Modelica Wind Turbine Models with Structural Changes Related to Different Operating Modes

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Abstract

Investigation of large technical systems by simulation of long time periods requires effective methods. One possibility to handle such problems is the implementation of simulation models which use suitably simplified descriptions of the real behaviour of technical systems. In some cases, however, operating modes with highly dynamic processes have to be investigated. These processes may occur suddenly within long time periods of behaviour with none or very low dynamics, which can be considered as static behaviour. In such cases, it would be advantageous to be able to switch from the simplified model mentioned above to a more complex model describing the real behaviour in more detail.

In the paper, four different Modelica models for wind turbines are presented. On the one hand, two static models – the “simple static model” and the “static mechatronic model” – are shown representing two different instances of a simplified behaviour. On the other hand, two dynamic models – the “mechanical model” and the “dynamic mechatronic model” – are presented which describe the dynamic behaviour of a wind turbine in more detail. Furthermore, a method will shortly be proposed to exchange one model with another one at certain points in time (see also [5]). Such structural changes allow the application of that particular model of behaviour which suits the current situation best. Using this method, the simulation of a complex mechatronic system like a wind turbine can very effectively be carried out. Additionally, some simulation results will be given to show the advantage of the method proposed.

1 Introduction

The proportion of renewable energy in industrial countries is growing with increasing speed. The usage of wind turbines plays an important role among these forms of power generation. A wind turbine is a complex mechatronic system consisting of mechanical parts, electrical components, and a very complex control strategy.

Investigation of wind turbines using numerical simulation becomes more and more important. Therefore, design, construction and scheme of operation of the turbine under investigation must be taken into account. The level of detail which is necessary for a special model depends on the questions which are to be answered by the simulation results. On the one hand, we have to distinguish between models of single turbines and whole wind parks. In the paper, model types suitable for both situations will be presented. On the other hand, behavioural models describing only the flow of electrical energy stand in opposition to models which use voltage and current as time-depending electrical quantities. Again, both types of models are introduced here.

Every type of a wind turbine model presented in this paper is suitable for a well determined level of detail. Every model uses a particular set of physical quantities to describe the corresponding physical behaviour. All models are equipped with interfaces that allow a simple exchange of one model with another one at arbitrary points in time. This property makes it possible to investigate a complex mechatronic system like a wind turbine as exact as necessary depending on the current situation of operation simply by using the actually best suiting model of behaviour.

In the following section, the general logical scheme of operation of the construction type of wind turbine considered in this paper is outlined. The four models are presented in section 3. Some simulation results are given in section 4.

2 Scheme of operation

There is a great variety of types of existing wind turbines (see e.g. [6], [7], [8], [14]). All of them have advantages and disadvantages. However, the most widely used type of a wind turbine is equipped with a so-called pitch control and an asynchronous generator ([6], [9]). With such a turbine, the energy harvested from the wind can be influenced by controlling the pitch angle which is the angle of the rotor blade across

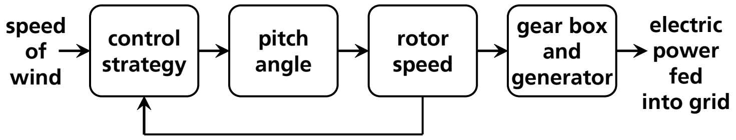

Figure 1: Wind turbine's logical scheme of operation

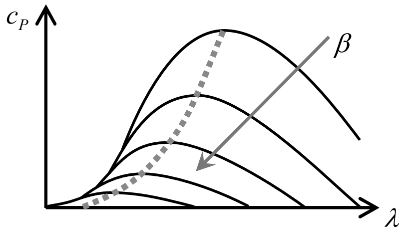

Figure 2: Array of curves of power coefficient

its longitudinal axis. The simplified logical scheme of operation of such a wind turbine is shown in **Fig. 1**.

The controller always tries to harvest as much as possible energy from the actual wind. To this end, the controller uses the actual speed of wind and the actual speed of rotor as input signals to calculate the pitch angle. This angle then again mainly determines the angular momentum acting on the rotor. Hence, the rotor speed and, therefore, the speed of the electric generator, is influenced by the controller. Going into more detail, the controller endeavours to put the point of operation into a maximum of the power coefficient's array of curves, which are exemplarily depicted in **Fig. 2**. In this figure, c_P is the power coefficient, λ stands for the speed ratio between blade's tip and wind ($\lambda = R\omega/v_W$, R – radius of rotor, v_W – speed of wind), and β denotes the pitch angle. In **Fig. 2**, five curves of the whole array for fixed values of β are shown (solid lines). The dotted line depicts an approximation of the connecting curve of the maximum points of all c_P-curves using the pitch angle β as a parameter. Using such an array of curves, the controller chooses a pitch angle which determines the rotor speed in such a way that as much as possible energy can be harvested from the actual wind. A realistic array of c_P-curves – implemented in the models of the next section – was taken from [15].

3 Wind turbine models

In this section, four different models of a wind turbine characterized by a pitch angle and an asynchronous induction generator are presented. All these models use the speed of wind as an input variable. Number and physical quantity of the output variables depend on the particular model. The direction of the wind (and the variation of the direction) is not considered in any turbine model presented here. Hence, investigations of changing wind directions, their measurement, as well as the dynamic behaviour of a turbine when rotating across its vertical axis (i.e. when "turning into the wind") are not included in the models considered in this paper.

The range of applicability of every model depends on its level of detail. The simplest one is called "simple static model". It is suitable for energy flow considerations of whole wind parks. The "mechanical model" allows simple dynamic investigations of the mechanical part of a single turbine. With both models, no interaction between the turbine and the energy grid can be considered. Compared with this, the "static mechatronic model" and the "dynamic mechatronic model" are physical models with a more sophisticated design. They use characteristic quantities of both mechanical and electric domain. Because of the usage of electric quantities like current and voltage of the generator, many interations between turbine and energy grid can be taken into account. Hence, these models are well suitable for investigations of the mutual influence of different turbines within a wind park.

3.1 Simple static model

The "simple static model" is the simplest possible model describing the physical behaviour of a wind turbine. The only input is the actual speed of wind. The output quantity is the electric power which can be harvested from the actual wind under the assumption of an optimal operation of the turbine's controller.

The relation between speed of wind and electric power is shown in **Fig. 3**. It consists of two main areas: the partial load range and the full load range (see e.g. [16]). Within the partial load range, the speed of wind is slower than a value v_{Wnom} which is called the nominal speed of wind. Here, the electric power is a cubic function of the speed of wind. The full load area is the range

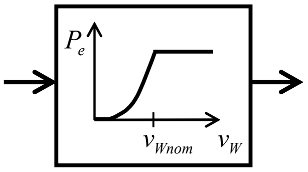

Figure 3: Characteristic curve of the "simple static model"

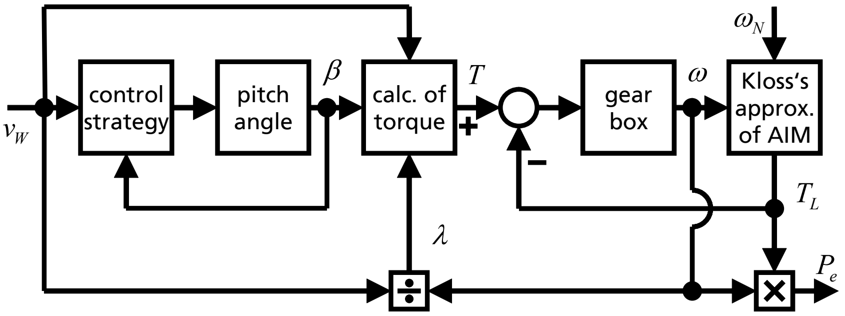

Figure 4: Logical scheme of the "mechanical model"

of wind speeds which are higher than the nominal value. Here, the electric power does not depend on the actual speed of wind. Instead, it is assumed to be constant. Finally, the electric power is set to zero for both very small values and very high values of v_W. Within these ranges, the system is not in operation because of inefficiency and safety, respectively.

The "simple static model" describes a simple relation between speed of wind and electric power without any dynamics. No more characteristic quantities of a turbine are used. Therefore, the model can only be used if all components of the turbine work correctly. Of course, behavioural simulations with this model are really very fast. Hence, the model is suitable for considerations of energy flows with single turbines as well as with whole wind parks (consisting e.g. of 100 or more installations). The determination of bottle necks within the energy grid while assuming typical wind profiles for the park location may be of special interest in this context.

3.2 Mechanical model

The "mechanical model" implements the main properties of the turbine's mechanical subsystem. Like with the "simple static model", the actual speed of wind is used as the only input and the electric power is the output. In the model, some dynamics of mechanical components are included.

The appropriate logical scheme is shown in **Fig. 4**. The pitch angle is governed by the controller according to the maximum power coefficient principle (see **Fig. 2**). Depending on the actual speed ratio λ between the blades' tip and wind, the nominal pitch angle is choosen so that the power coefficient becomes a maximum value (i.e. the point of operation is located on the dotted line in **Fig. 2**). After a change of wind speed, the pitch angle has to be readjusted. This has to be done in consideration of the limited angular velocity and acceleration of the rotor blades. The profile of angular velocity assumed here is a so-called trapezoid profile (see **Fig. 5**, where the angular velocity $\dot{\beta}$ is plotted against time t). It consists of an acceleration region, a range with constant speed and a deceleration region. Using this profile, the pitch angle is changed if necessary. This way, the so-called pitch dynamics is included in the "mechanical model". Then, the actual pitch value influences the driving torque via the array of curves of the so-called torque coefficient. A sketch of this array is shown in **Fig. 6**. In this figure, c_T denotes the torque coefficient, where λ is again the speed ratio and β is the pitch angle. The realistic array of c_T-curves implemented within the "mechanical model" is taken from [15]. The same array is also applied within both mechatronic models (see sections 3.3 and 3.4). Using the actual value of c_T at a time, the driving torque T is calculated according to

$$T = c_T \frac{\rho}{2} \pi R^3 v_W^2 \tag{1}$$

(ρ – air density). After computation of driving torque, the rotor acceleration is determined using the following torque balance

$$\tilde{J}\dot{\omega} = T - T_L - \kappa\omega \tag{2}$$

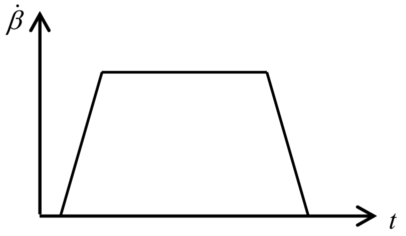

Figure 5: Profile of pitch angle velocity

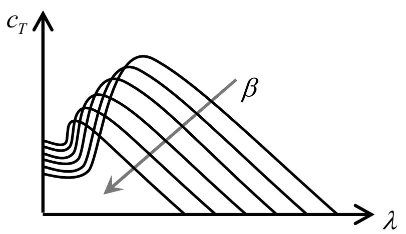

Figure 6: Array of curves of torque coefficient

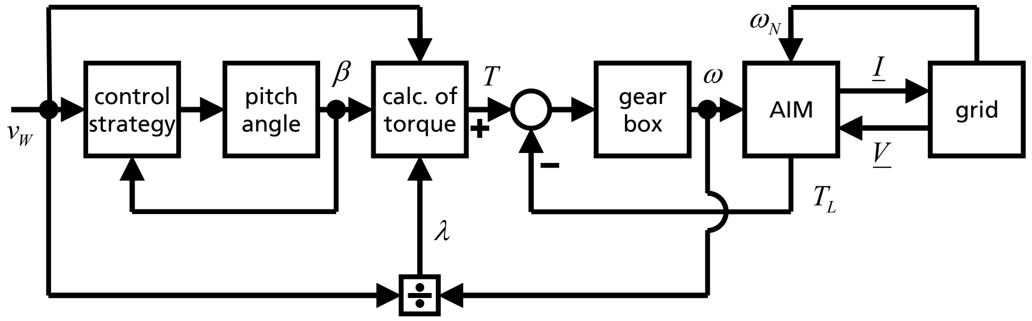

Figure 7: Logical scheme of the “static mechatronic model”

($\tilde{J}$ – rotor’s moment of inertia related to gear box ratio, T_L – load torque, κ – damping coefficient). For this purpose, the generator’s load torque is calculated by Kloss’s approximation for an asynchronous induction machine (see e.g. [13])

$$T_L = \frac{T_B}{s/s_B + s_B/s}, \tag{3}$$

where $s = (\omega_N - \omega)/\omega_N$ denotes the slip (T_B – breakdown torque, s_B – breakdown slip, ω_N – grid’s angular frequency). Finally, the electric power P_e fed into the grid (the model’s output) is assumed to be equal to the mechanical power (a given efficiency factor may be taken into account).

The “mechanical model” describes the electrical power fed into the grid as a function of the speed of wind. This description includes the main dynamics of the wind turbine’s mechanical subsystem and takes into account the correct calculation of the driving torque using the pitch-depending torque coefficient. Therefore, many of the mechanical characteristic quantities are provided for a dynamic simulation by the model. The model is suitable for investigations of the dynamic behaviour of the mechanical part of a single wind turbine if the dynamics of the electrical part is either negligable or not of interest. An example for such investigations is e.g. the problem of finding the optimal time interval for measuring the speed of wind and – corresponding to this question – the optimal strategy for controlling the pitch angle.

3.3 Static mechatronic model

The “static mechatronic model” extends the “mechanical model” mentioned before by an electrical subsystem. Like with both models before, the actual speed of wind is used as an input. But additionally, the voltage of the energy grid is used as input, too. The output is the electrical current fed into the grid. Therefore, the mechatronic models (the static one here and the dynamic one in the next section) implement a fully bidirectional connection between the turbine’s electrical subsystem and the energy grid.

The appropriate logical scheme is shown in **Fig. 7**. Most of the mechanical subsystem is realized in the very same way like in the “mechanical model”. This concerns the pitch angle adjusting with its dynamics, the calculation of driving torque, and the determination of rotor’s acceleration via torque balance. Only Kloss’ approximation of an asynchronous induction machine is substituted by an equivalent circuit.

The electrical subsystem of the “static mechatronic model” realizes only its steady state behaviour. Considering only steady states, the phasor description of sinusoidal quantities leads to an adequate mathematical model for the electrical subsystem (see e.g. [2], [12]). An appropriate equivalent circuit for the asynchronous induction generator (see **Fig. 8**) is used. Please note that all underlined symbols in this figure denote phasors ($\underline{V}$ is a voltage phasor, $\underline{I}$ is a phasor of an electric current – both are also used in **Fig. 7**) whereas R, L, ω, and s denote ohmic resistor, inductance, angular frequency, and slip, respectively.

The electrical subsystem is implemented using a special Modelica library for phasor domain-based systems. This library was already presented at the last Modelica conference (see [3]). Hence, details to the phasor description and the special library shall not be given here. In [3], we also pointed out that – with such a model – a so-called quasi-stationary mode can be described under some weak assumptions. With a wind turbine, such an operating mode is characterized by slow dynamics of the mechanical subsystem and a sequence of steady states of the electrical subsystem. See [3] for more details.

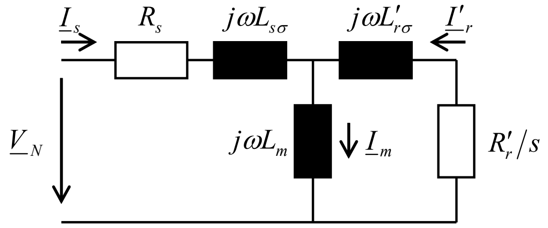

Figure 8: Equivalent circuit of an asynchronous induction machine using phasor description

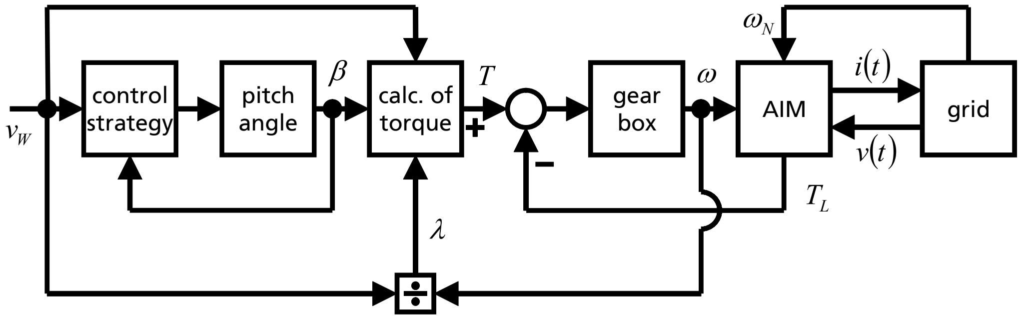

Figure 9: Logical scheme of the “dynamic mechatronic model”

The “static mechatronic model” realizes a complete mechatronic system of a wind turbine consisting of a controlling part, a mechanical part, and an electrical part. Due to the application of phasor domain-based electrical quantities, the high dynamics of the electrical subsystems (usually the 50 Hz or 60 Hz sinusoidal oscillations) do not carry any weight concerning dynamic simulations of the whole system. Hence, this model is well suitable for investigations of the behaviour of many turbines of a wind park, especially for considerations of mutual interactions between the turbines and the grid or between different turbines connected with the same part of the grid.

3.4 Dynamic mechatronic model

The “dynamic mechatronic model” is the most complex one described within this paper. Like with the “static mechatronic model”, the actual speed of wind and the voltage of the grid are used as inputs while the output is the electric current fed into the grid. Hence, the model implements a fully bi-directional connection between turbine and grid.

The appropriate logical scheme is shown in **Fig. 9**. The mechanical submodel is completely equal to that of the static mechatronic model. The important difference to this model mentioned above is the implementation of the fully dynamic behaviour of an asynchronous-type generator. Please note that time-depending electrical quantities ($v(t)$, $i(t)$) are used in **Fig. 9** instead of phasors. In the usual case of a three phase grid, such a model of a generator consists of six time-depending electrical currents (three stator currents and three rotor currents) which require, of course, six differential equations to calculate them. One extra (algebraic) equation is necessary to determine the load torque produced electrically (see e.g. [4]). Because of the generator equations and the sinusoidal electrical quantities appearing there, high dynamics is involved in the turbine’s model. Hence, a dynamic simulation using such kind of model needs small solver steps. This fact leads to time-consuming simulation experiments.

The “dynamic mechatronic model” realizes a fully dynamic model of the mechatronic system of a wind turbine. Both subsystems (mechanical and electrical) are described by differential-algebraic equations. Merely, the power electronics with its switching effects is neglected. Hence, this model is well suitable for investigations of the behaviour of a single wind turbine taking into account many dynamic effects from mechanical and electrical domain. Especially, the interaction between a wind turbine and the energy grid can be considered in a detailled way with this model. Enormous simulation times because of the high dynamics of many electrical quantities are a disadvantage of this model.

3.5 Model exchange

Investigations of interesting questions concerning wind turbines often require dynamic simulations over very long time periods. To carry out such analysis in a conveniently effective manner, special simulation methods are necessary. The main influence to the dynamic behaviour of a turbine is exerted by the wind. On the one hand, there are long time periods with only few variations of its speed. Within these periods, a simulation model consuming as less as possible calculation time is of interest. On the other hand, there are short time intervals, where the speed of wind is changing very fast. In such critical cases, the compliance of given conditions of operation is very important. Hence, a dynamic simulation with a sufficient level of detail is of essential importance.

To handle the problem of changing demands to the level of detail of a model, the exchange of one submodel with another one at proper points in time is proposed. The points in time of a necessary change from the simple model to the detailled one can e.g. be found by monitoring the acceleration of the wind (i.e. the variation of the speed of wind). If the accerelation value exceeds a well defined border then the model change is necessary. Switching on and off of main consuming devices may also be of interest. Here, the points in time are predetermined. The switching back from the de-

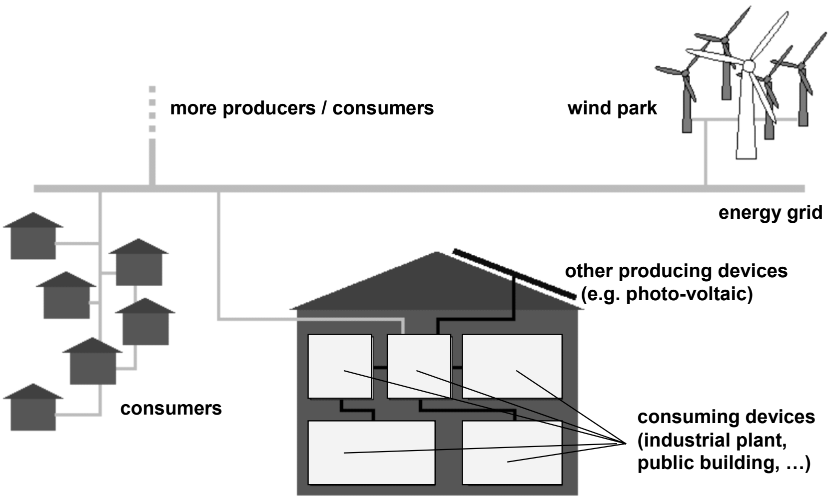

Figure 10: Energy grid with wind park and consumers

tailled model to the simple one may be carried out if the dynamics of the complete system is faded away.

Both switching operations – from low level to high level of detail and vice versa – have to be performed taking into account the possibly changing number of differential and algebraic equations. That means that three steps are to be done:

- The dynamic simulation may be terminated at a certain point in time.
- The actual state of the old model has to be transformed into the new model.
- Consistent initial values for the complete set of equations of the new model have to be found.

For more information concerning this way of realisation, please refer to [5].

3.6 Model implementation

The models presented here have been implemented using the Modelica Standard Library, extended by some physical relations and algorithms in order to provide an arbitrary wind profile, to model the whole turbine's control strategy, to handle the pitch angle adjustment, as well as to carry out some approximations concerning the coefficient's arrays of curves (power coefficient, torque coefficient) included in the models. Additionally, a Modelica library for phasor domain-based description (see [3]) is used in case of the "static mechatronic model".

Unfortunately, a real switching between different levels of detail – i.e. an exchange of model parts in such a way that the equations of the "inactive" part at a time are excluded from the equation set of the numeric solver – is not supported by most Modelica simulators until now. For this reason, parts of the following results are achived by a kind of "step-wise" simulation.

4 Simulation results

Considering the four models of wind turbines presented in section 3, the mechatronic models are the most interesting ones. Therefore in this section, some simulation results are shown which were reached using these two models.

Please imagine a little wind park connected to some consumers. A similar (but simplified) scenario is shown in **Fig. 10**. Dynamic simulations of such a complex system using the "dynamic mechatronic model" would require a huge simulation effort. An investigation of the system's behaviour for, say, one year would hardly be possible. The only way to earn some results within a reasonable time effort is to operate with changing submodels. To this end, the "static mechatronic model" and the "dynamic mechatronic model" are alternately applied. Depending on the actual situation, either the static model or the dynamic model is used to describe the complete system.

4.1 Functionality test

First, a functionality test for the two mechatronic models is presented. This this end, a rapid change of speed of wind – a zooming ramp which is nearly a step – is assumed as input signal at time $t = 1\,\mathrm{s}$ (see **Fig. 11**). Such a sudden step is admittedly very unlikely for a real wind turbine. But the functionality test was intentionally performed under extreme conditions.

The step responses of the two wind turbine models are shown in the following figures (**Fig. 12** ... **Fig. 15**). In all these figures, the prefix "smm" (corresponding to a solid line) means that the result originate from the "static mechatronic model" while the string "dmm" (corresponding to a dashed line) indicates the "dynam-

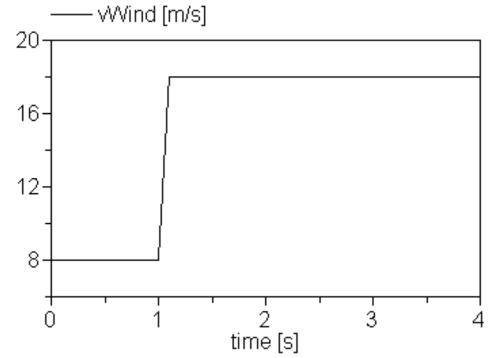

Figure 11: Sharp change of wind speed

ic mechatronic model”. In **Fig. 12**, the time progress of the pitch angles is depicted. Both angles are very fast justified by the controller from 0° to 20°. The small difference of the ramp’s increase is caused by the fact that the controller uses both the speed of wind and the rotor speed as input signals. The rotor speed is shown in **Fig. 13** for both models. Here, the different behaviour of both models is illustrated. The static model calculates significantly higher values than the dynamic model. This is valid in the time interval of the changing pitch angle as well as in the time of constant rotor speed. The same behaviour is demonstrated in **Fig. 14**.

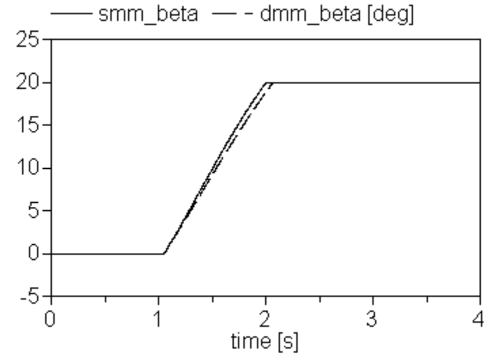

Figure 12: Pitch angle

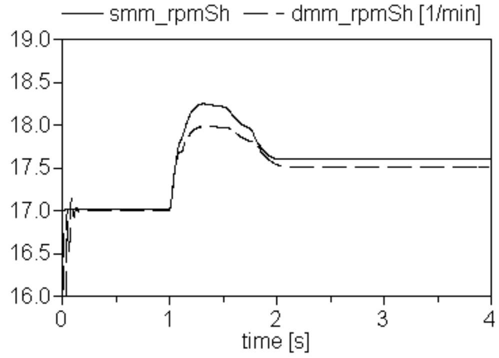

Figure 13: Turbine’s rotor speed

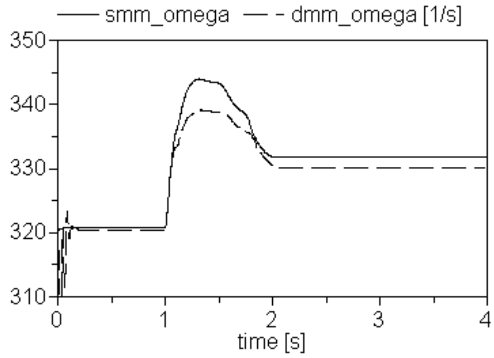

Figure 14: Generator’s angular velocity

This figure contains the curves of the angular velocity of the generator which is connected to the rotor via an ideal gear with a speed ratio of 1:180. **Fig. 13** and **Fig. 14** show after a very close look that the dynamic model needs less more time to react to the sharp change of wind speed. That means on the other hand that the static model does not yield correct results in such cases. Finally, the same effect is shown in **Fig. 15** which depicts the corresponding time history of the electric power produced by the turbine and fed into the grid. Though in this diagram, the difference between both results is not such significant like with the turbine’s rotor speed of with the generator’s angular velocity. However, the dynamic model needs less more time to reach the area of constant electric power.

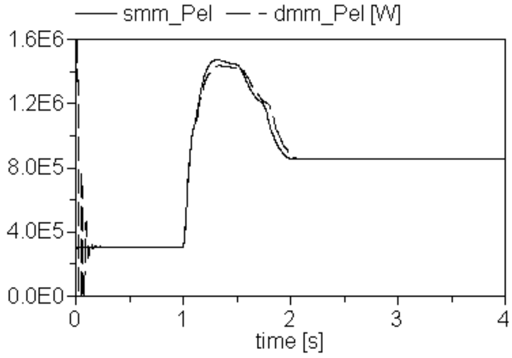

Figure 15: Electric power

4.2 Long-term simulation

In this section, results of a long-term simulation are given. Using such investigations, on the one hand the suitability of different models and on the other hand the rate of effectiveness of model exchange can be determined. As already pointed out in section 3.6, a “stepwise” simulation method is necessarily applied here because of the inability of most Modelica simulators to handle models with exchanging parts correctly. In this context, “step-wise” simulation method means that the three step mentioned in section 3.5 were carried out not driven by the simulator but forced by the user. In other words, different tasks had to be performed where the model exchanges were done by transforming the actual state into the new model and starting a further simulation task. Possibly, new developments (see e.g. [1], [5], [10], [11]) will improve the situation in the near future.

The simulation period shall have a length of 1200 s. The used wind profile along the complete time interval is a realistic profile near to wind data meassured in reality. The shape of the wind profile is depicted in **Fig. 16**. It has three regions with relatively low wind speeds between 5 m/s and 10 m/s (time intervals: 0-30 s, 60-80 s, 100-120 s). In contrast, there are two regions with high or middle speeds of wind of about 20 m/s and 15 m/s, respectively (time intervals: 33-55 s, 80-100 s).

First, the complete task was computed using the "static mechatronic model". On a nowadays standard PC (Intel T2400 dual-core CPU with 1.8 GHz each), the simulation took only 1.8 s. But the results can only be understood as a sequence of steady states (see [3]). In highly dynamic situations, the numeric error of such a calculation method may not be neglected. But if performing the complete task using the "dynamic mechatronic model", it takes much more time to finish. On the same PC, a time effort of 43.5 s was needed.

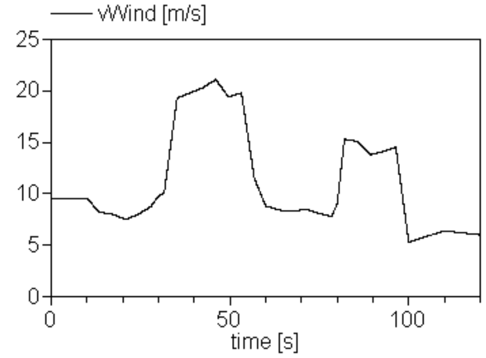

Figure 16: Realistic shape of wind speed

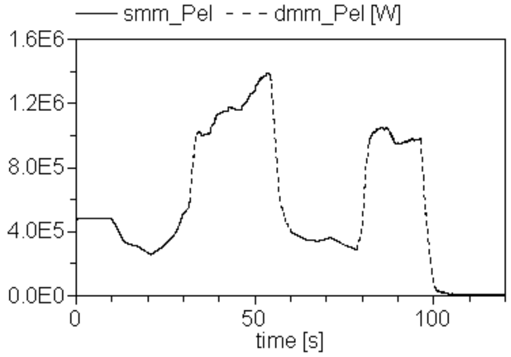

Figure 17: Electric power with switching models

A compromising solution is shown in **Fig. 17**. The five regions mentioned above are investigated using the "static mechatronic model" because the wind shows only low dynamics there. The corresponding time history of the turbine's electric power is indicated by solid lines. However if monitoring high wind dynamics, the "dynamic mechatronic model" is used. The corresponding power curves are indicated by dashed lines. The dynamic model is used during the four short time intervals between the five steadied regions. This way, a model exchange is needed at eight points in time. These are marked in **Fig. 17** by changing line types.

5 Summary

A wind turbine is a complex mechatronic system consisting of mechanical parts, electrical components, and a very complex control strategy. The article deals with a widely used type of wind turbines which is equipped with a so-called pitch control and an asynchronous generator. Four different models for describing the static and/or dynamic behaviour of such a wind turbine are presented. Every model implements a well determined level of detail and uses a particular set of physical quantities to describe the corresponding physical behaviour. All models are equipped with interfaces that allow model exchanges. This property makes it possible to investigate a complex mechatronic system like a wind turbine as exact as necessary depending on the current situation of operation simply by using the actually best suiting model of behaviour.

In the paper, two static models are shown representing two different instances of a simplified behaviour (a simple characteristic curve and a static model using mechanical and electrical components). Furthermore, two dynamic models are presented which describe the dynamic behaviour of a wind turbine in more detail (respecting only the dynamics of the mechanical subsystem or taking into account the dynamics of mechanical and electrical components). In addition, a method of model exchange at certain points in time is proposed. Such structural changes allow the application of that particular model of behaviour which suits the current situation best. Using this method, the simulation of a complex mechatronic system like a wind turbine could very effectively be carried out.

Additionally, some simulation results using the two mechatronic models are given. Both a functionality test performed under extreme conditions as well as an investigation using a realistic wind profile are included.

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