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RISØ

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Abstract (max. 2000 char.):
This report describes the development of a stand-alone version of the 11kW Gaia wind turbine. Various possible configurations are investigated and a configuration using a back-to-back converter is chosen. A model is developed for controller design of the fast controllers of the unit. Controllers are designed and a prototype is built for testing. The report documents the performance of the prototype through measurements done on the full scale prototype installed in a test facility where it has been tested both as a stand-alone unit and in parallel with a diesel genset. For system wide power quality assessment and controller design a dynamic performance assessment model has been developed.

The work has been supported by the Danish Energy Authority, j.no. 51175/00-0025.

Contents

Preface

This report is part of the reporting done as part of the project "The Gaia wind turbine applied in wind diesel systems and as a stand-alone unit". The project has received support from the Danish Energy Authority, j.no. 51175/00-0025.

The project partners are

Wind Energy Department, Risø National Laboratory

Gaia Wind A/S

Mita-Teknik A/S

Institute for Energy Technology, Aalborg University

1 Introduction

The standard Gaia Wind 11kW wind turbine is designed for normal grid operation. It uses a standard induction machine as generator. This generator is connected directly to the grid. It therefore requires a grid in order to operate (it needs a supply of reactive power).

Throughout the world there are many places that have not been electrified. The load in these places will initially be quite low (supplying e.g. a health clinic or school), but will often increase dramatically (lighting, refrigerators, telecom, small machines etc.) as soon as electrical power is introduced.

The conventional way of introducing electrical power is by diesel generator sets. These are cheap and robust and local people can often do the required day-to-day maintenance to keep the genset running.

If the local wind resources are fair, wind energy can be a very good alternative energy source for such communities. Wind power can then replace some or all the diesel power. The requirement is that the wind power system in many ways is similar to a diesel power system. This include that it should be simple to operate and maintain, should deliver power of adequate quality and should be able to be part of an expanding power system.

Wind turbines are normally designed to be connected to a grid where other equipment controls frequency and voltage. Often, they also require a source of reactive power in order to produce power. This is e.g. the case for wind turbines using induction generators connected directly to the grid.

It is necessary to modify the wind turbines in order to enable them to control voltage and frequency and to be able to supply power on demand and not when the wind blows. Such wind turbines are usually termed stand-alone wind turbines, SAWT.

The report describes initially the requirements to a SAWT in order to make such a component suitable in small rural power systems. Then follows an investigation of the various technical options for such systems including the chosen system layout. This is then modelled from both a control design and performance assessment in terms of voltage and frequency fluctuations point of view. Finally, there is a presentation of the performance of the prototype.

2 The Gaia wind turbine

The wind turbine is of course a key component in a stand-alone wind turbine unit. There are several important issues to take into account when choosing the most appropriate wind turbine for a particular application. This includes available documentation of performance and design, robustness and maintenance requirements, ease of integration in a small power system and a positive track record. For small systems(5-50kW), the number of wind turbines in that range available is very limited and only few of them can satisfy the issues above.

The 11kW Gaia wind turbine was developed as part of the Danish "household wind turbine programme", [1], and it has been certified according to the procedure that was

part of this programme. This is a slightly simplified version of the general certification scheme in Denmark. It has been supplied to and installed in more than 90 places since 1995. The operational experience is good with a good availability and they survived the very severe storm in December 1999 without problems. It is therefore one of the few small wind turbines with a good track record and reliable performance according to the measured power curve and guaranteed availability.

The wind turbine in the standard configuration is a 2-bladed, teeter hub, down wind, free yawing, stall controlled wind turbine. It has an induction generator and a capacitor bank for no-load compensation of the reactive power consumption of the induction generator. The standard wind turbine also has an soft-starter in order to reduce the in-rush current during connection. The main data for the wind turbine is presented in Table 1.

Figure 2 Gaia Wind 11kW wind turbine

The wind turbine for testing in wind diesel systems connects to the grid via an advanced grid connection module that softens the cut-in in order to mitigate the grid impact even further compared to the standard soft-starter when operating in a wind diesel system.

Table 1 Main data for the Gaia wind turbine

Item	Value
Rated power	11kW
Hub height	18.2m
Rotor diameter	13m
Rotor speed	56rpm
Nacelle weight	900kg
Total weight	2400kg

3 Requirements

The purpose of installing any kind of power producing units is to provide or satisfy a demand for certain services. These services range from very basic things such as provide lighting to ensure 24h uninterrupted power supply for safety-critical equipment.

The objective of the SAWT is for it to be able to provide power to village power systems in rural areas in developing countries. The stand-alone wind turbine system requirements are divided in several categories, which are detailed below.

3.1 General requirements

The SAWT will be changed as little as possible from the original design.

The operating conditions of the wind turbine should not be changed radically from the original design. The wind turbine has to be well controlled even when operating in variable speed mode (tight power control, avoidance of critical rotational speeds).

It is also a requirement that standard equipment is used as far as possible i.e. standard power electronic units in order to reduce cost of investment and maintenance, maximise availability of components and reduce risk of failures.

The system should also be rugged and robust and require a minimum of maintenance in order to enable it to be used in systems with a weak infrastructure.

3.2 Overall operating conditions requirements

The system is an AC system and should be able to supply power of adequate quality to standard appliances. The equipment connected to the system will be standard AC equipment of the same type as for the national grid.

The unit should be able to start a black grid. In many systems, the unit will be the first (and often only) generator to be connected to the load during a system startup. The system will have a procedure for energising the grid (e.g. disconnect load from bus bar, ensure battery state of charge, start turbine, start grid inverter, connect inverter to bus bar, connect load (in sequence))

The unit should not depend on energy from outside in order to start (the wind turbine can have a small battery for supply of controller etc.)

After start up the SAWT should immediately be able to pick up load.

The SAWT should be able to supply the following types of loads:
· **Group 1**
· Light: light bulbs, low energy
· TV
· Telecom
· Computers
· Small machines: drills, lathes etc.
· **Group 2**
· Heat: Space heating
· Cold: freezers, refrigerators, ice making
· Pumps: groundwater, reservoirs
· Desalination plants: reverse osmoses

The types of load are grouped in two groups. The first group are loads that require constant availability of the system i.e. some kind of storage or other type of generation is needed to overcome the fluctuations in the wind power and provide a satisfactory service. The second type of load does necessary require that the power is available constantly. These loads can be serviced when power is available to a large extend.

The types of load to be serviced therefore include relatively large loads, asymmetrical loads and non-linear loads.

3.3 Power quality requirements

The turbine should be able to control the voltage and frequency within the requirements set in the standard EN50160, [2].

The dynamic performance should ensure that the voltage as well as frequency is well controlled and that instability, flicker etc. are avoided.

It should further be assured that the system does not cause inconvenience or problems for costumers or equipment due to low power quality. This include loss of load incidents especially short duration events.

3.4 Connection of large loads

The unit should be able to handle connection of "large" induction machines (50-75% of rated power). In small power systems the individual loads are often quite large compared to the rating of the generators. It is therefore necessary for the generators to be able to handle such situations and with adequate control of frequency and voltage in order to restore both at the specified level after a dip that is not too large.

Due to the small size of the systems, the ability of the system to pick up load is an issue that is not covered by standards for large interconnected systems. Standards for small systems with diesel genset exist, [3].

3.5 Protection and other operating conditions

It is very essential for systems that will be in service in rural areas of developing countries that they have a very robust design philosophy with respect to protection (of both persons and equipment) and asymmetrical loads, short circuits.

Protection of persons and equipment is paramount in the system design. One of the challenges is the design of a robust protection system the works securely in systems with a low power level. The main issue is the isolation of a short circuit since the the available power is limited for fuses to blow. standing short circuits can result in fires if they are not isolated from the system or the complete system will have a black out if the generating unit has to isolate itself from the grid in order to protect it.

3.6 Power system configurations

The basic concept is to have the SAWT to perform equivalently to a diesel generator set in terms of controllability of voltage and power. It should therefore be able to act as a unit in a larger power system with other types of generation.

These other types of generation include
*   Conventional diesel gensets
*   PV panels
*   Small hydro
*   Central energy storage

A basic system is shown in Figure 1

It is therefore necessary that the system can interface with standard system control equipment (e.g. load sharing units)
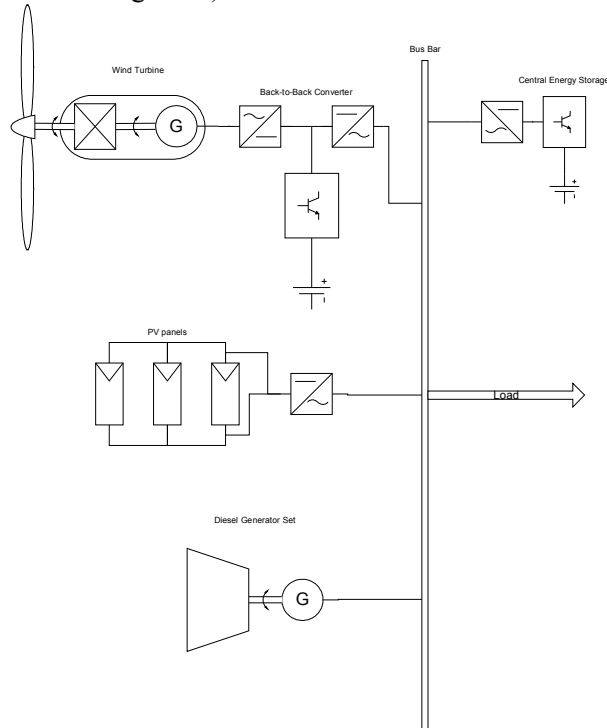

Figure 1 System configurations. The units except stand-alone wind turbine and load are optional. There can be more than one of all the units.

The stand-alone wind turbine should be able to operate in the following configurations:
·   Alone, supplying loads
·   In parallel with diesel generator sets
·   In parallel with other wind turbines (conventional and stand-alone)
·   In parallel with energy storage (central unit)
·   In parallel with other types of generation (small hydro etc.).

The wind turbine should be able to synchronize with a grid
The wind turbine should be able to participate in active and reactive load sharing

4   Technical solutions

As described above the main issues involved in order to make it possible for a wind turbine to be the only generating unit in the system are the ability to control voltage and frequency and to be able to supply power independently of the instantaneous wind.

The generator types available are either synchronous or induction. The synchronous generators with permanent magnets are the most interesting of the synchronous type. They can be produced with higher efficiency and the rotor can be very simple and robust. It does also not require an external source of energy for startup. It can also be made with many poles so that the wind turbine can be gearless thus reducing

maintenance and increase availability. Permanent magnet machines can be made in relatively small physical sizes for small power ratings. PM machines cannot control the voltage since the magnetisation is constant. The voltage is proportional to the rotational speed. Another and major disadvantage of synchronous machines is their stiff connection to the grid. The power output of the machine depends on the angular position of the rotor magnetic field relative to the stator magnetic field, [4], i.e. it behave equivalently to a spring. This is very disadvantageous in combination with the fluctuations in the wind and will usually result in large oscillations in the drive train. Further, it is necessary to synchronise (rotational speed, phase angle and magnitude of voltage) a synchronous generator to the grid before it can be connected.

Synchronous machines are being used in wind turbine (both small and large). They are, however, always connected to the grid via a frequency converter. This way the mentioned oscillations can be avoided as well as the problems regarding synchronisation. The frequency converter can in principle be a simple diode rectifier/igbt inverter combination, but in many cases the best solution is a IGBT based back-to-back converter since it makes it possible to utilise the machine better, [5], (because it can compensate for the internal inductive voltage drop through reactive power supply).

Several manufacturers are offering PM synchronous machines, but the vast majority of the machines are with a low pole count e.g. 4 or 6 which means that it is still necessary to include a gearbox. Only very few manufacturers exist who can readily supply multi-pole machines. Further, the number of units being shipped by these companies is quite low. The result being that costs are relatively high (compared with other generators). Often manufacturers of wind turbines with synchronous generators design the generator themselves and also manufacture it or have it manufactured.

The use of a back-to-back converter also improves the control of the wind turbine. The actively controllable converter on the turbine side enables direct control of the turbine by controlling the frequency or the torque explicitly.

The use of induction machines in wind turbines has proved to be very successful for grid connected wind turbines. The squirrel cage induction machine is a simple and robust construction that is very well suited for applications where low maintenance is a requirement. The development of power comes from the rotor not rotating at synchronous speed so that a field is induced in the rotor by the stator field, [4]. The power is depending on the slip which is the speed difference between the synchronous speed and speed of the rotor. In the system it therefore acts like a viscous damper adding compliance to the drive train reducing resonance peaks. As it can be deduced from the above, the induction machine requires an external source of voltage in order to be able to deliver power. Further, it draws a very large current (up to 6 times the rated current) when it is connected directly to the grid. It has to be connected to the grid via current limiting device during cut-in. This will typically be a thyristor-based softstarter.

For stand-alone applications there are two options for using a induction machine. The first option is to use a power converter (back-to-back converter) in order to separate the control of the wind turbine from the control of the grid. A fully controllable converter on the generator side means that it will act as a voltage source supplying reactive power to the generator in order to magnetise it so that it can supply power. This will also enable control of the frequency of the generator side and thus control the rotational speed of the wind turbine. The dc-link will separate

the generator side from the grid side. The grid side converter will control voltage and frequency of the grid.

The second option is to use controllable supply/source of reactive power connected in parallel to the wind turbine. This will magnetise the machine of the wind turbine thus enabling it to deliver power. The unit can be a controllable reactive power source such as a capacitor bank that can be controlled continuously or it can be a power converter that can generate a grid e.g. igbt-based. This unit then has the tasks of the genset in a standard power system to control voltage (and can also participate in the power control depending on the technology used if a storage is included). The unit does not have to be situated close to the wind turbine. The wind turbine can be an almost non-modified wind turbine designed for grid connection. Issues such as cut-in and reactive power requirements have to be taken into account when this solution is chosen since the reactive power source has to be able to supply all the reactive power/current needed especially during cut-in of the wind turbine and when large motors are started.

Energy storage options have to be thought into the design from scratch. The technology that is relevant for the typical applications is lead-acid batteries. Other types of batteries could be relevant in the future, see below. The most natural solution to where the battery storage should be placed in the system depends on which solution for the wind turbine that is chosen.

In a system with back-to-back converters, the dc-link will be the natural place for the storage. This system layout is illustrated in Figure 2. In the figure is also shown a controllable resistor. This is used for maintaining the active power balance in all situations also when the battery storage is fully charged. This type of system integrates the generation and the storage tightly and the result is one unit that from the outside can behave as a normal diesel genset i.e. from the outside only the grid side converter is seen and it can be controlled to mimic conventional voltage controllers and speed governors. Further, if the electrical construction of the wind turbine is changed e.g. from the standard induction generator/gearbox design to a PM-multipole design it will not be visible to the rest of the system i.e. the grid side part will be the same and as well as the power electronics on the generator side. Only the control of the generator side converter will have to be changed.

The alternative system layout is to include the wind turbine as it is (with induction generator) and have the storage installed together with the grid-forming unit in parallel to the wind turbine. This layout is shown in Figure 3. The system will be operated as if the unit with power electronics and the battery is a genset. This unit can be situated e.g. at the power station. The unit has to be able to supply the complete system with reactive power also during cut-in of a wind turbine.

Many issues have to be taken into consideration when comparing the two basic layouts. This include overall system efficiency, controllability, flexibility, robustness, ability to cope with large transients and faults, impact on other components, changes in configuration during operation etc. It has to be viewed in the light of the application in remote rural areas with a poorly developed infrastructure. This will be discussed further.

The overall efficiency of the system is of course very important. In the system with back-to-back converters, the complete current is passing one converter and most of it will also pass the second (power dissipated in the dump load and power lost in the battery will not pass the second converter). Some of the energy will be buffered in the battery. This transfer through the converter will of course contribute to the losses. In the case with the central converter only the difference between the instant

production and consumption goes through the converter. It will, however, pass the converter twice – in and out of the battery. The amount of energy going through the battery is practically the same in the two cases.   In the case that none of the power passes the battery the losses in the back-to-back configuration will have twice the converter losses and the central will not have any related to active power. It should be remembered that the central converter has to provide the reactive power for the induction generator. This will off course also result in losses. The efficiency of the central system will be higher than that of the bak-to-back system but the difference will decrease as the penetration level increases and an additional amount of the energy will have to pass the battery or will be dumped.

The more of the energy that has to through the battery and the lower the efficiency of the battery the smaller will the difference between the two systems will be. In systems with very high penetration systems, a very large fraction of the energy in such systems will go through the battery (and some of it will even be dumped) since production and consumption will not match well in time.

The back-to-back configuration will however enable the wind turbine to operate at variable speed so that it can operate at maximum efficiency (Cpmax). This will compensate for some of the losses in the power converters depending on the aerodynamic design of the wind turbine and the wind speed distribution. In the current case with the Gaia wind turbine the gain will not be very high since the aerodynamic design is already designed for low wind speed regimes (i.e. it has its peak of the efficiency at low wind speeds, 5-6m/s).

In both configurations a power converter will be the grid-forming unit i.e. it will be the unit controlling the voltage of the grid. In the back-to-back configuration the grid side converter will only have to handle the consumer loads. The generator side converter will control the wind turbine. The fluctuations in power from the wind turbine will therefore not be visible at the grid side (or at least they will be significantly smaller). In the central converter configuration, all the fluctuations of the wind turbine will be transmitted to the grid and the central converter will have to compensate these fluctuations in addition to the fluctuations in the consumer load. This is especially significant during cut-in of the wind turbine. During the cut-in the central power converter has to supply all the required active as well as reactive power while still supplying the consumer load. The cut-in of the wind turbine in the back-to-back configuration will be invisible in the grid. In the central converter case it will always be visible and in order to prevent to large impact the wind turbine will have to be equipped with an advanced soft-starter that can provide good control of the current during cut-in.

Grid faults and large transients can occur very often in small grids. It is therefore very important that the impact of these events are minimised both from the point of view of the consumers but also for the point of view of the equipment since the events can have a large impact on wear and tear of the equipment. The back-to-back configuration will provide a better performance with respect to grid faults and transients. The grid converter can prevent the faults and transient to be seen on the generator side and the battery storage and dump load can sink the power if it cannot be absorbed by the grid. This will prevent the wind turbine from disconnecting and supply can be restored as soon as the fault is cleared or the transient has disappeared. In the central converter configuration the wind turbine will often have to be disconnected from the grid in order to prevent it from overspeeding or in order to prevent a voltage collapse after when the voltage is restored if the generator has not been disconnected.

The system with back-to-back converter can operate with any kind of wind turbine. For wind turbines with synchronous generators, it is necessary to have converters for synchronisation, eliminate torsional vibrations and convert frequency in case of a gearless design (since it often will have a (lower) pole number that is optimal with respect to generator cost, but will require a lower stator frequency. For stall controlled wind turbines with directly connected induction generators there is a limited time for connecting it to the grid during cut-in. This means that in high wind speeds the cut-in has to be very fast resulting in large current excursions on the grid. These currents can be reduced be using a softstarter but they are completely eliminated when the wind turbine is connected through a power converter. For pitch controlled wind turbines the main issues are limitation of the instantaneous power and the loading of the gearbox, both of these are mitigated using power converters.

Table 2 Comparison of features between the two configurations

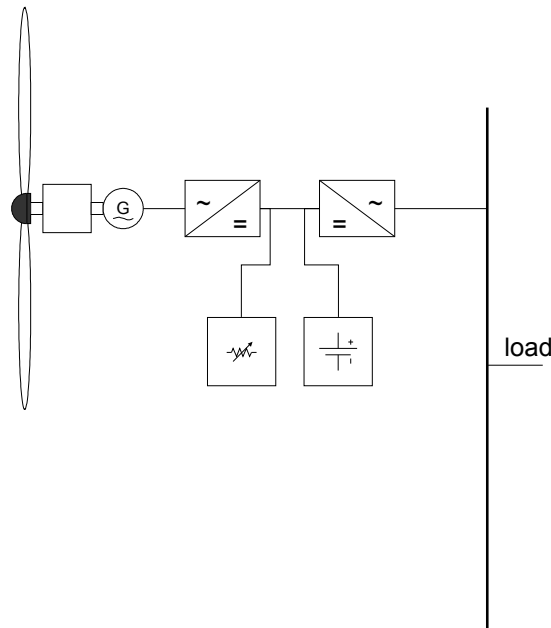|	System with back-to-back converter	System central converter
Efficiency: electric	-	+
aero	+	-
Controllability	+	-
Flexibility	+	-
Ability to handle transients and faults	+	-
Impact on other components	+	-
Cost	-	+

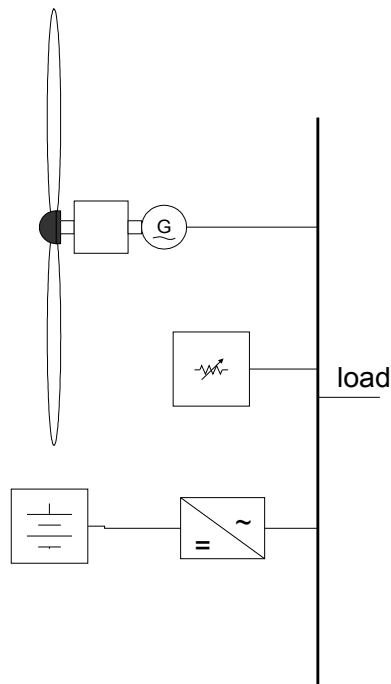*Figure 2 Configuration of Stand-alone wind turbine with back-to-back converters and storage in the dc-link*

Figure 3 Configuration of Stand-alone wind turbine with grid forming unit and battery system in parallel to wind turbine (with induction generator)

4.1 Chosen system configuration

Based on the above discussion the primary configuration that is further studied in this report is the system with back-to-back converters.

The basic configuration of the stand-alone wind turbine consists of the following components
- Gaia wind turbine with induction generator
- Back-to-back converter
- Controllable brake load
- (Battery storage in the dc-link)
- Wind turbine controller with supervisory controller functions
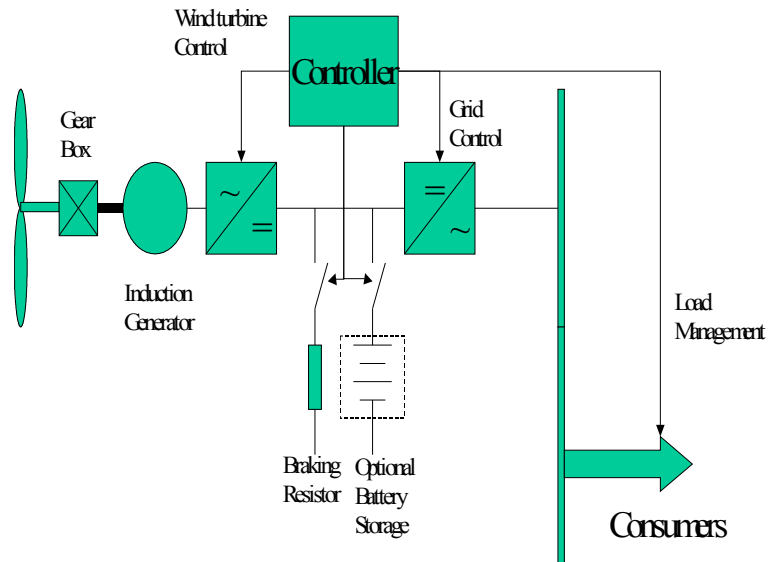- Controller system with dynamic controllers and supervisory controller

Figure 4 Configuration of Stand-alone wind turbine

5 System modelling and control

There are two main modes of operation of the system. The first mode is when it is connected to a grid with other generators. In this case it is assumed the the other generators form the grid i.e. control frequency and voltage. The wind turbine system will then deliver as much power to the grid as it can extract from the wind at a given power factor setting. This power factor setting will usually be cos φ =1. The control of the system will ensure that the system can synchronise and will stay synchronised to the grid. The amount of power delivered to the grid is determined by a controller that controls the dc-voltage of the dc-link between the generator side converter and the grid side converter. The change of dc-link voltage is a measure of the power balance. When the voltage increases it means that the generator side converter supplies more power to dc-link than the grid side converter is supplying to the grid

The other mode of operation is when the system is operating in stand alone mode. In this mode of operation the grid side converter is controlling the grid voltage and frequency. In this mode of operation the dc-link voltage is only controlled to be within specified limits. When the voltage increases above the maximum limit a braking resistor is used to dissipate power. This resistor is controlled by a chopper (single transistor whose duty cycle is controlled). When the voltage goes below the minimum limit, it is a sign of power deficit in the system (there is no storage in the system). In order to avoid a complete blackout the voltage of the grid is decreased.

From the above it is clear that there is a strong link between the grid side converter control and the dc voltage control.

The modelling of the system (in the current context) serves several purposes. The first one is to enable controller design. The models for this purpose have a high bandwidth since they must be valid for up to the sampling frequency. The second modelling objective is to have models suitable for system studies i.e. configurations that includes more generating and consuming units mainly for studying frequency and voltage variations as a result of variations in wind input and consumer load.

First is the controller design model developed and presented. After that follows the system model.
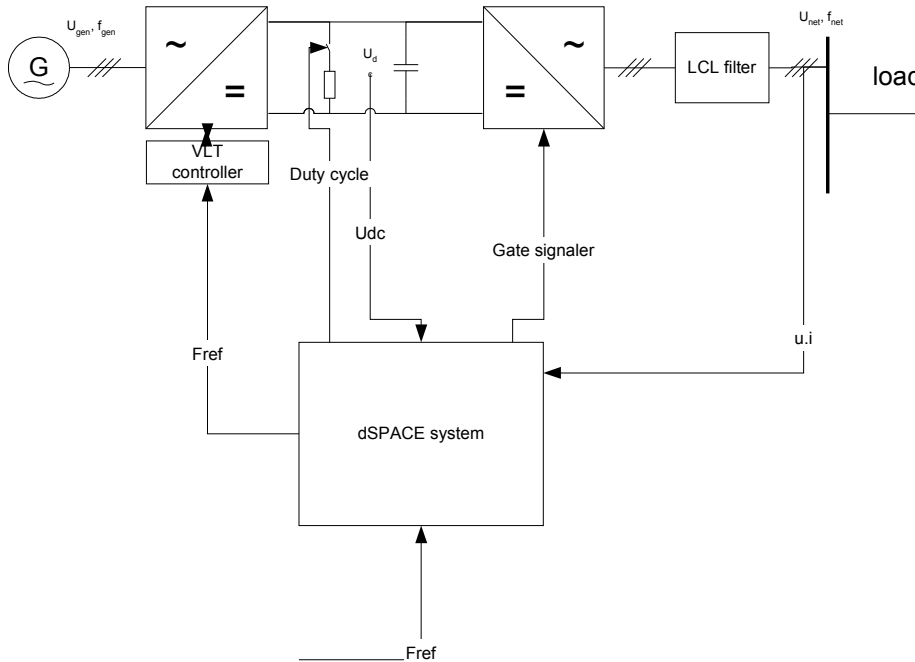

Figure 5 Configuration of Stand-alone wind turbine

5.1 Controller design model

The most comprehensive modelling task is the modelling of the grid side converter since this includes the task of controller modelling and design. The grid side model includes the power converter, output LCL filter, grid and voltage controllers. The controller design has been a core activity of the project. This part of the complete system is on the right side of the figure showing the control loops, Figure 6.

It links to the wind turbine side of the system via the dc-link. It also contains a controller for controlling the dc-voltage. The system is much simpler than the grid side. It is in the middle of the figure.

The last part of the system is the wind turbine control. In the current implementation of the system the standard controller of the power converter controls the rotational speed of the turbine. The control of the system is vector based with encoder feedback. This calls for a relative simple model of the system. The main complexity in this part of the system is modelling of the wind input and the aerodynamics. These models are especially important when

Each of the systems is described below. More details can be found in [6].
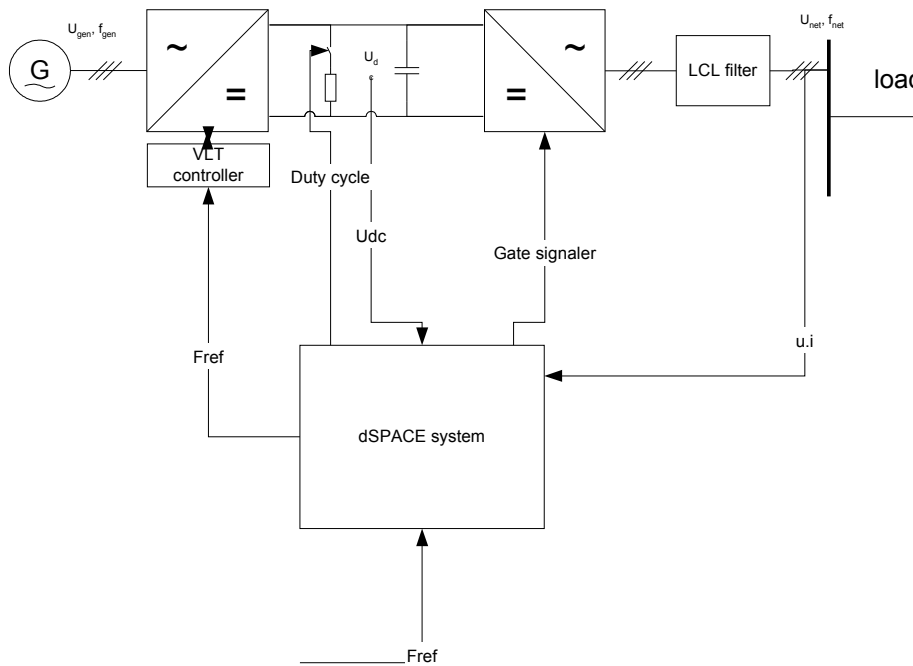
Figure 6 Configuration of Stand-alone wind turbine

5.1.1 Grid side subsystem

This part of the system consists of the following components:
  power block i.e. IGBT full 3 phase bridge
  LCL filter
  Grid i.e. equivalent load
  dc link (interface to rest of the system)
  controller
  I/O

The description of the unit will mainly be in the stand-alone mode of operation.

The objective of this subsystem is to provide the consumers with power with a adequate power quality i.e. good control of voltage and frequency. The unit will be the grid forming unit.
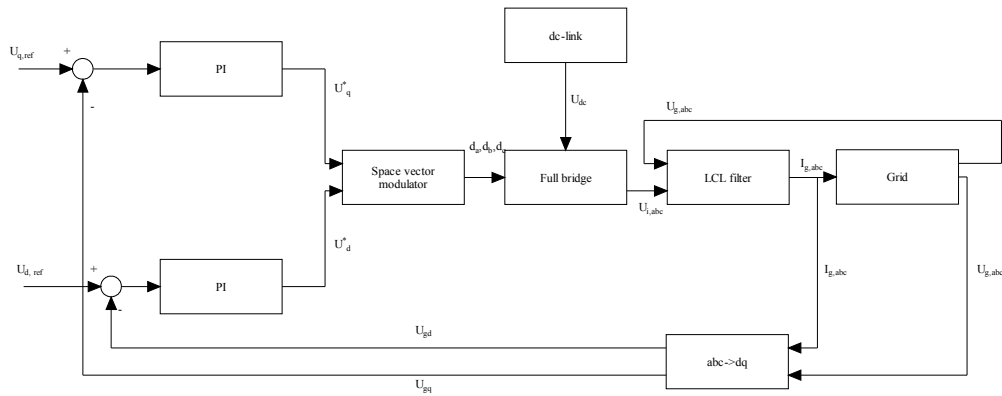
Figure 7 Grid side control system

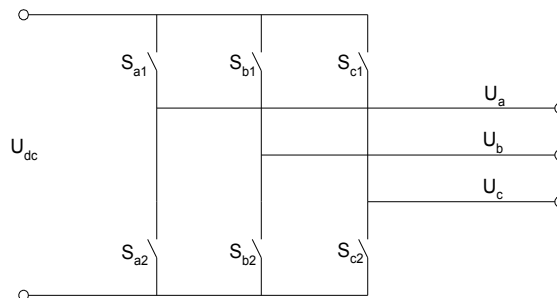The basic component of the system is the power block. The block consists of six IGBT based switches.

Figure 8 Full bridge three phase converter

The switches are closed and opened by the control system in order to form the grid voltage. The switches connects two phases (phase-phase) to the dc-link. The switches in one branch are controlled so that if the top switch is closed the bottom switch is open and vice versa.

The modelling of the grid subsystem is done in several reference frames in order to ease the modelling.

The usual three phase system (a,b,c) is transformed to a two phase stationary rectangular reference frame (x,y) as seen in the figure, Figure 7.
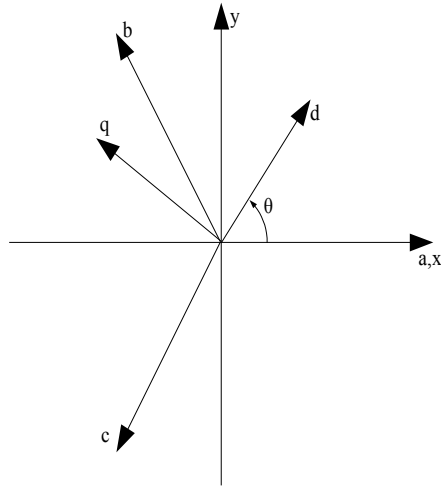
Figure 9 Coordinate transformation from 3-phase system to stationary and rotating 2-phase system

From the figure the relation between the three phase system and the two phase stationary system is directly identified. The transformation is in (1). The factor K can be chosen to different convenient values. Here it is chosen as 2/3, which makes the transformation amplitude true.

$$
\begin{bmatrix} u_x \\ u_y \\ u_0 \end{bmatrix} = K \begin{bmatrix} 1 & -\dfrac{1}{2} & -\dfrac{1}{2} \\ 0 & \dfrac{\sqrt{3}}{2} & -\dfrac{\sqrt{3}}{2} \\ \dfrac{1}{2} & \dfrac{1}{2} & \dfrac{1}{2} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}
\tag{1}
$$

In the system under study there are only three conductors i.e. u_0=0. This equation is therefore ignored in the rest.

Instanteneous active and reactive power, p and q, are calculated from the formulaes

$$
p = \frac{3}{2}(u_x i_x + u_y i_y) \quad , \quad q = \frac{3}{2}(u_x i_y - u_y i_x)
\tag{2}
$$

It can further be very convenient to have a rotating reference frame since constant amplitudes in a synchronously rotating frame (d,q) will be transformed to constant values. With reference to Figure 7 the transformation is

$$
\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} u_x \\ u_y \end{bmatrix}
\tag{3}
$$

After these preliminaries the modelling of the system starts at the grid end.

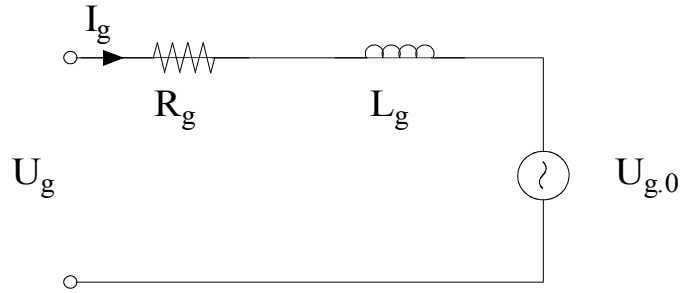The grid is asumed to be modelled as a reactive/resistive load, Figure 10.

Figure 10 Single phase grid equivalent circuit

From the figure the following voltage equation is found for each phase

$$u_g = R_g i_g + L_g \frac{d i_g}{dt} + u_{g0} \tag{4}$$

In the dq-system i.e. the synchronously rotating system this transforms into (assuming constant frequency)

$$u_{g,dq} = R i_{g,dq} + L \begin{vmatrix} 0 & -\omega \\ \omega & 0 \end{vmatrix} \frac{di_{g,dq}}{dt} + u_{g0,dq} \tag{5}$$

It is noticed that the d- and q-directions cross couples through the derivative term.

Between the grid and the inverter there is a LCL-filter for reduction of harmonics generated by the inverter. The single phase equivalent is in Figure 11 including the grid equivalent.
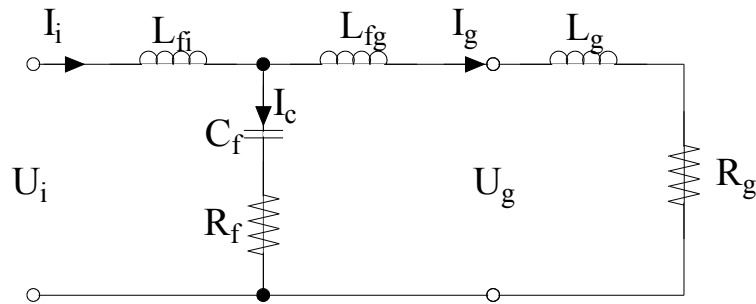

Figure 11 Single phase LCL filter and grid equivalent circuit

Typically the resonance frequency is chosen close to half the switching frequency. This is the case here. Neglecting the capacitor the model becomes in dq coordinates

$$u_i = L_f \begin{vmatrix} 0 & -\omega \\ \omega & 0 \end{vmatrix} \frac{di_g}{dt} + u_g \tag{6}$$

u_i is generated by the inverter.

The full bridge is capable of generating 8 states. The modulation technique appled is the so-called Space Vector Modulation (SVM), [7]. Two of these states are zero as seen in Figure 12.
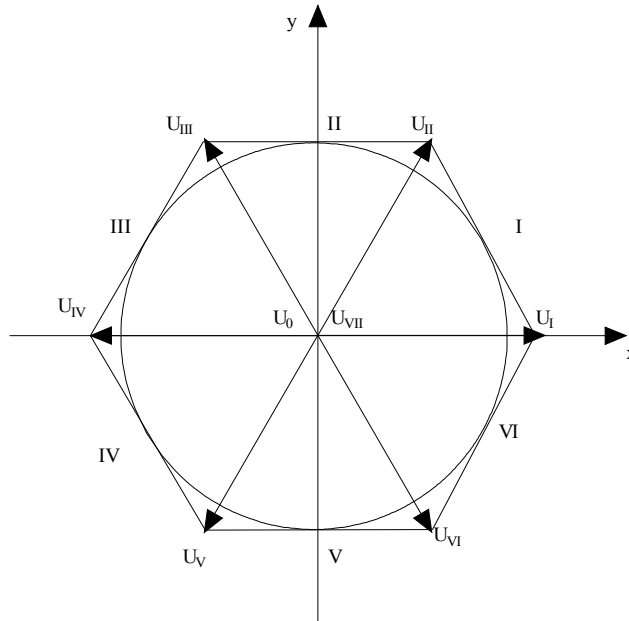

Figure 12 Inverter states: active states (U_I-U_{VI}) and zero states (U_0, U_{VII})

The generation of a particular voltage is done by switching between two states of the inverter (+ zero states). As an example a situation in sector I is studied, Figure 13.
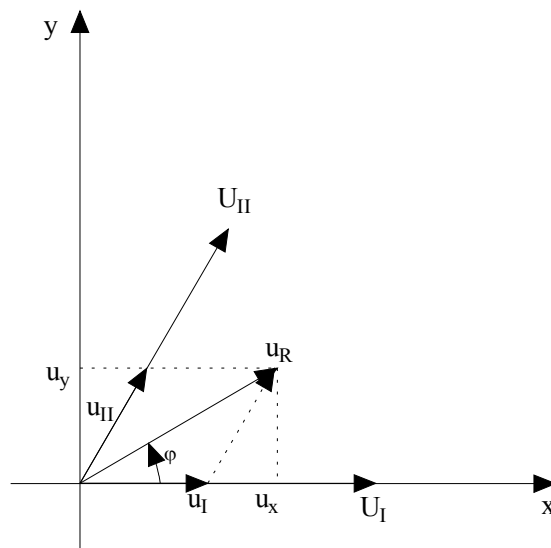

Figure 13 Construction of voltage by two inverter states

The target vector voltage, u_R, can be constructed as the vectorial sum of the two adjacent inverter voltages (in sector I).

$$u_R = u_I + u_{II} + u_0 \qquad (7)$$

The length of the vectors are controlled by controlling the duty cycle, which means the ratio between active states and zero states e.g. for u_I

$$u_I = \frac{T'_I}{T_s} U_I \qquad (8)$$

where T_I is the duration of U_I and T_s is the total sampling period, $T_s = T_I + T_{II} + T_0$. The generation of u_{II} is similar. The general expression of the duration in terms of u_x and u_y will have the form

$$T_R = K(a_R u_x + b_R u_y) \quad , \quad K = \frac{3}{2}\frac{T'_s}{U_{dc}} \quad , \quad R = \{I...VI\} \qquad (9)$$

In sector I the u_I values for a and b are

$$a_I = 1 \quad , \quad b_I = \frac{-1}{\sqrt{3}} \qquad (10)$$

and for u_{II}

$$a_{II} = 0 \quad , \quad b = \frac{-2}{\sqrt{3}} \qquad (11)$$

This is converted to a switching pattern for the converter. It is very important for the overall efficiency that the number of switchings are kept at a minimum. This is here done by having the sequence U_0, U_I, U_{II}, U_{VII}, U_{II}, U_I, U_0 and to have it symmetric around $T_s/2$. For each time step this is fed to the LCL-filter and the grid model via a (dq->) xy-> abc transformation.

The reference to the Space Vector Modulator, SVM, is generated by controllers. There are two control loops, one for the d-direction and one for the q-direction. There is also a decoupling between the two axis in the control loop. The controllers are PI-type with anti reset wind up. they are designed for good performance and robustness.

The appropriate transfer function for controller design is (in the z-domain i.e. discrete time)

$$u_g = H(z) u_i \qquad (12)$$

i.e. from inverter voltage to the grid voltage

In the s-plane (continues time) the tranfer function for the single phase equivalent is (with a load, R_g, L_g)

$$\frac{u_g}{u_i} = \frac{(sL_g + R_g)(C_f R_f s + 1)}{(L_{fi} C_f (L_{fg} + L_g))s^3 + [L_{fi} C_f (R_f + R_g) + (L_{fg} + L_g)C_f R_f]s^2 + [L_{fi} + L_g + + L_{fg} + C_f R_f]} \qquad (13)$$

The transfer function is transformed to the z-domain including a zero order hold (at the sampling frequency of 5kHz) as well as a unit time delay coming from the modulator.

The controllers for the two axis are designed neglecting the cross-coupling between them i.e. the controllers are designed as SISO (single input – single output) systems. The controller type is PI, which is adequate for this application. Both limitation of the output signal and anti reset windup is implemented in the controllers.

As seen in (13) the transfer function depends on the load both active and reactive. It should therefore be designed so that good performance is obtained for all load situations.
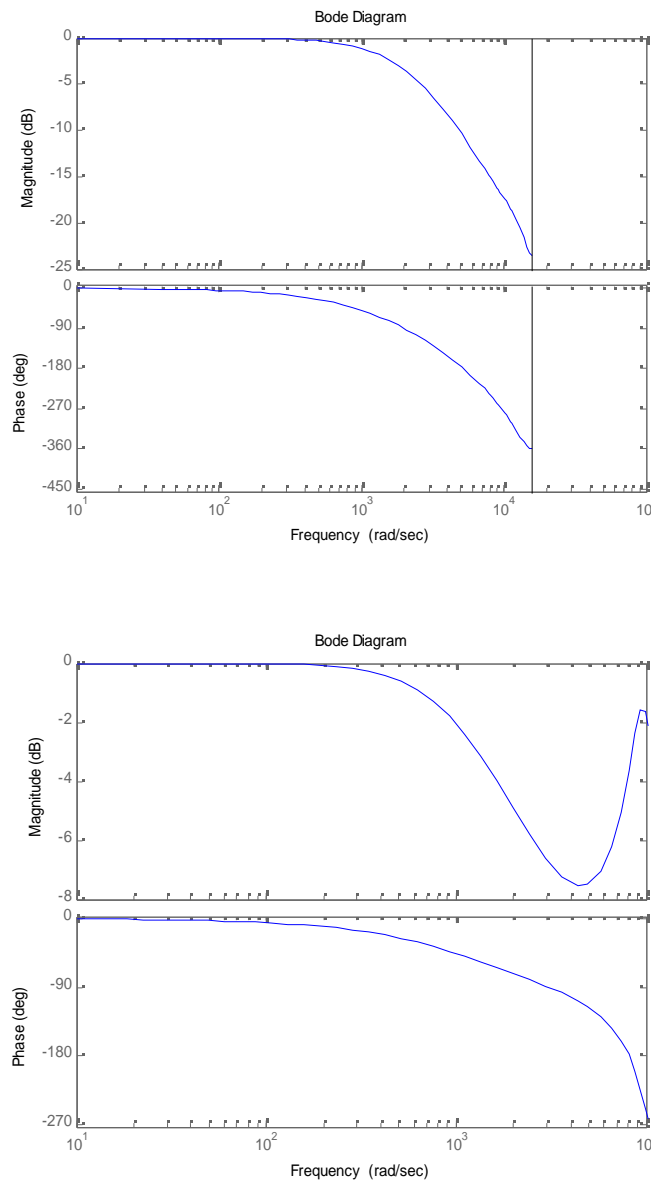

Figure 14 Bode plot of closed loop transfer function from voltage reference (u_d^*) to grid voltage (u_{dg}) for two load cases: top: Nominal active load (11kW) and bottom: Full load S_n @ cos φ=0.8

The transfer function depends on the load. The poles of the system are shown for two load cases:

- Nominal active load i.e. P=11kW, Q=0kvar
- Nominal apparent load, same current, but cos φ=0.8, P=8.8kW, Q=6.6kvar

The controller is designed for the first case. One of the poles is canceled by proper selection of Ti. Kp is chosen so that the closed loop poles are all real. The closed loop bode plot are in Figure 14. In the figure it is noticed that stability is maintained also in the other load case.

The dc-link connects the input from the wind turbine with the output to the grid. It is basically a capacitor, Figure 15.
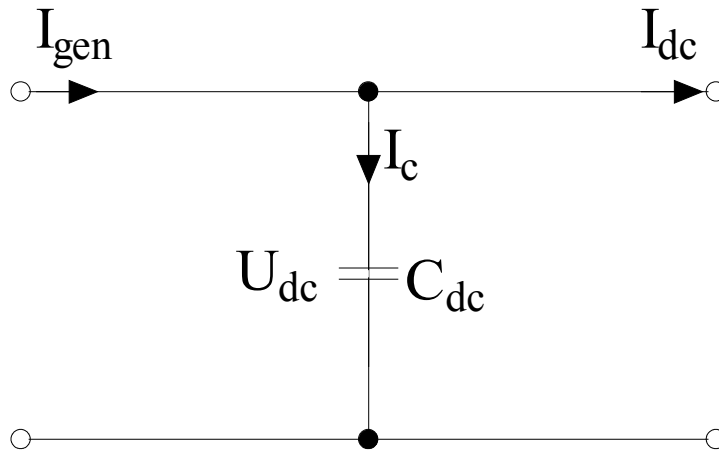

Figure 15 dc-circuit

$$C \frac{du_{dc}}{dt} = i_{wtg} + i_{dc} \tag{14}$$

where i_{dc} is calculated from the power balance

$$u_{dc} i_{dc} = \frac{3}{2} \left(u_d i_d + u_q i_q \right) \tag{15}$$

assuming a loss-less converter. i_{wtg} is calculated in a similar way from the wind turbine side power balance.

5.1.2 Generator side subsystem

The generator side subsystem consists of the wind turbine incl. its controller and the power converter incl. its controller.

For the controller desing and analysis the input to the system is assumed deterministic. This means that the power fed to the dc-link as a result of the power conversion of the wind turbine in the model will be a constant or step function in order to study the dynamic performance of the grid side system.

The total produced power is fed to the dc-link in the form of a dc-current.

5.1.3 dc-link control and current limitation

The dc voltage has to be controlled to stay within a minimum and maximum value. The minimum value is determined by the output voltage. The maximum voltage is determined by the specification of the components in the converters.

As seen previously the dc-link voltage is determined by the power balance in the system. It increases when there is a surplus of power fed to the dc-link and vice versa since the voltage of the dc-link is the of the capacitor in the link.

When the voltage is a certain level there is a need to dissipate power. This is done through a controlled resistor in the dc-link. A P-controller has been implemented which controls the duty cycle of the switch, Figure 16.
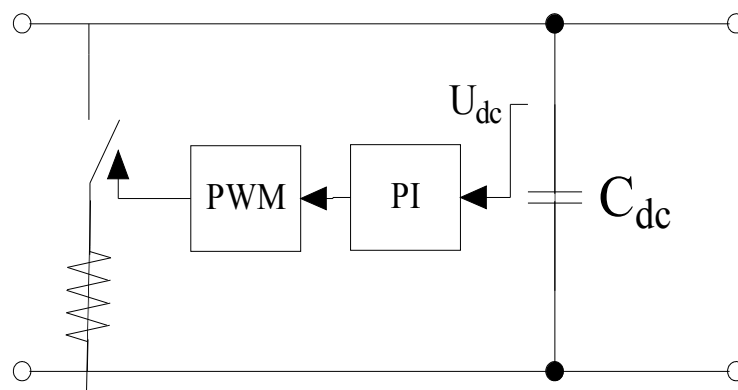

Figure 16 dc-circuit voltage control

To keep the dc-link voltage above the minimum level a reduction of the output voltage on the grid side has been implemented. This control loop operates in parallel to the normal voltage control loop.

5.1.4 Simulation results

The grid converter system is simulated using the model. The model include all the switching of the converter. The simulations require very small time steps. The important issues include response time and distortion as well as behaviour during situations with operating conditions close to the limits.

The first simulation is during normal operation. The input to the system is a constant current of $16A_{dc}$, which corresponds to full load at $700V_{dc}$. The load of the system is increased from half to full load and back in steps.
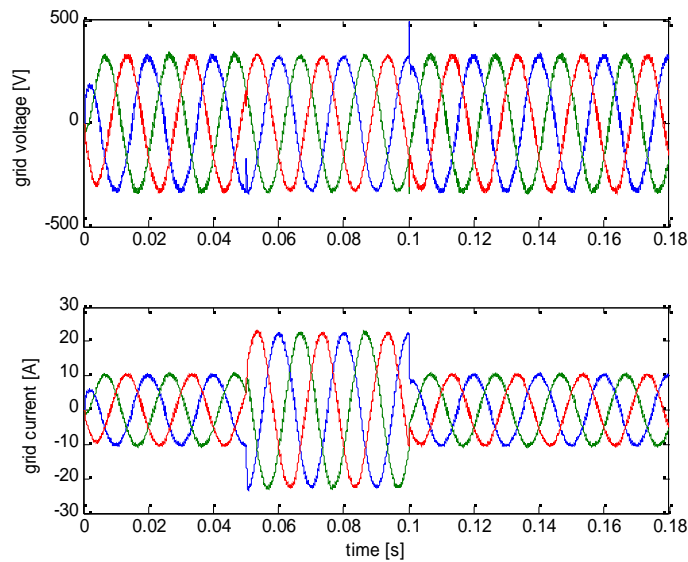
Figure 17 Instantaneous voltage and current at the load during load steps from half to full load and back
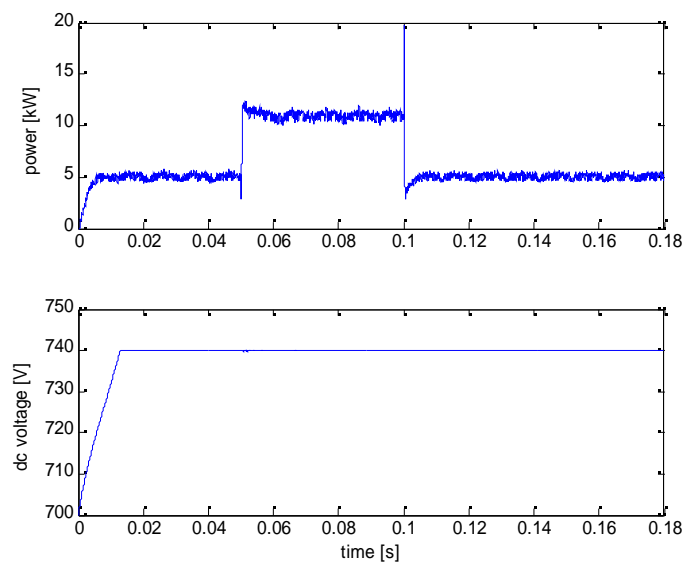

Figure 18 Load power and dc-link voltage during load steps from half to full load and back

It is seen from the figures, Figure 17 and Figure 18, the the system responds very fast to load changes both in positive and negative direction. Because there is a surplus of input power the dc-link voltage is in it higher limit. The output voltage and current only have very short transients in the response. The amplitude is otherwise constant. The distortion of the voltage is 4.7% (THD) after the LCL-filter. As it is seen the system responds well in the normal operation situation.

If the system is overloaded the voltage controller will reduce the output power by reducing the output voltage as a response to the reduction in dc-link voltage. This behaviour is illustrated in the next two figures,Figure 19 and Figure 20. At t=0.05 the load of the system is increased to 22kW since this is twice the input power the voltage controller reduces the output voltage as a response to the reduction in dc-link voltage. It is seen in Figure 20 (lower curve) how the dc-link voltage decreases during the period with high load. It will however reach an equilibrium voltage when the input power matches the output power. In upper curve in the same figure the reduction in output power is seen. During the lastpart of the simulation the power is almost constant. In Figure 19 (upper curve) the reduction in output voltage is seen. After the initial readuction the voltage decrease is quite small since the output power is close to the input power. The level of THD does not change significantly (4.8%). The system behaves as expected in the overload situation.
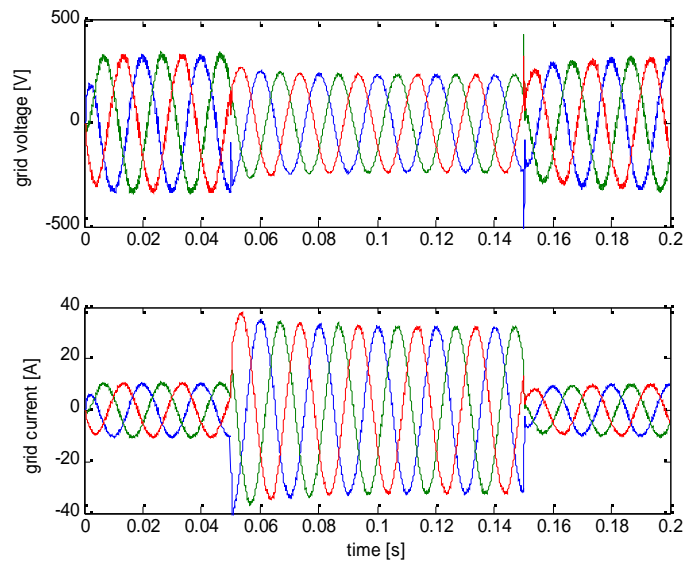

Figure 19 Instantaneous voltage and current at the load during load steps from half to full load and back. During full load the input current is reduced to half of the initial value
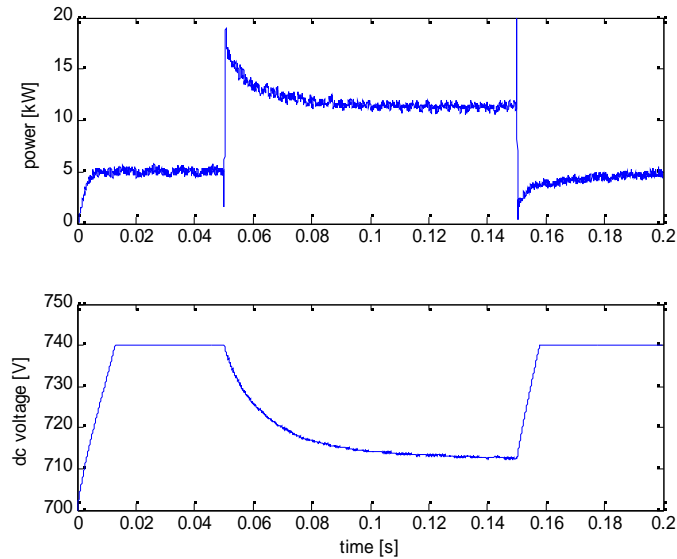
Figure 20 Load power and dc-link voltage during load steps from half to full load and back. During full load the input current is reduced to half of the initial value

The final simulation the load is again stepped from half load to full load and back. During the period with high load the input current is reduced from 16A to 8A (@t=0.1). The results is in Figure 21 and Figure 22. It is observed from the figures that as soon as the input current is reduced the dc-link voltage also starts to decrease. After some time the dc-link voltage is below the threshold value at which the voltage controller will begins to reduce the output voltage. The output power will therefore begin to decrease. When the load steps down the dc-link voltage begin to increase because the input power is now above the load demand and the output voltage begins to recover.
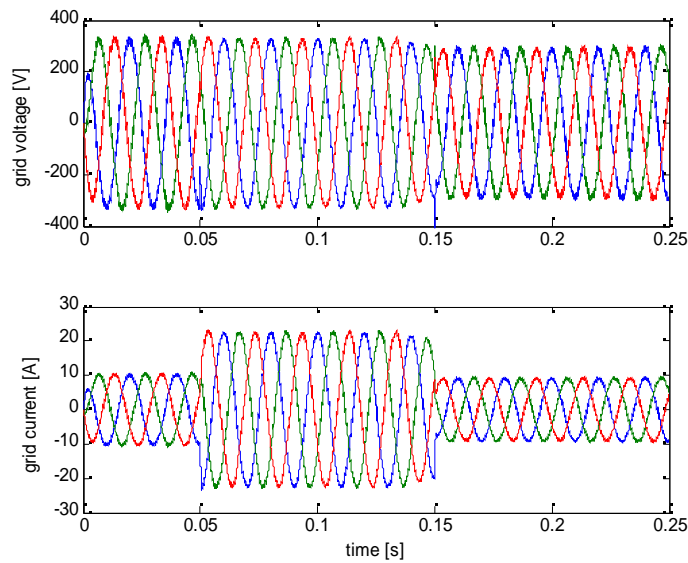
Figure 21 Instantaneous voltage and current at the load during load steps from half to 2 x full load and back
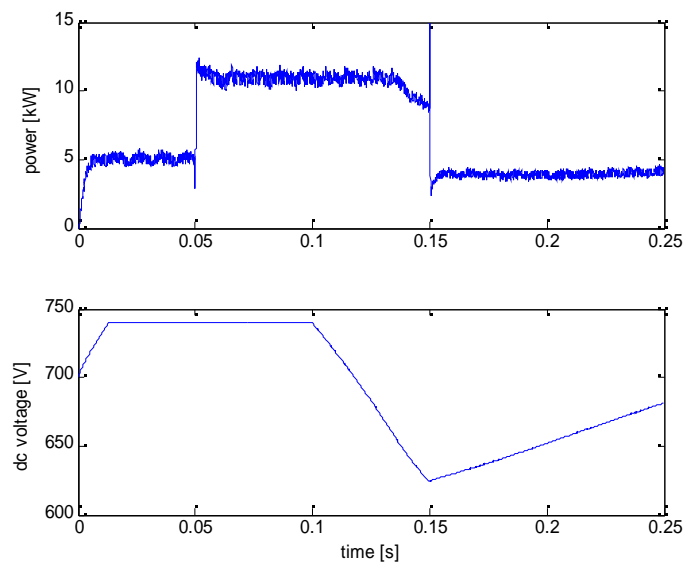

Figure 22 Load power and dc-link voltage during load steps from half to full load and back

As it is seen from the simulation results the system performans well both when there is a surplus of input power and when there is a deficit. In the final version of the system a battery storage will be included in the dc-link and operation terefore only at rare occasions be when there is not enough power available to supply the load.

5.2 System performance model

The purpose of the system performance model is to enable power quality assessment of complete isolated power systems with multiple generators and wind power input. The system performance model therefore includes models of diesel generators including their governors and voltage controllers, dump load including controller and wind turbines, standard or stand-alone types. The model also includes a network model. In order to be able to assess the performance of the system in terms of voltage and frequency fluctuations in a frequency range up to several Hertz the submodels are dynamic. Internally the model works in per unit, but the interface converts to engineering units.

5.2.1 Wind energy converter model

The wind turbine is fixed blade angle stall controlled. This means that power control relies on the ability to control the rotational speed of the rotor since the pitch angle is fixed. The performance of the wind turbine can in the current context be described by the Cp-λ curve. In Figure 23 is the Cp-λ curve for the Gaia wind turbine shown. The Cp-λ curve describes how much of the available power in the wind that is converted to mechanical energy depending on the rotational speed of the rotor and the wind speed ($\lambda=\omega R/u$). It is seen that the Cp-λ curve has a maximum. The part of the curve to the left of the maximum is the stall region in which the aerodynamic features of the rotor make the flow around the profile increasingly less laminar (the flow separates). The maximum produced power from the wind turbine can then be controlled by changing the reference rotational speed. This is illustrated in the next fig, Figure 24. Here are several power curves i.e. P vs. u with the rotational speed as parameter.
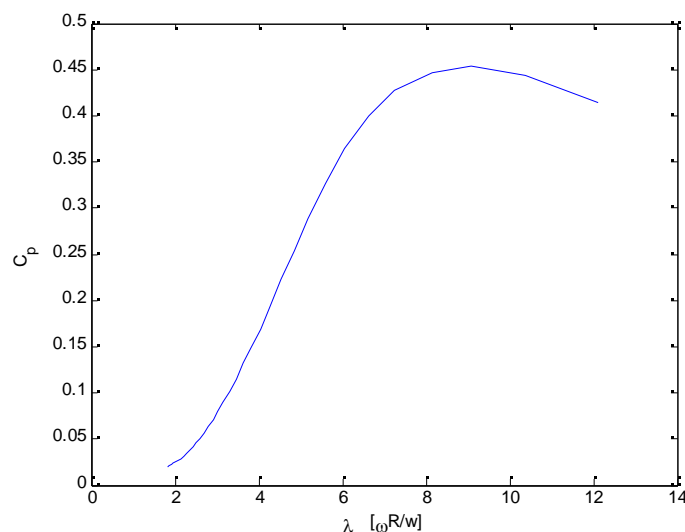

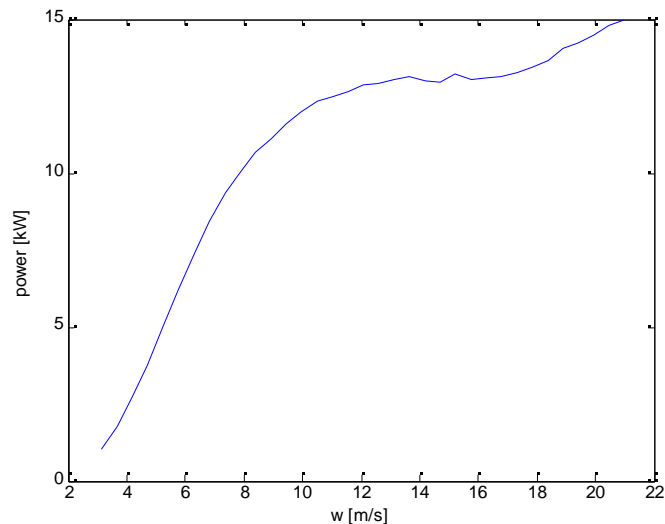*Figure 23 Cp-curve for the Gaia wind turbine*

Figure 24 Power curve for the Gaia wind turbine

Due to its construction with fixed pitch stall control and squirrel cage induction generator the Gaia wind turbine is a passive wind turbine in a control sense in the standard version (i.e. directly connected to the grid). The wind turbine controller acts as a supervision system monitoring the operating conditions of the turbine ensuring that they are within the operating conditions envelope.

The power converter system is a industry standard system used here without modifications. The wind turbine is speed controlled as mentioned above. The generator speed is measured and fed back to the controller of the power converter. The control scheme of the converter is standard vector control with feed back. The speed set point is fed from the wind turbine controller. In the current setup the turbine is operated in constant speed mode since the Cp-λ curve has its maximum at low wind speed values and there is no gain in operating in variable speed mode.

The power fluctuations from the wind turbine can be reduced by lowering the rotational speed since this will force the turbine to operate in stall region from a lower wind speed. This reduction in fluctuations, of course, comes at the cost of lower energy production since the power level at which the turbine stall is also lowered.

The bandwidth of the control loop for the rotational speed of the turbine will be rather high especially since it in the current configuration has speed feed back. It can therefore be assumed that the rotational speed is constant. The model for the wind turbine then reduces to the generation of aerodynamic power assuming loss-less generator and converter.

The model for the production of power consists of two submodels. The first one is the wind speed model, [8]. The second part is the aerodynamic model having the wind speed as input together with the rotational speed of the turbine, Figure 25. The aerodynamic model calculates the aerodynamic power based on the Cp-curve and the rotational speed of the rotor and the wind speed. The aerodynamic model includes a dynamic model for the stall, [9], that takes the delays in the flow around the profile into consideration also in the stall region so that a change i wind speed

will result in a temporary change in the output power even if the steady state power is the same at the two wind speeds.

The dynamic stall model, as implemented in the model, is based on Cp-curves for three cases.: Attached flow, separated flow and nominal, Figure 28. The first two gives the range of in which the must lay. The nominal is the static (steady state) Cp-curve (from power curve measurements). The Cp value at which the rotor is operating is not allowed to change instantaneously. The Cp value is determines as the weighted value between the separated and the attached values where the weight is the fraction the Cp, nominal to the range between attached and separated fed through a first order time lag, Figure 27.
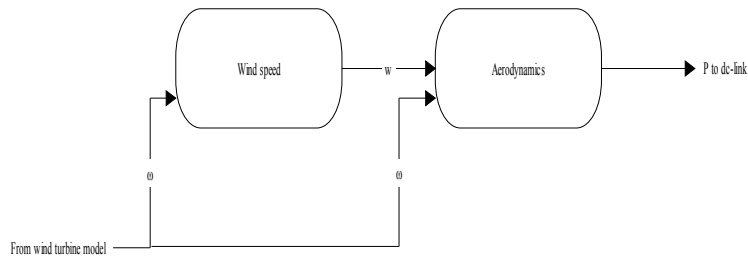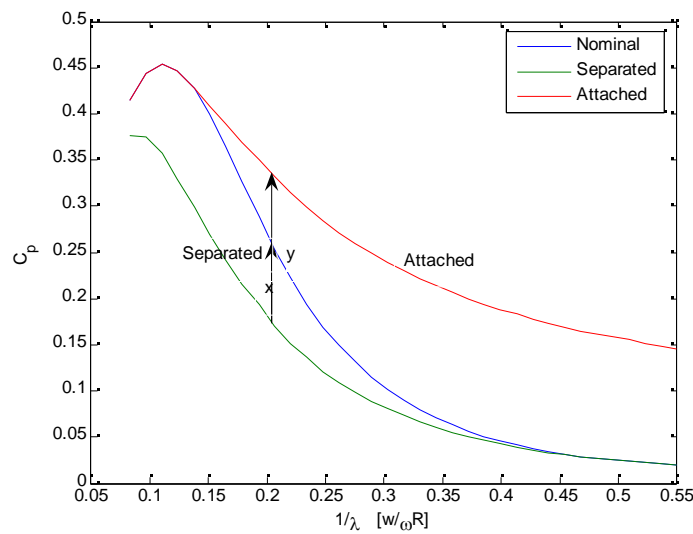

Figure 25 Calculation of power fed to the dc-circuit

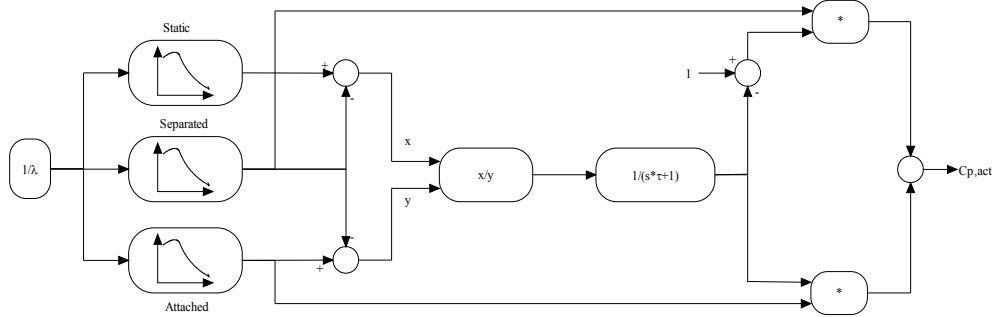*Figure 26 Aerodynamic curves used by the dynamic stall model*

Figure 27 dynamic stall model

In order to study the performance of the controllers of the grid side subsystem deterministic wind input is being applied to the system i.e. mainly step input. For investigations of system performance stochastic wind input is being used. The stochastic input constructed from a description of the turbulence of the free wind and its interaction with the rotor. The rotor interaction takes the spatial averaging effect of the rotor into account as well as the rotational sampling, which is the redistribution of the energy depending on the number of blades and the rotational speed. The wind speed is modelled as a sum of different contributions. The wind speed is split in mean wind speed and turbulent part. since the turbulent part is not uniform over the rotor there will be a redistribution of the energy in the turbulence due to the interaction between the turbulent wind field and the rotor. This is being modelled as a sum of contributions from each harmonic of the rotational speed time the number of blade of the rotor. The basic description of the turbulence is based on a spectral description of the turbulence, here is the Kaimal spectrum chosen. The spectral shape is then modified by the interaction with the rotor.
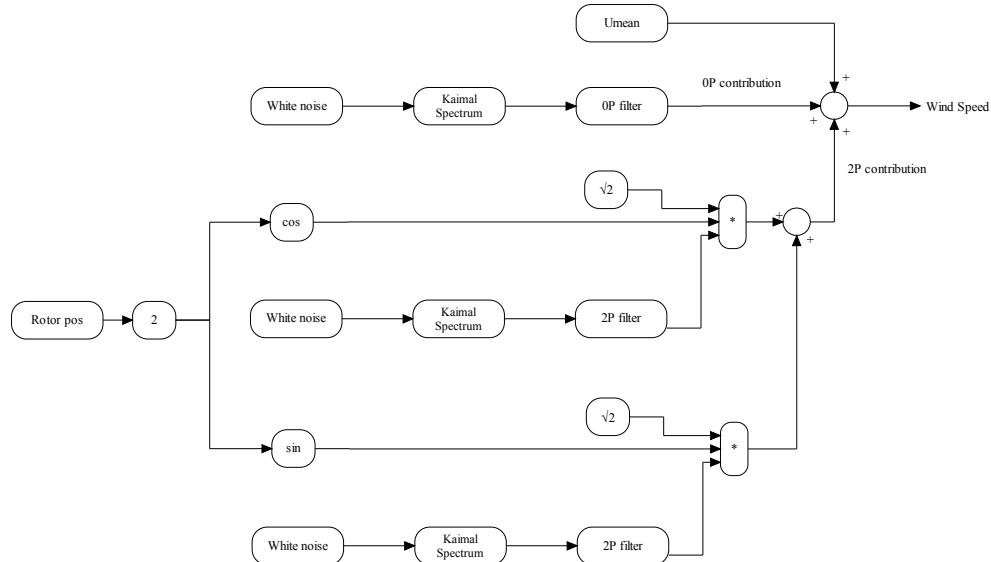

Figure 28 wind speed model

The drive train of the WEC is modelled as a two inertia-system with a stiffness and damping between the two inertias. The inputs to the model are the aerodynamic torque and the generator airgap torque. The model is based on the equation of motion of the system.

The model of the generator is a standard dq-model where the rotor dynamics are included and the stator dynamics are neglected.

5.2.2 Diesel genset model

The diesel genset model consists of five submodels. These are
· Combustion/torque
· Governor
· Drive train
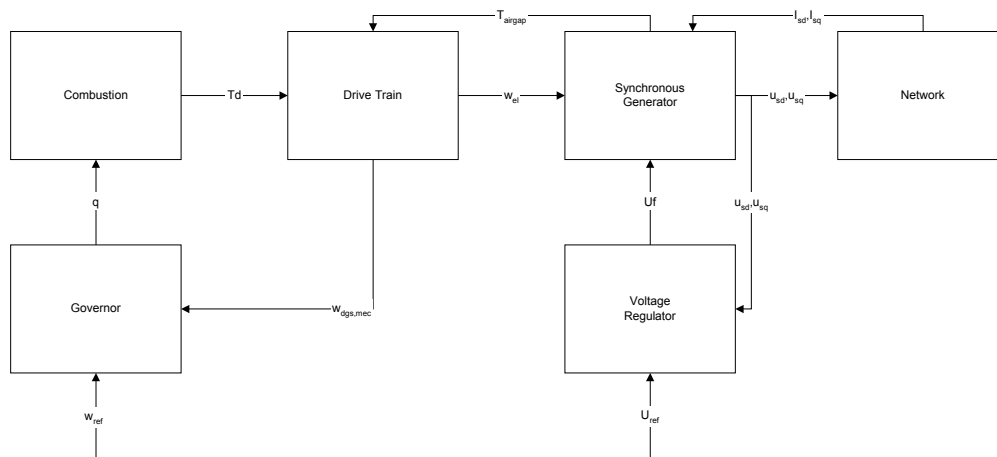· Synchronous generator
· Voltage regulator

Figure 29 Diesel generator set sub-models including signals

The combustion is modelled as first order system in series with a pure time delay and a non-linear function for the relation between fuel and torque. The input to the model is the fuel flow and the output is the developed torque. The time delay accounts for the delay in the fuel injection system.

The governor is a PID controller. The model structure is from [10]. Its parameters are determined based on steps in the load and the resulting speed changes.

The drive train of the genset is modelled in the same way as the wind turbine drive train i.e. as a two inertia system.

The synchronous generator is modelled as a standard dq-model including saturation

The voltage regulator is as the governor a standard IEEE model, [11]. The implementation is as in [12]. It includes saturation.

5.2.3 Dump load model

The dump is a controlled resistor. It is controlled by a limited PI controller. The characteristic of the dump load controller is chosen so that it is much steeper than the characteristic of the diesel governor. This ensures that the load of the diesel genset will not be too low even i situations with a high wind power surplus.

5.2.4 Network model

The model can include multiple bus bars. The network lines are all passive. The network is then reformulated so that only the bus bars at which generating components are connected has external connections. The network model is based on [10].

The node equations are, in matrix formulation,

$$I = YV \tag{16}$$

where I is the output current vector and V the input voltage vector. Both consists of n elements where n is the number of nodes. Each element is

$$I = \begin{vmatrix} I_{di} \\ I_{qi} \end{vmatrix} \quad , \quad V = \begin{vmatrix} V_{di} \\ V_{qi} \end{vmatrix} \quad , \quad i = 1..n \tag{17}$$

The matrix Y is the admittance matrix

$$Y = \begin{vmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{12} & Y_{22} & \cdots & Y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{nn} \end{vmatrix} \tag{18}$$

Each of the Y elements are

$$Y_{ij} = \begin{vmatrix} G_{ij} & -B_{q,ij} \\ B_{d,ij} & G_{ij} \end{vmatrix} \tag{19}$$

G_{ij} is the conductance and $B_{dq,ij}$ are susceptance for the two axis.

The network equations can be reduced so only the nodes at generating unit are connected is input respectively output.

$$Y_r = K - LM^{-1}L^t \tag{20}$$

The matrices K, M and L are found as submatrices fro the full admittance matrix Y. K is the square matrix that results from keeping all rows and matrices that have active input. M is the square matrix with all the remaining nodes. L is off-diagonal connecting the retained nodes with the eliminated. In a four bus example where buses 1 and 3 are kept the matrices are the following

$$K = \begin{vmatrix} Y_{11} & Y_{13} \\ Y_{13} & Y_{33} \end{vmatrix}$$
$$M = \begin{bmatrix} Y_{22} & Y_{24} \\ Y_{24} & Y_{44} \end{bmatrix} \tag{21}$$
$$L = \begin{bmatrix} Y_{12} & Y_{14} \\ Y_{32} & Y_{34} \end{bmatrix}$$

In the simulation model the nodes with either a wind turbine generator or a genset synchonous generator are retained. Other nodes are eliminated, however, the node voltages and currents can be calculated after the simulation based on the retained bus voltages and currents.

5.2.5 Simulation results

The simulation model is used to simulate the system behaviour for a system consisting of one wind turbine (with directly connected induction machine), one diesel genset, one dump load, one consumer load and the network. The distance from the wind turbine busbar to the genset bus bar is 300m. The system is simulated for the different wind speeds, 6m/s respectively 12m/s, in order to show differences in power distribution between the components and to see the impact on bus bar voltages.
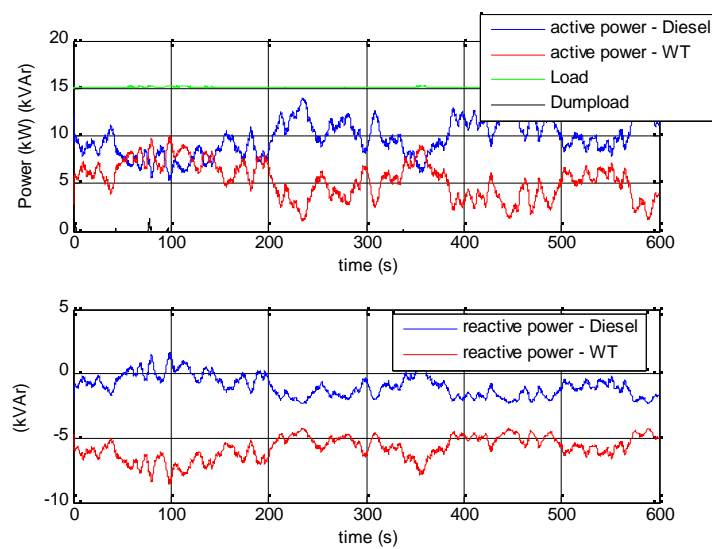

Figure 30 Power balance (active: top, reactive: bottom) for 6m/s mean wind speed case

For the first case is the power balance shown in Figure 30. The load is constant so the variations in wind turbine output has to be compensated for by the genset set. It is seen that since the wind power production is low almost no power is dissipated in the dump load.
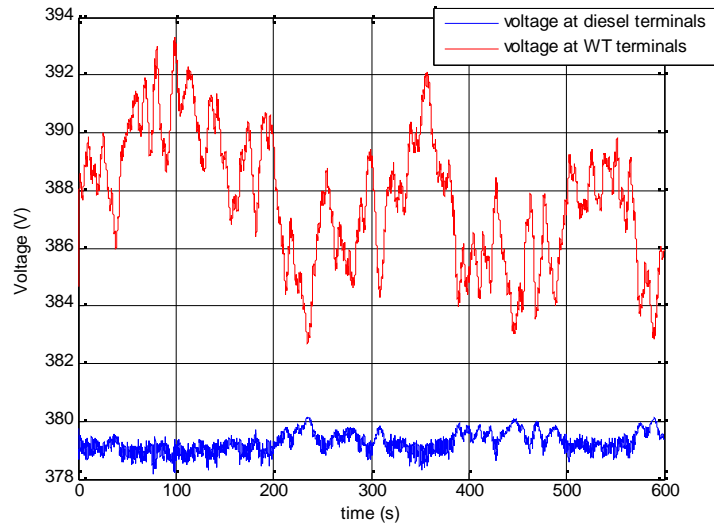
Figure 31 Terminal voltages of the genset and the wind turbine generator for 6m/s mean wind speed case

Because the wind turbine is situated 300m from the genset the voltage at the terminals of the two components can be very different. Due to the impedance of the cable connecting the wind turbine to the system the voltage at the wind turbine generator terminals is higher than at the system bus bar where the genset is connected. This is seen in Figure 31. It is also noticed that the level of fluctuations is much higher at the wind turbine generator terminals.
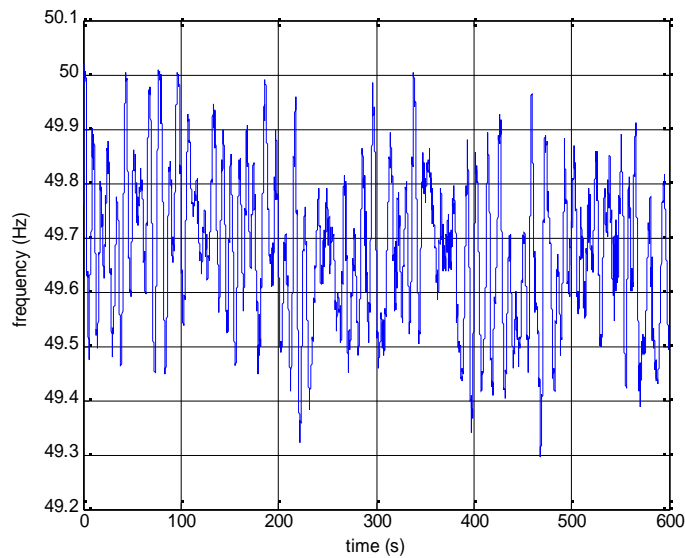

Figure 32 System frequency for 6m/s mean wind speed case

The system variations follow the variations in genset power, Figure 32. It is seen that the variations are quite small, however, the variations in output power is also limited.

For the 12m/s-case the output of the wind turbine is off course higher. With all other input being equal the impact of the higher wind speed is a shift in the power balance

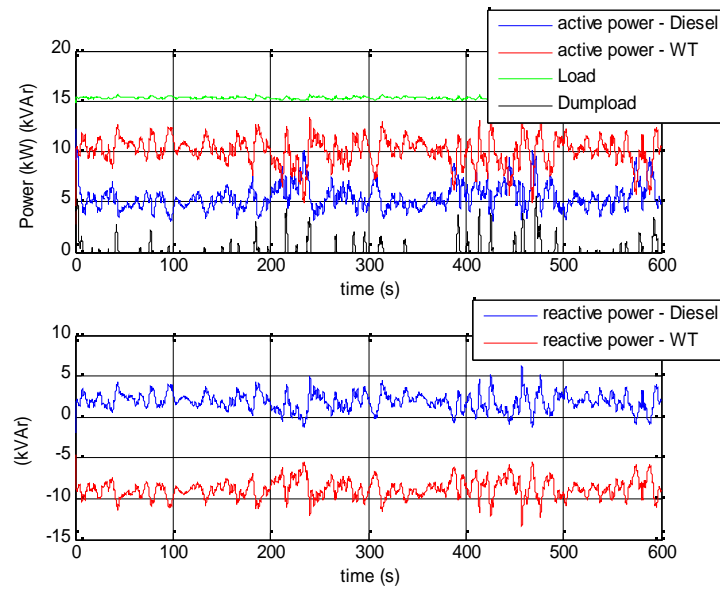*Figure 33 Power balance (active: top, reactive: bottom) for 12m/s mean wind speed case*
of the system.

In Figure 33 is the active and reactive power balance at this higher wind speed. the load of diesel genset is reduced and the dump load is now much more active. This means that more power is being dissipated.
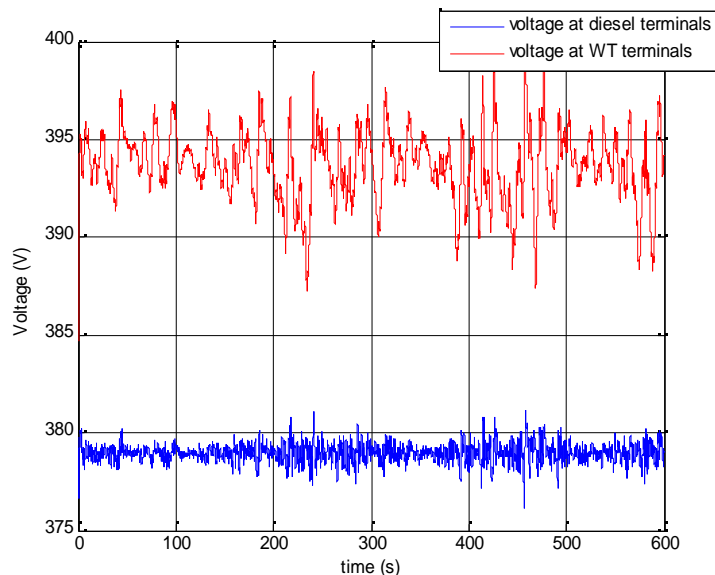

Figure 34 Terminal voltages of the genset respectively wind turbine generator for 12m/s mean wind speed case

The higher wind turbine output also has an impact on the voltage of the wind turbine generator terminals. It is seen in Figure 34 that the level and the variations are higher at this wind speed. It is off course important to include load flow analysis in a real system to ensure that the voltage levels at all the bus bars are within a prescribed range. It is also important to ensure that the level of voltage fluctuations is below a threshold where it could create disturbances at the consumers.
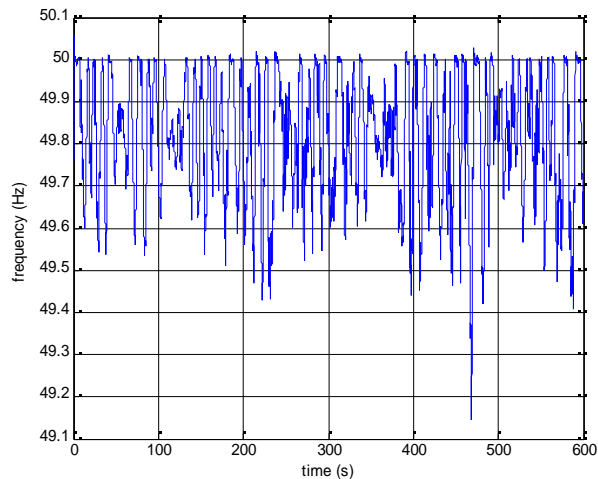

Figure 35 System frequency for 12m/s mean wind speed case

The nature of the frequency time trace is very different for the high wind case since the dump load is active for much of the time. The dump load has a very steep characteristic compared to thegovernor characteristic. This means that when the dump load is active the frequency variations are significantly reduced. It is seen in Figure 35 that the frequency does not reach values much higher than the dump load controller setpoint value of 50Hz.

The above simulation results illustrate the performance of the dynamic performance assessment model. In its current state it can simulate systems with more diesel gensets and wind turbines, however, the wind turbine type has to be stall controlled with dorectly coupled induction generator.

6 Prototype

The prototype plays an essential role in the project. All the activities in the project are centred around validation/documentation of performance through measurements. The construction of the prototype is done in collaboration between all the project partners.

A main criteria for the design and the selection of components has been that components are chosen with the final product in mind, but at the same time it has been very important that the setup was flexible enough to allow for the necessary development work.

The hardware is more throuroughly described in "Hardware description of the Gaia stand-alone windmill" by Remus Teodorescu, [13].

6.1 Selection of components

Two main decisions where involved in the selection of the hardware. The first was the power electronic hardware and the second was the control system. With the experience at IET/AAU in mind the decision for both issues were based on the developed laboratory facilities at IET. The power electronic hardware selected was 22kW VLT frequency converters from Danfoss, [14]. These units are well proven and with the addition of a interface card can be controlled from another source.

The main data of the power electronic hardware is in Table 3. They are overrated but chosen in order to be sure that it can handle all situations. The generator side converter is a standard frequency converter including the flux vector control. The grid side converter has the standard controller removed and replaced by a IET/AAU developed interface card for direct control of the switching of the power switches.

Table 3Danfoss VLT5022 power stage main data

Supply voltage 380-500V	3x380/400/415/440/460/500V	±10%
Normal overload		10.00%
Output current	IVLT,N (380-440V)	37.5A
Output current max	IVLT,N (60s, 380-440V)	41.3A
Output apparent power	SVLT,N (380-440V)	28.6kVA
Input current	IL,N (380V)	37.5A
DC voltage	UDC,MAX	850V
Max pre-fuse		63/50A

The control of the power electronic is done in a dSPACE software/hardware combination, dSPACE DS1103, [15]. The hardware consists of a ISA card which interfaces to the system via a signal conditioning unit, signal conversion unit and the power electronic interface card.

The ISA card hosts a powerful RISC/DSP system and extensive I/O capability including fast DAC and ADC's. This powerful and fst hardware allows for direct control of the switching of the grid side power stage.

The real advantage of the dSPACE system is software part because it makes it possible to interface the hardware with MATLAB/SIMULINK, [16]. This enables development of the complete controller in MATLAB/SIMULINK followed by an almost automated transfer to hardware. The software therefore allows very flexible and fast transfer from models to test on the physical system.

The dSPACE system is ideal for controller development and testing but the final design has to be ported to dedicated hardware for production units.

6.2 System construction

Figure 36 Prototype rack with power converters, controller and interfacing equipment (power converters are shown)

The prototype has been built at IET. It is installed in a mobile rack. The filter is mounted in the bottom. Then follows the control computer and interface hardware. Above that is the power converters mounted, Figure 36. In the top is the dump load mounted together with cooling fans. The system is connected to the wind turbine controller to ensure safe operation. This include the safe start up and shut down as well as emergency circuit.

7 Prototype testing

The prototype has been tested in several steps. The initial test was performed as part of the development at IET/AAU. The development was done on a test rig to make it possible to test the individual part of the controller on hardware. The test rig had the same type of generator installed as the wind turbine, but was driven directly by another machine. This test setup was used for the development and testing of the grid side part of the system in both modes of operation.

The next test phase was done at Mita-Teknik. Here the system was tested together with a Gaia wind turbine. The purpose of these tests were to run in the system with a real wind turbine especially to tune controller parameters. Another important issue was the communication between the wind turbine controller and the dSPACE system. Also some stability issues were solved in this test phase.

The final testing was done at Risø. Here the prototype was installed as part of the existing test facility, [17]. This test facility provides both flexibility in terms of different test configurations as well as several sensors and a data logging system.
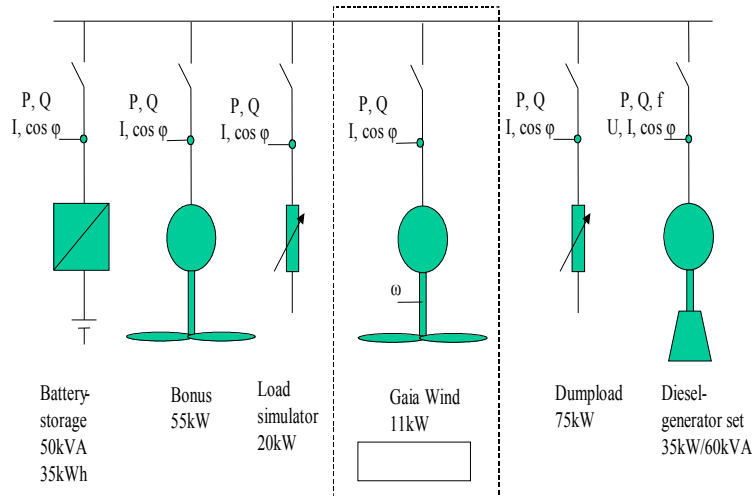

Figure 37 Ttest facility for testing isolated power systems and components

The test facility is build around two AC bus bars. One of the bus bars connects to the national grid, the other forms an independent grid. In Figure 37 is shown the isolated grid configuration. This makes it possible to test units under many different conditions. Also part of the test facility is a number of sensors mounted at the switchboard. These sensors include voltage, current, active and reactive power and frequency. The signals from these sensors are digitized and are logged by a data logging computer. The measurement software can accept signals from many sources also in serial form. This is exploited by having a distributed measurement system.

The Gaia wind turbine has been installed 300m from the switchboard together with the power electronics and the controllers. Also a local measurement system is placed there that measures signals from the wind turbine and from a meteorological mast. These signals are digitized and transmitted through an optic fiber cable to the data logging computer.

The modes of operation of the wind turbine unit in which it can be operated in the test facility include normal grid connected, operation in parallel with a diesel genset, operation in parallel with a diesel genset and another (larger) wind turbine, and stand-alone operation.

The testing reported here include two modes of operation: opeartion in parallel with the diesel genset and in stand-alone mode.

7.1 Tests runs in parallel with diesel genset

In this test the unit is connected to a system that consists of a diesel genset, a dump load and a load. In this mode of operation it is the diesel genset and the dump load that determines the frequency and the voltage. The voltage is controlled entirely be the genset, whereas the the frequency is controlled by the diesel genset when the

dump load is inactive. When the dump load is active the load is shared between the two (diesel genset and dump load) so they are both controlling the frequency, however, the frequency load characteristic of the dump load is much steeper (larger df/dP) so in reality it is the characteristic of the dump load that determines the frequency.

For the test unit the situation is very similar to normal grid connected operation except that the grid is much softer i.e. the variations of frequency and voltage are larger than on a large interconnected grid.

The objective of the test is to investigate if the unit stays synchronised to the grid during these variations and if the reactive power can be controlled satisfactorily.

Test results are shown in the figures Figure 38 and Figure 39. In the first of these two figures the operating conditions of the unit are shown in terms of the diesel load, dump load and wind input. It is noticed that the load of the diesel is slightly negative and the majority of the variations of power is balanced by the dump load. The wind speed range is between 5.5m/s and 9.5m/s which is the part of the power that is steepest i.e. the power fluctuations will be at its maximum (for a given turbulence). In the next figure the out put from the wind turbine is shown it is seen that the power fluctuations follows the wind speed fluctuations. It is also seen that the reactive power is very well controlled. It is being controlled to be very close to 0kvar. In the figure is also the resulting system frequency and bus bar voltage. The frequency variations are mainly a result of the characteristic of the dump load. The voltage variations are due to the voltage regulator of the diesel genset. The voltage variations are very small since the load variations of the diesel are very small in this mode of operation.

The main result is that the stand-alone unit stays synchronised and controls reactive power very well with the other generator.
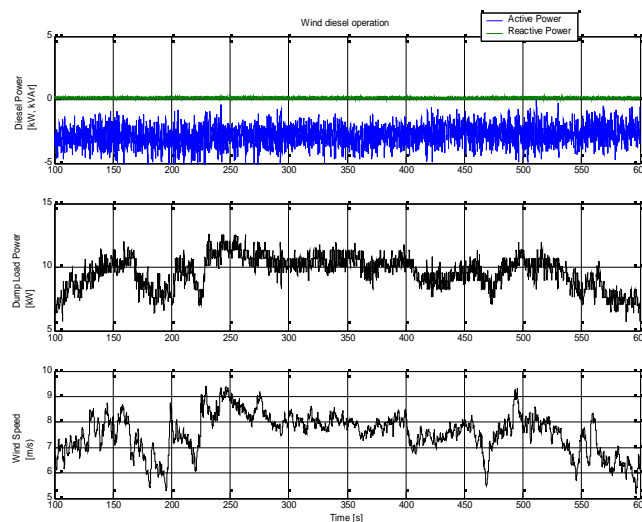

Figure 38 Time trace of prototype system operating in parallel with diesel genset. (top curve: diesel genset active (blue) and reactive (green) power, middle: dump load power, bottom: wind speed)
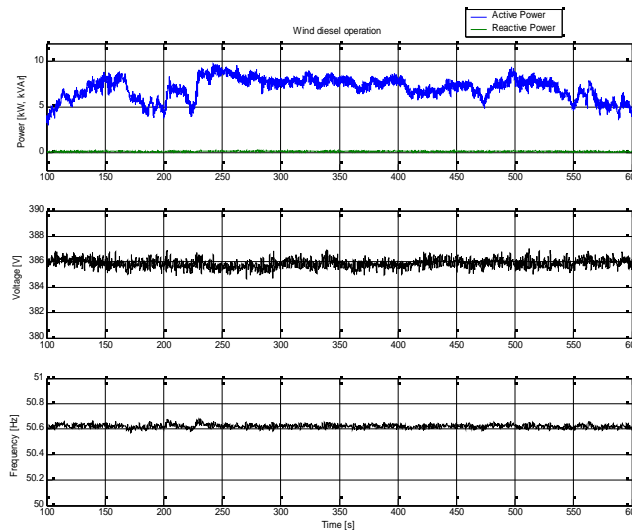
Figure 39 Time trace of prototype system operating in parallel with diesel genset. (top curve: SAWT active (blue) and reactive (green) power, middle: system voltage, bottom: system frequency)

7.2 Stand-alone operation

This is the main mode of operation of the system. During these tests the stand-alone unit was feeding a variable resistive load. The stand-alone unit and the load are the only two components in the system. Control of voltage and frequency is therefore the responsibility of the stand-alone unit.

Four different situations are presented here. They are the all with wind turbine input. These cases are

1. Small step reduction in load
2. Large step reduction in load
3. Step increase in load
4. Longer time series including the two former but also showing the voltage limitation due to power deficit.

The main objective of the tests are to study the voltage variations and the frequency variations during variable wind conditions and during changes in the load. This include both the long term conditions and the dynamic performance.

Initially is shown the time traces when the system is exposed to a small step change in load. The change in load is 600W. It has to be remembered that large variations in the mechanical input to the wind turbine constantly impact the system on the input side. The performance of the system is illustrated in the figures, Figure 40-Figure 42. In the first figure the change in load and the response of the stand-alone unit is shown. It is clearly seen that the stand-alone unit controls the system very well with a very fast response. This is a consequence of good control with voltage. In the next figure is the voltage of the bus bar shown. This confirms that control with the voltage is indeed very good. The variation in voltage is only 0.5V. There is a tendency for a low frequency oscillation. The origin of this will have to be investigated. System frequency is almost constant as shown in Figure 42. It changes only a small fraction of a Hertz during the time range.

In all, the system shows very good and fast control of the system as a response to a small step change in the load completely isolating the fluctuation of the wind input from the output of the system.
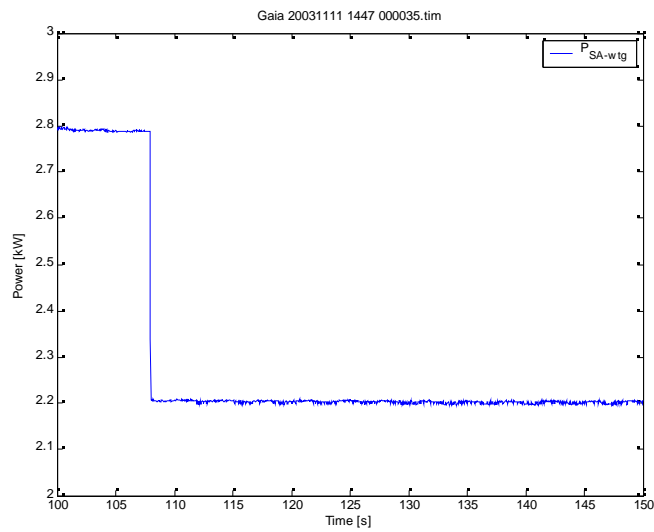

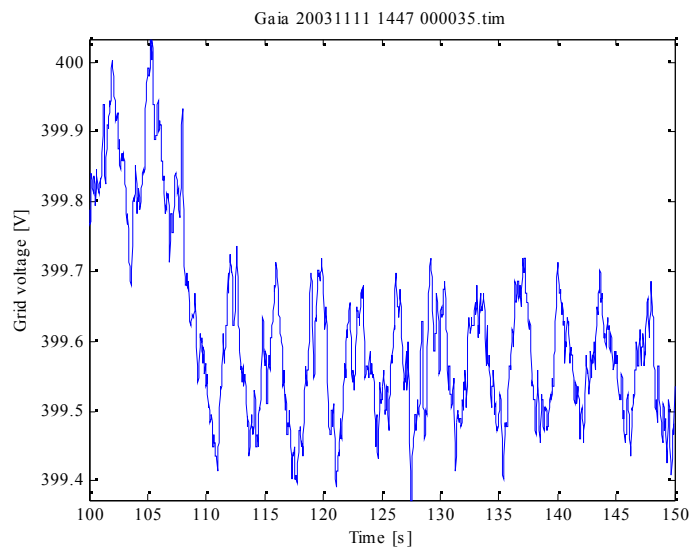*Figure 40 Stand alone system response in output power to small load reduction.*

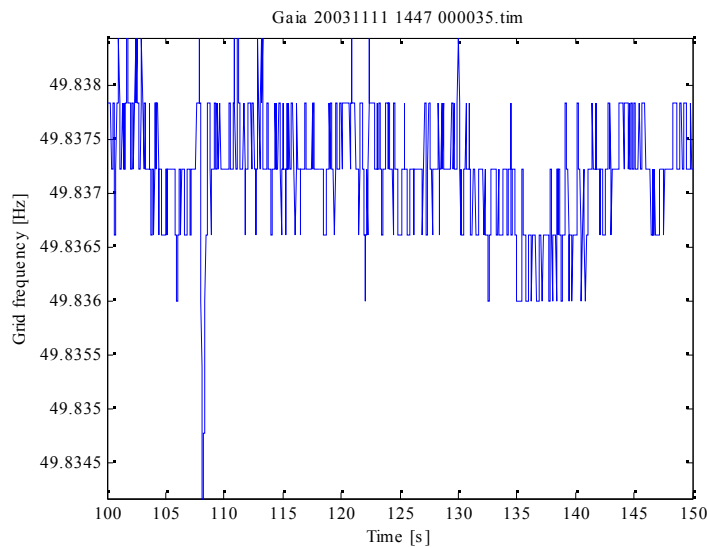*Figure 41 Voltage response of stand alone system to small load reduction*

Figure 42 System frequency response of stand alone system to small load reduction.

The next example of the operation of the unit is when it is exposed to a larger step in the load. The step is 3600W i.e. a third of the system rating. Again the same three time traces are shown, Figure 43-Figure 45. The response in power is similar to the response with the smaller load step. It is very fast and well controlled without overshoot. The voltage is also very similar to the time trace in Figure 41. The step is higher (0.7V), but it is still well controlled. Again is the oscillation noticed. The period of the oscillation is about 3s and the amplitude is small. It should, however, be investigated the source of it and how it can be eliminated or reduced. The variations of the system frequency is minimal. The variations are negligible. The performance of the system in terms of voltage and frequency control is also in this case good.
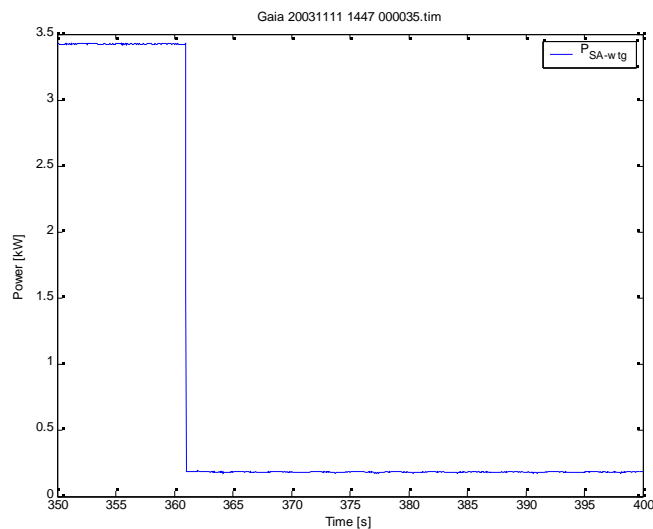

Figure 43 Output power response of stand alone system to large load reduction
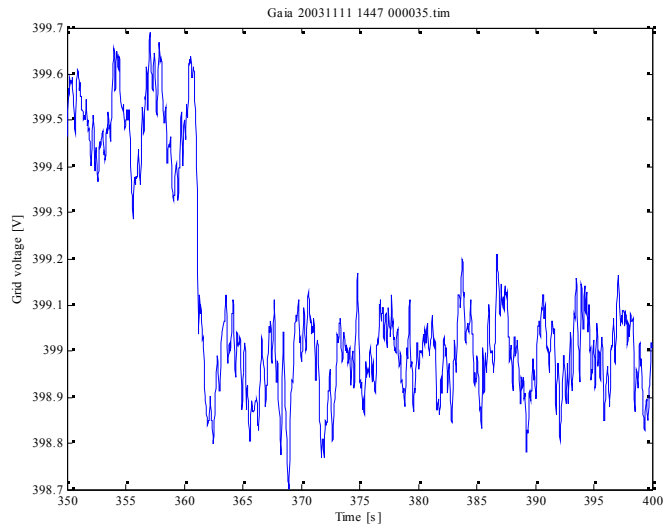
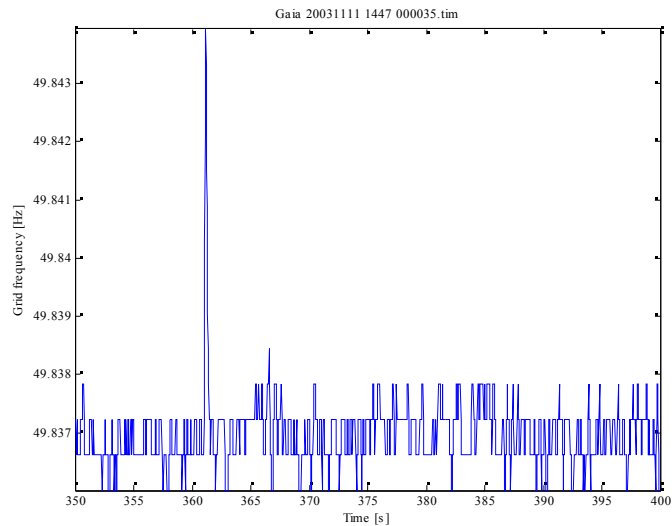*Figure 44 Voltage response of stand alone system to large load reduction*

Figure 45 Frequency response of stand alone system to large load reduction

In both the previous situations the load has been reduced. This means that less power is taken from the dc-link. It can therefore be expected that the system will react fast to such changes. When the load is increased the more power is drawn from the dc-link. Since the energy storage capacity of the capacitors of the dc-link is limited it can be expected that the response is slower because the dc-voltage will drop.

In the next figures are shown a situation where the load is increased. It is done in two steps of 600W each. In Figure 46 is the response of the unit shown. When compared with the prevous figures it is noticed that the response is almost just as fast. The corner of the curve seems slightly more rounded than in the reduced load case (it is important to notice the difference in time axis).

The variations on voltage are again very small, about 0.5Vpp, however, the oscillation is still visible. There is not a pronounced response in the voltage to the
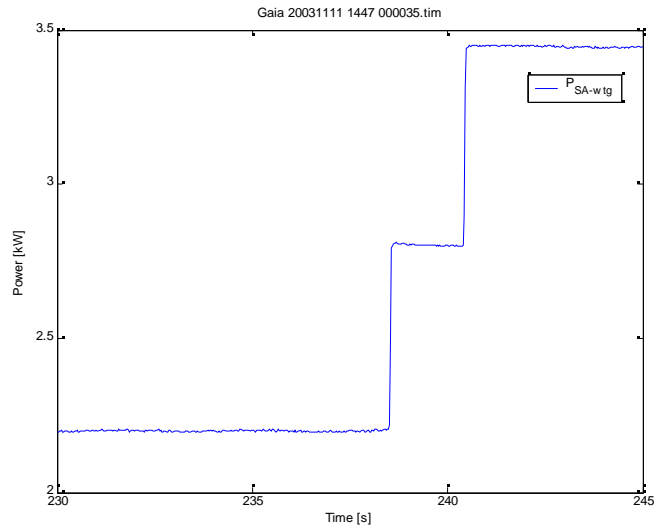
Figure 46 Power output response to load increase

change in load. The steps in the load are visible in the frequency, but the level is very small. In general there is not a significant difference in the behaviour of the system depending on whether it being loaded or unloaded.
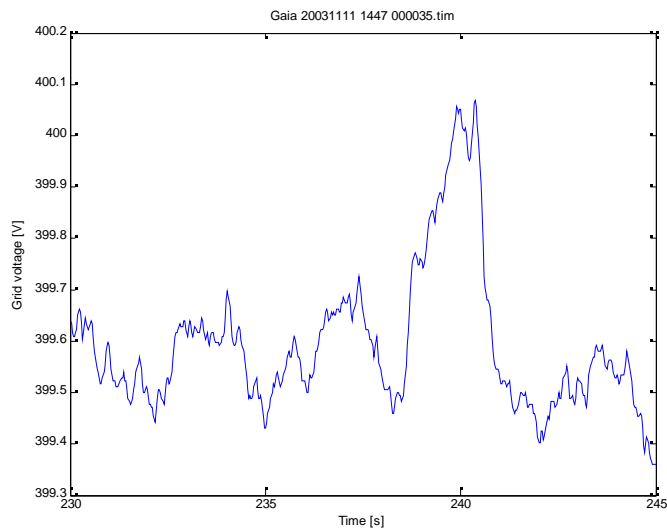

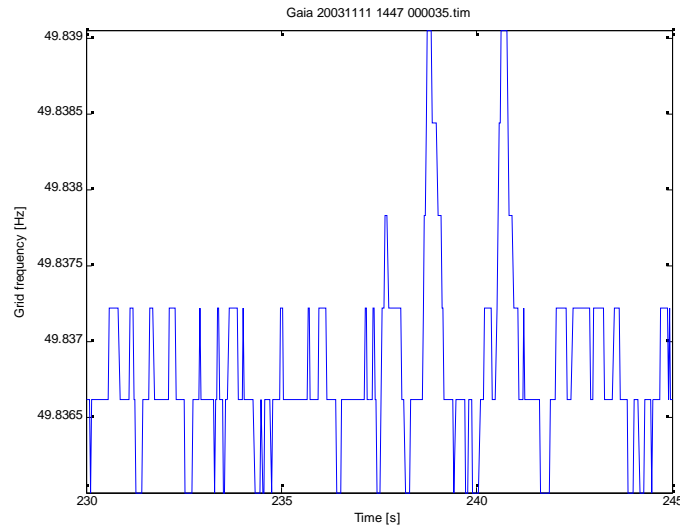*Figure 47 Voltage response to load increase*

Figure 48 Frequency response to load increase

For all the the three situations above where the load has been changed in steps it is clear that both the voltage and the frequency are very well controlled as long as there is suffiencent power in the wind to supply the load. Especially the frequency variations are very small. In the voltage there is a slow oscillation with a small amplitude. This amplitude is well below limits for flicker, however, the source will be indentified and reduced or eliminated.

The next figures confirmes the good voltage and frequency control. In these figures 10min of stand-alone operation is shown (the previous figures are excerpts of the same time series). In Figure 49 is the power from the unit shown. It is seen how the power is changed during the period. It is especially noticed that periods exist where the load fluctuates strongly. When compared to the next figure (Figure 50) where the voltage is shown it is clear to see that the strong power fluctuations occur when there is a power deficit in the system and the controller reduces the output voltage of the system in order to reduce the load. It is further confirmed that when there is enough power to supply the load the voltage control is good. The frequency of the system is controlled well during most of the period. There are some spikes during the period, but in general the control is good. The spikes occur when the voltage has large dips. Otherwise is the voltage almost indedendent of the voltage variations.

The control of the system has not been optimised to work without energy storage. The very rapid fluctuations in the output power as a result of power deficit has not been attempted to be minimised. However, the energy stored in the dc-capacitor is not very large and the voltage therefoe has to be reduced rapidly if a complete blackout is to be avoided.
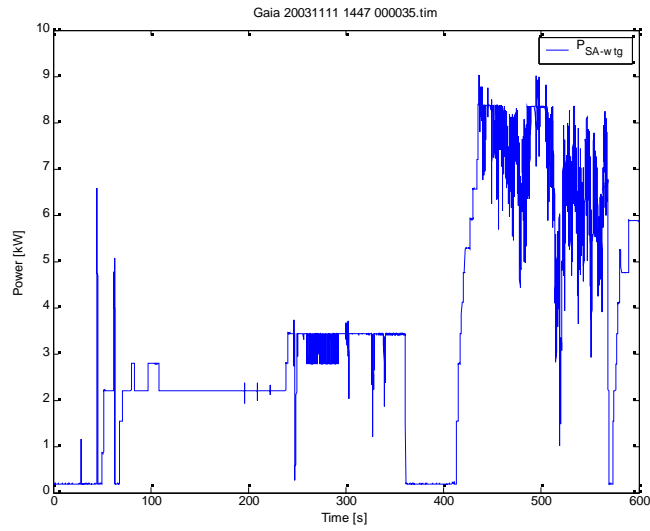
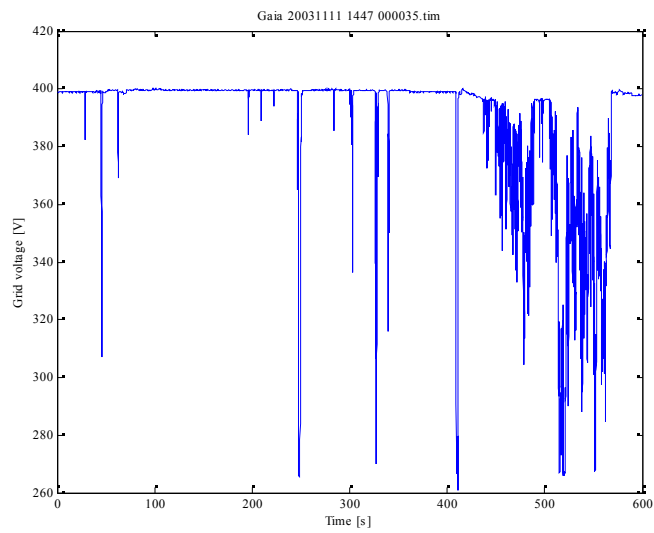*Figure 49 Output power time trace for 10min run of stand alone system*

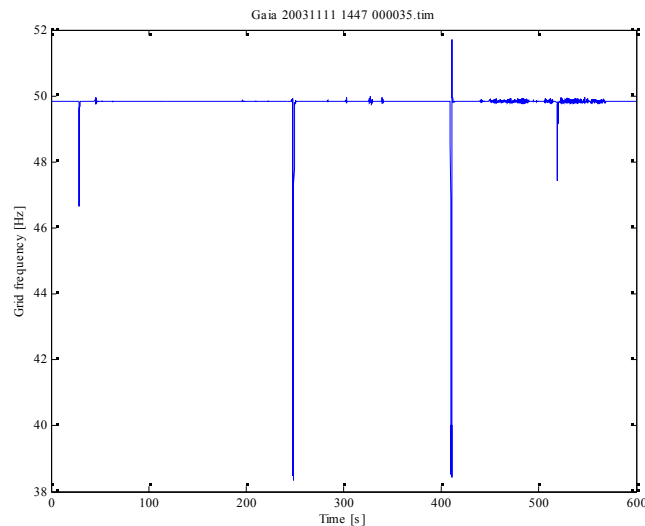*Figure 50 System voltage during 10min run*

Figure 51 System frequency during 10min testrun

In the output from the unit the fluctuations in power from the turbine due to its rotations is not present i.e. the capacitor of the dc-link is large enough to smooth these fluctuations and the controllers of the system are fast enough to regulate them out.

8 Energy storage

It is necessary to include a storage in the system in order to enable it to supply power independently of the instantaneous wind. As mentioned in the section on selecting the configuration of the stand alone system the type of storage will be lead acid batteries. This is due to the low cost and high availability of lead acid batteries throughout the world.

The battery can be connected either directly to the dc-bus or it can be connected through a bidirectional dc-converter. The direct connection of the batteries storage to the dc-link requires many batteries to be connected in series in order to reach the required dc-voltage for the converters to be able to generate standard system voltages e.g. 400Vrms. Many batteries in series are difficult to control to ensure that they are all in the same state of charge. If the batteries are connected to the dc-link through a bidirectional dc-converter the complexity of the system is increased as well as the dc-current level. Fewer batteries in series are much easier to control in terms of equal charge level.

It is necessary to include a battery management system regardless of the configuration in order to ensure that the batteries are operated within their operating range (voltage, state-of-charge) and to ensure regular full charges in order to prevent accelerated degradation. If the voltage is too high or too low the grid of the electrodes are corroded fast resulting in an increased internal resistance and in loss of active material. If the batteries are operated at low SOC for extended periods of time the batteries will deteriorate fast. This is due to several mechanisms. Mainly will low SOC result in sulphation of the positive electrode i.e. large sulphate

crystals are created which are difficult to dissolve during a charge period. This is further amplified by the stratification that will also often result from long periods at low SOC.

The sensitivity of the batteries to the different ageing mechanisms depends on the construction of the battery. Some batteries are very robust to certain types of stress, but are not very well suited for other parts of the operating regime or they are very costly. The cheapest type of battery is car battery type. This is a flat plate type battery. They particularly good at delivering a high current, but they are not constructed to be cycled often. This type of battery should be avoided in renewable energy systems since their short life in the system is not compensated for by the low cost. A more robust battery type is the so-called fork-lift type. They are of the tubular plate type. It is constructed to be used rather heavily, but will require often (daily) full-charge to recover the battery. There exist also batteries constructed especially for use in photovoltaic systems. They also have good cycling properties, but they have not been constructed specifically for the high currents that they will be exposed to in a system with wind power.

It is still an area of research how a system with wind power should be combined with batteries and what type of batteries that is the most suited and economical. This uncertainty includes both which type of batteries and how long a particular battery can be expected to deliver the required performance.

9 Further work

Further work on the system will include four major items:
- Implementation of battery energy storage
- Improvement of the dynamic control of the system
- Implementation of a overall unit controller with system interface
- Overall system wide controller

The implementation of the battery energy storage is a key issue in order to obtain a final system. This include selection of appropriate batteries as well as developement of controllers to ensure both the supply of the load and good operation conditions of the batteries for a long battery life.

The improvement of the dynamic control involves especially the parallel operation of the unit with other generating units. It is important to ensure that the parallel operation avoids any intermachine oscillations and enables load sharing of both active and reactive power.

In order t have the stand-alone unit to be a flexible part of a power system it is necessary to have an overall unit controller with a system interface that can communicate with a system wide controller. Because the unit often will be the first generating unit to be installed a system wide controller capability will also be important. This include the scheduling of the unit and demand side management which can be very beneficial in such a small system in order to increase the utilisation of the wind energy.

10 Perspectives

There is a very large potential market for small wind turbines that can operate either as stand-aloen or as generating unit parallel with other either similar unit or other generating unit (pv, biomass or coventional diesel gensets)

There requirement for this potential market to materialise is that technical sound solutions are brought to the market. This requires units that have been developed with the difficult market in mind, have been extensively tested before they are shipped and where the performance has been documented.

It is therefore very important that the focus is not only on advanced technical solutions but also includes the aspects difficult operating conditions and documentation of the performance. A key issue is is also the development of criteria for performance assessment, testing and documentation.

Activities within this area will assist in providing the right, finalised technology to open this very large potential market.

11 Conclusions

A study has been executed on which stand-alone configuration is the most suitable based on the existing Gaia wind turbine. The configuration chosen includes an almost standard Gaia wind turbine, a back-to-back power converter configuration using standard massproduced power stages.

A controller design model for this configuration has been developed and applied to the design of the fast dynamic controllers of the system. A prototype has been built and the controller has been impemented using an advanced controller prototyping hardware/software solution that has enabled rapid and flexible controller development, implementation and testing.

The prototype unit has been tested at IET, Mita-teknik and Risø with differnt objective and in different system configurations.

The testing at Risø shows that the prototype is capable of operating both as a stand-alone unit and in parallel with a diesel genset. The tests have also shown that the dynamic control of both voltage and frequency is good as long as there is sufficient power available in the wind. The prototype can handle large steps up and down in the consumer load and the dump load of the ensures that the power balance of the system is maintained. The dc-link provides a very good separation between the wind turbine and the grid isolating the grid from the fluctuations of the wind power, when the is enough power available.

The prototype shows good potential as a commercial system, but it still requires development work. The most important is to include a battery energy storage. Also system functionality has to be implemented in a final system.

A well developed and tested system with documentation of performance will have a large perspective in the potential market for village power systems

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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.

Vision

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.

The efforts made **shall benefit** Danish society and lead to the development of new multi-billion industries.