Model Calibration of a Vertical Wind Power Plant using Dymola/Modelica

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Abstract

Wind energy has been used by mankind since ancient times and the last decades have seen large technological advancements in the field of wind turbines. One technology, although not very common, for harnessing the energy in the wind is the vertical axis wind turbine (VAWT).

For researchers and developers, identifying and assessing losses occurring in a wind turbine or in any electricity generating device is important for finding potential improvements. The losses can be dependent on a range of parameters. A method has been developed in this project, focusing on vertical axis wind turbines, with the purpose to assess and quantify these parameters using Dymola, a dynamic simulation tool. Models of the different components of a wind turbine have been developed to be used for calibration, that is, assessing the parameters. The calibration has been conducted by using the calibrate function in the Design Library in Dymola.

Some of the models are based on previous master thesis work which were translated from a previous version (SPOT) to the Electric Power Library (EPL). The data collected for the calibration were mainly synthetic data taken from a Dymola model of the entire wind turbine system. An approach using real measurement data from an AC/DC/AC-converter was also attempted.

The methodology for calibration of the parameters is shown to be functional for the rotor and generator component. The calibration of the converter is troublesome since only one parameter is affecting the outputs. Calibration using synthetic data is performed, however no calibration using real data were finalized.

Nomenclature

β	Pitch angle
ε	Error function
λ	Tip speed ratio
ρ	Air density
ρ	angular velocity
θ	Vector of parameters
A	Area
C_1-C_6	C_p equation coefficient
C_p	Power coefficient
D_M	Set of values that defines θ in a specific model
F_{switch}	Switching frequency converter
HSW_{nom}	Switching loss
M	Model structure
M^*	Model structure with restrictions on parameters
R	Radius
r	Resistance
r_s	Self reactance
snr	Signal to noise ratio
U	Wind speed
V_N	Positive scalar error function
V_n	Forward threshold-voltage
Z^N	Data set including inputs and outputs
AC	Alternating Current
DC	Direct Current

1 Introduction

Wind power is growing increasingly important for the world´s electricity generation. This is mainly due to that environmental policies and technological developments have made wind power more economically feasible. Additionally, the price volatility and the awareness of the finiteness of fossil fuels have boosted the rapid growth. In some countries in Europe, wind power will contribute to the replacement of electricity generated from nuclear and fossil fuels and also to meet an increase in electricity demand. The world´s demand for electricity is projected to increase from 17 200 TWh in 2009 to over 31 700 TWh in 2035 and 44 % of this increase is believed to come from renewable sources, dominated by wind and hydro [1].

Wind turbines can be divided into two categories, vertical axes wind turbines (VAWTs) and horizontal axes wind turbines (HAWTs). Up until now the large expansion of constructed wind turbines has consisted of HAWTs, VAWTs have so far not been able to compete. However, VAWTs have a potential market, especially for smaller sized turbines. Some advantages of vertical systems are independence of wind direction, lower noise and they handle strong and gusty winds better than horizontal systems. Additionally, the design of VAWTs is more simple and robust which reduces investment and maintenance costs[2][3].

The Faculty of Engineering (LTH), Lund University, has in cooperation with a local business constructed and mounted a prototype of a VAWT that is mounted on the roof of the M-building. This prototype is in focus for the models presented in this project and data from the turbine will soon be available for verification and validation of the models.

2 Wind Characteristics

All the wind resources of the earth originate from the sun and its uneven heating of the earth by solar radiation. This creates convective cells in the lower layers of the atmosphere and these circulations are greatly influenced by the seasonal variations of incoming solar radiation as well as the rotation of the earth. The uneven distribution of solar radiation creates variations in the atmospheric pressure field, causing air to blow from high to low pressure.

The mass flow rate in the wind can be expressed with the mass conservation equation below.

$$\frac{dm}{dt} = \rho \cdot A \cdot U \qquad (1)$$

$\frac{dm}{dt}$ is the mass flow rate of air flowing through an area A with the velocity U and density ρ.

The kinetic power of the flow can be expressed by:

$$P = \frac{1}{2} \cdot \frac{dm}{dt} \cdot U^2 = \frac{1}{2} \cdot \rho \cdot A \cdot U^3 \qquad (2)$$

The ratio between the mechanical power extracted by the turbine and the available power contained in the undisturbed air stream is known as the power coefficient, C_p[4].

$$C_p = \frac{\texttt{Rotor power}}{\texttt{Power in the wind}} = \frac{P_{rotor}}{\frac{1}{2} \cdot \rho \cdot A \cdot U^3} \qquad (3)$$

C_p is often expressed as a function of the tip speed ratio (TSR), λ. The tip speed ratio is the tangential velocity of the rotor blades tip in relation to the undisturbed wind velocity. TSR can be expressed with equation 4

$$\lambda = \frac{\texttt{Blade tip speed}}{\texttt{Wind speed}} = \frac{\omega \cdot R}{U} \qquad (4)$$

where ω is the angular velocity of the rotor and R is the radius of the rotor.

3 Components of in a Wind Turbine

Regardless if working with a VAWT or a HAWT most of the components are similar. The components treated here are the rotor, the generator and the converter.

3.1 Rotor

The rotor is considered to be the first part of the turbine since it starts the energy conversion of a wind turbine by converting wind energy to mechanical energy. Equation 2 describes the energy in the wind, however all of that energy can not be extracted which is expressed by equation 3. When modeling vertical wind power plants, a common way of describing the power coefficient is shown in equation 5

$$\begin{cases} C_p(\lambda, \beta) = C_1 \left(C_2 \lambda_i - C_3 \beta - C_4 \right) e^{-C_5 \lambda_i} + C_6 \cdot \lambda \\[2mm] \lambda_i = \dfrac{1}{\lambda + 0.08 \cdot \beta} - \dfrac{0.035}{\beta^3 + 1} \end{cases} \qquad (5)$$

where β is the pitch angle (the angle between the blade chord and the tangent to the rotation) and C_1-C_6 are parameters determined by the shape of the rotor [2].

3.2 Generator

The generator converts mechanical energy to electrical energy. In the generator, electromagnetic induction creates an electrical voltage. In the wind power unit the shaft is connected to a magnetized rotor which, when rotating, induces a voltage in the windings.

Asynchronous motors have been the most used motor for wind energy applications, however, the permanent magnet synchronous machine (PMSM) is getting more and more common. This is due to the increased popularity of gearless i.e. direct-driven wind turbines, avoiding expensive gearboxes that need much maintenance. Figure 1 illustrates a wind turbine system using power electronics instead of a gearbox. The PMSM consists of a rotor with permanent magnets and a stator with a three phase winding.
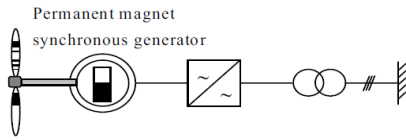

Figure 1: Wind turbine system with permanent magnet synchronous generator[5]

3.3 Converter

Inverters (DC to AC) and rectifiers (AC to DC) are both types of converters and are important parts of many electrical devices including wind turbines. They make it possible to control and alter the voltage and current in an efficient manner. The power electronic converter consists of, diodes, transistors, inductors and capacitors usually in combination with PWM (Pulse Width Modulation). A circuit diagram of a three phase converter is shown in figure 2, the transistors T_1 to T_6 are controlled by a modulator unit using PWM.

4 Modeling

Modeling is the production of equations and algorithms that can predict the behavior of systems. For small and simple models, equations that describe the system can be written down. This approach is too time consuming and demanding if larger systems are defined. The problem can be solved by having parts of the system already modeled and using them to build a system. This is called component-based modeling. Dymola, the tool used during this project enables component based modeling. The mechanical components
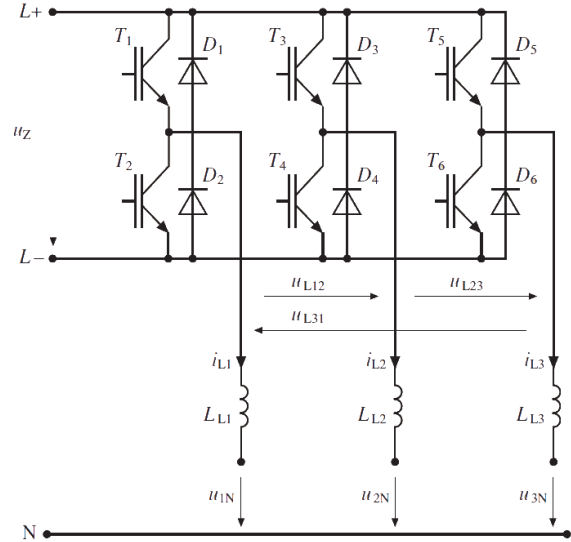

Figure 2: Circuit diagram of a three phase converter with transistors, diodes and inductances [6]

used are to be found in the standard Modelica Library and the electrical components used are from the Electric Power Library (EPL).

Models can be created in some different ways. One option is to use well known physical relations such as Kirchhoff´s voltage law, stating that the potential differences around an electrical loop has to be zero and Kirchhoff´s current law stating that the sum of all currents to a node has to be zero to create a model. This is referred to as physical modeling. If the laws of a system are not well known one can use the system identification method that relies solely on measurements of inputs and outputs. A third case, the one focused on in this project, is a combination of the two mentioned. A model is made using known physical relations and measurements are used to estimate unknown parameters in the model[7]. By conducting the calibration procedure in this way, it is possible to identify parameter values that have a real physical meaning. An aim of this project is to calibrate the parameters of an existing model in order to assure that it in a reliable and accurate way describes the actual wind turbine.

5 Calibration

Parameter Estimation When a specific model structure M has been created it can be altered by changing the parameter set θ, the parameters are restricted by $\theta \in D_M \subset R^d$. The restriction of θ can be a maximum and a minimum value of a parameter, in special cases it can also be restricted to e.g. integer numbers. The set of available models are then defined

by

$$M^* = \{M(\theta)|\theta \in D_M\} \qquad (6)$$

Models in the set will predict the future in its own way, that is, give different outputs. To identify parameters included in a system, measurements have to be done. The dataset can be denoted as Z^N,

$$Z^N = \{u(t_0), y(t_0), ..., u(t_N), y(t_N)\} \qquad (7)$$

where u are inputs to the system, y are outputs from the system and N is the number of datapoints for each input/output. Apart from the parameters θ, the equations of the model are known and defined by M. The unknown parameters of the system can then be tuned to make the equations produce results which fit the outputs in the measured data as good as possible[8].

To evaluate how well a model with a specific set of parameters estimates the results, an error function, ε, is commonly used.

$$\varepsilon(t, \theta^*) = y(t) - \hat{y}(t|\theta^*) \qquad (8)$$

where θ^* is a suggestion for parameter values and $\hat{y}$ is the output from the model using the suggested parameters. One of the most commonly used ways of evaluating the value of the errors (8) is the least square method described in equation 9[8].

$$V_N(\theta, Z^N) = \frac{1}{N} \sum_t^N \frac{1}{2}[y(t) - \hat{y}(t|\theta)]^2 \qquad (9)$$

V_N generates a positive scalar value that is related to the errors at each point, by choosing the parameters θ correctly it can be minimized.

6 Experimental Setup and Results

6.1 Method

The method developed in this project can be described as follows. Firstly, data are collected, either synthetic or real. The synthetic data are collected from a developed wind turbine model (referred to as the main model, see figure 3) including all its components. Submodels (referred to as test benches) of the components are constructed to be used for calibration including signal connectors to be used for inputs, see figures 5,9 and 12. The real or synthetic data are collected, and used as inputs to run the test benches. The difficulty developing the test benches is to make the submodel behave in the same way as the whole system. For example, in the generator test bench (see figure 9), the voltage

source on the right side in the figure has to behave in a way that it corresponds to the influencing characteristics given by the converter and grid component in the main model. The Design Library in Dymola contains functions and a GUI (graphical user interface) that is used for calibration and optimization of systems. Analyzing the influence of tuning parameters is done using the perturbParameters function of the Design Library, giving an indication of how to use the tuners in the calibration, see figure 6. Subsequently the calibration is done using the calibration function of the same library.
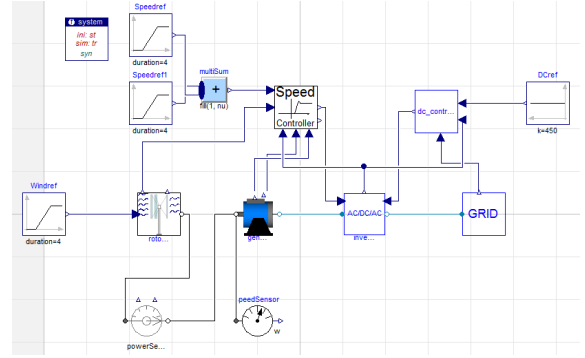

Figure 3: The wind turbine main model

6.2 Data

The synthetic data used are collected from simulations of the main model. When generating synthetic data it is important that the data contains the information and dynamics necessary for identifying and assessing the tuning parameters when calibrating.

Rotor Dataset For the rotor case the parameters of the Cp equation (5) are analyzed and it is important that the λ-value changes throughout the data. This can be achieved by keeping the rotational speed constant while the wind speed is varied or the other way around, keeping the wind speed constant and varying the rotational speed. By running the main model shown in figure 3 with a constant wind speed of 8 m/s and having the speed controller set to 100 rad/s, a dataset containing wind speed, rotational speed and mechanical power is obtained. This simulation results in a λ-value ranging from 0 to 13 which in this case is the interesting region since the Cp equation is close to constant outside this interval. By introducing noise to the values the case can be made similar to real measurements. For this calibration, two sets of noise data is produced, with two different *signal − to − noise − ratios* or *snr*. A lower *snr* value means larger disturbances.

Generator and converter data set No real measurement data was available for the generator and instead synthetic data was used for the calibration of the component. Synthetic data were collected by simulating the main model, shown in figure 3. The rotational speed of the rotor and the wind speed is changed throughout the data collection. The wind speed and the reference rotational speed are inputs, the rotational speed is output, all three are shown in figure 4. The simulation case used for the data collection of the converter is the same as the generator case, however other values are collected.
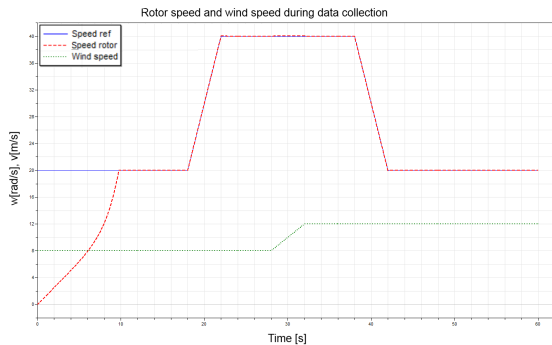
Figure 4: Reference rotational speed, rotational speed of rotor and wind speed when simulating the main model for the data collection of the converter and generator experiments

6.3 Rotor

The test bench for the rotor component is shown in figure 5. The test bench uses wind speed and rotational speed as inputs. In the rotor calibration case the resulting power output is used as reference. The power is measured as positive when flowing from left to right in the figure.
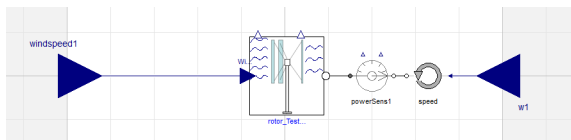

Figure 5: Rotor test bench used for calibration of the rotor.

The parameters which are to be calibrated in the rotor model are the coefficients in the C_p-equation, see equation 5. As a first step, a perturbation of the parameters in the equation is performed to get an idea of which parameters are influencing the result the most. The perturbation function increases the value of the

parameters with 10% in turns and plots the result. As indicated by figure 6, the parameters C_2,C_4 and C_5 are influencing the result the most. They are lumped together to form a parameter group 1. Parameters C_1, C_3 and C_6 are referred to as parameter group 2. The parameters are put into groups of three because the calibration tool can not manage to estimate all six parameters at once.
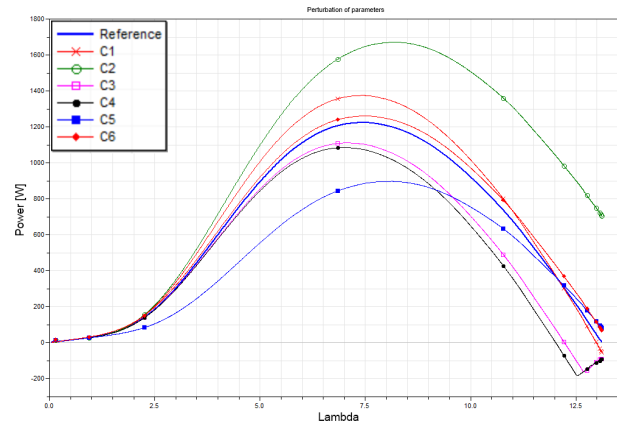

Figure 6: The figure shows how the parameters $C_1 - C_6$ affect the power output of the system at different λ values

To perform the calibration of the rotor, the values of the parameters $C_1 - C_6$ are all slightly changed from their default values, to resemble initial guesses. The calibration process is split up into two cases each containing two steps, the first case is illustrated in figure 7. The start values of all six parameters are used in the first calibration step where parameters in group 1 are calibrated. In the second calibration step the parameters of group 2 are calibrated using the new values for parameters in group 1. In the second case, the parameters of group 2 are calibrated before the parameters in group 1.
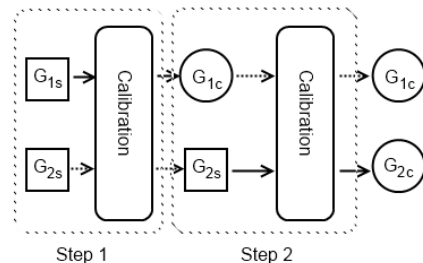

Figure 7: Block view of the first calibration case. The subscript s and squares indicate starting values of parameters, subscript c and circles indicate calibrated parameters

The two cases are run using datasets with different noise levels, referred to as no noise, *snr*80 and *snr*60 in figures and tables.

In figure 8, C_p-curves using different parameter values are shown. The values used are from the first and second case (snr80) as well as using start and default values. It should be noted that there is a small difference between the two cases. More details can be found in [9].
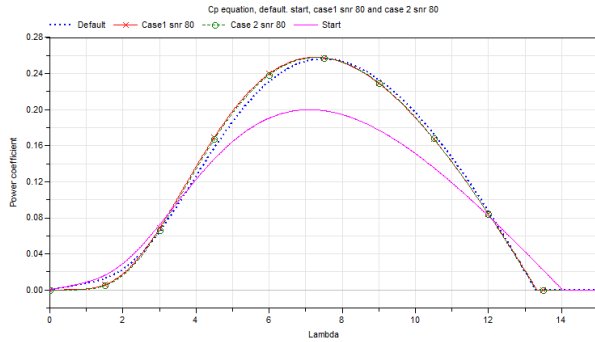

Figure 8: The figure show different C_p-curves. The dotted blue curve uses the default calues, the pink curve uses the start values, the red curve with crosses uses values from the first calibration case (snr80) and the green curve with circles uses values from the second case (snr80).

6.4 Generator

The generator test bench can be seen in figure 9. The rotational speed input determines the rotational speed of the rotor which gives the voltage induced by the generator. The torque of the rotor gives the current, in the test bench the torque is not set and thus allowed to vary (if not allowed to vary, the test bench would be overspecified). Other inputs are the nominal voltage, phase and the electrical frequency.
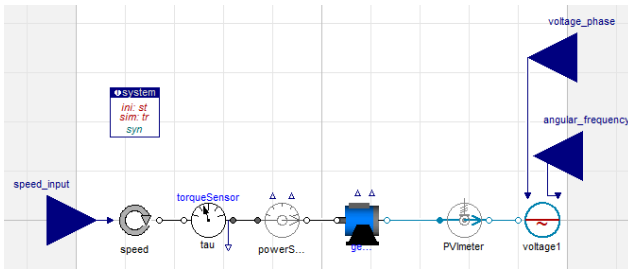

Figure 9: Test bench for the generator component

The generator component contains five tunable parameters which should affect the power output of the
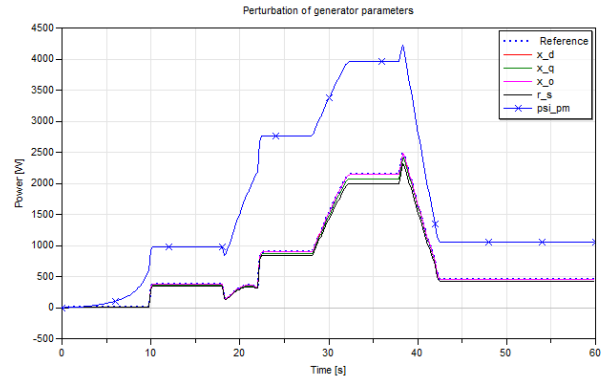

Figure 10: Results from the perturbation of the parameters in the generator.

generator. These parameters influence the magnetization, reactance and resistance of the PMSM. A perturbation test was done, the results from the test is shown in figure 10. It shows that the parameters psi_{pm}, r_s and x_q are the most important and are thus lumped together forming a tuning group. psi_{pm} is the magnetization, r_s is the resistance in the armature and x_q is the reactance in the reactive frame. If calibration of the other parameters, x_d (reactance active frame) and x_o (reactance o frame) are attempted, the values of these parameters tend to go to the upper or lower limit, this is due to their neglectable influence of the output. This might not be the case if other dynamics and sizes of the inputs were used in the simulation.

Due to the lack of real data for the generator, the calibration of the generator model was made with synthetic data. Before being used in the calibration, all parameters are slightly changed to resemble initial guess values, the changed values are referred to as start values.

In figure 11 the resulting electric power curve of the generator test bench can be seen, before and after calibration using the data without noise. The upper black curve is the result when simulating using start values for the parameters. The blue-dotted curve is the reference output from data, the red curve is resulting output after calibration.

When calibrating the generator it was found that the output was mainly dependent on three out of five tunable parameters. To be able to determine the other two it might be useful to drive the main model in another way, as the parameters might be more important at other speeds or powers. More details can be found in [9].
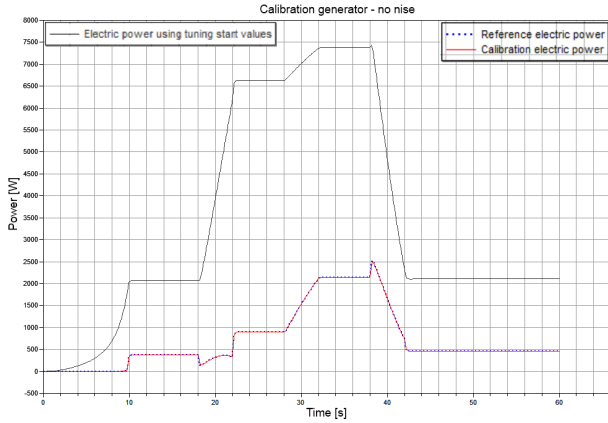
Figure 11: Calibration of generator test bench

6.5 Converter

The test bench for the converter is shown in figure 12. The left and the right side of the test bench consist of AC-voltage sources which are simulating the dynamics of the generator and the grid respectively. The values of nominal voltage, phase and frequency can be set as input values from a measurement file. Between the AC-voltage sources, an AC/DC/AC-converter block is connected. The inputs to the AC/DC/AC block are control signals.
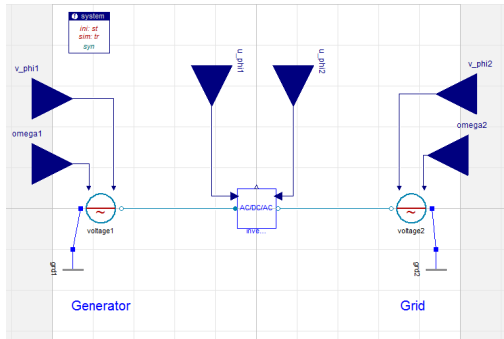

Figure 12: Test bench for the converter component

A parameter perturbation is performed in order to indicate which parameters are affecting the results and in what way. The parameters available for the converter is the forward threshold-voltage, V_f, the switching loss, HSW_{nom} and the switching frequency, f_{switch}. The parameters of the inductors (the AC/DC/AC block includes two inductors) are the resistance, r, and the reactance, r_s, can also be included as tuning parameters. However, the parameter sweep shows that the parameters HSW_{nom} and f_{switch} do not affect the results. This is due to a bug in the structure of the EPL converter component (the mentioned parameters affect the heat loss but the energy lost due to heat is not seen as

a loss in electrical energy). The power balance is thus not correct. In order to be able to use these parameters as tuners the component has to be modified.

The results from the parameter perturbation can be seen in figure 13. All of the parameters seem to have similar effect on the output but on different scales. This indicates that it will be difficult to tune many parameters at the same time.
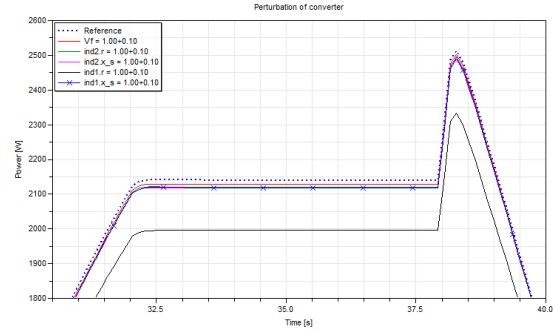

Figure 13: Power on the grid side of the converter test bench when parameters are perturbed. The plot is zoomed to the 30-40 seconds interval in order to show the differences.

The calibration of the converter is done with V_f as the only tuner. This is because the other parameters mentioned affects the results in a similar way as V_f and make the results unreliable.

A calibration of the converter was conducted by introducing noise to the same synthetic measurement signals as before and using the default values on all parameters except V_f. The start value of V_f is set to 6 V and the default value of V_f is 1 V. The *snr* values used for this calibration was 80, 100 and 120, as well as one calibration where no noise was added. The result from the calibration using *snr* 100 is shown in figure 14.

The calibration gives good parameter values and simulation results but requires that the other parts of the system are well known. Components such as the inductances have to be close to equal between the main model and the testbench. More details can be found in [9].

Real data Real data was collected from a laboratory set-up of the back to back AC/DC/AC converter, the device will later be used in the LTH test unit. Since the test unit was not operating at the time of this project, the converter data collection was done in the laboratory. A three phase generator was used and the generator rotor was driven by a DC-motor. The generator was connected to the converter which on the other
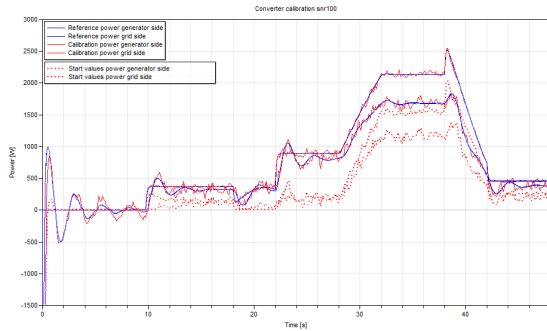
Figure 14: Simulation from converter testbench using data with *snr*100. Blue lines show reference values, red dotted lines show simulation outputs using start values and the red lines show simulation results after calibration

side was connected to the grid. By having access to the control system of the converter and with help from staff at the university, data could be collected.

Since the available values differ from the measurements done in Dymola, the testbench is altered slightly. The version used for real measurements is shown in figure 15.
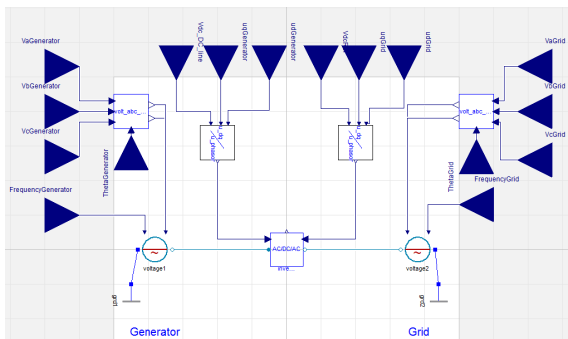

Figure 15: Test bench used for the real data set

Some effort has been put into filtrating the measurement data and inserting it into the test model described in figure 15. However, no realistic results have been achieved when doing this. A possible reason for this can be that the model structure is too far from the real system. Other possible sources of error can be that the data have been filtered in an incorrect way or that the inputs are treated in the wrong way. Another more fundamental problem with the testbench is that many inputs are needed and that a small error in one or two of the signals can result in a large error. However if a good filtration and implementation of the data is done we belive that the method will work.

7 Conclusion

The purpose of this project was to calibrate a model of a vertical axis wind turbine to data collected from a prototype turbine located at Lund University. In order to do this, a previously developed wind turbine model [2] based on the SPOT-library was converted to the EPL. This was followed by the development of test benches for the calibration of the rotor, the generator and the converter. The calibration against real data were preceded by a calibration against synthetic data. Calibrations were performed, using both disturbed (with added noise) and undisturbed data. The rotor model and the generator model contained several parameters suitable for tuning and the calibration against synthetic data can be regarded as successful. For the converter model, only one parameter was found suitable for tuning. To be satisfied with the converter calibration, at least one or two more parameters should be tunable. Real data were taken from the AC/DC/AC-converter. The data have been examined and filtered as a preparation for calibration.

Since calibration against real measurement data has not been succeeded, the origin of the energy losses have not been identified. This is partially due to the non-availability of measurements from other components other than the converter. The other components should be easier to calibrate against real measurement data since they do not have control signals as inputs. However, the experience from the converter case shows that even if data from other parts of the plant are collected, a considerable amount of work is needed before calibration using real measurement data can be finalized. To be successful with calibration using real data, it is important that all components in the test bench are accurately modeled. Efforts should also be put into filtering the measurements in a good way.

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