A Cell Controller for Autonomous Operation of a 60 kV Distribution Area

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1 Introduction

The power systems of Denmark are characterised by a high penetration of distributed generation (DG) comprised of small to medium scale combined heat and power plants (CHP) and wind turbines (WTs). This is especially true in the western part of Denmark where 75% of all Danish WTs are situated. In 2004 local CHP made up 30% and WTs 23% of the electricity consumption of that area.

Today, more than 50% of the total production capacity is dispersed throughout local distribution grids of 60 kV voltages and below. As a consequence, it has become more difficult to predict and to control the total electricity generation.

The daily operation of a power system with massive infeed from uncontrolled CHP and WTs is not without problems as the CHP units operate on the basis of heat demand and time of day tariffs and WTs according to the wind, whereas the demand profile is determined by the consumers. So far, the strong interconnections to neighbouring areas and efficient international power markets have prevented malfunctions.

However, the impacts on power markets, system operation and security of supply are causing concern. Hence Energinet.dk, the transmission system operator (TSO) of Denmark, is developing new solutions for optimal management of the large DG base at hand.

This paper shortly introduces the newly formed Energinet.dk, the power system of western Denmark and the need for a new system architecture. The concept of 60 kV distribution grid cells is introduced before concentrating on the Cell Controller Pilot Project that Energinet.dk is currently undertaking.

2 About Energinet.dk

On 24 August 2005 the Danish Minister for Transport and Energy established the independent public corporation Energinet.dk. The company is the new national power and gas TSO established through a merger of the former TSO companies Eltra, Elkraft and

Gastra operating the power systems of western Denmark, eastern Denmark and the national natural gas transmission system, respectively.

Figure 2 shows the power transmission systems of Denmark. The power system of western Denmark (former Eltra) comprises the peninsula of Jutland, the island of Funen and a number of smaller islands. To the south it is AC-connected to Germany and hence part of the UCTE grid. To the north it is interconnected to Norway and Sweden through a total of five HVDC links. The power system of eastern Denmark (former Elkraft) comprises the Islands of Sealand, Lolland and Falster and a number of smaller islands. To the north it is AC-connected to Sweden and hence part of the NORDEL grid. To the south it is interconnected to Germany through one HVDC link. The two areas are not electrically interconnected.

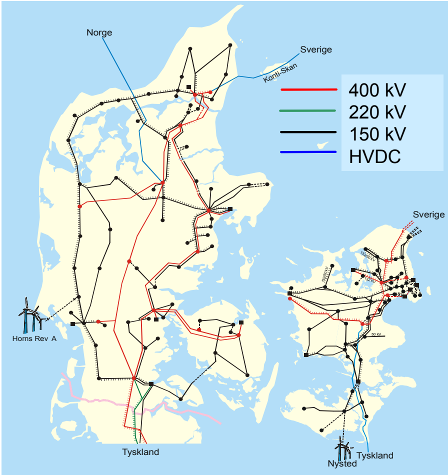

Figure 2. The two power systems of Energinet.dk.

3 A Transformed Power System

Since the late 1980s Denmark has experienced a vast growth in DG. The power system was characterised by a few large CHP units situated in or near each of the major cities for district heating purposes. The electrical power was fed into the power system at 400 or 150 kV level from where it flowed in a unidirectional way down through the voltage levels towards the loads at the low voltage end of the distribution system. Today, in the western part of Denmark, more than 50% of the installed production capacity is dispersed throughout the entire distribution system as illustrated in Figure 3 (a) and (b).

The annual growth in installed DG for the western part of Denmark can be seen in Figure 4 together with the primary production capacity compared with the consumption.

The present situation is characterised by the fact that the distribution networks have become active power producers. Several distribution companies have today installed DG capacity that outnumbers their total load many times over on windy days. They have become net power exporters.

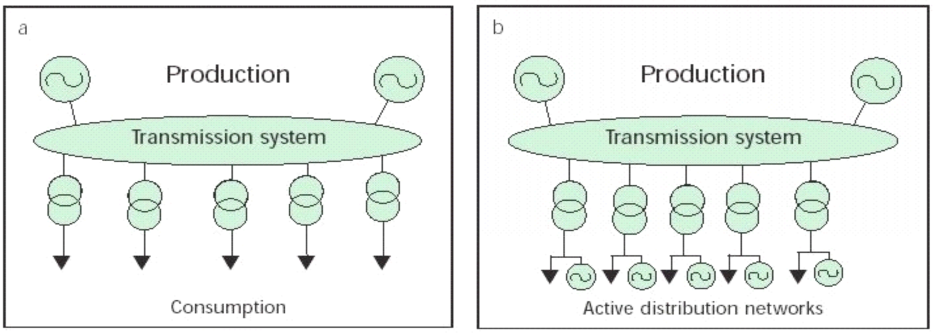

Figure 3. The transition from primary production (a) to local production (b).

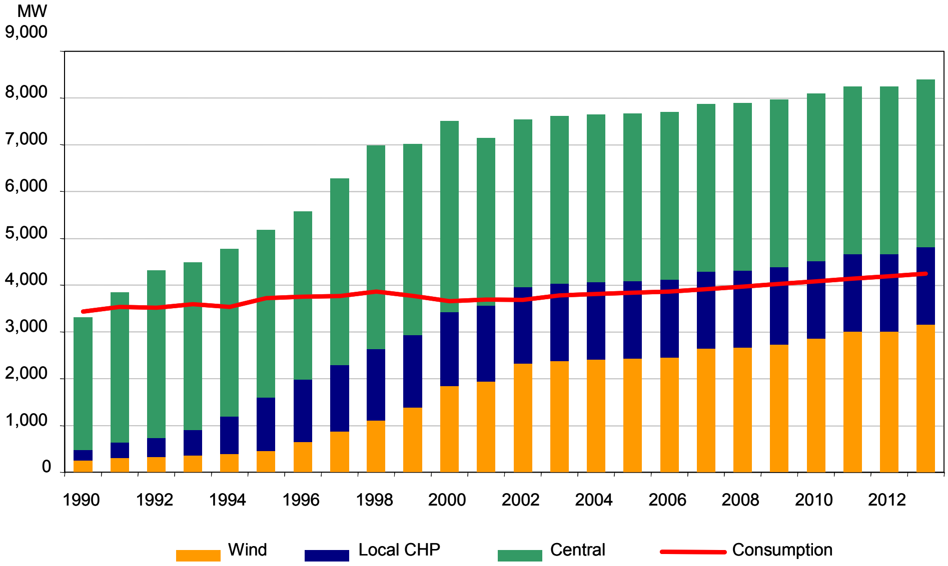

Figure 4. Development of the power balance in western Denmark.

The present installed production capacity per voltage level in the western part of Denmark is depicted in Figure 5. The total installed capacity in this area can be summarised to 3,502 MW primary CHP, 1,643 MW local CHP and 2,374 MW WTs totalling 7,519 MW. In comparison, the minimum load of the area is approx. 1,150 MW and the maximum load is approx. 3,800 MW.

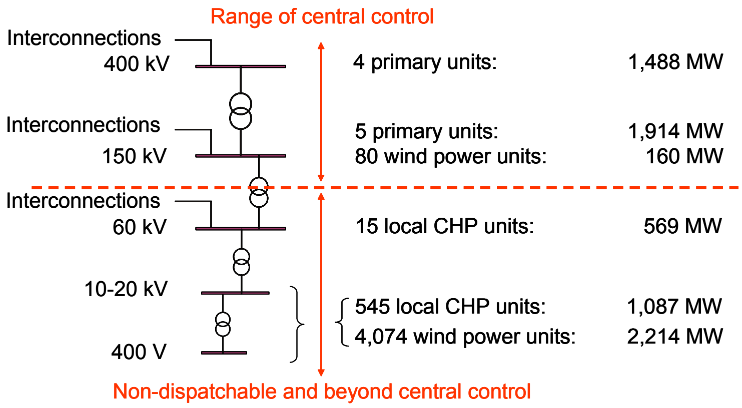

Figure 5. Production capacity per voltage level in western Denmark.

4 A New System Architecture

In the present power system of western Denmark the following security problems have been identified:

- Local grids cannot maintain normal n-1 security if local generation exceeds local demand and if separation of generation and consumption is insufficient.
- Security analysis has become less accurate due to missing information on local generation and unpredictable wind power.
- Protection relays trip local generators after distant faults on the high-voltage transmission grid.
- Traditional under-frequency load shedding schemes will disconnect both load and generation.
- Restoration after fault has become more complicated and more time consuming.

The conclusion reached is that to maintain efficient and safe operation of the power system with a continuous and even increasing high share of DG it requires the traditional system architecture to be redesigned.

The targets identified so far as part of the redesign process are:

- Sufficient domestic resources must be available to maintain a balance between demand and generation.

- Improved operator knowledge of actual system conditions both locally and centrally.
- Efficient system control particularly during emergencies.
- Black starting capabilities using local generators.

To fulfil the above targets, one important element of the new system architecture will be closer integration between TSO and distribution system operators (DSOs). This requires a new communication system encompassing the entire infrastructure. Another element will be to abandon the prioritised operation and fixed electricity prices for local CHP plants. The CHP process can save energy, but only if there is a demand for both heat and electricity. Therefore, local CHP plants should generate electricity only when needed. Efficient electricity markets do provide proper price signals for optimisation of electricity output.

In a traditional power system, the large generating units are decisive for system stability. When the share of these units is falling, the power system must increasingly rely on smaller units regarding fault-ride-through capability and black-start capability. Local grids and production units must be renovated in order to meet such new requirements.

Numerous other measures must be adopted, and the transition into the new system architecture will be a long process. Several international research and development programs are focusing on new power system architecture and on efficient operation of DG.

5 Definition of a 60 kV Distribution System Cell

The 60 kV distribution systems in Denmark were traditionally constructed as meshed networks with at least two infeeds to every station to secure supply of the underlying area even during faults on any 60 kV line. The 60 kV systems are connected to the 150 kV transmission grid through a number of 150/60 kV transformers. However, in Jutland, the main land of western Denmark, the 60 kV network parts below each 150/60 kV transformer are operated as radial networks by opening a sufficient number of 60 kV line breakers in selected substations and thus sectioning the meshed networks. This is done to prevent the 60 kV distribution networks from taking part in any power transit flowing on the transmission system either north-south or south-north between the hydro-based systems of Norway and Sweden and the fossil and nuclear based systems of western Europe. An example of such a 60 kV distribution system is depicted in Figure 6.

A small part of a radially operated 60 kV distribution network below one 150/60 kV transformer might look as in Figure 7.

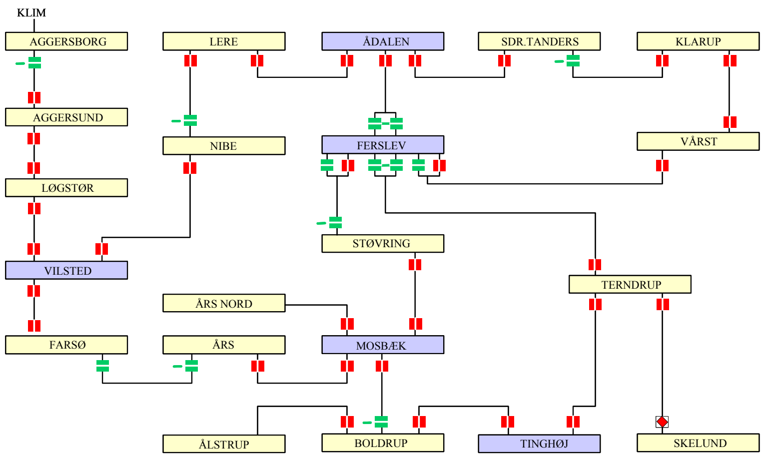

Figure 6. Typical 60 kV grid of a distribution company in western Denmark. Bluish (dark) substations are 150/60/10 kV substations. Yellow (light) substations are 60/10 kV substations. The radial operation is indicated by the position and color of the power circuit breaker sympols (red: closed, green: open).

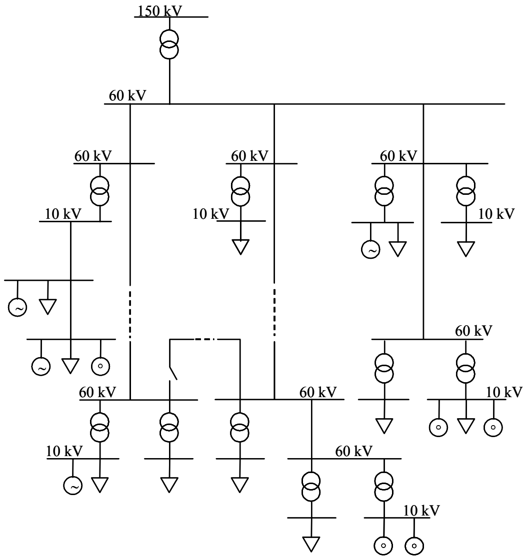

Figure 7. Sketch drawing of a small part of a 60 kV distribution network below one 150/60 kV transformer. Load, WTs and CHP indicated at 10 kV busbars only.

These distribution systems are characterised by a large number of WTs and to a lesser extent CHP units scattered all over the 10 kV, 0.6 kV and 0.4 kV networks (only 10 kV grid connections are shown in Figure 7 for reasons of simplicity).

The uncontrolled operation of WTs and to a lesser extent the heat constrained operation of CHP plants have caused severe uncontrolled reactive power flows both ways through the 150/60 kV transformers of each radially operated 60 kV network, as illustrated in Figure 9. The figure shows the total reactive power transfer between the 60 kV distribution grids and the 150 kV transmission grid in western Denmark in 2003.

As a consequence Eltra, the former TSO of western Denmark, in 2004 imposed limits on the acceptable level of reactive power transfer on each 150/60 kV transformer. This Mvar-Arrangement, as it is called, introduces Mvar limits in three steps towards the final limits in 2004, 2005 and 2006, respectively. The responsibility of keeping these limits rests with the distribution companies. The Mvar-Arrangement is controlled and supervised by Energinet.dk.

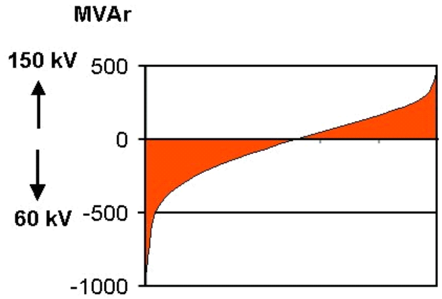

Figure 9. Total reactive power transfer between distribution and transmission levels in western Denmark in 2003.

Each sectionised, radially operated 60 kV network below each 150/60 kV transformer was in 2004 defined as 60 kV distribution cells in order to give a clear definition of the areas that cause excessive reactive power flows in corresponding 150/60 kV transformers. This definition also enables a clear discussion of responsibilities as technicalities like borders of ownership are also taken care of.

It has become clear to both the TSO and the DSOs that in the end the Mvar-Arrangement necessitates some form of intelligent reactive power control or voltage control within each cell area.

6 Cell Controller Pilot Project

In recent years power systems in North America, Italy, Sweden and Denmark have 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 are 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 is believed that such blackouts can and will happen again.

This perception 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 cell in the CCPP is being defined as explained in section 5 of this paper. The project aims for the High Ambition but the project will be fully accepted if only the Moderate Ambition can be fulfilled.

The High Ambition aims 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. In fact the CCPP is the first pilot towards utilising the voltage and frequency control capabilities of the more than 1,600 MW synchronous generators locally installed at CHP units in western Denmark.

The CCPP aims to:

- Gather information from the international community about the feasibility and approaches to utility-scale microgrids (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 pilot cell

In order to ensure a timed stepwise approach towards a fully implemented pilot cell the CCPP has been divided into a number of phases with the following contents and project schedules:

A. This is 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 CHP units and WTs of that area. Two of the workshops were held in Denmark and one in the USA. In this phase the requirements specifications and preliminary design of a pilot cell were worked out. This phase was initiated in November 2004 and was recently completed in early 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 will be carried out. This phase awaits the approval of the CCPP phase B application and budget by the board of directors of Energinet.dk. This phase is expected to last one year with a probable start in December, 2005.

C. Here the actual pilot implementation and testing of the cell controller in a selected part of the pilot cell will take place. This phase is expected to last one year with a probable start in early 2007.

Upon successful completion of phase C the process will be repeated by new phases B and C with increasingly larger parts of the pilot cell until the entire pilot cell is controlled.

As indicated above one of the progressive distribution companies of western Denmark has agreed to be part of the CCPP and a suitable 60 kV cell of that company has been selected as the pilot cell.

The participants of the CCPP are:

- Spirae Inc, Fort Collins, Colorado, USA. Dedicated to designing, implementing and enhancing the business infrastructure for distributed energy.
- Energynautics GmbH, Langen, Germany. Provides consultancy services to the energy industry focusing on renewable energies and innovative energy applications.
- Sydvest Energi Net A/S, Esbjerg, Denmark. Independent Distribution Company and DSO located at the south-western parts of Jutland.
- Energinet.dk, Skærbæk, Denmark. National power and gas TSO of Denmark.

7 Cell Controller Functionality

To fulfil the High Ambition of the CCPP the cell controller needs 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.
- 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 10. 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 fault situations do not lose power production, short-circuit power, reactive power, spinning inertia etc. by unintentional 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.

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 DSO 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. It is also from either the DSO or the TSO that the request to provide black-starting support will be sent to the cell controller.

The advantages for the DSO to be able to communicate with and request services from the cell controller are plentiful in a future power system. For a start 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 the Mvar-limitations imposed in the Mvar-Arrangement are kept at all times.

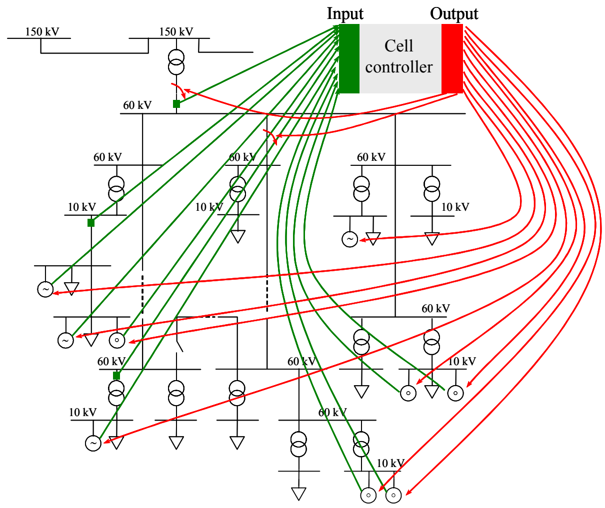

Figure 10. Cell controller functionalities. Measuring and monitoring of load and production indicated by (green) arrows pointing towards the cell controller. Control actions on generators, load feeders and main power circuit breakers indicated by (red) arrows pointing away from the cell controller.

Other obvious advantages for the DSO are:

- Highly improved 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.
- Other automatic control functions envisioned by the DSO.
- 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:

- Emergency transfer to islanded operation with preservation of maximum possible power supply.
- Black-starting support for the high-voltage grid.

8 Identified Knowledge Gaps So Far

A number of knowledge gaps have been identified during the first phase A of the project. During the coming phases of the project these will have to be dealt with one by one. These knowledge gaps are discussed briefly in the following subsections.

8.1 Relay Protection of 60 kV Cell Area

The present protection of Danish 60 kV distribution grids is based on distance relays mounted on roughly 50% of the lines - primarily those lines emerging from the 60 kV busbars of the 150/60 kV substations. The main contribution of the necessary short circuit current to drive these distance relays is coming from the 150 kV grid. This implies that when a 60 kV cell area is in island operation the contribution of short circuit current is exclusively from dispersed CHP and WT units located on 10 kV and 0.4 kV distribution feeders. Under such circumstances the distance relays most likely will not function properly due to lack of short-circuit current. Currently, it is therefore believed that the future protection of a 60 kV cell area should preferably be based on differential relays on all 60 kV lines.

8.2 Relaxation of Synchronous Generator Relay Protection

All synchronous generators installed in all CHP plants have had to comply with the requirements on generator protection schemes and recommended settings as stated in the Eltra Power Station Specifications. Especially, the requirement of and the recommended settings of the synchronous under-voltage relay is of concern in connection with the ability of the cell to successfully transfer to islanded operation. The main purpose of this relay is to avoid unintentional islanding of the generator by distance relays disconnecting a faulted 60 kV line followed by automatic reclosure causing an asynchronous reconnection of the generator with a possible severe implication of the generator shaft system.

The general recommended setting of these synchronous under-voltage relays is a voltage trip level of 70% of generator nominal voltage and a timer delay less than 50 ms.

The actual settings on each relay have been calculated individually due to different local conditions such as e.g. the presence of nearby generators etc.

These settings must be relaxed for a number of seconds when the cell transfers to island operation to avoid tripping of synchronous generators within the cell area due to the unavoidable dynamic voltage variations during the transition period.

This is not foreseen to pose a big problem as modern relays today already have the possibility of switching between two sets of settings based on an external signal.

8.3 Cell Controller Early Warning System

In normal parallel operation with the main grid large power imbalances within the cell area can be expected due to uncontrolled wind and CHP production. The cell controller then needs lead time to bring the cell close to power balance prior to transferring it to islanded operation in case of an impending system break-down. Hence an Early Warning System capable of estimating the risk of an imminent system break-down is deemed a critical necessity for the cell controller.

In another pilot project Energinet.dk introduces PMUs into the HV transmission grid with the purpose of gaining knowledge and experience with such measuring equipment and the type of data they produce. The PMUs measure phase voltages and currents and their corresponding angles forming a set of voltage and current phasors. The PMUs then attach to each phasor a very accurate time stamp originating from a GPS satellite. The novelty of the PMUs is that these very accurate time stamps make it possible to calculate e.g. voltage phasor angle *differences* across large distances and without having to hardwire a connection between any two measuring equipments. These inter-area angle differences can then form the foundation of establishing a power system surveillance tool for assessing the level of system stress in the daily operation of the power system. This is illustrated in Figure 11 and Figure 12.

It is presently believed that such a PMU based power system surveillance tool must be rule based to take into account all transmission system constraints, operator experience and established rules of daily operation.

It is presently also believed that based on experience with such a surveillance tool, criteria can be established to determine the point of no return for e.g. an impending voltage collapse in an extreme stressed situation. Hence a signal can be sent to the cell controllers allowing them to initiate an emergency transfer to islanded operation of the cells. The success of such a transfer will then depend on factors like the amount of lead time gained, the level of power imbalance within each cell, the available controllable active and passive components within each cell, etc.

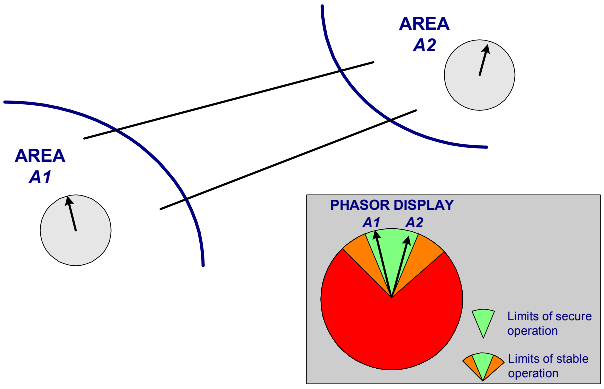

Figure 11. PMU based system surveillance. Large inter-area angle differences imply static system stress.

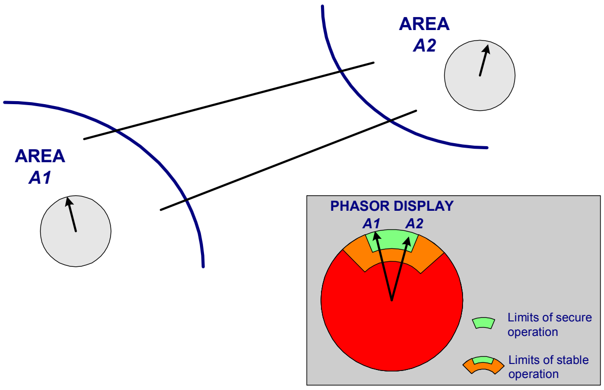

Figure 12. PMU based system surveillance. Depressed transmission voltages imply a risk of voltage instability.

8.4 Definition of Point of No Return

To fulfil the High Ambition the CCPP also needs to address and solve the problem of defining the point of no return i.e. the ultimate time in a severely stressed situation where the power system can no longer be saved and a black-out is imminent.

Two approaches have so far been discussed. These are voltage collapse proximity indexes (VCPI) and QV-curves, the on-line calculation of which will be greatly improved by the introduction of PMU based measurements as mentioned above.

The VCPI for any given busbar is defined as:

$$VCPI_{Qi} = \frac{\sum \Delta Q_{gen}}{\Delta Q_i} ,$$

Where ΔQ_i is the maximum possible additional reactive load on the selected busbar that still results in a stable situation (solved load-flow). $\sum \Delta Q_{gen}$ is the resulting total change of reactive power production of all generators within the power system needed to supply the increased reactive power demand (ΔQ_i). The larger from unity the VCPI becomes the more stressed the power system.

For the western Danish power system normal values of VCPI with intact network is in the range of 1,05 to 1,08. For an extreme n-15 contingency a value of 2,91 has been calculated.

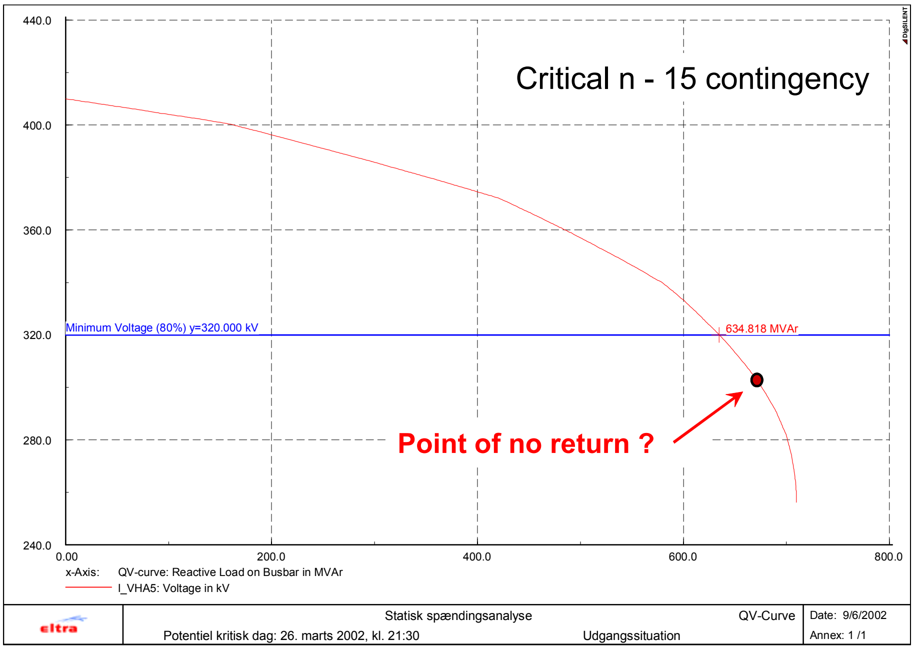

Figure 13. QV-curve calculated for a critical n-15 contingency situation for the power system of western Denmark. How do we define the point of no return?

Turning to QV-curves these can be on-line calculated based on PMU-measurements. For the same extreme n-15 contingency situation the QV-curve depicted in Figure 13 has been theoretical calculated. In this QV-curve the indicated point of no return needs to be defined.

8.5 Controlled Operation of CHP Units

The distributed CHP units in Denmark have all been designed with the primary function of providing hot water for local district heating systems. To achieve a high fuel efficiency the smaller units are mostly constructed with one ore more gas engines the exhaust gasses of which is fed into an exhaust boiler producing hot water for the district heating system. The generator control systems of such units have been designed for parallel operation with the grid. The units are either operated at full load to produce hot water for the hot water storage tank or they are disconnected. The implication of this is that the control system of these units is designed to primarily serve the hot water production with less emphasis on the electrical power production. An overview of a typical control and communication system for a Gas Engine CHP unit designed for parallel operation with the grid is depicted in Figure 14. Please notice that the control and communication system for the exhaust boiler, hot water storage tank and district heating system is not shown.

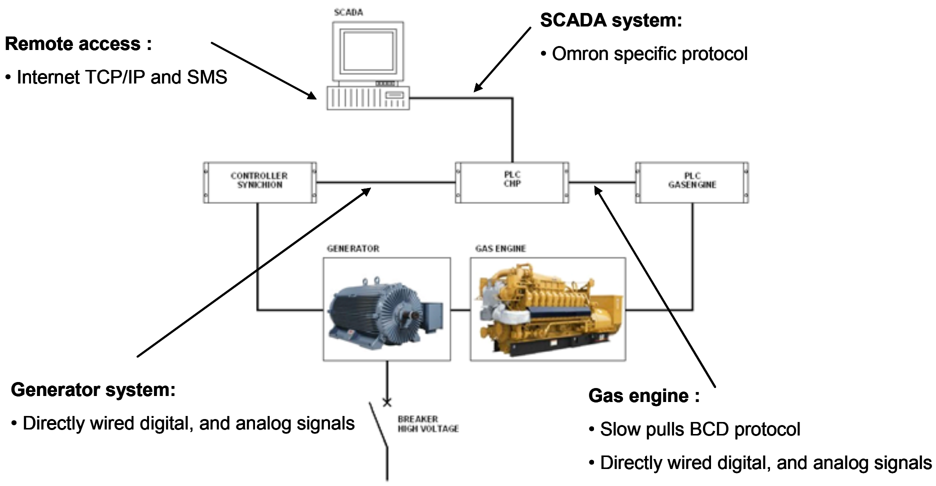

Figure 14. Typical control and communication system for a Gas Engine CHP unit.

Compared to the communication speed necessary for cell controller remotely controlled voltage and frequency regulation on each gas engine the existing control and communication systems are deemed to slow. Hence there is a need to upgrade the control and communication systems of most of these units:

- Rewiring the control circuit for faster communication.
- Fast external communication of set points for voltage and speed control.
- Fast external communication to the power management system.
- Changing the SCADA system to handle new or more strategies.
- Re-programming the control system to switch between parallel and island operation.

8.6 Controlled Operation of WT Units

Almost all of the WTs installed in Denmark are of the so-called Danish concept type, i.e. a three-blade rotor connected through a gearbox to an induction generator which is directly connected to the grid eventually through a step-up transformer. The WTs come from all of the different Danish vendors and are in most areas of different vintages and types. These WTs are either no-load reactive power compensated or in recent years full-load reactive power compensated by switchable capacitor banks. The turbines are either pitch or stall controlled leaving only little hope for the possibility of doing any active 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.

Still the control of local wind power, i.e. downward regulation of wind power production, will be an important asset for the performance of the cell if at all possible. In theory, wind power generation can not only be used for downward regulation, but also for upward regulation, as long as wind power production is initially limited to a certain percentage of possible production (delta regulation). In an attempt to make these possible capabilities available for the cell operation, a detailed understanding of the control possibilities of especially the latest types of WTs will be necessary.

9 Conclusion

The Cell Controller Pilot Project presented in this paper along with a PMU pilot project and other development projects forms the first steps on a long road towards new solutions for optimal management and active grid utilisation of the large amount of distributed generation present in Western Denmark.

The initial phase A of the project was finalised with a project report in October 2005. This also implies that this project has a long way to go. There are many unanswered questions and a list of knowledge gaps have been identified so far to which the attention will be directed in the next phases of this and other projects.

The promising aspects of the CCPP as seen from the perspective of both the TSO and the local DSO's is that a well-functioning cell controller provides a number of new promising possibilities for medium-voltage distribution areas with a high degree of DG in any mode of normal operation. In the much more difficult modes of stressed operation of the power system the cell controller is envisioned to provide additional possibilities such as emergency transfer of the cell area to islanded operation with preservation of power supply to as many consumers as possible.

All of this can be made possible by getting access to and actively utilise the already existing distributed generation facilities in the medium- and low-voltage grids of Denmark.