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Initial results of local grid control using wind farms with grid support

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Risø National Laboratory
Roskilde
Denmark
September 2005

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Contents

Preface

This report describes results of the project titled “Control of wind power installations”. The project was funded by the Danish TSO, Elkraft System as PSO project FU 2102, and it was carried out in cooperation between Risø National Laboratory, Technical University of Denmark, Aalborg University and Energy E2.

1 Introduction

This report describes initial results with simulation of local grid control using wind farms with grid support. The focus is on simulation of the behaviour of the wind farms when they are isolated from the main grid and establish a local grid together with a few other grid components.

The idea of simulating the behaviour of the wind farms when they are isolated from the main grid is inspired from a previous version of Danish grid codes: “Specifications for connecting wind farms to the transmission network” [1]. Here “control in case of frequency transients after system faults where all international a.c. connections are disconnected or where a minor subsystem including the wind farm is isolated from the rest of the system” is mentioned, as an example where power control of the wind farm is needed with “dead band and droop”, i.e. as automatic, primary frequency control.

Although the support of wind farms to isolated subsystems is not mentioned explicitly in the new Danish grid codes for wind turbines, the primary frequency control function is required and specified quite detailed, and the use of this functionality to support control of isolated grid subsystems is still considered obvious by the authors.

The isolated subsystems used in the work presented in this report do not intend to simulate a specific subsystem, but they are extremely simplified single bus bar systems using only a few more components than the wind farm. This approach has been applied to make it easier to understand the dynamics of the subsystem.

Models for three different types of wind farms were developed and described in [2]. Two of these wind farm models are used in the work described in this report. Both wind farms consist of active stall controlled wind turbines, but in the first case the wind turbines are directly connected to the AC grid, while the second wind farm is connected through a dedicated HVDC link. The third wind farm model consists of AC connected doubly-fed induction generators (DFIGs). Simulations with this third model on isolated local grid have caused some problems of a simulation technical character, which are not solved at the present state. Therefore, no results with DFIGs are presented here. However, it is expected that DFIG wind turbines and other wind turbines with power electronics will be advantageous for grid support, because the control of active as well as reactive power is extremely fast.

The work presented in this report has an initial character. It is a collection of work with the HVDC connection first presented by Iov in [3], and new work with the AC connection. The HVDC simulations were done earlier, when the active stall wind turbine model was only available with a slow power control, and no wind farm controllers were implemented. The AC simulations were done very close to the deadline of the funding project. Still, the initial results are found to be interesting, and are therefore reported here.

The main observation is that the fast dynamics of the wind turbines seem to be able to contribute significantly to the grid control, which can be useful where the wind farm is isolated with a subsystem from the main grid with surplus of generation. Thus, the fast down regulation of the wind farm using automatic frequency control can keep the subsystem in operation and thereby improve the reliability of the grid.

2 Grid component models

2.1 Combined Heat and Power plant

In order to obtain the characteristics of a local grid a dynamic model of a small CHP unit is implemented in DIgSILENT.

Various technologies are used in embedded (small) CHP plants [4] e.g. back pressure steam turbines, pass-out condensing steam turbines, gas turbine with waste heat recovery, etc.

CHP units are typically controlled, or dispatched, to meet the heat demands and not to export electrical power to the utility distribution system [4]. The heat output is generally controlled as a function of ambient temperature. Alternatively, a CHP unit can be controlled to meet the electrical load demand or may be run to supply both heat and electricity in an optimal manner [4]. However, the last mode of operation requires a more complex control system.

Currently, the Danish small CHP plants are mainly controlled to meet the heat demand.

Usually, the small CHP units are equipped with a self-regulated brushless synchronous generator (alternator). The rated power is in 2-10 MVA range with voltages in the 3-13.8 kV. Power generating sets are generally manufactured to meet specific requirements [5].

The generator consists of a primary internal pole machine (G1), an external pole exciter (G2), an equal-pole type of auxiliary exciter (G3) and a voltage regulator with a thyristor control element as shown in Figure 1.

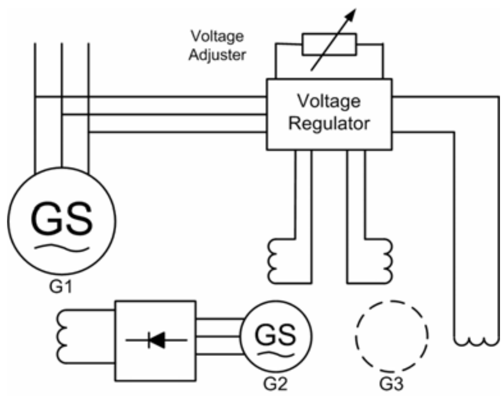

Figure 1. Block diagram of a self-regulated brushless alternator type AvK.

Some protection schemes are included such as:

- External short-circuits – in a multi branch mains system the circuit breakers should operate selectively in such a way that the switch nearest the short-circuit trips as fast as possible while all others remain in circuit. In this way the short-circuits are always isolated within the main grid and do not cause the generator switch to trip. So, the alternator short-circuit protection normally operates as a stand-by protection device.
- Overload – this is the main protection device for the generator;
- Unbalanced load – an unbalanced loading cause a temperature rise in the machine;

- Short break in the mains voltage – the generators operating in parallel with the main grid have a high risk in the case of a fault in the main grid particularly if the rating of the main grid is higher than the generator rating. The recovery voltage from the main grid may catch the generator in an asynchronous phase position and can cause high currents similar to short-circuit currents and the possibility of mechanical damage. Disconnection of the generator from the main grid should take place in less than 200 msec [5].
- Protection against reverse power – if the prime mover fails the machine becomes an electric motor and drives the generating sets (turbine)
- Asynchronous operation – can occur as a result of a failure of the excitation system or the grid voltage collapsing during short-circuits;
- Exciter failure;
- Underspeed and overspeed protection;
- Overvoltage – this type of protection is used on medium voltage alternators. A 2-stage protection relays are used typically for 30% over voltage. Voltage monitors will not protect the alternator against external voltage peaks (switching peaks or atmospheric effects);
- Overfrequency – is used if there is a risk of dangerous over speeds caused by the prime mover.

Since the principal method of control for small CHP unit is based on active power and reactive power/power factor as shown in Figure 2 it requires a connection with an infinite bus bar.

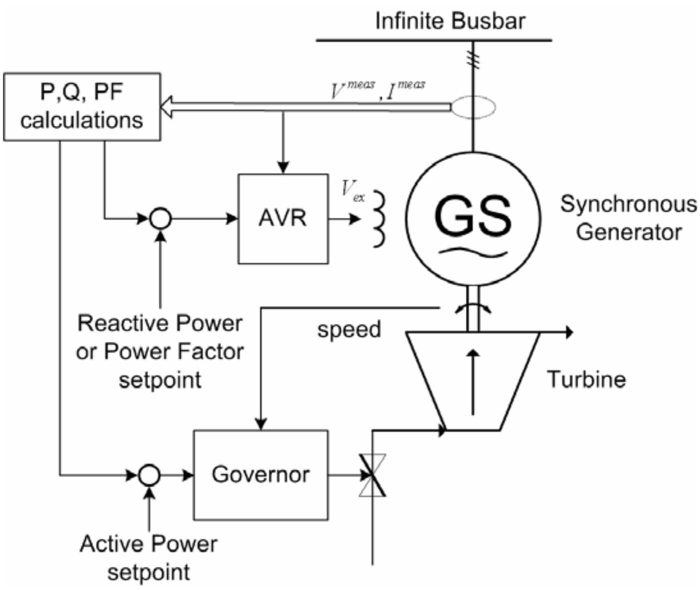

Figure 2. Typical control scheme for a small CHP unit.

A voltage measurement is supplied to the Automatic Voltage Regulator (AVR) and a speed/frequency measurement to the governor. However, in this mode of control these signals are not used.

The error between the active power set point and the measured ones fed to the governor. This governor controls the steam/gas supply to the turbine.

Similarly, the excitation of the generator is controlled based on reactive power or power factor. The error signal between the set point and the actual value is passed to the AVR and exciter. The exciter controls the field current and thus the reactive power output (power factor) of the generator.

Using this control method the operational points of the CHP are as shown in Figure 3. Usually, the CHP operates at unity power factor during the night while during the day it works at 0.8 power factor. The active power is related with the heat demand.

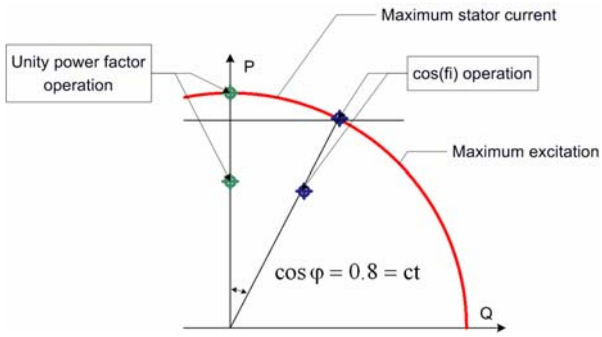

Figure 3. Operational points for a synchronous generator used in a small CHP.

It is clear that such a control scheme does not take into account the grid conditions. The active power is set to a value which do not take into account the frequency of the system whereas the reactive power set point (or power factor) does not consider the grid voltage. Moreover the operation at non-unity power factor increases the electrical losses in the generator, while changing the active power delivered to the grid according with the grid frequency will affects the prime mover if the unit operates as a CHP.

The model, which was implemented in DIgSILENT during this project has the above mentioned control characteristics. The control variables are the active power and the power factor. However, additional signals namely frequency and voltage are available. Thus, this model can be extended so that the possibilities of despatching the unit can be explored in the future.

The block diagram of the model implemented in DIgSILENT during the project is shown in Figure 4.

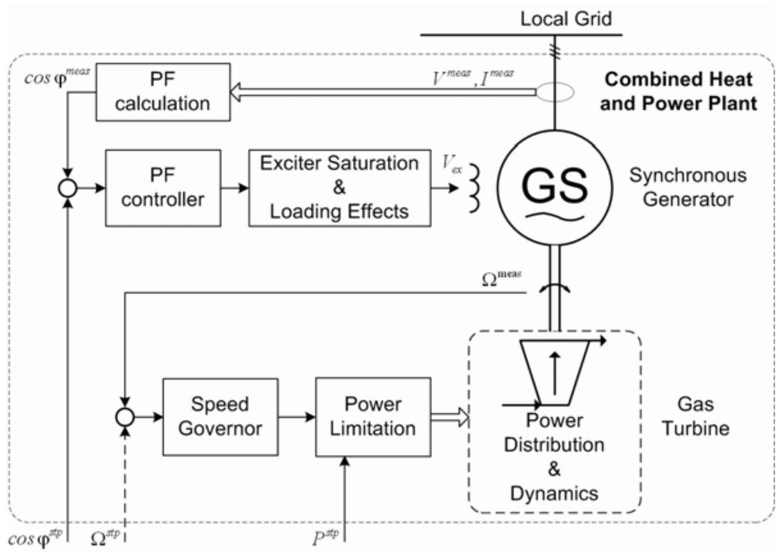

Figure 4. Block diagram of the small CHP unit implemented in DIgSILENT.

An AvK generator type DIDB 160 h/4 with 5.4 MVA rated power is used for the CHP model [6]. The prime mover model is based on a GEC Alsthom gas turbine Type GT8C2 [7].

The excitation system is IEEE Type AC5A, which is a simplified model for brushless excitation systems [8]. This model can be used to represent small excitation systems and has been widely implemented by the industry [8].

2.2 Static load

DIgSILENTs general load model [9] is applied. The static load is used corresponding to constant shunt resistance and shunt reactance, i.e. P and Q varies with the square of the voltage.

2.3 Motor load

DIgSILENTs standard model for an asynchronous machine [9] is applied. The single-cage version without current displacement modelling is used. Data for the motor is for an 8 MW machine in DIgSILENTs standard library. In order to increase the inertia in the system, the acceleration time constant of the 8 MW machine has been increased to 10 sec.

3 Active stall controlled wind turbines with AC transmission

3.1 System overview

The system used in simulation of active stall controlled wind turbines with AC transmission is shown in Figure 5. The wind farm is simulated as 3 wind turbines connected in a single line to the “Station 2” local system bus bar as shown. The simulations are performed with different combinations of a static load, an induction motor load and a local CHP, which are connected directly to the local system bus bar as shown in Figure 5. The dashes indicate that the unit is not connected in the specific case, e.g. static load and CHP are not connected in case B. The local system bus bar is connected to a strong ac grid through a 50/10 kV transformer, and the isolation of the system is simulated by opening the 10 kV grid in the “disconnection point”.

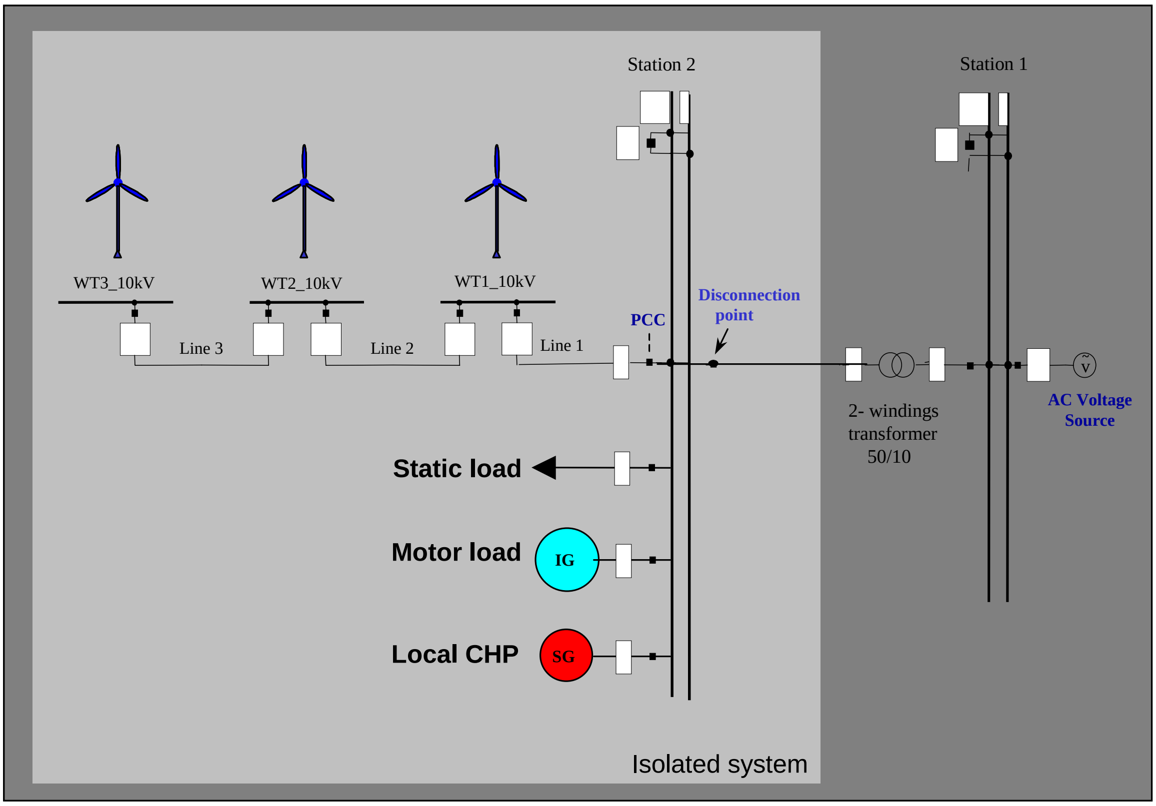

Figure 5: Wind farm grid layout.

3.2 Simulation examples

Four different simulation cases, A-D, are simulated. The cases are characterised by the initial flow in the disconnection point just before the breaker is opened. The breaker is opened at time 5 sec, ensuring that the states are reasonably steady just before the breaker opens. The initial conditions of each case are quantified in Table 1. Consumption sign convention is used for the static load and the motor load, generation sign convention is used for the CHP and wind farm, and export sign convention is used for the connection point line.

Case	Static load	Motor load	CHP	Wind farm	Conn. point
A	3.10 MW 2.32 Mvar	_	_	3.00 MW 2.28 Mvar	-0.11 MW -0.04 Mvar
B	_	3.12 MW 1.81 Mvar	_	3.00 MW 1.85 Mvar	-0.12 MW 0.04 Mvar
C	5.99 MW 2.25 Mvar	_	2.87 MW 2.10 Mvar	2.97 MW 0.10 Mvar	-0.15 MW -0.04 Mvar
D	_	6.03 MW 2.80 Mvar	2.87 MW 2.10 Mvar	2.97 MW 0.82 Mvar	-0.19 MW 0.12 Mvar

Table 1. Initial conditions of simulation cases.

All simulations are performed with a constant 16m/s wind speed. The wind farm controller set points for active and reactive power have been selected to balance the flow in the disconnection point close to zero before the local grid is isolated. From the table it is seen that there is generally a small import (negative export) of 110 – 190 kW to the local system.

The frequency control set point is 50 Hz, with ±0.1 Hz dead band and 4% droop (4 % of 50 Hz = 2 Hz, i.e. for 6 MW installation 6 MW / 2Hz = 3 MW/Hz controller gain)

To provide the necessary wide-ranging reactive power support from the wind farm, each wind turbine has a 20 × 0.1 Mvar capacitor bank, which is controlled very quickly assuming thyrister switched dynamic phase compensation as described in [2].

The voltage control set point is 10 kV with ± 0.5 kV dead band and 3.6 Mvar/kV controller gain.

Case A:

This simulation case is with a local grid consisting only of the wind farm and the static load with power factor 0.8 as described in Table 1. This means that the wind turbines produce reactive power, not only to their own induction generators but also to the load.

Figure 6 shows the simulated frequency, power and voltage in the wind farm PCC, while Figure 7 shows power, pitch angle and speed variables on one of the wind turbines.

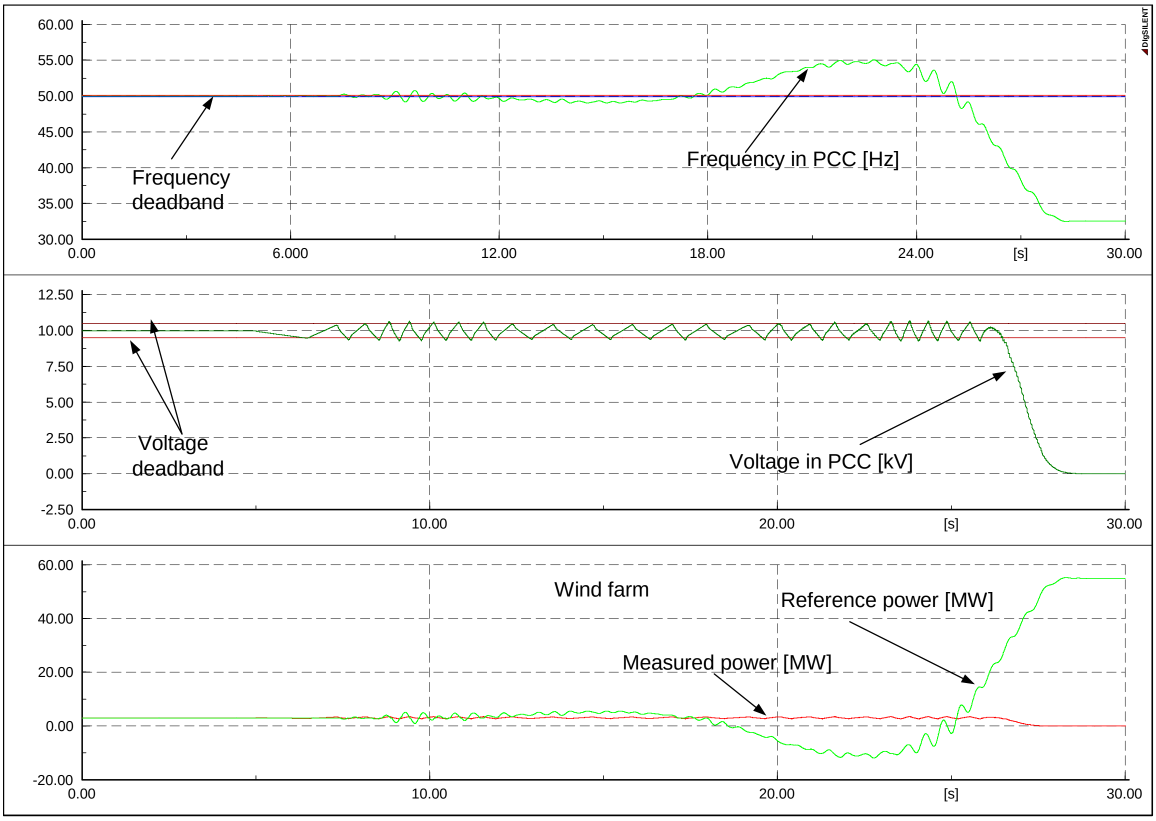

Figure 6: Case A - frequency and voltage in PCC.

It is seen from in Figure 6 that in the moment of disconnection (t = 5 sec), the frequency starts oscillating with a period time of approximately 0.5 sec. The frequency fluctuations exceed the dead band (0.1 Hz) significantly, because the active power control in the wind turbines is not fast enough to mitigate the oscillations.

The voltage also oscillates but it is kept close to the dead band (0.5 kV), because the reactive power control of the dynamic phase compensation in the wind turbines is sufficiently fast.

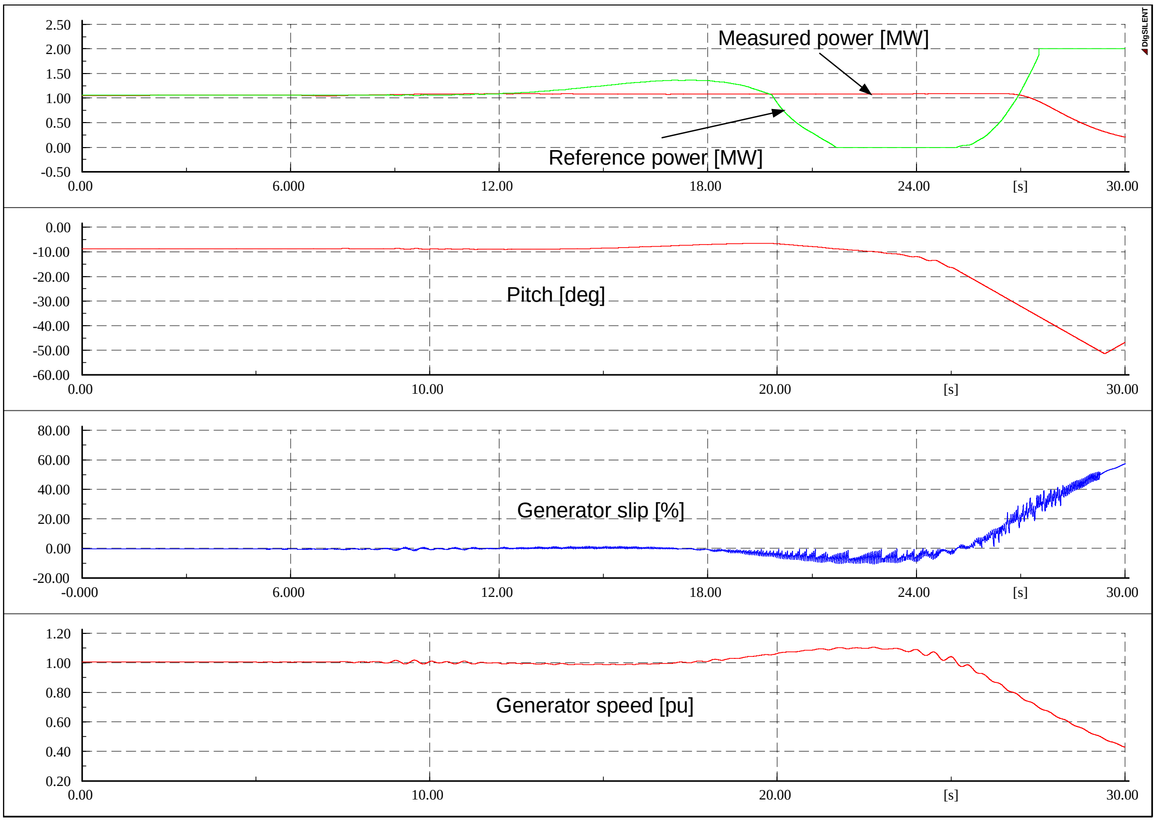

Figure 7: Case A - wind turbine situation.

The frequency also starts a slow oscillation, apparently negatively damped oscillation. From t=12 sec to t=17 sec, the frequency is slightly below 50 Hz, from t=18 sec to 25 sec the frequency oscillates above 50 Hz to a maximum above 55 Hz, and finally it drops towards zero. Obviously, an over frequency or over speed protection would have disconnected and stopped the wind turbines earlier, but the protection is not implemented in the simulation.

Comparison of the slow frequency oscillations to the wind turbine reference power, measured power, pitch angle, generator slip and speed in Figure 7 illustrates the problem in the control during this isolated system operation. When the frequency is too low from t = 12 sec to t = 17 sec, the wind turbine decreases the pitch angle as it should to increase the aerodynamic torque. However, the wind turbine electric power does not increase correspondingly, because the power is determined by the static load, which depends on the voltage but not the frequency. This causes the wind turbine to accelerate, also as it should. But the problem is that after the frequency again exceeds 50 Hz around t = 17.5 sec, it first takes a couple of seconds before the wind turbine reference power comes below 1 MW, and another couple of seconds before the wind turbine has pitched to an angle where the aerodyanmic torque becomes lower than the generator torque and the generator starts to decelerate. In the mean time, the generator speed has reached approximately 1.1 p.u.

An obvious way to try to stabilise this system is to add inertia on the load as is done in case B. Alternatively, static frequency dependent load could be tried, but this has not been tested in the present state.

Case B:

This simulation case is with a local grid consisting only of the wind farm and the dynamic motor load as described in Table 1. Like in case A, the wind turbines produce reactive power, not only to their own induction generators but also to the load.

Figure 8 shows the simulated frequency, power and voltage in the wind farm PCC, while Figure 9 shows power, pitch angle and speed variables on one of the wind turbines.

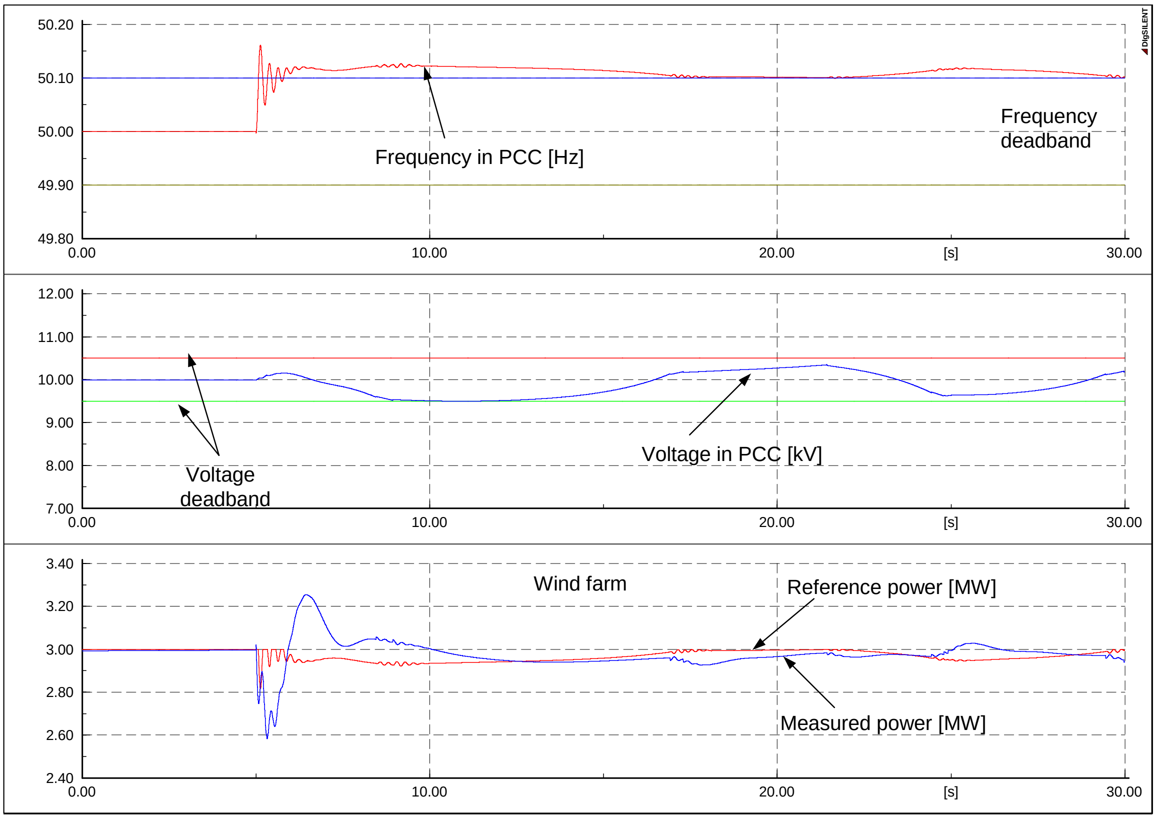

Figure 8: Case B - frequency and voltage control.

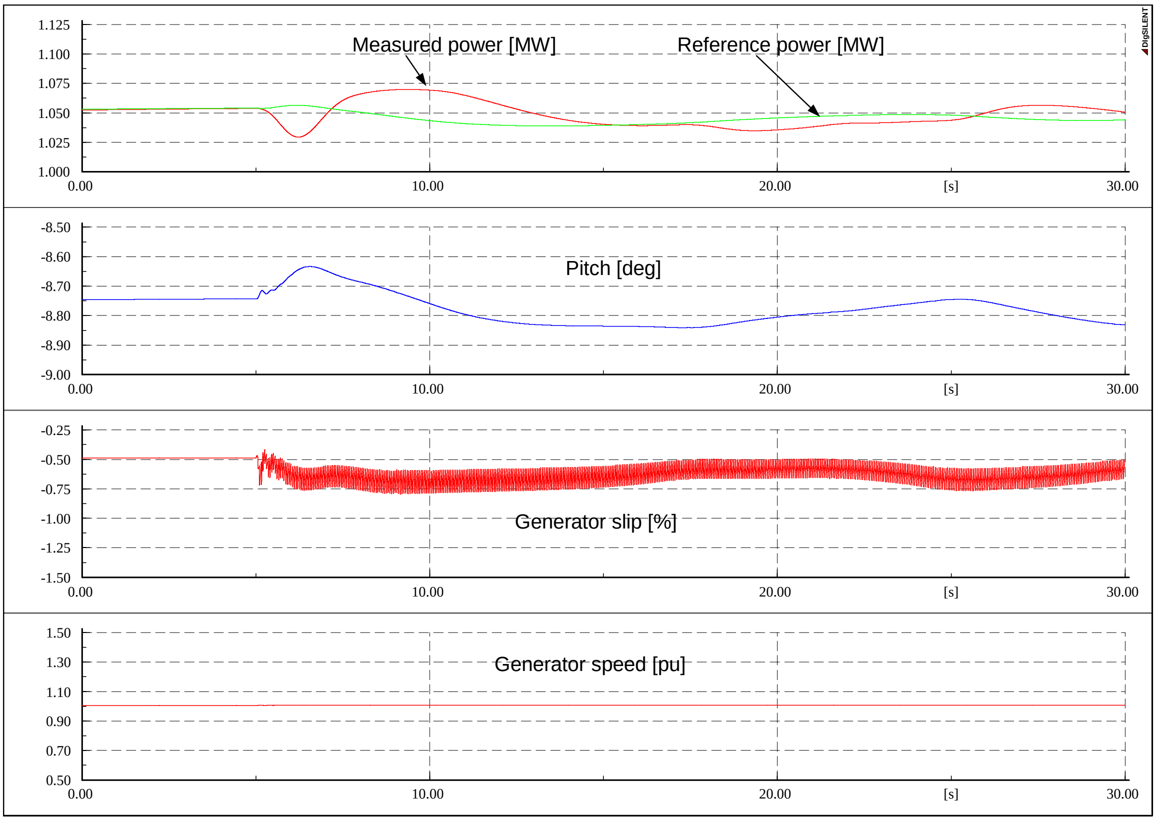

Figure 9: Case B: wind turbine production, pitch, slip and generator speed.

Comparing the case B simulation to the case A simulation, it is clear that the inertia load stabilises the isolated system. The fast frequency oscillations right after the disconnection at t = 5 sec are damped effectively, and the frequency is controlled close to the dead band.

Case C:

This simulation case is with a local grid consisting of the wind farm, the static load and a CHP as described in Table 1. Compared to case A, the CHP is added here and the load is increased correspondingly. In case C, the CPH supplies reactive power, while the wind farm reactive power is close to zero.

Figure 10 shows the simulated frequency, power and voltage in the wind farm PCC, while Figure 11 shows power, pitch angle and speed variables on one of the wind turbines. Like in case A, the conclusion is that the power control of the wind turbines is not fast enough to control the frequency on this local grid.

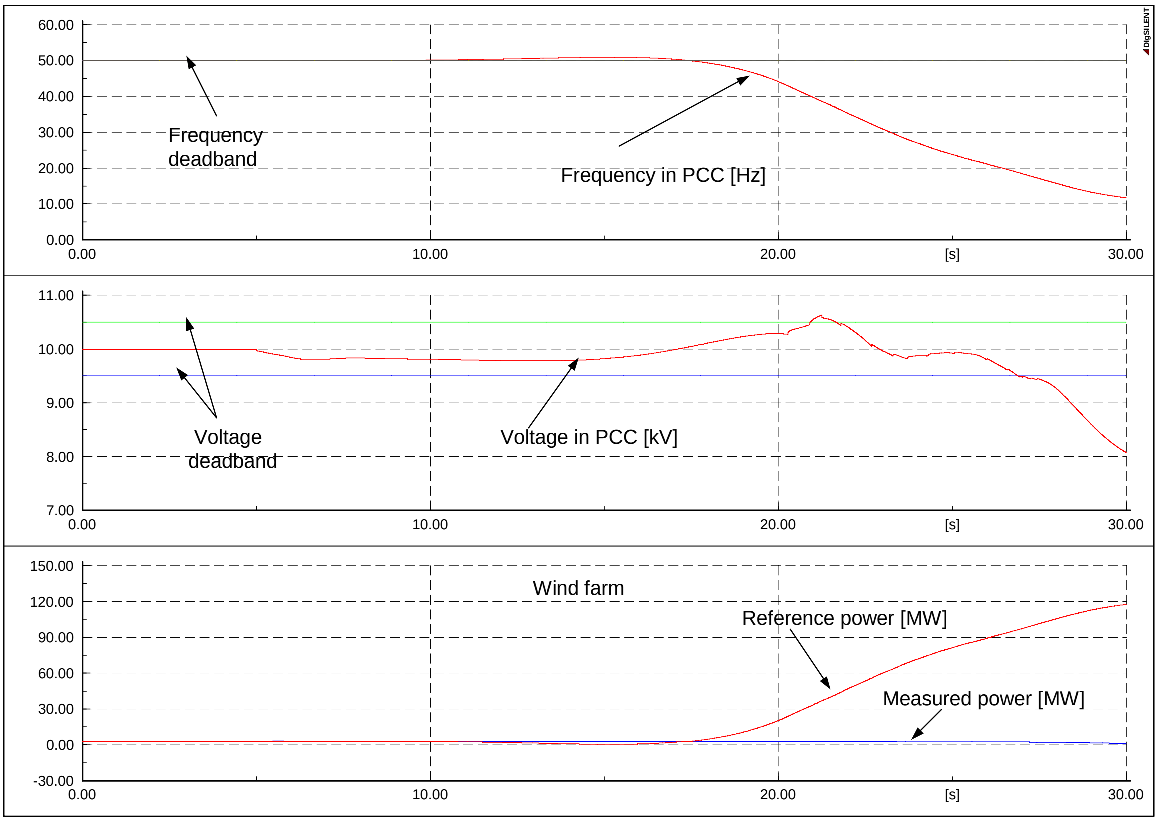

Figure 10: Case C: Load with CHP - frequency and voltage in PCC.

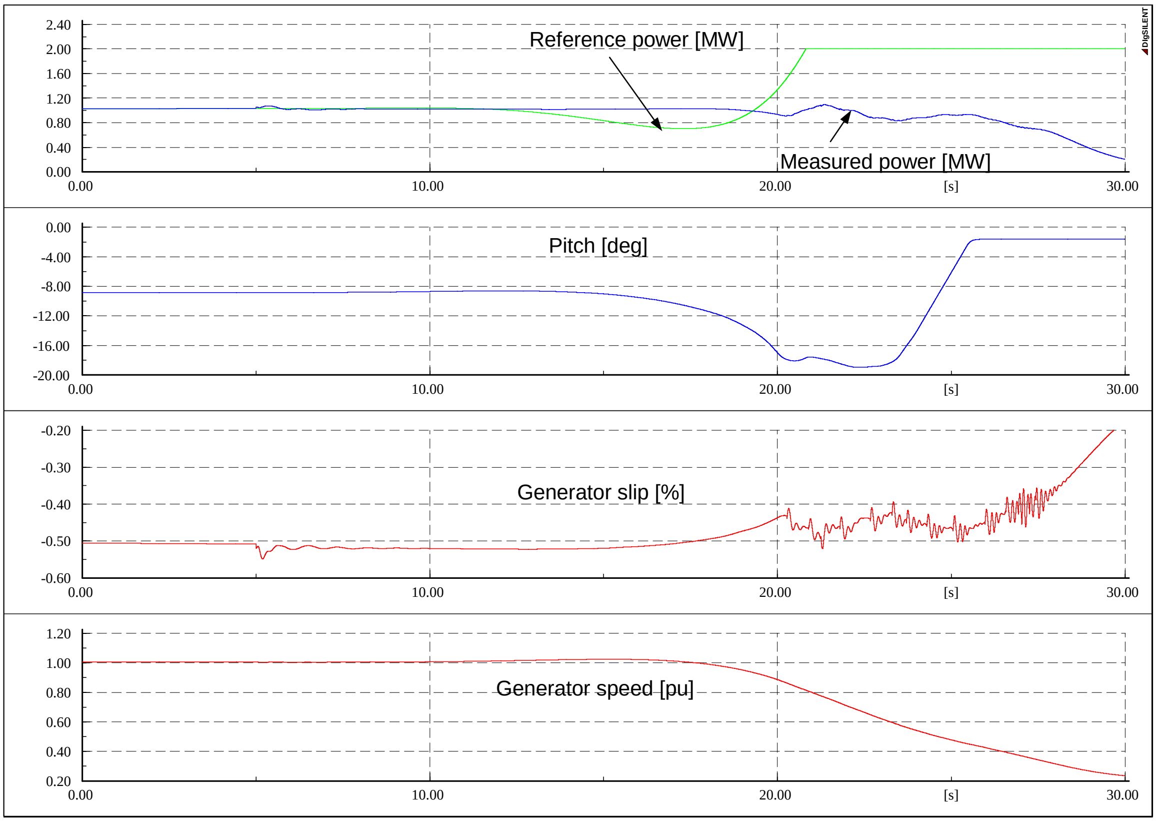

Figure 11: Case C Load with CHP - wind turbine

Case D

This simulation case is with a local grid consisting of the wind farm, the dynamic motor load and the CPH as described in Table 1. Figure 12 shows the simulated frequency, power and voltage in the wind farm PCC, while Figure 13 shows power, pitch angle and speed variables on one of the wind turbines. It is seen that the power control is not stabilised by the inertia as it was in case B without the CHP. The reason for this has not been quite cleared up, but obviously there is a damping problem in the system.

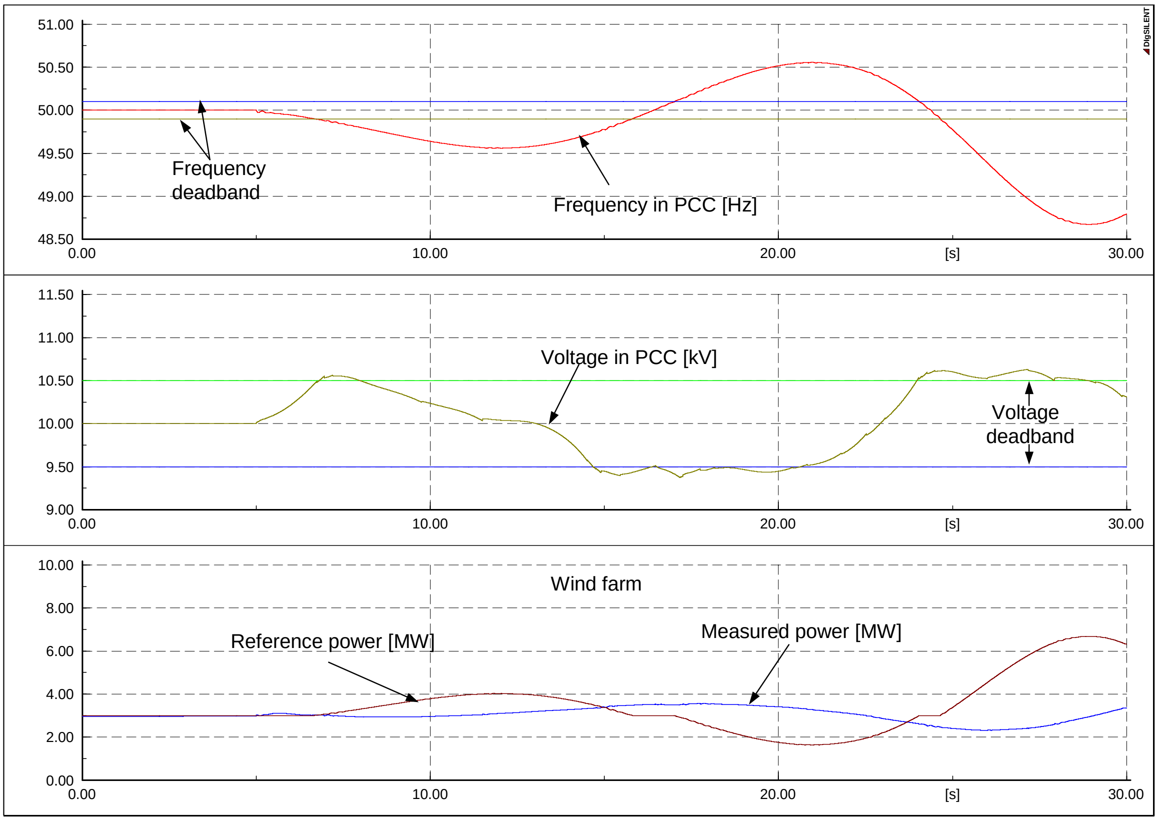

Figure 12: Case D - motor and CHP - Wind turbine response

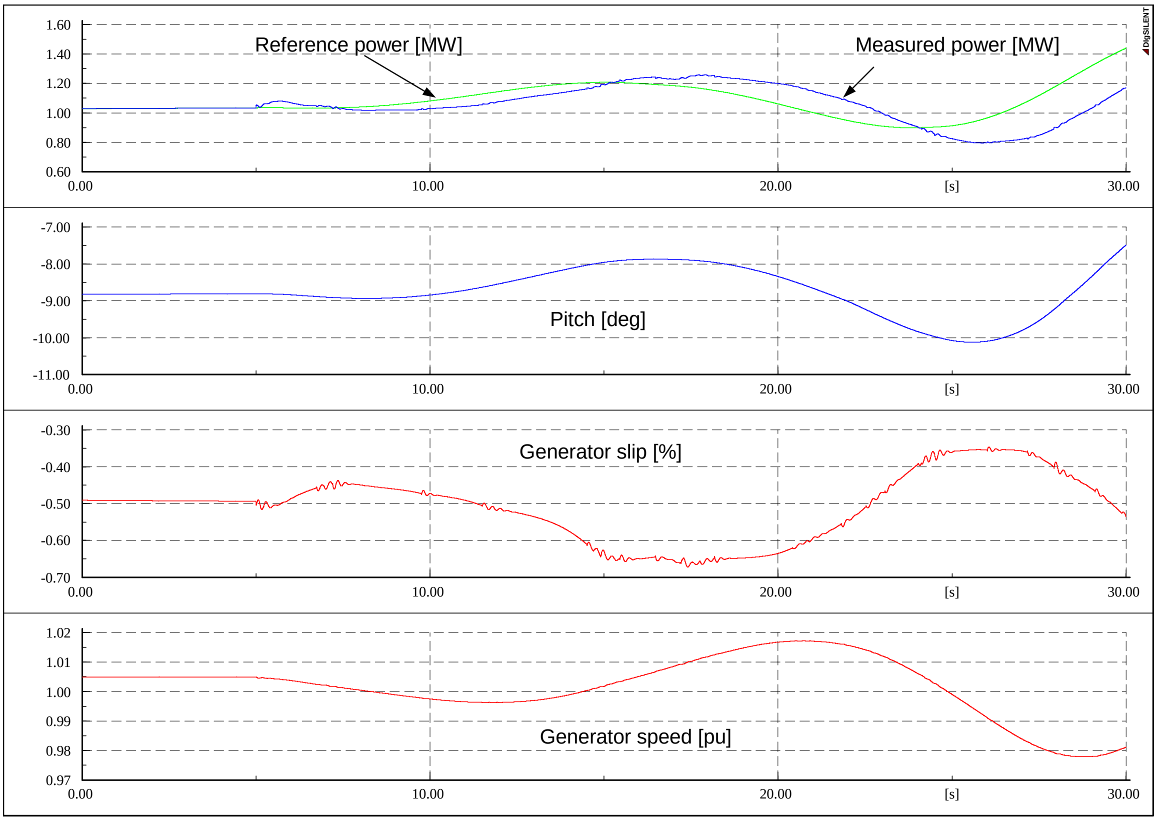

Figure 13: Case D - CHP with motor - frequency and voltage in PCC.

4 Active stall controlled wind turbines with HVDC/VSC transmission

4.1 System overview

The structure of the system implemented in the power system simulation tool DIgSILENT is presented in Figure 14.

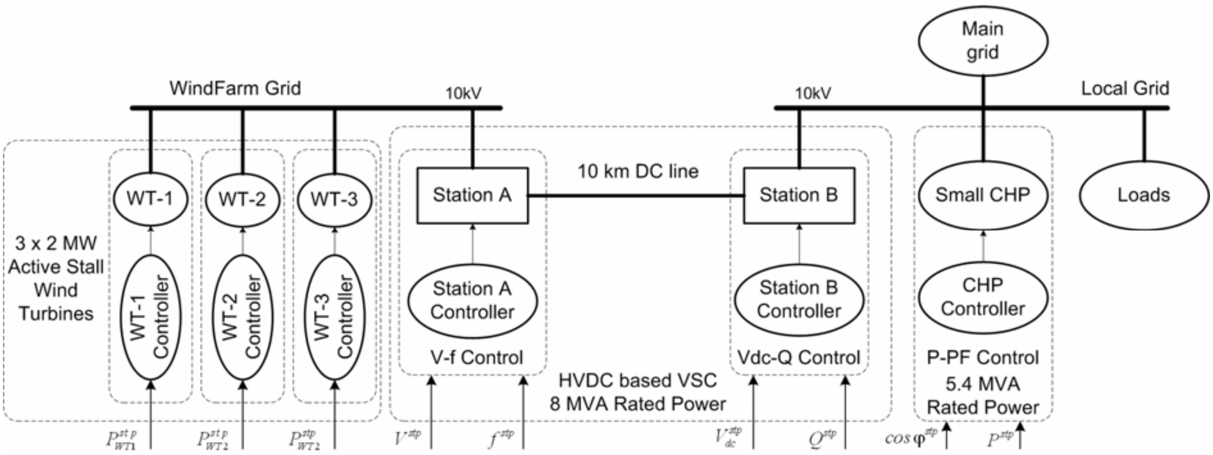

Figure 14. Structure of the system implemented in DIgSILENT.

The simulation scheme comprises an active stall wind farm, a DC transmission system, a small CHP and some loads.

Three active stall wind turbines models the wind farm, each turbine being equipped with a 2 MW squirrel-cage induction generator. The power set point from the wind turbine control is available.

The DC transmission system is based on IGBT-Voltage Source Converters. There are two stations, on the wind farm side (Station-A) and on the local grid side (Station-B) respectively. A 10 km DC cable (± 9kV) connect these two stations. The rated power of the transmission system is 8MVA.

The wind farm and the Station-A are connected at a 10 kV wind farm grid while the Station-B, a small CHP with 5.4 MVA rated power and some loads (8 MVA rated power) forms a local grid. A connection with the main grid, which is relatively stiff, (5000 MW short circuit power) is also present.

The wind farm grid has some particular characteristics as:

- The wind farm delivers variable active power and draw reactive power according with the operational point of each wind turbine.
- The voltage and frequency can vary in some limits. A variable frequency in this case will allow a better wind power conversion especially in the case of low wind speeds.
- The voltage stability is dependent on the wind farm demand for reactive power

On the other hand the local grid has the following characteristics:

- The CHP is non-despatchable, which means that the active power delivered depends on the heat demand. The reactive power produced has a fixed value. Usually, a power factor of 0.8 or 1 is used in operation.
- The voltage and frequency are controlled via the main grid. The Station B should control the voltage and frequency when this connection is not available.

In fact all these characteristics make this system to be a MicroGrid [10]. From the utility point of view the system should act as a single controlled cell of the power system. On the other hand from the customer point of view the system should meet some specific needs such as voltage and frequency support, island operation when the connection with the main grid is not available, etc.

A MicroGrid/Wind Farm Controller should perform the overall control for each component from this system based on the System Operator requests or based on the demand of the local loads during island operation.

4.2 Simulation example

The entire system is analysed when the connection to the main grid is lost. There are several events in the system in this case as:

- The average wind speed is kept constant to 8 m/sec so that the wind turbines controller will operate in optimization mode;
- A 100% increase in the load occurs at time 50 sec. The load is 2.5 MW rated power.
- The CHP operates first at 0.7 p.u. turbine power and a power factor of 0.8. The power setpoint of the turbine is increased to 1 p.u. at time 200 sec;

- The circuit breaker for connection to the main grid is opened at time 300 sec. The system will operate in island mode.

The reactive power set point for Station B is kept to zero as well as the frequency droop coefficient k_f in Station A (sending end station). Therefore a fixed reference for frequency (50 Hz) is used.

The wind time series for each wind turbine as well as the pitch angles are shown in Figure 15.

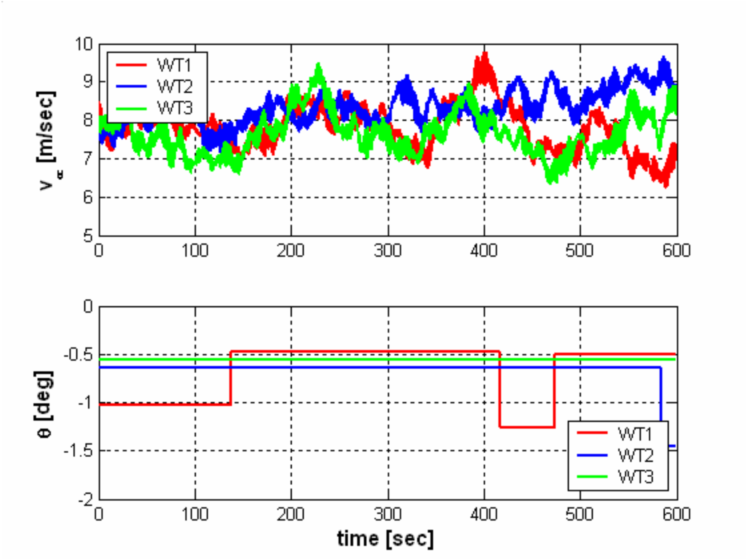

Figure 15. Wind speeds and pitch angle for each wind turbine.

The active and reactive powers for wind turbines are shown in Figure 16, the power balance in the connection point is shown in Figure 17, and the voltages and frequencies for each terminal of the DC connection are shown in Figure 18.

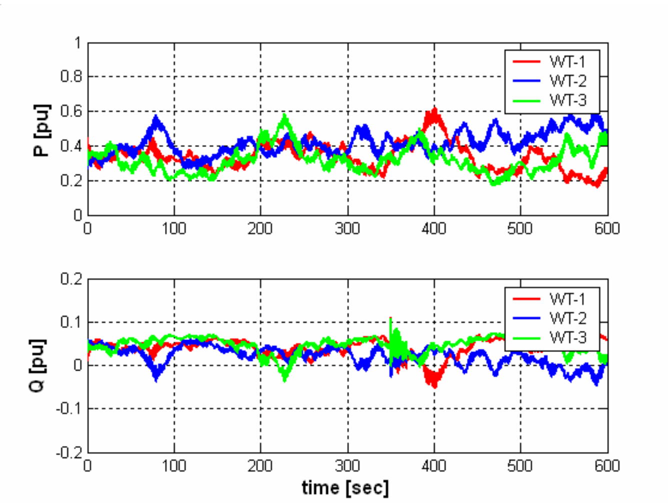

Figure 16. Active and reactive power for wind turbines.

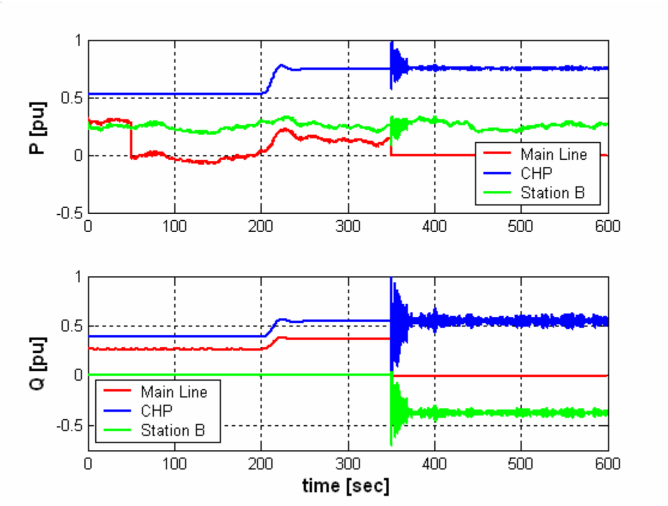

Figure 17. Active and reactive power on the connection point.

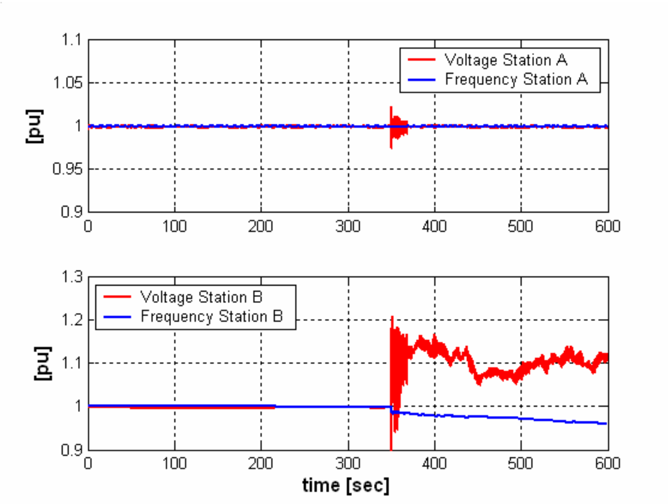

Figure 18. Voltages and frequencies in each terminal.

The DC-link voltage is shown in Figure 19 while the CHP output in Figure 20.

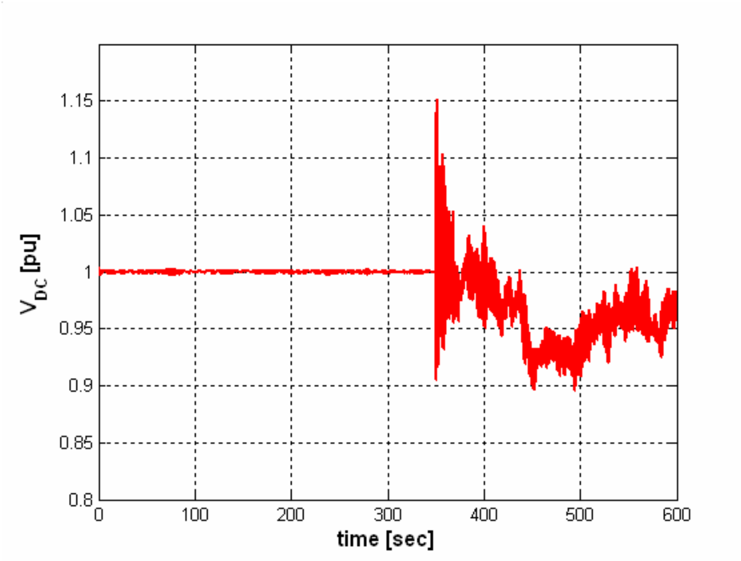

Figure 19. DC-link voltage.

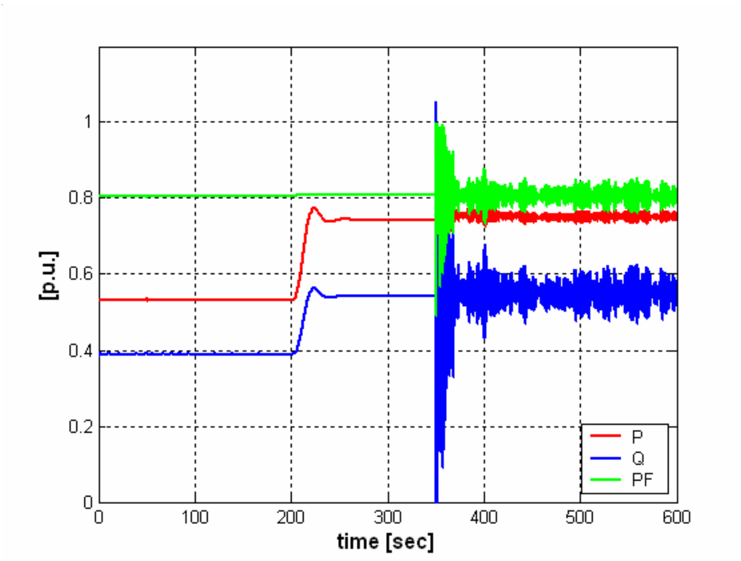

Figure 20. CHP output.

From the above figures it can be concluded that the control scheme for the receiving end station (Station B) is not able to regulate the voltage and the frequency of the local grid because of the following reasons:

- There is no active power balance in the local grid. Since the wind farm is not controlled, the production of the wind farm and the CHP output does not match the load demand.
- The reactive power set point for station B is kept at zero whilst the CHP operate at constant power factor. Therefore there is no reactive power balance in the local grid.

Using a wind farm controller, the set points for each wind turbine can be given according with the load demand as well as the set point for the reactive power in station B.

However, the station B controls the DC-link voltage and an AC voltage control might be necessary.

5 Conclusions

The work presented in this report has an initial character, mainly because it was finished close to the deadline of the funding project. Still, some of the initial results are found to be interesting, and are therefore reported here.

Isolated grid operation has been simulated with two different wind farm setups. In both cases, active stall controlled wind turbines are used in the wind farm. The first setup is with AC connected wind turbines with power set points controlled by a wind farm controller. The second setup is with HVDC / SVC connected wind turbines and autonomous wind turbine control, i.e. no actual wind farm controller.

In the AC connection case, the active stall control in the wind turbines have been tuned to what we consider minimum possible response time. The fast dynamics of the wind turbines seems to be able to provide important support to the grid control, which can be particularly useful where the wind farm is isolated with a subsystem from the main grid. However, with active stall connected wind turbines, it was not possible to stabilise the isolated grid with a static load depending only on the voltage. In the present work it is shown that a dynamic motor load with sufficient inertia can stabilise the local grid, so that the wind farm controller is able to control frequency and voltage. A static frequency dependent load may also be sufficient, but this has not been simulated.

A controller for the HVDC has been developed. However, there is no active power balance control (frequency control) in the local grid. Since the wind farm is not controlled, the production of the wind farm and the CHP output does not match the load demand. Moreover, the reactive power set point of the HVDC grid side converter is kept at zero whilst the CHP operate at constant power factor. Therefore there is no reactive power balance in the simulated local grid. However, a wind farm controller similar to the one applied in the AC connection case can be applied in future investigations, controlling the local grid frequency by means of the power set points in the wind turbines and controlling the local grid voltage by the grid side converter.

A model for a doubly fed wind farm controller has also been developed, but it has not been completed for isolated local grid operation. However, it is expected that this and other wind turbine concepts with power converters for variable speed control would be better to control the frequency, because the power control of these wind turbines is much faster. However, it might be necessary to change control mode when the local grid is isolated. This issue has not been studied in the present work.

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Mission

To promote an innovative and environmentally sustainable technological development within the areas of energy, industrial technology and bioproduction through research, innovation and advisory services.

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Risø's research **shall extend the boundaries** for the understanding of nature's processes and interactions right down to the molecular nanoscale.

The results obtained shall **set new trends** for the development of sustainable technologies within the fields of energy, industrial technology and biotechnology.

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