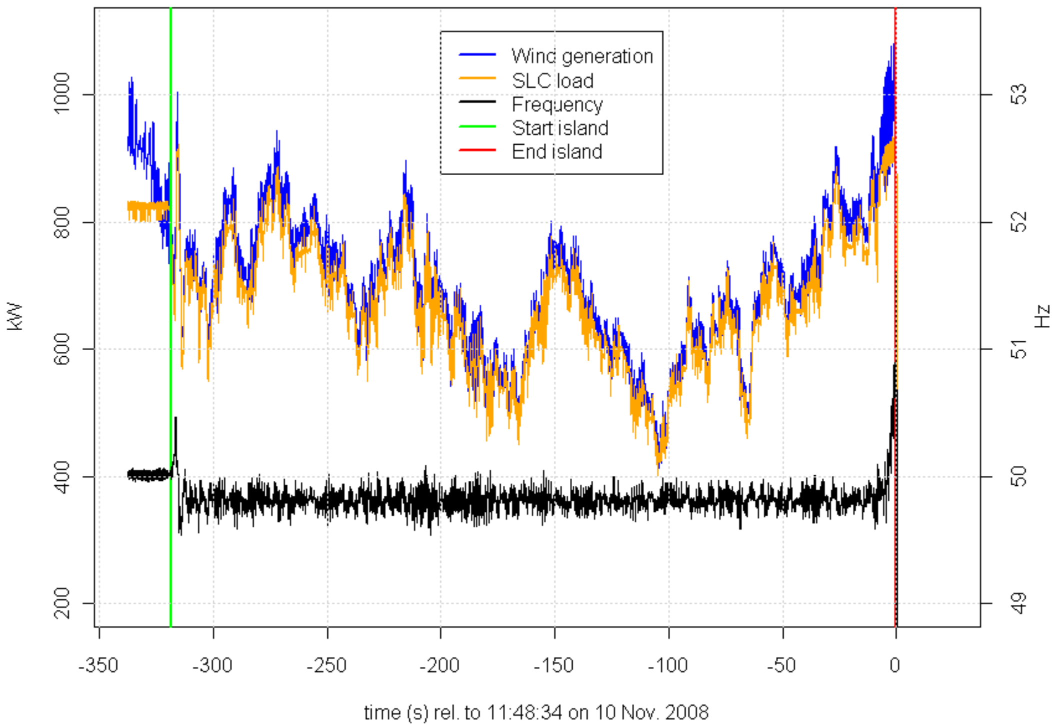


Figure 27 *Effect of SLC during the Mini-Island Test. The black trace plots the observed frequency (Hz); the blue and orange traces plot wind generation (kW) and the SLC response (kW), respectively. The Cell Controller was able to maintain a stable frequency (nominal 50 Hz) during the test prior to black out. Note the SLC's ability to balance the wind generation.*

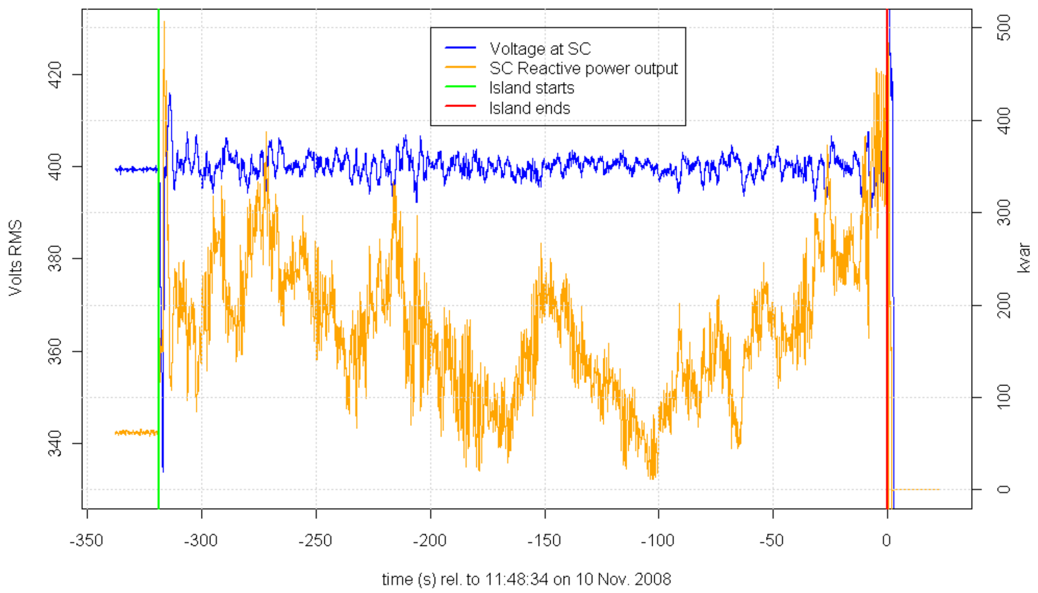


Figure 28 *Effect of SC during the Mini-Island Test. The blue and orange traces plot the voltage and kVAR, respectively, measured at the SC. The Cell Controller was able to maintain a stable voltage until black out; as expected, the trace of the SC closely follows the wind generation trace.*

7.5 Cell Controller Islanding – L1 Testing

7.5.1 Objective(s)

This test is representative of many tests used to validate control algorithms and to tune each of the L1 based control modes *prior* to proceeding to full island testing.

7.5.2 Test Setup and Initial Conditions

- Cell configured to minimum island; system configured and back fed as illustrated in Figure 29.
- All wind turbines at substations included in the cell were offline.
- SC and SLC were online.
- CHP units at BID and HEJ were online.
- Cell Control Master and Substation Controllers were disabled during this test.

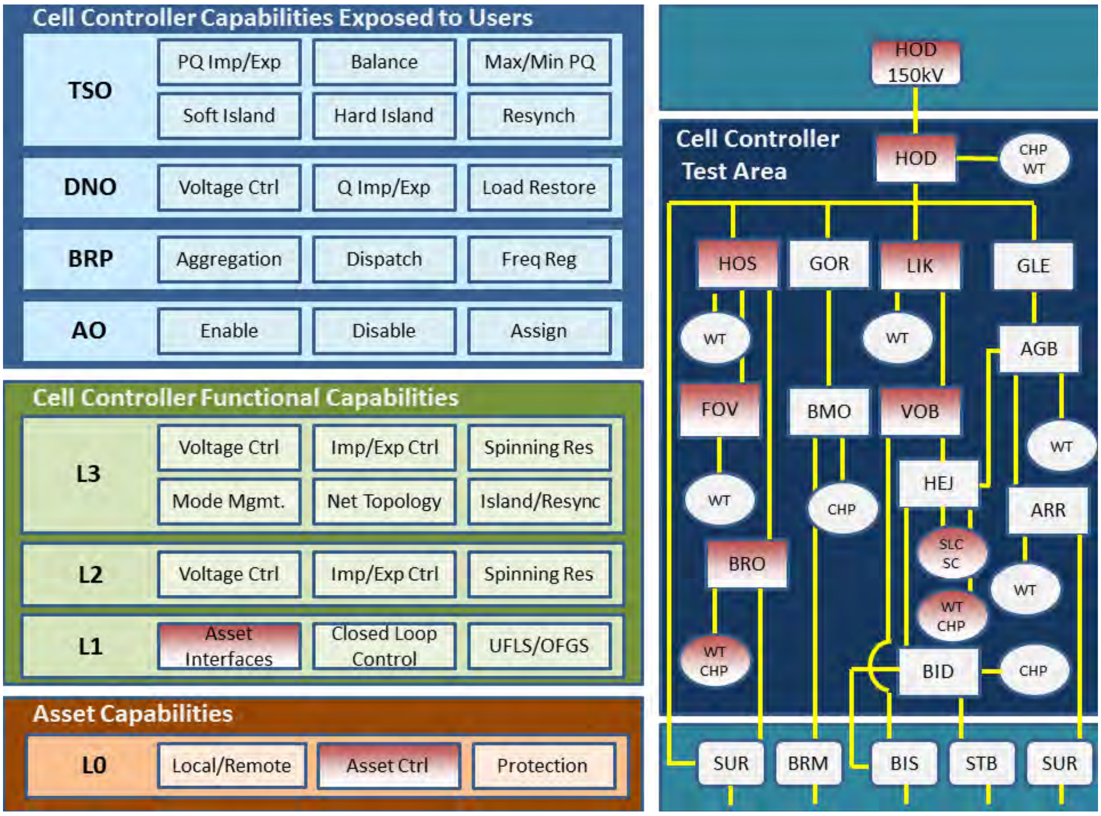


Figure 29 Cell Configuration during L1 Testing. The left panels indicate which Cell Controller capabilities were being used during the test (highlighted in red) and the right panel highlights the Holsted Cells assets involved in the test.

7.5.3 Result(s)

Figure 30 and Figure 31 show the performance of the Brørup CHP in L1 droop mode; droop mode allows the CHP to adjust its output based on the measured cell frequency and voltage as well as a configurable droop parameter. The cell frequency remained steady for the duration of the test, so no noticeable output change due to the droop components of the control mode occurred. At 14:08:30, the Brørup CHP active power set point was increased from 2800 kW to 3100 kW to adjust for changing cell conditions.

Completion of this and other Level 1 (L1) controller tests, where the L1 controllers are the asset-level interfaces with which the Cell Controller application communicates, allowed testing to proceed to the higher capability testing, particularly full scale islanding and service operations.

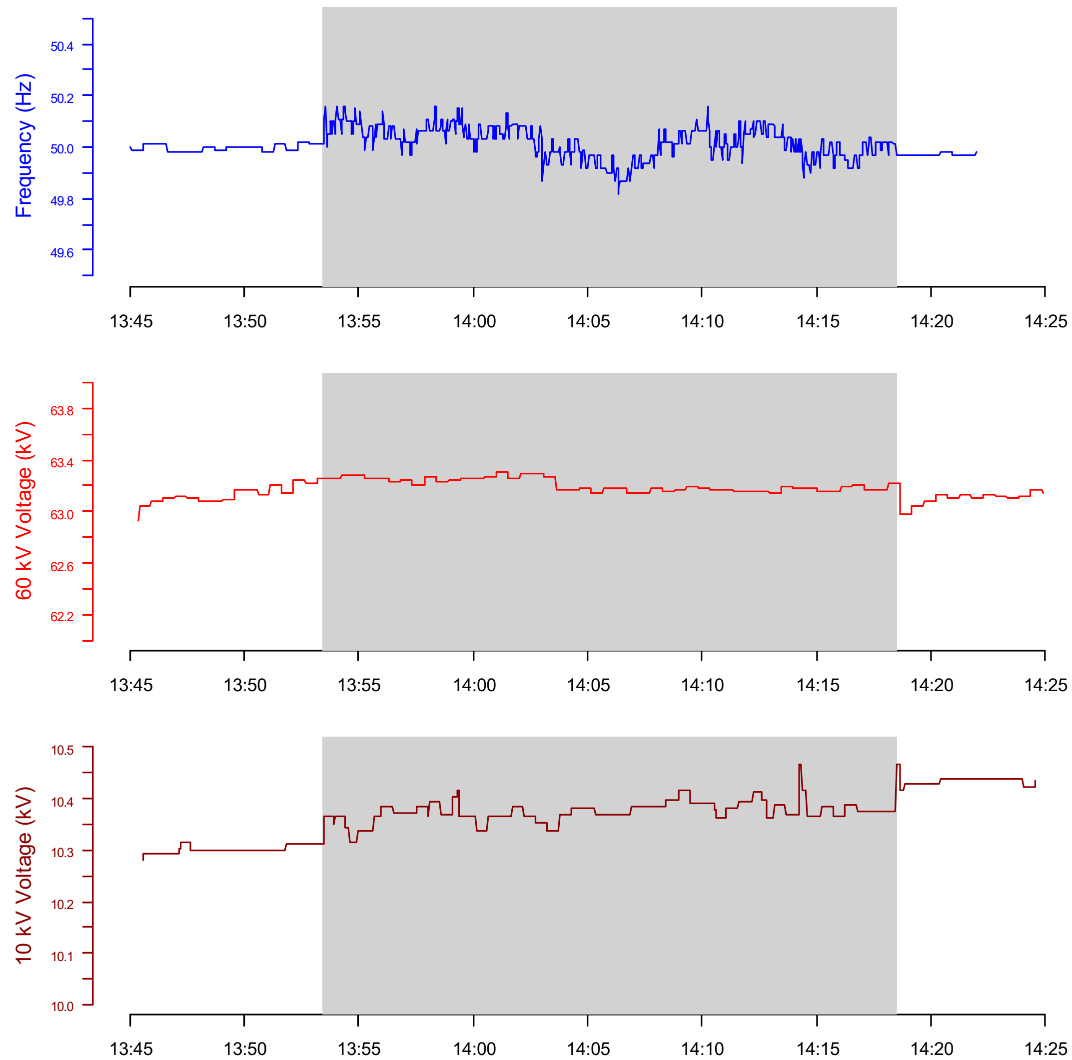


Figure 30 Brørup CHP in L1 Droop Mode. The traces, from top to bottom, plot the cell frequency (Hz), the 60 kV voltage, and the 10 kV voltage as measured at the Holsted substation. The region shaded grey indicates the time where the primary interconnect was open.

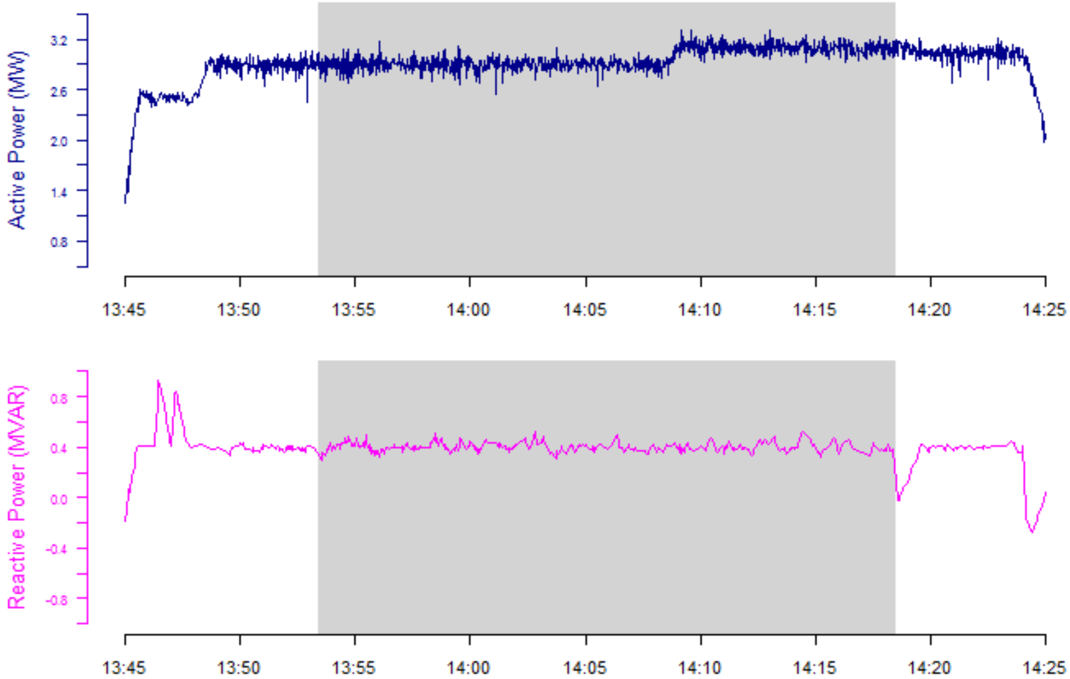


Figure 31 Brørup CHP in L1 Droop Mode. The active power of the cell (MW), the reactive power (kVAR). Note the stability of each trace; the active power was intentionally raised at 14:08 to accommodate changing condition within the cell. The region shaded grey indicates the time where the primary interconnect was open.

7.6 Cell Controller Managed Islanding

7.6.1 Objective(s)

This test was performed to exercise the islanding functions without significant import or export to manage during the transition. Test goals included verification that the Cell Controller would make the correct mode changes, be able to control voltage at both the 10 kV and 60 kV level, and be able to resynchronise with the grid.

7.6.2 Test Setup and Initial Conditions

- BID 1–3 and HEJ (as needed) online in BRP day-ahead market operation
- HOD and BRØ online and available
- SLC online.
- All tap changers available
- All WTs offline
- Approximately 12–13 MW load online.

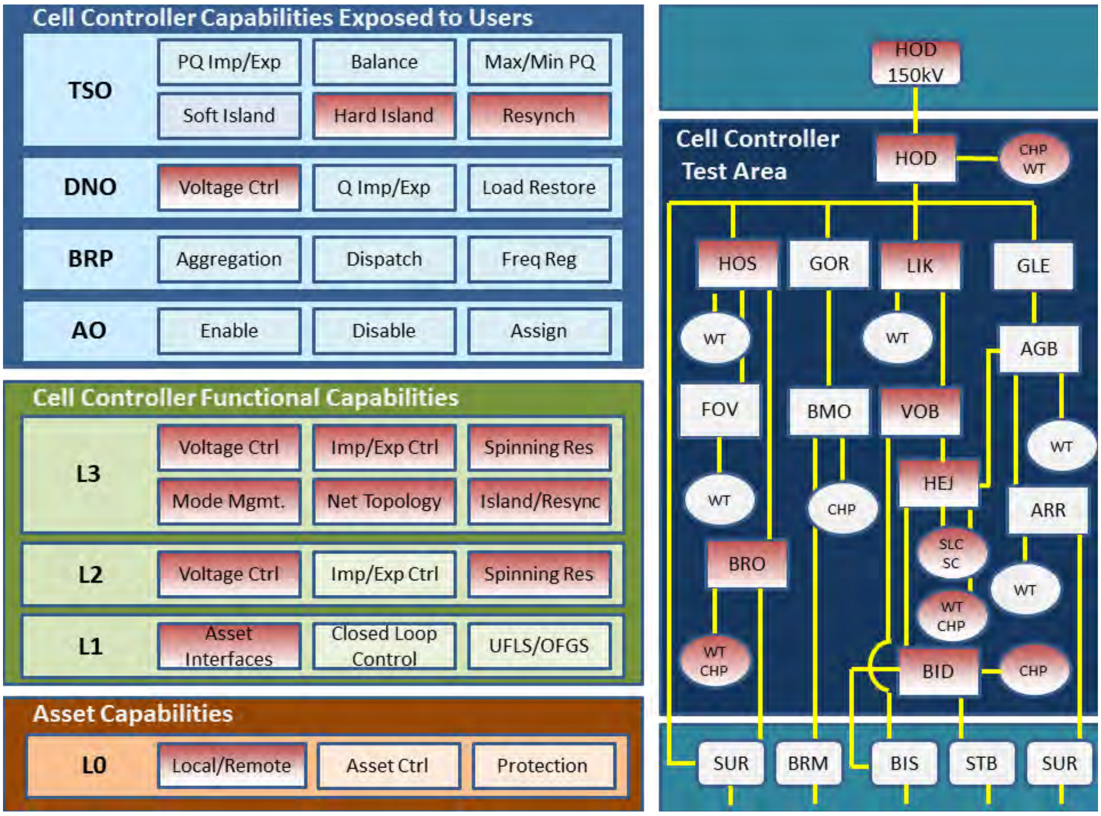


Figure 32 Cell Controller Configuration During Managed Island Test. The left panels indicate which Cell Controller capabilities were being used during the test (highlighted in red) and the right panel highlights the Holsted Cell assets involved in the test.

7.6.3 Result(s)

- 14:45 - DNO enabled 10 kV, 60 kV voltage control; TSO issued soft trigger (i.e. ordering the import/export of the cell to zero); SLC online at 500 kW in local control.
- 14:50 - TSO issued hard trigger.
- 14:51 - Grid breaker opened.
- 15:26 - TSO enabled resynchronisation.

Figure 33 shows the cell frequency and main 60 kV voltage control at the primary interconnect at Holsted during the test. The largest frequency excursion of +0.33 Hz occurred shortly after the cell was islanded at 14:52:01. All CHPs were issued initial mode change control words within 1.8 seconds of the grid breaker opening. To prepare for islanded operation, the soft trigger was used to drive the import/export of the cell to zero. This kept the preload plan control within its dead-band and allowed a transition into islanded state without shedding any assets. The imbalance within the cell was reduced to 50 kW import and 170 kVAR export before the grid breaker was opened.

Figure 34 shows the voltage control performance at the Billund substation (BID). The Billund CHPs were responsible for regulating the 10 kV voltage and the tap changer at the substation transformer regulated the 60 kV voltage. The 10 kV voltage peak at 14:47 was due to the increased reactive power generation to balance the cell before islanding. No tap changes were required to adjust the 60 kV voltages during the test.

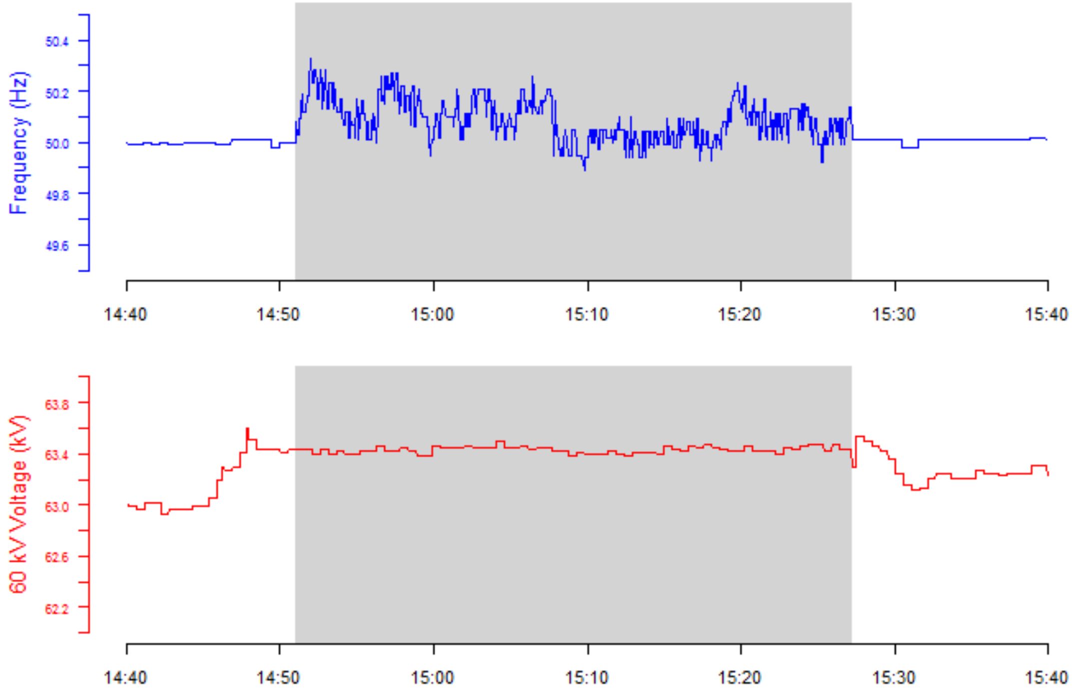


Figure 33 Cell Frequency and 60 kV Island Voltage Control as measured at the primary interconnect at Holsted. The region shaded grey indicates the time when the primary interconnect was open.

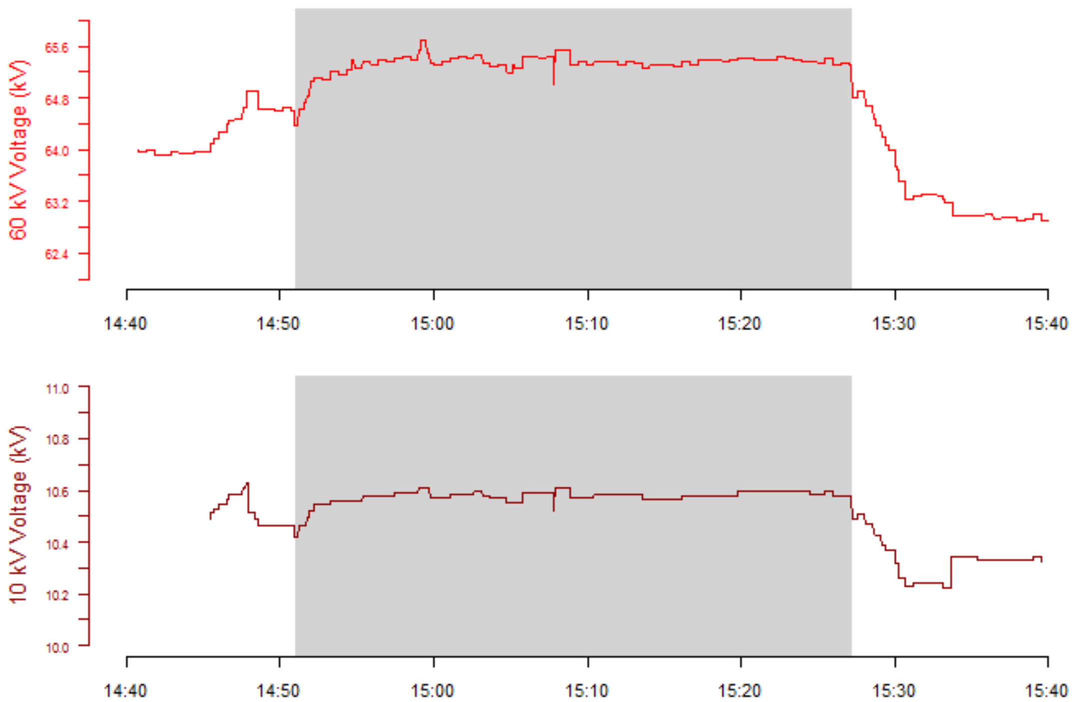


Figure 34 BID Substation Voltage Control during Islanding (60 and 10 kV). The traces compare the 60 kV and the 10 kV voltages at the BID substation during the test.

7.7 Cell Controller Islanding – Preload Plan with Small Import

7.7.1 Objective(s)

This test was implemented to verify (i) the preload plan (PLP) operation when cell assets were participating in day-ahead market and (ii) the load restoration operation.

7.7.2 Test Setup and Initial Conditions

- BID, HOD and BRO CHPs participating in BRP day-ahead market and available.
- HEJ CHPs offline but available.
- SLC online and available.
- Approximately 15 MW of load online (includes load at WT feeders) distributed across substations; system configured and back-fed as in Figure 35.
- Approximately 4 MW of wind online, 2 MW of wind offline but available.

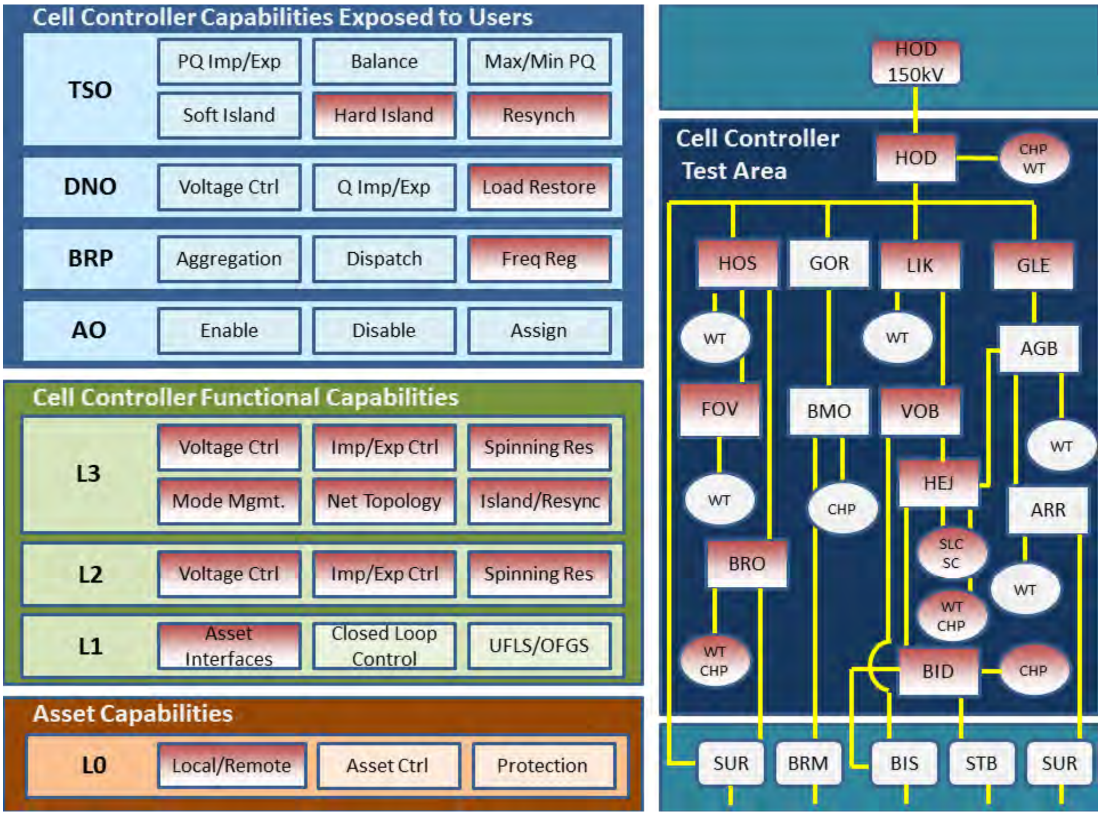


Figure 35 Cell Controller Configuration during Preload Plan with Small Import Test. The left panels indicate which Cell Controller capabilities were being used during the test (highlighted in red) and the right panel highlights the Holsted Cell assets involved in the test.

7.7.3 Result(s)

- 15:04 – Test commenced; BRP regrouped all CHPs.
- 15:05 – DNO enabled 60 kV and 10 kV voltage control.
- 15:07 – TSO enabled active power import with a set point of -2.0 MW; TSO enabled reactive power export with a set point of 1.5 MVAR.
- 15:20 – Hard trigger issued by TSO; 2 load feeders (BID:SØK and VOB:VOB) and 3 WTs (WT09, WT10 and WT22) shed due to PLP operation

- 15:21 – TSO enabled load restoration; BID:SØK and VOB:VOB restored.
- 15:28 – TSO enabled resynchronisation operation.

This test was a complete success: the preload plan functioned as expected, the load restoration was successful, and the cell was resynchronised to the grid after eight (8) minutes of island operation. The cell frequency remains stable throughout the test with a maximum frequency excursion of -0.69 Hz which occurs at 15:21:14 (Figure 36) which coincides with the restoration of the Billund SØK load (Figure 37). Due to the significant presence of wind generation, the Cell Controller successfully dispatched the generation of reactive power to balance the cell as depicted in Figure 37.

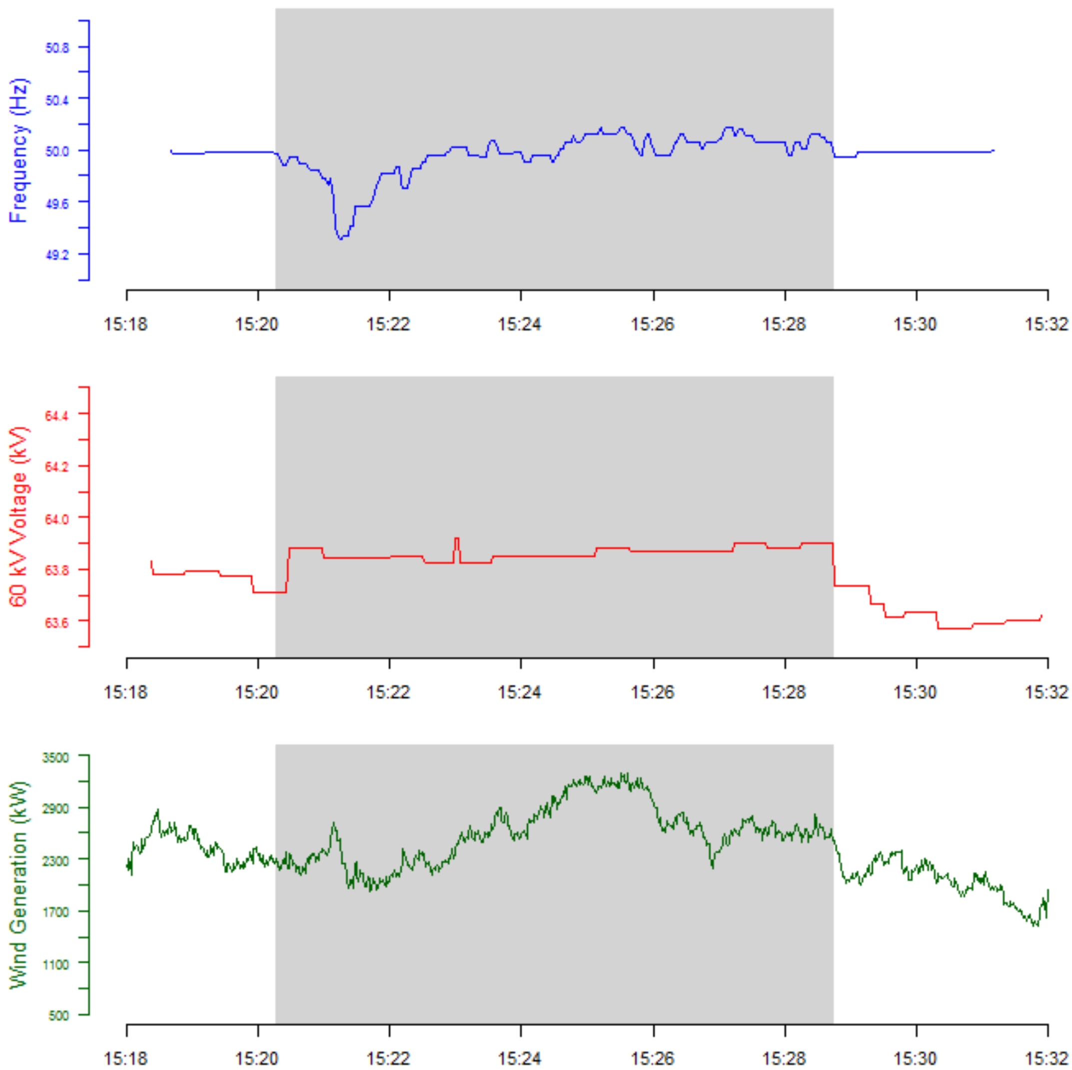


Figure 36 Island Frequency and Voltage Stability during Preload Plan with Small Import Test. The traces plot the cell frequency (Hz), the 60 kV voltage, and the total wind generation (kW). The region shaded grey indicates the time where the primary interconnect was open. The cell was able to maintain stable voltage and frequency in the presence of significant wind generation. The largest deviation in frequency occurs at 15:21:30 which coincides with a drop in wind generation and the restoration of the first load.

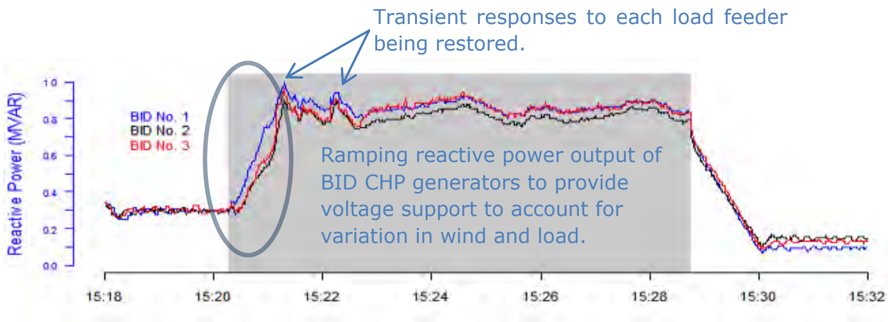


Figure 37 Reactive Power Support during Preload Plan with Small Import Test. Due to the significant presence of wind generation, the Cell Controller successfully dispatches the generation of reactive power to balance the cell.

7.8 Grid Connected Multi-Function Testing

7.8.1 Objective(s)

During October-November 2010, a number of test cases were conducted comprising the full Cell area in normal parallel operation with the grid. These tests were designed to illustrate the Cell Controller's ability to provide multiple services to the various stakeholders simultaneously. The one selected for presentation here demonstrates these multiple functionality capabilities of the Cell Controller while at all times managing a large uncontrolled wind power production on top of all load variations within the area.

The test plan included having the TSO enable and disable both active and reactive power import/export, having the BRP form groups of CHPs for the day-ahead market, and having the DNO initiate and maintain 10 kV and 60 kV voltage control with limited resources depending on the operations being serviced at the time (e.g. only tap changers available during TSO reactive power import/export operation).

7.8.2 Test Setup and Initial Conditions

- BID/HOD/BRO CHPs participating in BRP day-ahead market and available.
- HEJ CHPs offline but available.
- All wind turbines in local control, i.e., the wind turbines need not be stopped or started during testing.

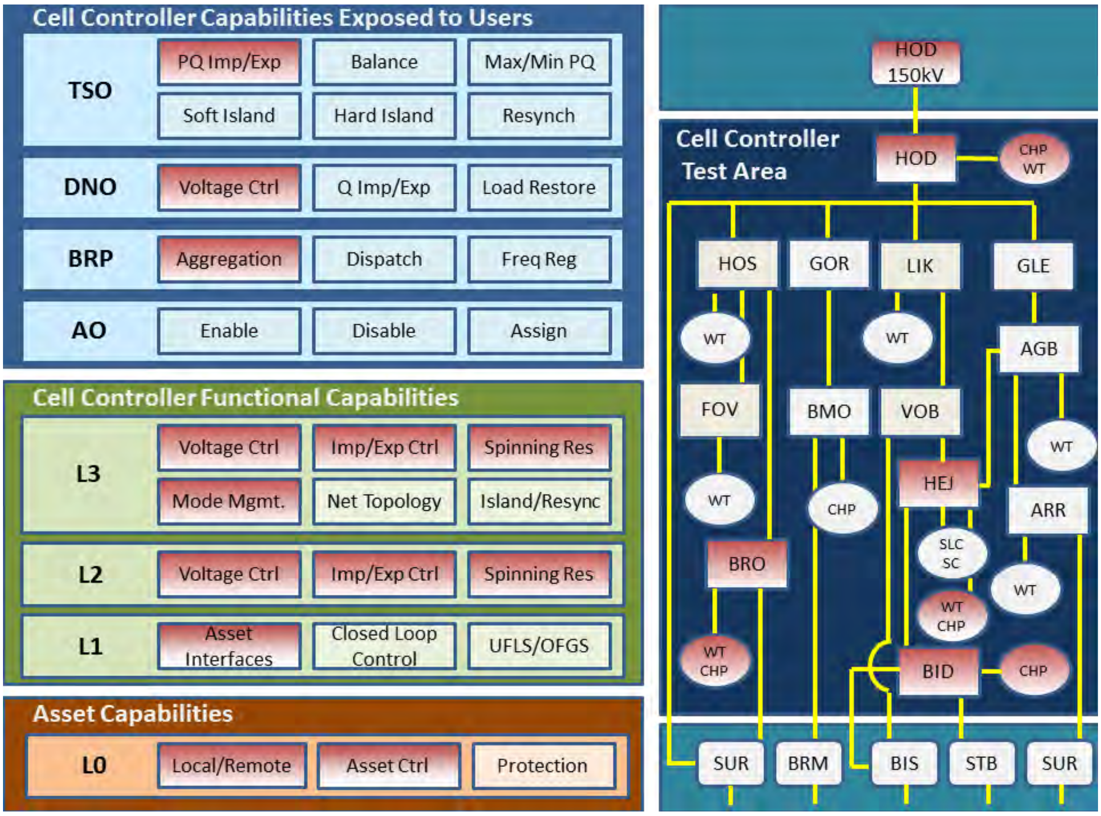


Figure 38 *Cell Controller Configuration during Grid Connected Multi-Function Test. The left panels indicate which Cell Controller capabilities were being used during the test (highlighted in red) and the right panel highlights the Holsted Cell assets involved in the test.*

Figure 39 illustrates the setup for the test case. The power market is supposed to be in normal operation without any interference from the Cell Controller. Hence the different market bidding has determined which CHP-plant generators and wind turbines were on-line. In reality the starting and stopping of machines was done by the test operator in setting up the planned initial conditions for the test.

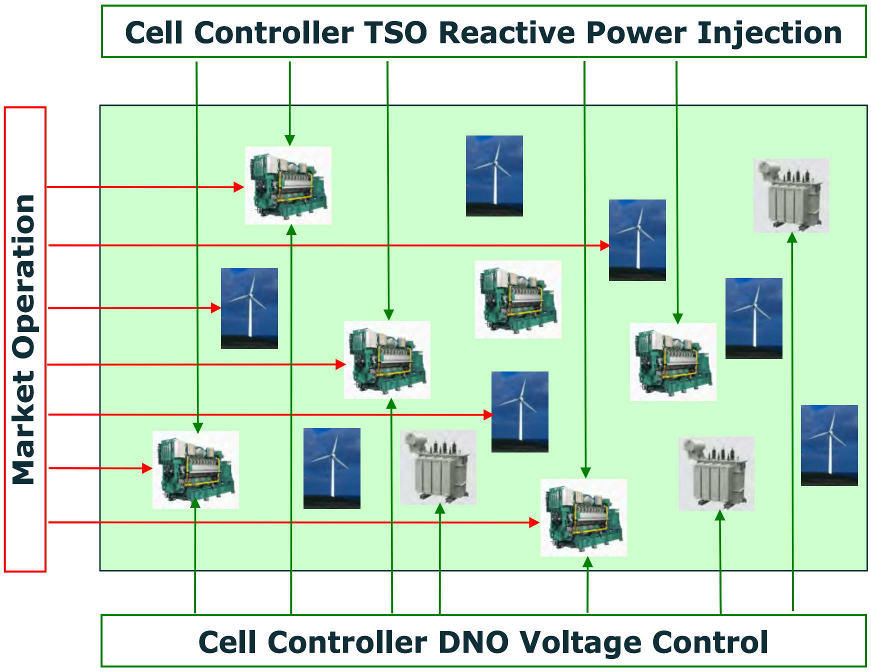


Figure 39 Multiple functionality of Cell Controller while in normal market operation

7.8.3 Result(s)

The Cell Controller was performing distribution network operator (DNO) voltage profile control throughout the Cell area when the TSO requested a reduction of reactive power transfer to the Cell area from the transmission system to a constant value of 7 MVAR (the request was done by the test operator). The Cell Controller responded by operating the Cell area as a technical virtual power plant fulfilling the TSO import/export request while at the same time maintaining the prescribed voltage profile within all DNO voltage boundaries. Figure 40 shows the resulting total reactive power import to the Cell area.

As an example of the ongoing management of the DNO 60 and 10 kV voltage profiles, Figure 41 shows the Cell Controller issuing a tap-changer command to a selected 60/10 kV distribution transformer at the instant that 10 kV voltage went outside the DNO preferred range during the test run.

The test was ruled a full success as the Cell Controller maintained both the DNO voltage profile within the Cell area and the TSO request of a reduced fixed reactive power import to the Cell area with all occurring load variations and a substantial variation in total wind power production within the Cell area which is shown in Figure 42.

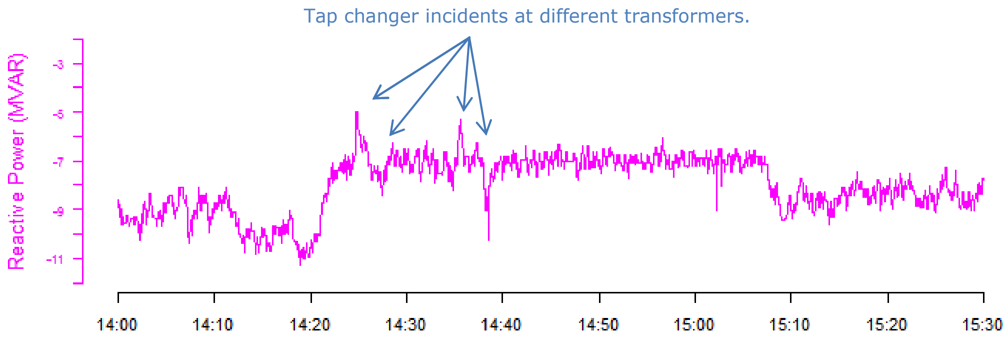


Figure 40 Resulting Cell area total reactive power import

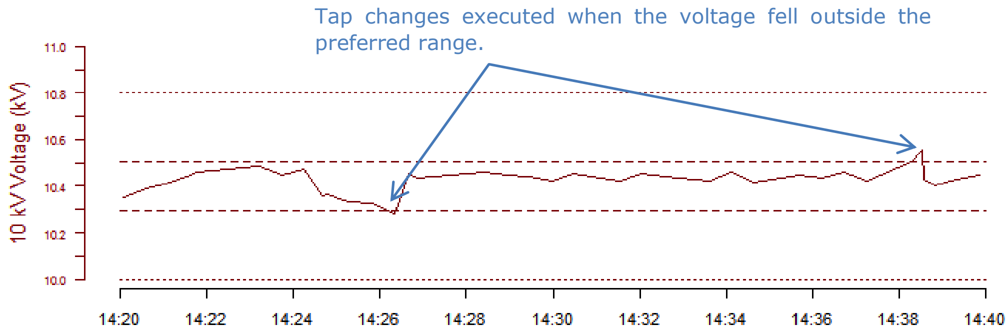


Figure 41 Example of Cell Controller adjusting tap on 60/10 kV transformer. The preferred and allowable ranges are indicated by the dashed and dotted lines, respectively.

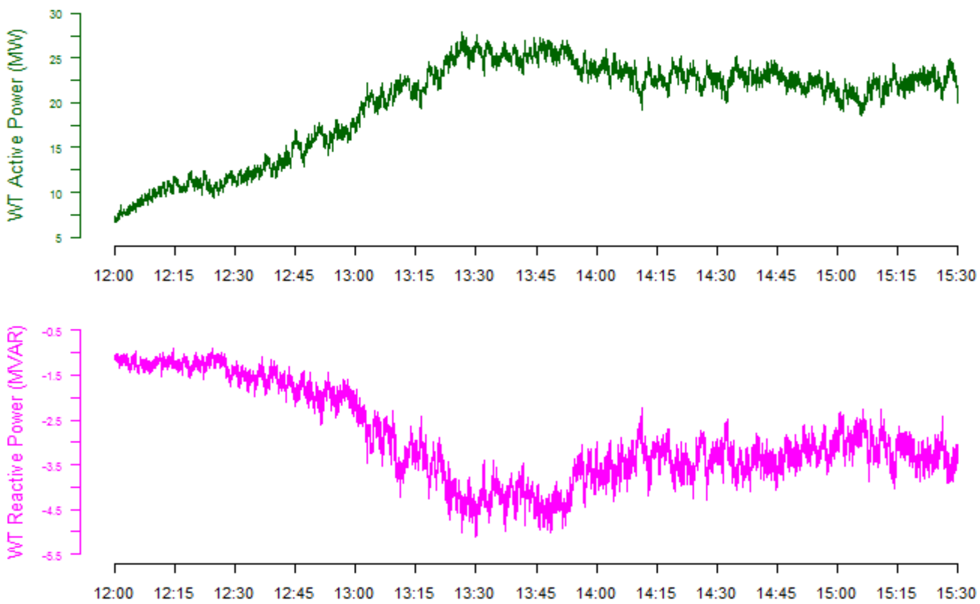


Figure 42: Total wind turbine power production and reactive power consumption

7.9 Grid Connected Multi-Function Extended Run Testing

Not all field tests were successful on their first attempt. Since testing was done over a long period of time, in many different phases, using different resource combinations, and with different objectives, there were many surprises and challenges that the Cell Controller team faced during the course of the project. Some of the causes of failures were easy to identify and fix while others were more complex. An example of a complex test run where software process failures resulted in the failure of that test run is given below. While the objectives of this test run were not fully met due to these failures, it should be noted that the test team was able to resume testing after the failed processes were restarted and basic maintenance carried out.

7.9.1 Objective(s)

This test was designed to illustrate the Cell Controller's ability to provide multiple services to the various stakeholders in succession. An extended run in excess of 4 hours was planned during which the various stakeholders would issue market operation requests to the Cell Controller.

The test plan included having the TSO enable and disable both active and reactive power import/export, having the BRP form groups of CHPs for the day-ahead market, and having the DNO initiate and maintain 10 kV and 60 kV voltage control with limited resources depending on the operations being serviced at the time (e.g. only tap changers available during TSO reactive power import/export operation).

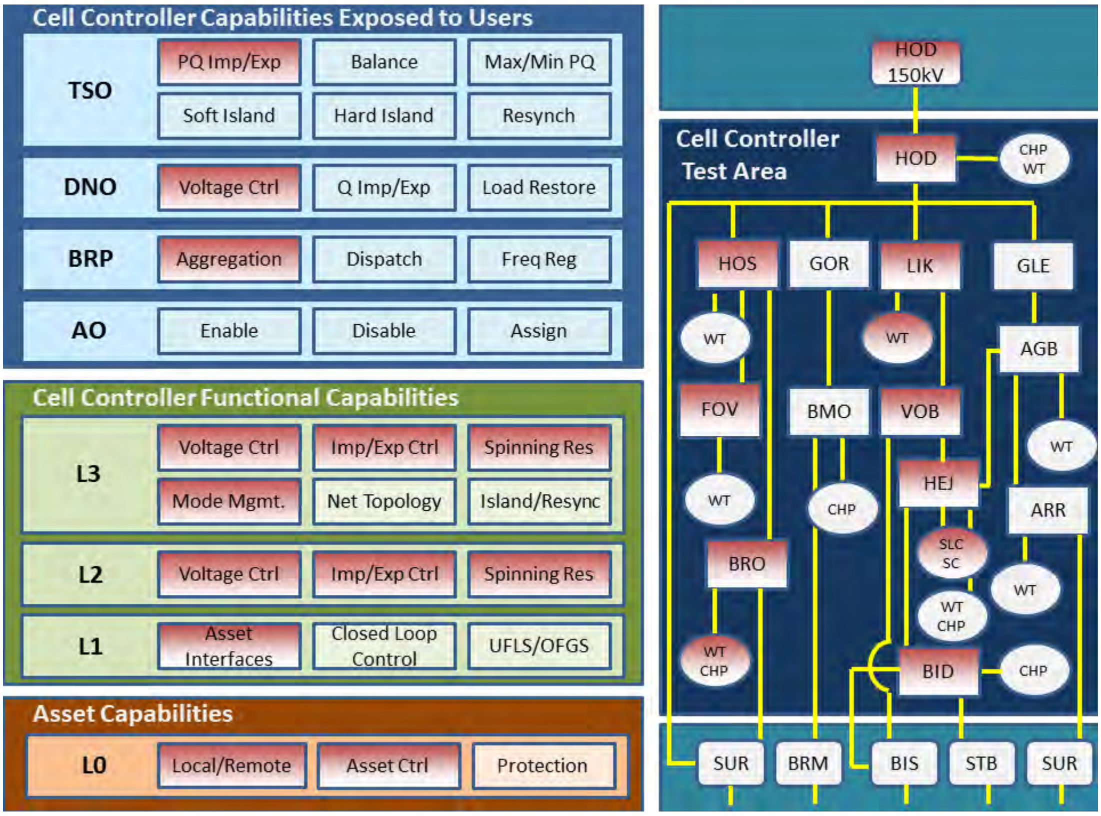


Figure 43 Cell Controller Configuration during Grid Connected Multi-Function Extended Run Test. The left panels indicate which Cell Controller capabilities were being used during the test (highlighted in red) and the right panel highlights the Holsted Cells assets involved in the test.

7.9.2 Result(s)

- 08:42 – BRP formed all CHPs into groups; 10/60 kV voltage started.
- 09:17 – The DNO changes the 60 kV set point to 62 kV; the 150/60 kV KT31 transformer is correctly tapped down and the set point is returned to 63 kV. The 10 kV voltage control responds correctly by ramping up the Holsted CHP instead of tapping the Holsted 60/10 kV KT21 transformer.
- 09:53 – The DNO operator taps down the KT31 transformer (for test purposes) which is immediately (and correctly) tapped up again by the Cell Controller.
- 11:35 – HOD SCC application crashed; restarted and testing resumed.
- 11:44 – The 60 kV voltage control is disabled; the 10 kV voltage control remains enabled.
- 12:32 –TSO reactive import/export control enabled.
- 12:46 – Reactive import/export set point changed to -2 MVAR (import).
- 12:50 – Reactive import/export set point changed to +1 MVAR (export).
- 12:58 – HEJ SCC application crashed; restarted and testing resumed.
- 13:03 – Reactive import/export set point changed to -3 MVAR (import).
- 13:20 – SC manually shut down for maintenance.
- 13:25 – BRP issued stop command to all 3 generators at BID CHP.
- 13:32 – BID SCC application crashed; restarted and testing resumed.
- 13:44 – TSO active power import/export enabled; Spinning Reserve was not able to start LIK wind turbine no. 21 (incorrectly configured prior to test).
- 13:57 – Cell Controller crashed terminating the test run.

The test was ruled a partial success due to the correct operation of the Cell Controller and the SSC logic, but application crashes (e.g. the HOD SSC at 11:35), most likely caused by field deployments onto an older, less reliable Operating System than that used during development in the laboratory environment and in the simulation environment, prevented the test from being classified as a complete success. Figure 44 and Figure 45 plot the active and reactive power measurements and the high and low side voltages (kV) at the primary interconnect, respectively, for the duration of the test.

This example illustrates both the robustness of distributed control and the difficulties often encountered during field testing. In the presence of SSC application crashes, the Cell Controller was able to continue managing the multiple ongoing operations. Furthermore when an asset (the synchronous condenser) was disabled during testing for maintenance, the Cell Controller was able to continue operation as designed.

Finally the results of this test clearly shows the present R&D nature of the Cell Controller prototype as no time or effort was spend in the course of the project in achieving industry grade robustness like redundancy, uptime, error handling etc.

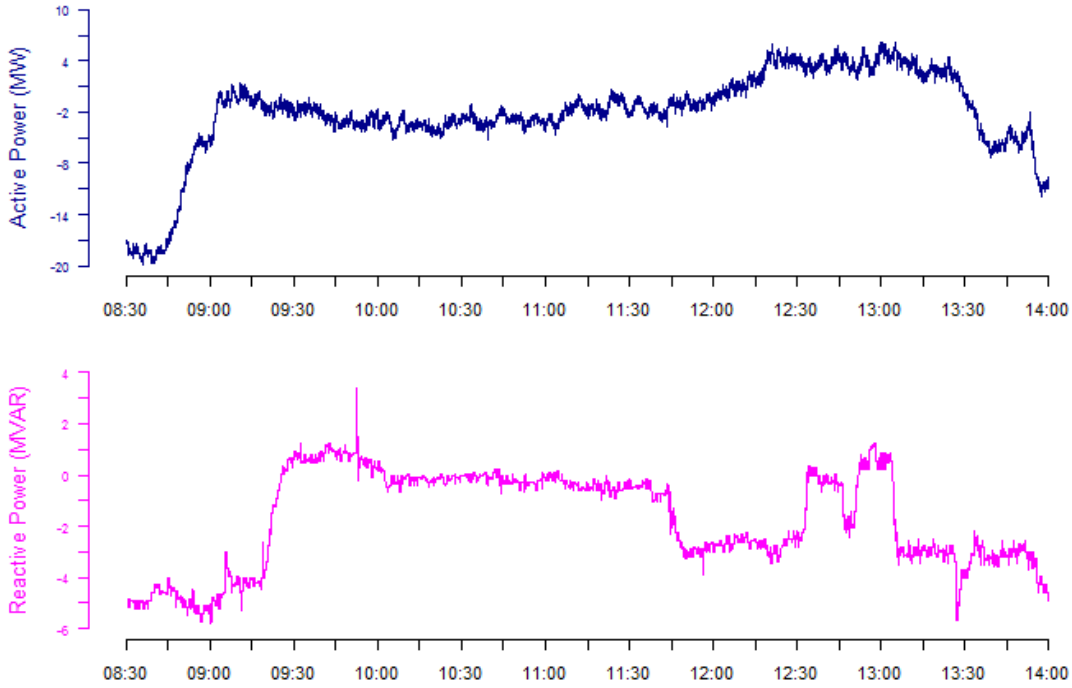


Figure 44 Recorded active (MW) and reactive power (MVAR) measurements while testing Multi-Function Operations over the course of the extended test.

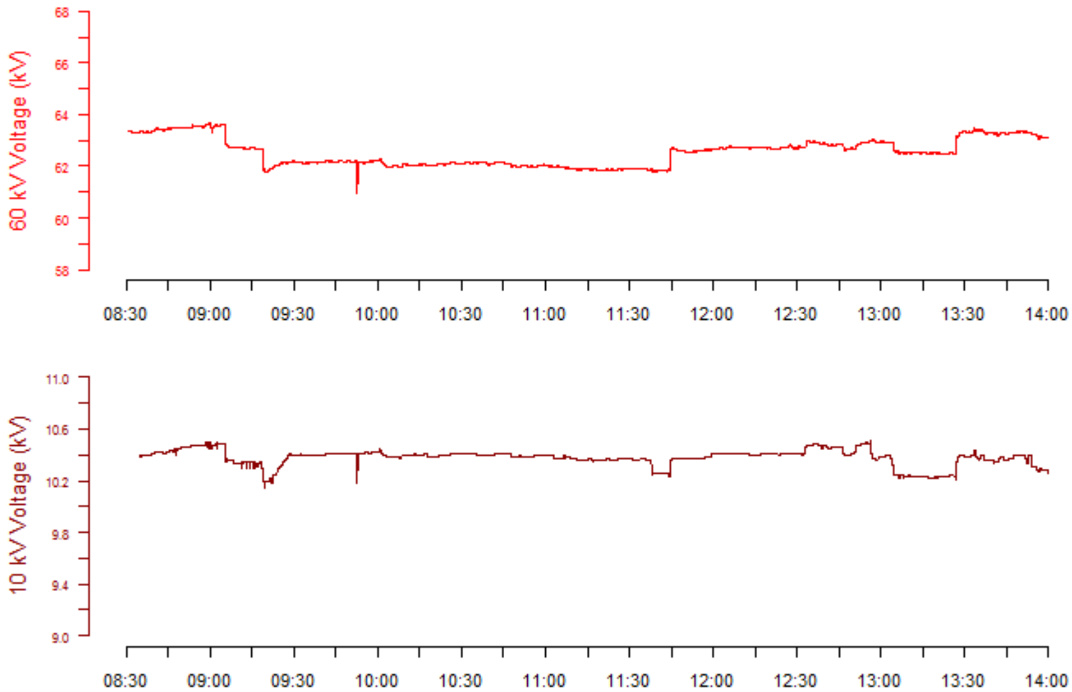


Figure 45 Recorded high (60 kV) and low (10 kV) side voltages at the primary interconnect (HOD) during testing of Multi-Function Operations

8. Project Outcomes, Conclusions and Lessons Learned

8.1 Project Outcomes

The initial goal of the CCPP was to develop and field test a control system with a distributable control architecture capable of rapidly islanding a distribution network below a 150/60 kV substation upon receiving a one-second trigger signal from the transmission system operator. In particular, the system was envisioned to quickly achieve (near) power neutrality at the primary interconnection point between the high-voltage transmission grid and the medium-voltage distribution network and separate from the grid. While islanded, the system would maintain stability of the cell until the cell was requested to rejoin the grid at which time the system would resynchronise with the main grid, re-connect, and return to normal operation.

The CCPP has successfully achieved this goal by carefully designing, modelling & simulating, building, and testing in both the laboratory and the field a distributed control system (Cell Controller) that safely islanded the Holsted Cell. The Cell Controller coordinated one 150/60 kV substation with tap changer controlled transformer, 13 substations (60/10 kV), 5 CHP plants, 47 wind turbines, 69 load feeders, and numerous additional assets (breakers, SLC, SC, etc.) to separate from the high-voltage transmission grid (150 kV), operate independently, and ultimately resynchronise and re-connect when commanded by the TSO.

Implementation of the Cell Controller required the deployment of a hierarchical communication structure through which critical information was to be passed rapidly and reliably from the individual (controllable) assets to aggregator nodes (substation controllers) to the cell control master and back. Thus the cell was effectively designed to be "self-aware" at all times. Hence, the scope of the CCPP was expanded to illustrate the potential to provide multiple services to various stakeholders simultaneously such as active power services, active and reactive power balancing operations, and voltage control services when the cell was running parallel with the high-voltage transmission system in its normal operation state. Each of these potential services was successfully demonstrated using carefully constructed interfaces that mimicked stakeholder interactions with the Cell Controller.

Other key achievements obtained by the CCPP include:

- Active distributed control of a large power system over existing communications infrastructure.
- AGC-like controls achieved through low cost software upgrades to existing, not island-capable machines.
- Reliable state estimation in a distribution grid with high DG penetration; able to monitor voltage/loading on portions of the network where no direct telemetry available.
- Controls-in-the-loop testing: distributed controls running on deployable hardware tested for runs against transient power system simulation in lieu of field power system.
- Topology data analysis in real time.
- Stable two-level voltage control.
- Perform frequency control of islanded power system with fast-switching load bank (SLC) in the presence of high DG transients.

8.2 Major Conclusions

The future of land based energy generation and distribution is clearly moving away from the traditional centralised model. As the penetration level of distributed generation continues to increase there will inevitably be more and more opportunities to define cells (regions where local generation meets or exceeds local loading) to which coordinated control can be deployed. The CCPP successfully demonstrated that coordinated control of DER is not only possible, but adds significant benefits and potential services to all stakeholder levels.

- *Transmission System Operator*: Interface to request services from the cell for frequency balancing, PQ import/export operations, etc. In the event of an emergency condition, the TSO can island the cell (i.e. separate it from the grid) and reconnect the cell after the event passes. Future deployments of cell control will be able to black start the local transmission grid.
- *Distribution Network Operator*: Expanded ability to maintain control of the local distribution network (e.g. voltage control, load restoration) with large amount of distributed energy resources.
- *Balance Responsible Party*: Able to examine the available assets and post bids for power services (e.g. day-ahead frequency balancing market).
- *Asset Owner*: Provide a centralised and standardized interface with which to enable/disable his asset from cell operations; allows the asset owner to choose to participate in additional services which will generate new revenue streams.
- *Consumer*: In the event of a large scale transmission level failure (black or brown out), the local cell can island from the grid and continue to serve the local loads without (or with limited) interruption. In addition, as new consumer appliances are introduced to the market (e.g. heat pumps, controllable electric water heaters, photovoltaic arrays, electrical vehicles, household wind turbines and fuel cells), individual consumers can be given the opportunity to participate in cell operations thereby subsidising their own energy use.

The CCPP was able to achieve successful island operation by leveraging the existing field assets and communication infrastructure (the addition of new assets, e.g., SLC and SC, was kept to a minimum), modelling & simulating, building and testing controls using readily available software packages (e.g. PowerFactory, C++) and the InteGrid Laboratory (Fort Collins, Colorado, U.S.A.), and ultimately field testing in an active distribution network (the Holsted Cell).

8.3 Lessons Learned

Over the course of the CCPP many challenges and obstacles have been faced and overcome. As plans are being outlined for the Cell Controller Version 2.0 several "lessons learned" are being considered.

- Highly detailed models of third-party deployed controls - AVRs, speed controllers, plant management systems and all sorts of power electronic systems, among others - are very useful for fault and transient stability studies. Such models can be cumbersome to maintain, however, and may have a strong, negative impact on simulation performance when used for controls-in-the-loop regression and system testing or for software demonstration. Consequently, future projects of this nature should consider maintaining low- and high-fidelity versions of power system models.
- State estimation in distribution systems may use simplified system models so long as careful attention is paid to which measurements are used. For example, a substation feeder serving a string of wind turbines for which individual power measurements are available may be simplified by assuming that all turbines are connected to a common bus just beyond the feeder breaker. In that case, the active power measurements at the turbines can be used by

state estimation while voltage and reactive power measurements should be considered only at the feeder head.

- The convergence of state estimation is highly sensitive to the accuracy of the incoming telemetry. Consequently, deployment of state estimation is a valuable tool for debugging the data acquisition system: communication paths, scaling of analog points, types of digital points (e.g., 2-state vs. 3-state switch position indicators), etc. must all be correct in order to achieve convergence. In case of non-convergence, a process of network subdivision can quickly isolate misconfigured or malfunctioning telemetry.
- Advanced meter disturbance and waveform recording, when combined with historical SCADA data and appropriate software logging, provide sufficient detail for analysis of system performance and *ex post facto* root cause analysis in case of a power system, hardware or software fault. That being said, such meters should be protected with sufficient backup power to allow them to finish writing recordings to non-volatile memory in the event of a blackout.
- A robust, island-capable system must, invariably, include load shedding functionality. Field testing such functionality requires careful customer outreach and engagement and advanced communication of the time windows during which outages may occur.

Figure 46 Site Acceptance test at CHP plant.

9. Smart Grid and the Role of Cell Controllers – The Path Forward

9.1 Danish Perspective

In the future, the power system will be very different from the power system we have today. Climate challenges and the political focus on geopolitical security of supply require a conversion of the power system.

Political visions and decisions regarding the expansion of the power system with many new onshore and offshore wind farms, subsidising installation of distributed energy resources, and, in Denmark, an extensive cabling of the grid will challenge the power system. It is also to be expected that the operating conditions of the major coal-fired power stations will change, and therefore that electricity generation will be increasingly based on renewables, some of which are at the lower voltage levels. Figure 47 illustrates the expected changes in the Danish energy system towards 2020. The development in data communication and data processing is set to continue at a rapid pace. This opens up for the future control and regulation of all conceivable volumes of electricity generation and production.

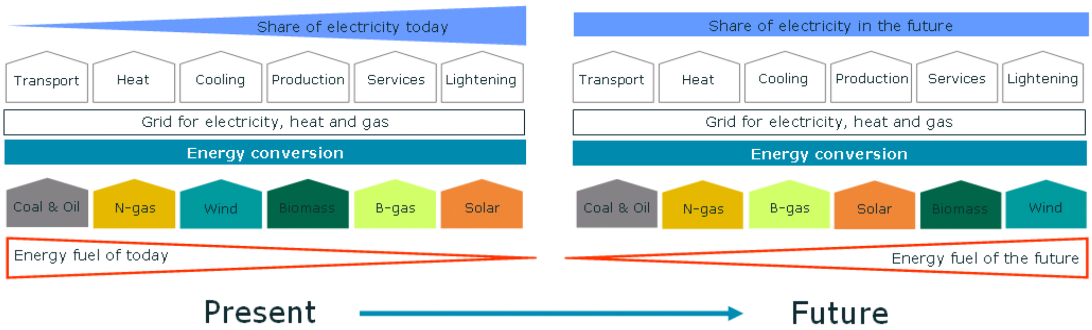


Figure 47 The shifting paradigm of the energy system. Wind, Biomass and Solar Power dominate the future energy sources, and electricity is expected to be the primary energy carrier for the future.

Tomorrow's power system must ensure the effective integration of renewable energy on market terms, including large volumes of fluctuating wind power. Fossil fuels are being phased out not only in the power sector, but also as energy supply for heating/cooling and transportation. Electricity is expected to be the primary energy carrier in the near future. This evolutionary change of the power system requires three elements:

- A robust transmission grid with strong transnational connections,
- Utilisation of flexible power assets, both consumption and generation, in coherent energy systems, and
- More advanced measurement and control of power systems.

In other words, the future energy system must distribute available power in an energy efficient manner while being flexible and intelligent to maximise the utility of renewables.

Also, the power system must be developed to comply with, and accommodate, the political and regulatory framework conditions regarding climate targets, security of supply and effective socio-economics - the power system must be robust.

9.1.1 *Anatomy of a Strong Transmission System*

Control concepts related to more advanced measurement and control of power systems is closely linked to the development of a robust transmission grid with strong international connections, as well as flexibility in generation and consumption.

A strong transmission grid provides access to power generation and power consumption resources in a transnational context. Because of weather-dependent power generation, many renewable energy sources such as wind power and solar energy can advantageously utilise the interconnected power systems to even out fluctuations and balance generation across large areas.

Access to resources via strong transmission grids can only benefit security of supply if consumption and generation always balance and if the grid voltage in the entire system is always stable. The power system "anatomy" provides that energy and active power can be transported and balanced over large distances. Other power system essentials, e.g., voltage/VAR support and congestion management, must be supplied locally in order to maintain a well-functioning power system.

The link between power system control and coherent energy systems also yields a higher degree of flexibility in the power system. Increased use of electricity for transportation and for heat pumps utilised in power system markets creates an excellent opportunity for increased use of demand response.

In order to use the available power generation and consumption resources to balance the power system, the physical electrical access must be satisfactory and the individual power market actors must have the necessary knowledge to decide whether to activate the resource in question for power market or balancing purposes.

In order for resources to contribute to active voltage control in the power grid and supply other non-power balancing ancillary services to the power system, all necessary information for grid operation must be equally communicated to the grid operators responsible for voltage and power quality. This applies to all types of energy resources[1]. The various energy resources supply different ancillary services: a synchronous generator at a small or large CHP plant could potentially supply the entire range of power and system ancillary services, whereas photovoltaic cells and a great number of wind turbines, being inverter-based (DC/AC), can only supply some of them.

9.1.2 *Essence of a Power System Control Concept*

Fundamentally, the "essence" of the control concept for power systems is to ensure adequate and efficient control of the many resources in the power system, guaranteeing robustness and flexibility while being able to be scaled upwards to integrate large volumes of renewable energy sources into the electricity markets – and with an unchanged security of supply.

This should still be done by:

[1] E.g. electricity-generation facilities, electricity storage facilities and inverter-based electricity-consuming appliances such as electric vehicles, frequency-controlled heat pumps and motors.

- Controlling the power balance and the frequency stability, and
- Controlling the voltage and the voltage stability.

Today, this control is already being performed by the TSO control systems, predominantly based on major power stations using fossil fuels. The availability of these power stations is expected to be reduced in the future, and therefore other resources are required to ensure stability and security of supply.

At an overall level, a high degree of observability in the power system is expected in the future, and it is also expected that a substantial part of the power system resources will act flexibly in accordance with the requirements of the power system. To ensure sufficient flexibility and observability in both power balancing and the technical control of the power grid, the dissemination of data communication and data communication standards is necessary. Figure 48 illustrates the parallel monitoring and operations for power balancing in market operation and the technical voltage/var controls for active grid operation.

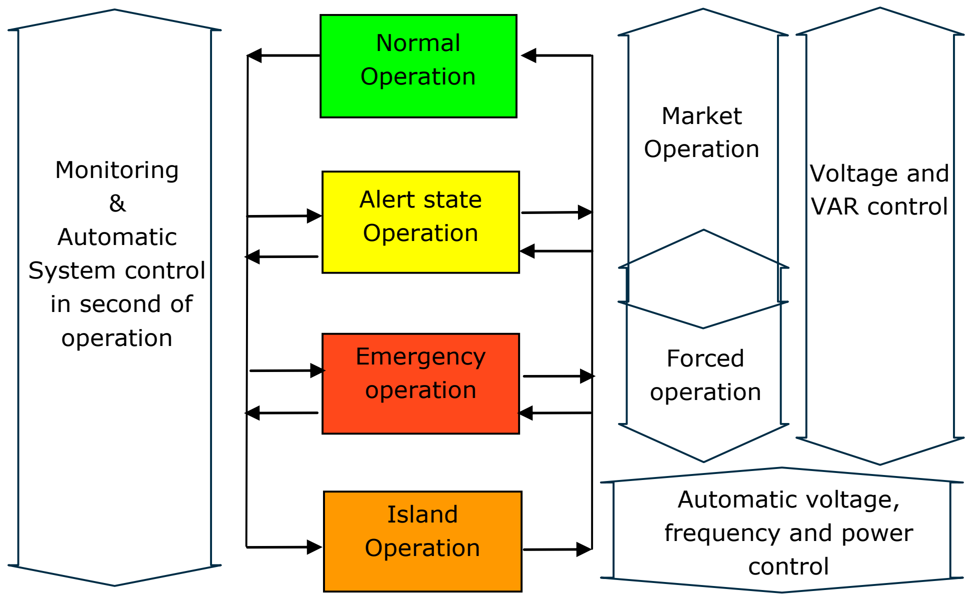


Figure 48 Parallel Operating Forms for Cells and Transmission Areas

A distinction is made between power balance and technical control of the power grid. The power system must continue to maintain well-functioning markets in which energy, power, and certain ancillary services are traded. Therefore, the electricity market also will be developed at both the national and European levels. An increasing degree of aggregation of many small production and consumption units is expected in order to optimise the electricity market. Such aggregations in the market are called commercial virtual power plants (VPPs) or market VPPs.

On the other hand is the concept of the technical VPP[2], which is used to denote decentralised control of technically aggregated resources in the distributed power system. The Cell Controller

[2] As opposed to commercial VPP, a technical VPP takes account of technical aspects in the local distribution networks. With the Cell Project, Energinet.dk has demonstrated a technical VPP with the

Pilot Project has successfully demonstrated a technical VPP. Technical VPPs may have different functionalities depending on local requirements, but they all support the same operating system and offer the same possibilities for data communication. In order for these systems to successfully interact, they must use the same open communication standards.

The principles of standardised control and data communication behind the Cell Controller Pilot Project rest on agent-based philosophy[3]. In this sense agents can act independently in accordance with fixed rules or receive orders from a superior agent.

To maximise the utilisation of the available resources, it is essential that the technical activation of resources, e.g. voltage and VAR control, can take place in parallel and simultaneously with the ordinary market operation of the individual resources. This technical activation of resources must in normal operation be done with as little interference as possible on the power market operations and business models. The Cell Controller concept demonstrates that this is possible. The Cell Controller concept is a major step in the direction of Smart Grid applications for the future power systems with very high penetration of renewable resources.

9.2 European Perspective

9.2.1 The SmartGrids ETP

Strategies for the development and implementation of Smart Grid concepts are developed in Europe in close cooperation between all relevant stakeholders such as public authorities, industrial stakeholders and research institutions. On the European level, the key platform for the crystallisation of policy and technology research and development directions for the smart grids sector is the European Technology Platform for Electricity Networks of the Future, also called SmartGrids ETP.

Technology platforms are industry-led forums, supported by the European Commission, intended to devise strategic research agendas and define deployment priorities based on input from all stakeholders. The SmartGrids ETP has published three documents:

- Vision and Strategy for European Electricity Networks of the Future (from 2006) available at: http://ec.europa.eu/research/energy/pdf/smartgrids_en.pdf
- Strategic Research Agenda, from 2007 available at: http://www.smartgrids.eu/documents/sra/sra_finalversion.pdf
- Strategic Deployment Document from 2010, available here:http://www.smartgrids.eu/documents/SmartGrids_SDD_FINAL_APRIL2010.pdf

The strategic deployment document defines six priorities:

- Deployment Priority 1: Optimising Grid Operation and Use
- Deployment Priority 2: Optimising Grid Infrastructure

Cell Controller as the primary control unit. BRPs' aggregation of minor units for the regulating power market is an example of commercial/market VPPs.

[3] An agent being an independent unit authorised to control a group of underlying units. The agent can either act independently in accordance with fixed rules or receive orders from a superior agent. The agent must at the same time be able to present its group's aggregated status and the properties of a superior agent or other interested parties having the right to receive this information.

- Deployment Priority 3: Integrating Large Scale Intermittent Generation
- Deployment Priority 4: Information and Communication Technology
- Deployment Priority 5: Active Distribution Networks
- Deployment Priority 6: New Markets Places, Users and Energy Efficiency

The work of the SmartGrids ETP does not include any specific project development or funding, however, the strategies and priorities defined are used by the European Commission as important input in the layout of the European research framework programmes.

9.2.2 The European Electricity Grid Initiative

Under the umbrella of the strategic energy technology plan (SET Plan), the EU has established European Industry Initiatives (EII) to provide further support in the policy-making process. Among these initiatives, the European Electricity Grid Initiative (EEGI) focuses on the requirements of the transformation of the European electricity grids towards a Europe-wide smart grid. Led by the associations of TSOs (ENTSO-E) and DSOs (EDSO-SG), a large number of research programmes and demonstration projects are laid out. These functional projects cover all levels of smart grid system innovation starting with consumer interaction and market design and ranging over regulatory and tariff incentives to extension and operation of transmission and distribution grids.

9.2.3 Other European Players

Further industrial stakeholders and DSOs are organised in Eurelectric. Recent publications by this entity emphasise the need for regulator action. Tariff structures as controlled by the regulators are the most important means to create incentives for large-scale deployment of innovative technology such as smart meters, while at the same time network operators remain responsible for reliable, secure and cost-efficient supply of their customers. The regulators can also use tariff schemes specifically to create incentives for further research.

The national energy regulators are represented on the European level in the Council of European Energy Regulators (CEER) and the Agency for the Cooperation of Energy Regulators (ACER). Both groups represent the same regulators and focus on complementary work to support the pan-European energy market regulation rules and processes.

9.2.4 Significance of the Cell Controller Project in the European Context

As emphasised in the EEGI implementation plan, demonstration projects play a very important role in the transformation of the European electricity grids as they bring together all relevant parties for field deployment of new technology. They provide the real-world test environment required for further development and later large-scale uptake by further network operators. The Cell Controller Pilot Project is a major project in this regard as it demonstrates a significant enhancement of intelligent distribution grid capabilities in the contexts of upholding a high level of security of supply in a future power system with massive amounts of DER. Important insights can also be derived from the experiences gained in advanced ICT application.

9.3 North American Perspective

In the United States, the Energy Independence and Security Act (EISA) of 2007 tasked the National Institute of Standards and Technology (NIST) with creating a Smart Grid framework using a systems approach. The framework had to build on work that has been previously done within the private and public sectors, be flexible, uniform, and technology-neutral. The NIST

Framework and Roadmap for Smart Grid Interoperability Standards therefore became the standard reference for Smart Grid interoperability. Release 2 of the framework was made available for public comment in October 2011.

While the NIST Smart Grid framework activity sought to develop a comprehensive technical framework for the future electric power system, it was the American Recovery and Reinvestment Act (ARRA) signed into law in early 2009 that provided the funding for large scale smart grid deployments. Two years later, ARRA funding had resulted in an array of projects across the US. There have been more than 300 recipients of ARRA funding with a total obligation of about $4.5 billion, including:

- 99 for Smart Grid Investment Grants (SGIGs),
- 42 for smart grid regional and energy storage demos,
- 52 for work force development programs,
- 6 for interconnection transmission planning,
- 49 for state assistance for electricity policies,
- 50 for enhancing state energy assurance,
- 43 for enhancing local government energy assurance, and
- 1 for interoperability standards and framework.

(Source: ARRA Paves Smart Grid Path with Cash, Kathleen Davis, senior editor, POWERGRID International, Electric Light & Power Magazine.)

Figure 49 shows the distribution of the different types of Smart Grid projects across the US. The vast majority of smart grid investments were in the Smart Grid Investment Grant category and they resulted primarily in Advanced Metering Infrastructure (AMI) projects targeting efficiency, consumer engagement and demand response benefits. Over 20 million smart meters have been deployed by about 660 Utilities by 2010. Attention is now shifting to Advanced Distribution Automation for capturing grid operations efficiencies.

While AMI was the primary focus of commercial deployments, the US DOE, NIST, and private and public sector stakeholders continued to develop and mature smart grid concepts beyond AMI. NIST systematised the seven Domains in the Smart Grid Conceptual Model. They are: customers, markets, service providers, operations, bulk generation, transmission and distribution. Within each of these Domains, information models were developed to describe communication and data flow:

http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/SGConceptualModel

Figure 49 Smart Grid projects across the US funded through the American Recovery and Reinvestment Act of 2009. Source: http://www.sgiclearinghouse.org/ProjectMap

Since interoperability between products from different vendors was a requirement for realising Smart Grid, NIST helped establish the Smart Grid Interoperability Panel (SGIP), a public-private partnership with over 600 member organisations and 2000 participating individuals. The mission of the SGIP is to provide a strong framework for coordination of stakeholders to accelerate standards harmonisation and development. The SGIP does not write standards, but instead develops and reviews use cases, identifies requirements, and proposes action plans for achieving these goals.

Another development was the grouping of various technologies that enable Smart Grid into five key technology areas. According to the National Energy Technology Laboratory (NETL) Modern Grid Strategy, these categories are: advanced components, advanced control methods, sensing and measurement, improved interfaces and decision support, and integrated communications.

The interest in Smart Grid has also heightened concerns about the cyber security of the electric power infrastructure. Developing and implementing effective strategies for securing the Smart Grid computing, communications, and control networks is essential to mitigate exposures caused due to the added complexity and new interdependencies and vulnerabilities. The high level components of the NIST proposed cyber security strategy, adapted from the US Department of Homeland Security, National Infrastructure Protection Plan, 2009, are: prevention, detection, response, and recovery. The NIST Guidelines for Smart Grid Cyber Security was released in September 2010.

In September 2011, the US Department of Energy released its Report on the First Quadrennial Technology Review (QTR) that sought to define a simple framework for understanding and discussing the challenges the energy system presents and establish a shared sense of priorities among activities in the Department's energy-technology programs. This framework (Figure 50) was developed in response to the US President's broad national energy goals for reducing U.S. dependence on oil, reducing pollution, and investing in research and development for clean-energy technologies in the US to create jobs. Specific goals include: i) reducing oil imports by one-third by 2025, ii) supporting the deployment of 1 million electric vehicles on the road by 2015, iii) making non-residential buildings 20% more energy efficient by 2020, iv) deriving 80% of America's electricity from clean-energy sources by 2035, and v) reducing greenhouse gas emissions by 17% by 2020 and 83% by 2050, from a 2005 baseline.

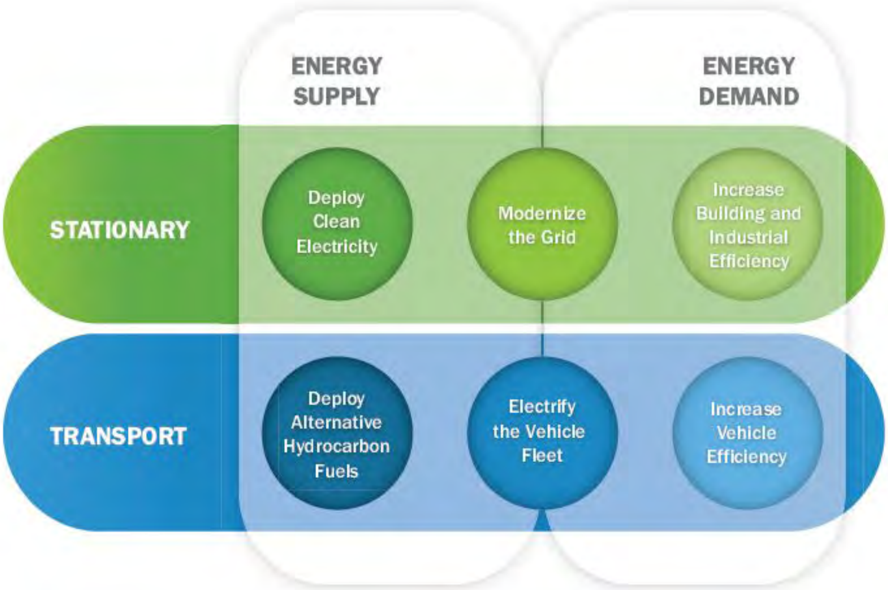


Figure 50 The six strategies framed by the QTR to meet national energy challenges

The QTR has been about developing the principles that will guide difficult choices between different technically viable approaches that cannot all be pursued due to limited resources. The outcome of the QTR clearly shows the central role that Smart Grid is likely to play in the future US energy system.

In the US, there is no exact parallel for the Cell Controller Pilot Project, but it is comparable to (and perhaps a hybrid of) distribution automation projects, microgrids, Net Zero Energy Districts and projects and initiatives that bring aggregated distributed energy resources to energy and capacity markets. Regional projects such as the FortZED project (http://www.fortzed.com) in Fort Collins, Colorado, Pecan Street Project (http://www.pecanstreet.org) in Austin, Texas, and Pacific Northwest Smart Grid Project (http://www.pnwsmartgrid.org) in the five-state region in northwest US best represent projects that integrate resources across the value chain from energy consumers to system operators while benefiting all major stakeholders. Another market segment that is rapidly growing is the "smart microgrid" segment targeting campuses, military bases, and large commercial and industrial facilities with reliability, renewables integration, and cyber security based value propositions.

The Cell Controller Pilot Project serves as a beacon project for these types of initiatives that focus on integrated operation of power systems using distributed energy resources.

9.4 Future of the Cell Controller

To demonstrate interoperability between market operation and grid management the Cell Controller technical virtual power plant concept is expected to be further developed and implemented in the power system on the Danish island of Bornholm in parallel with the EU FP7 funded 4 year project EcoGrid EU which commenced March 2011. The leading idea of the EcoGrid EU project is to enable low voltage DERs to contribute to the balancing of the power system in a new regulating power market based on broadcast of five minute price signals which will be developed and demonstrated in the project. The expected full scale demonstration of a market driven balancing of the Bornholm distribution system in parallel with a pure technical virtual power plant operation of the existing power system assets will constitute an influential prototype of the future intelligent power system. This prototype will most likely form the foundation for the basic concept and strategy of a carefully phased national Smart Grid deployment in Denmark. The Cell Controller will in this way be the reference for a number of Smart Grid systems being able to perform in a coherent national Smart Grid operation of the future power system at sub grid level. Usage of open international standards for communication and appliances and a novel information model combined with the visionary Cell Controller concept makes the overarching power system efficient and durable.

The principal Danish partners in the Cell Controller Pilot Project are currently working on setting up a full utility scale Smart Grid test facility utilising the existing Cell Controller installation in the Holsted cell area. This "Test Center Holsted" is expected to be open for all interested parties like Smart Grid related industries, research institutes and universities on commercial terms.

10. Appendix

10.1 List of Project Participants

Energinet.dk, based in Erritsø, Denmark, is the national transmission system operator for electricity and natural gas in Denmark which initiated, fully financed and did the conceptual design and overall management of the Cell Controller Pilot Project. Per Lund, Chief Design Engineer, and Stig Holm Sørensen, Chief Project Manager, lead the project for Energinet.dk. Major project participants from Energinet.dk were Carsten Strunge, Søren Friismose Jensen, Jens Ravn Skar Jacobsen and Thomas Krogh.

Syd Energi A/S (now known as SE), based in Esbjerg, Denmark, owns and operates the pilot cell's distribution network. Niels Graves Christensen was the project lead at Syd Energi with engineering support from Carlos Comvalius.

Spirae, Inc. of Fort Collins, Colorado, USA, was primarily responsible for specific design, development, implementation, commissioning, and testing of the Cell Controller. Sunil Cherian, CEO and Oliver Pacific, CTO provided management and technical leadership at Spirae. Major team members were Chris Jennings (software), Holger Kley (modeling/analytics), Mahesh Kumar (applications engineering), and Jeff Harrell and Nobin Mathew (Project Management).

Energynautics, GmbH of Langen, Germany, was primarily responsible for modelling and simulation work in the Cell Controller Pilot Project. Simulations for the project were conducted by Nis Martensen and Eckehard Tröster, and Thomas Ackermann, CEO managed the project at Energynautics.

Tjæreborg Industri, based in Tjæreborg, Denmark, was responsible for installation, operations, and maintenance of many of the major equipment including engineering support for CHP plant operations. John Dam was their project lead.

Pon Power Energy Systems, based in Esbjerg, Denmark, was responsible for upgrading and maintenance of CHP plant gas engines control equipment including engineering support as the sole certified CAT and MaK company in Denmark. Børge Jørgensen and Svend Jørgensen were major project participants from PonPower.

Rolls Royce Marine, based in Esbjerg, Denmark, was responsible for upgrading and maintenance of CHP plant gas engines control equipment including engineering support as the sole certified Rolls Royce company in Denmark. The principal participant from Rolls Royce was Erling O. Kaasen.

Note: CHP plant and Wind Turbine owners and operators as well as many other individuals were involved in different capacities during various phases of this project from 2005-2011 that are not listed above. Their contributions are gratefully acknowledged.

Figure 51 Part of Cell Controller Pilot Project Team November 2011

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10.3 Table of Abbreviations and Acronyms

AC: Asset Controller
AO: Asset Owner
AVR: Automatic Voltage Regulator
BRP: Balance Responsible Party
CC: Cell Controller
CCPP: Cell Controller Pilot Project
CMS: Cell Monitoring System
CHP: Combined Heat and Power Plant
DCHP: Dispersed Combined Heat and Power Plant
DER: Distributed Energy Resources
DG: Distributed Generation
DNO: Distribution Network Operator
MO: Market Operation
MS: Master Synchroniser
OPC: Object Linking and Embedding for Process Control
RTU: Remote Terminal Unit
SC: Synchronous Condenser
SCADA: Supervisory Control and Data Acquisition
SGS: Speed Governing System
SLC: Secondary Load Controller
SR: Spinning Reserve(s)
SSC: Substation Controller
TSO: Transmission System Operator
VAR: Volt-Ampere Reactive
VPP: Virtual Power Plant

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